Evaluation of New Methodology for Health Hazard Assessment of Repeated Shock in Military Tactical Ground Vehicles

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ABSTRACT

Anecdotal reports in the mid 1980's attributed adverse health effects to whole-body vibration (WBV) exposure in U.S. Army tactical ground vehicles (TGVs), even though these vehicles passed existing WBV standards (e.g., ISO 2631-1). The U.S. Army Aeromedical Research Laboratory (USAARL) conducted a research program to develop militarily relevant methodology for health hazard assessment (HHA) of TGV rides. The research culminated with the development of a new HHA method for repeated jolt that is tailored for TGVs but is valid for most vehicles where the seated occupant is exposed to repeated (multiple) low-level shocks (jolt). In this paper, we describe the new HHA method and present results of health risk prediction by the new multiple shocks standard (ISO 2631-5) compared to predictions by the current WBV standard (ISO 2631-1). The comparison focuses on two current indices - the weighted root-mean-square (WRMS) and the vibration dose value (VDV) that was designed to emphasize the shocks embedded in WBV - as well as the equivalent daily stress dose (Sed) that was introduced in the new standard. This article also describes a new software tool that implements both parts of ISO 2631 standard, then combines the results with the probability of utilization of a vehicle to assign a risk assessment code (RAC) as required by U.S. Army regulation AR 40-10. Results have shown that the new standard is more sensitive to cross-country rough terrain signatures than WBV methods, but produces similar predictions for ride signatures obtained over paved or secondary roads. The data analysis demonstrates the applicability of the new ISO 2631-5 standard to tactical ground vehicles, especially in the vertical axis.

1.0 BACKGROUND

Anecdotal field reports in the mid 1980's attributed adverse health effects to whole-body vibration (WBV) exposure in military tactical ground vehicles (TGV's), even though these vehicles passed existing WBV standards. According to one such anecdotal report, "hematuria was observed in 50% of the company" after completing a military exercise mission. Although no systematic surveys were conducted among Army TGV riders, there were sufficient anecdotal reports from the field to raise concerns over the validity of existing WBV standards.

The U.S. Army has established a health hazard assessment (HHA) program with the overall objectives to increase war-fighting capabilities by conserving or enhancing fighting strength and to help ensure successful Army modernization in a safe, efficient, and cost-effective manner. Those objectives include preventing combat casualties and performance decrements caused by routine operation of combat systems and reducing

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health-related readiness deficiencies [Department of the Army 1991]. Since repeated shock was identified as one of the potential hazards likely to be encountered during TGV operations, medical assessors and safety officers applied existing standards that were developed primarily for civilian applications and not necessarily for military scenarios. Clearly, concerns over the validity of HHA of repeated shock, which were based on existing WBV standards, appeared well justified.

As a result of these concerns, the U.S. Army Aeromedical Research Laboratory (USAARL) was requested to investigate the applicability of existing WBV standards to TGVs operating in military scenarios and to develop a new militarily relevant standard to use in evaluating the repeated jolt environment that is commonly encountered in military tactical vehicles. The USAARL then embarked on a multi-year multi-phase research program that culminated in the development of a new HHA method, the proposal and adoption of a new ISO standard, and the development of a graphical user interface (GUI) tool that implements the complete methodology. Much of the information presented here are drawn from a series of contractor reports written for USAARL by investigators from British Columbia Research Institute (BCRI) staff, the prime contractor who performed most of the research effort.

2.0 RESEARCH APPROACH

A five-phase research program was designed to develop a standard method for HHA of mechanical shock and repeated impact in Army TGVs. The experimental work was conducted at the USAARL multi-axis ride simulator (MARS) facilities in Fort Rucker, Alabama, and the data analysis and model development were completed at the BCRI facilities in Vancouver, British Columbia, Canada.

A detailed account of the BCRI/USAARL research effort is given in a series of Contractor Reports by the BCRI team and summarized in a final report on Phases 1-5 [Cameron 1998]. Since these reports may not be accessible to international members of the Research Technical Organization Applied Vehicle Technology (AVT) panel, the findings of five phases of the research program are briefly summarized below.

2.1 Phase 1 – Literature Review

Evidence exists that long-term exposure to vibration accelerates onset of lumbar spine disorders, and possibly adversely affects the gastro-intestinal and cardiovascular systems. There were a few human studies that investigated physiological and biochemical responses to repeated impact, but none investigated recovery. The review suggested potential approaches to development of an HHA method based on physiological, biochemical and biodynamic responses. The literature did not support using current vibration exposure standards for motion environments with high magnitude mechanical shocks and repeated impacts. Most existing biodynamic models were not designed to predict chronic health problems. However, certain biodynamic models, which range from single degree of freedom to three-dimensional and discrete parameter models, may have direct relevance to the development of a health hazard assessment index [Village 1995a].

2.2 Phase 2 – Characterization of TGVs signatures

Over 580 tri-axial WBV signatures from seven military vehicles, tested at Aberdeen Proving Ground, Maryland, were processed and characterized. The signatures were collected at various seat locations from the following TGVs: M1A1 tank, M1A1 HTT, M1026 HMMWV, B109A3 self-propelled howitzer, M923A2 5-ton cargo truck, XM1076, and an M2HS Bradley fighting vehicle. An automated procedure was developed to recognize impulses, including shocks and other transient or non-stationary motions within a background of

Gaussian random, or near-sinusoidal, vibration. Using this procedure, a motion signature was created mathematically to realistically simulate the motion environment of TGVs by synthesizing two signals: one to characterize the shocks, and the other to characterize the near-continuous background vibration [Roddan 1995]. This allowed the use of a handful of generic signatures to represent the majority of those that may be experienced in TGVs operating in military scenarios. These generic signatures were then used to drive the motion platform of MARS at Fort Rucker, Alabama, during subsequent experiments in Phases 3 and 4.

2.3 Phase 3 – Pilot Study

Ten subjects participated in pilot tests using the MARS facilities in Fort Rucker to determine the most sensitive human response measures to mechanical shock and repeated impact for use in the development of the experimental phase and in a dose-effect model. Spinal acceleration, internal pressure, chest and abdominal displacement measurements and electromyographic (EMG) activities showed similar frequency response patterns to the shocks applied at the seat and to the seat accelerations [Village 1995b]. That suggested seat acceleration might be used as the input parameter to the HHA method. The pilot study recommended that such methods should account for non linearity of response; differing responses to x, y, and z-axis inputs; and differing responses to positive and negative directions of shocks in the x- and z-axes.

2.4 Phase 4 – Experimental Study

Fifty-four healthy, 19-40 year old subjects participated in a series of short duration (ST1) and long duration (LT1-LT5) motion exposures at the MARS facilities, which were driven by standardized TGV signatures described earlier. Experiment ST1 assessed relative severity of shock characteristics. Experiments LT1-LT5 assessed fatigue and recovery to repeated shocks (up to 7 hours per day, or 4 hours per day for 5 days). Biomechanical responses at the spine were dependent on shock axis, amplitude and direction. The largest response resulted from vertical z-axis inputs. Subjective severity ratings to individual shocks were highly correlated with spinal acceleration. Subjects tolerated a vibration dose value normalized to 8-hour day, or VDV(8), limit of 15, recommended both by the existing British Standard BS 6841 [BSI 1987] and adopted in the current ISO standard 2631-1 [ISO 1997]. Some subjects were able to tolerate a VDV of 66 over a 7-hour period, or a daily VDV(8) of 60 over a 5-day period, without apparent health effects [Cameron 1996].

2.5 Phase 5 – Recommendations for a HHA Method

Based on the results of the previous four phases, this phase recommended that the HHA method incorporate: biodynamic models to predict spinal acceleration, regression models to predict peak compressive stress at the L4/L5 lumbar joint, given peak acceleration, a fatigue-based model to quantify the cumulative effects of repeated shocks, and an injury probability model that relates the cumulative dose to the probability of spinal injury within a normally distributed population [Morrison 1998].

3.0 METHODOLOGY FOR HHA OF REPEATED SHOCKS

Based on its recommendations at the conclusion of Phase 5, BCRI developed a new HHA methodology that incorporated four distinct models, as described below. Much of the information included here is extracted and/or paraphrased from the Phase 5 Contractor Report [Morrison 1998].

3.1 Biodynamic Lumbar Spine Response Models

3.1.1 Horizontal (x and y) Shock Response Model

The response to horizontal seat accelerations (x and y axes) was approximately linear suggesting that an existing linear model may be used. Such a model is the dynamic response index (DRI) model, commonly used in evaluating spinal injury risk in ejection seat scenarios [ASCC 1989]. However, the DRI model overestimated the lumbar kinematics in the horizontal plane. Hence, a single degree of freedom model (SDOF), shown in Figure 1(a), with a natural frequency f_n = 2.125 Hz and damping coefficient c = 0.22, was used to predict the spinal response to horizontal seat accelerations with reasonably good agreement with measured response.

3.1.2 Vertical (z) Shock Response Model

A different strategy was used to account for the non-linearity of response in the vertical axis. A recurrent neural network (RNN) was developed and, using accelerations measured in Phase 4, was trained to represent lumbar response to vertical seat accelerations. The RNN model is shown in Figure 1(b).

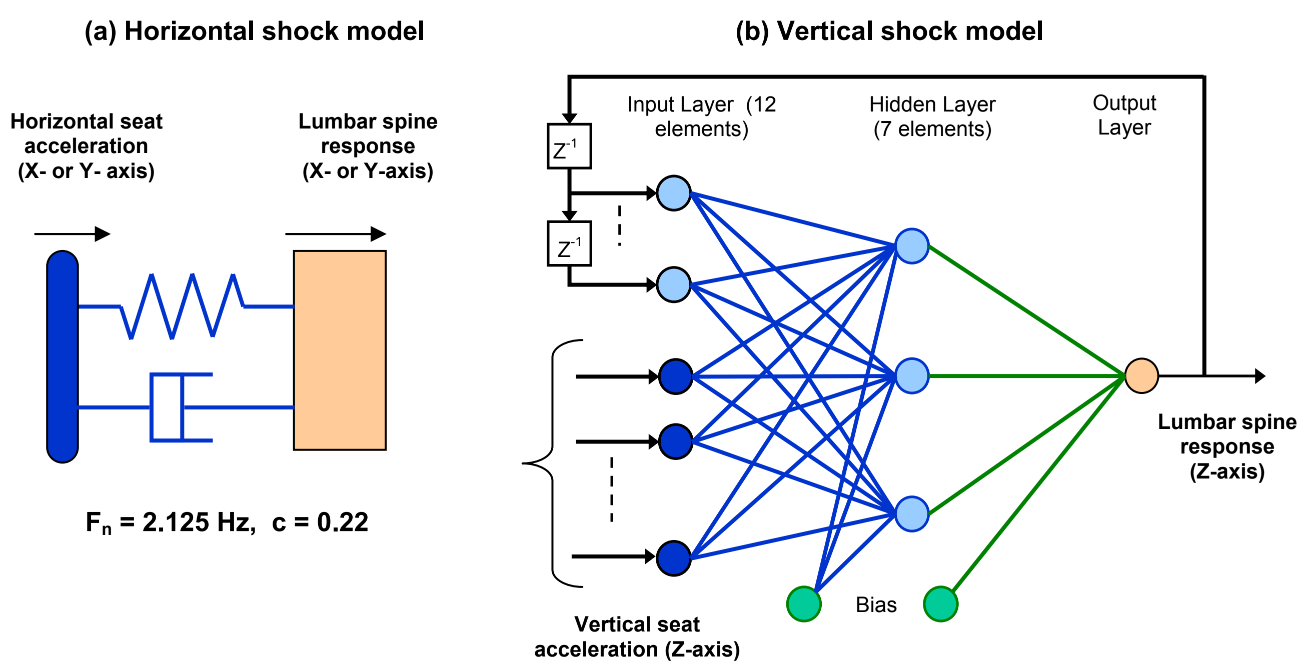

Figure 1: Biodynamic models for predicting spinal motion at the L4/L5 level in response to seat acceleration. [Morrison 1998]

3.2 Biomechanical Spinal Response Model

BCRI developed a biomechanical model to calculate the compressive force at the L4/L5 lumbar joint. The model was applied to the experimental data obtained from Phase 4 to provide information on the compressive forces generated at the lumbar L4/L5 joint in response to mechanical shocks in the x, y and z axes. This information then was used to relate the peak spinal accelerations predicted by the biodynamic response models to the compressive force acting on the L4/L5 lumbar vertebral joint. Details of this modelling strategy and the final biomechanical model may be found in the Phase 5 final contractor report [Morrison 1998].

3.3 Cumulative Dose-Response Model

Given published data on vertebral compressive strength, the relationship between acceleration and forces at the L4/L5 disk was used to estimate the number of low-level shocks that would result in fatigue failure of the L4/L5 joint. By estimating spinal motion from seat acceleration (using dynamic models) and subsequently converting the estimated motion to force (using the biomechanical model), it was possible to develop a dose-response model to predict fatigue failure (i.e., injury) of the L4/L5 caused by repeated shocks.

3.4 The New ISO 2361-5:2004 Standard

The biomedically-based approach of BCRI for modelling and assessment of repeated shock formed the basis for proposing an amendment to the existing ISO 2631-1 for evaluation of human response to whole-body vibration and shock [ISO 1997]. Since a similar effort was underway in the U.S. to develop a standalone ANSI standard that incorporates the BCRI method, the proposed ISO amendment and the draft ANSI standalone standard were combined and a new draft international standard (DIS) emerged which addresses specifically the repeated (or multiple) shocks. The new standard, which was adopted in 2003 and published in 2004, contains most of the elements of the modelling strategies that were developed by BCRI.

The new ISO 2631-5 standard [ISO 2004] relies on the dynamic models described above to generate acceleration response at the lumbar spine. Now that the spinal accelerations have been generated, an acceleration dose is calculated for each axis, $\boldsymbol{D_x}$, $\boldsymbol{D_y}$, $\boldsymbol{D_z}$, by summing peak acceleration responses that exceed certain thresholds. The dose is prorated based on duration of the available record and the expected length of the workday, to obtain $\boldsymbol{D_{xd}}$, $\boldsymbol{D_{yd}}$, $\boldsymbol{D_{zd}}$ and calculate the total daily exposure. Refer to the ISO document for details of the calculations.

The ISO standard provides, albeit in an informative annex, guidance for assessment of health affects on multiple shocks. Given the calculated total daily acceleration dose in each of the biocentric axes, they are combined to obtain an equivalent static stress compressive stress, $\boldsymbol{S_{ed}}$, as follows:

$$S_{ed} = [\ (m_x\ D_{xd})^{6} +\ (m_x\ D_{xd})^{6} + (m_x\ D_{xd})^{6}\ ]^{1/6}$$

where $\boldsymbol{m_x}$, $\boldsymbol{m_y}$, $\boldsymbol{m_z}$ are constants for the three directions. A daily equivalent static compression dose, $\boldsymbol{S_{ed}}$, is then computed, and used to compute a risk factor, $\boldsymbol{R}$, for use in the assessment of the adverse health effects. For a typical career, the standard suggests that, $\boldsymbol{R} < 0.8$ indicates a low probability of an adverse health effect and $\boldsymbol{R} > 1.2$ indicates a high probability on an adverse health effect. This is equivalent to stating that $\boldsymbol{S_{ed}} = 0.5$ and $\boldsymbol{S_{ed}} = 0.8$ are the lower and upper boundary of a caution zone for a normal person during a typical working day. Again, the reader is referred to the ISO 2631-5 document for details of the calculations.

4.0 IMPLEMENTATION AND VERIFICATION

4.1 The WBV-Jolt GUI Tool

Although the new ISO 2631-5 provides a Matlab® code that implements the new method, a more user-friendly GUI tool was needed to facilitate the application of the HHA methodology to signatures collected at various seat locations during testing of new U.S. Army TGVs.

4.1.1 Requirements for the GUI Tool

Some of the features and requirements that were incorporated in the WBV-Jolt GUI tool included:

- A stand-alone software program that runs any computer operating in Microsoft Windows 2000 or above; is independent of any computation engine, such as Matlab®.
- The software tool should implement both ISO 2631-1 (WBV) and 2631-5 (Jolt), because both use the same ride pad accelerations as a basis for evaluation.
- Is user-friendly, easy to use, intuitive and helpful, allowing automated "batch" processing of signals as well as interactive analysis.
- Displays time history plots of input signals, weighted acceleration and spinal response.
- Allows the reading of standardized-format text files, with no size restrictions, and is capable of processing seat accelerations sampled at any sampling rate.
- Computes key parameters for WBV (e.g., ***rms***, ***VDV***) for multiple shock (e.g., S_{ed}, ***R***) and appends new results to previous ones in an Excel file.
- Automatically assigns "severity categories" based on WBV and jolt key parameters, and guides the user in assigning "probability levels" as defined in the U.S. Army HHA regulation (AR 40-10).
- Produces risk assessment codes (RACs) as required by the same HHA regulation.

4.1.2 Implementation of ISO 2631 – Parts 1 and 2

The two ISO 2631 standards (Part 1 and Part 5) were implemented in a GUI tool, Jolt 4.5, which incorporates all the desired features listed in the previous section [Alem 2004]. USAARL and its in-house contractor, UES Inc., which holds the copyright to the software implementation, developed the Jolt software jointly. The software has been transitioned to the U.S. Army HHA program, where it has been successfully used to evaluate new Army systems.

Figure 2 shows is a block diagram of whole-body vibration and repeated shock HHA process, including the implementation of the ISO 2631-1 and 2631-5. A brief walk-through will aid in describing the various steps in the process.

The first step is to select the folder and text files containing the seat tri-axial acceleration signatures. The file format has been standardized to allow ease of data exchange between test facilities and assessors. The software allows the user to verify the selected signatures by displaying the file header information. Once a file is selected, the signals are processed to remove any DC bias, apply an anti-alias filter, and re-sampled to at the rate of 160 samples per second. This sampling rate is a requirement by ISO 2631-5 since the RNN model coefficients are specifically defined for 160 Hz input.

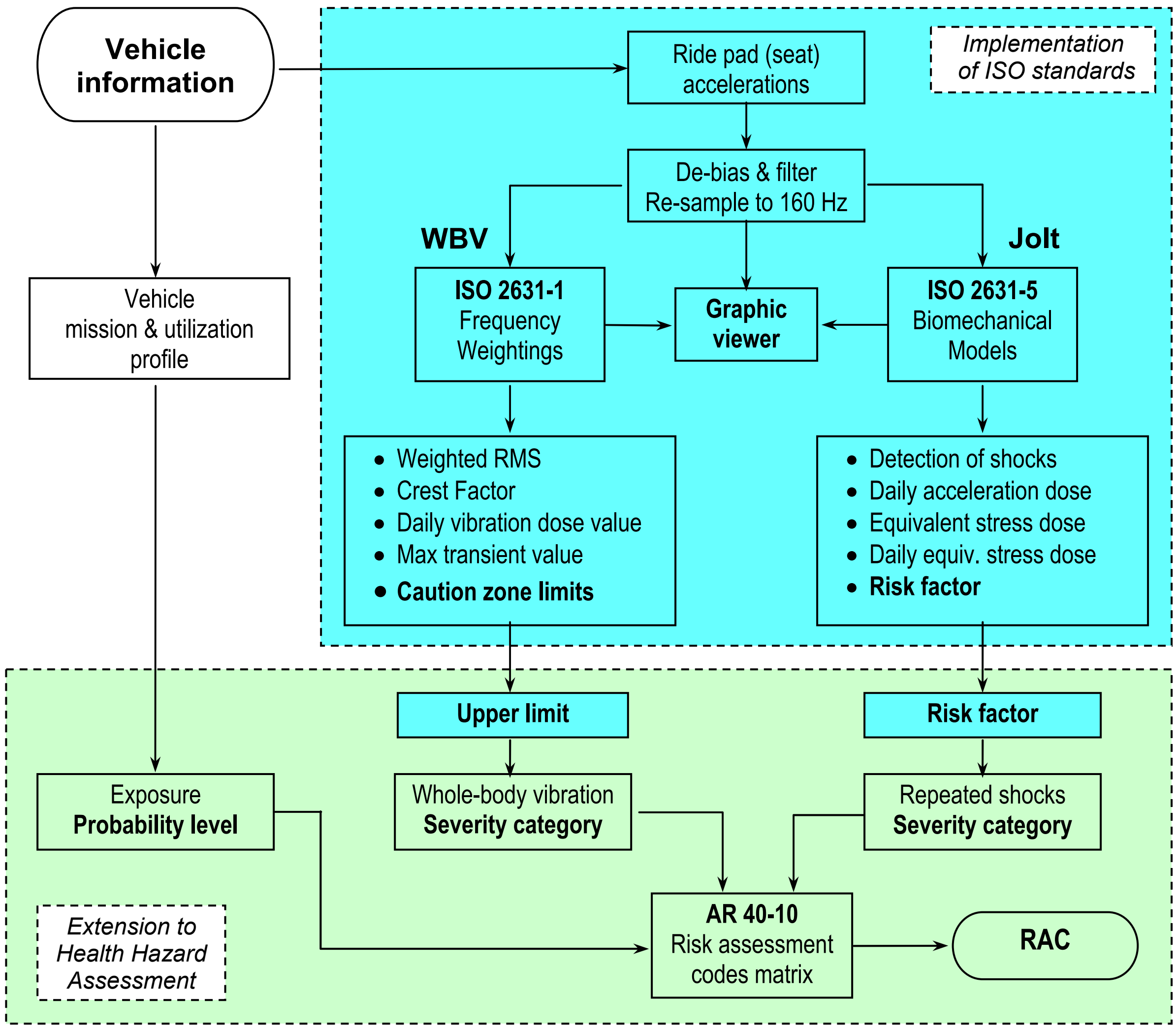

Figure 2: Block diagram of the ISO standards implementation and the AR 40-10 HHA extension, resulting in a risk assessment code (RAC)

On the other hand, ISO 2631-1 does not require any specific sampling rate, only that the frequency content of the signals in the range of 1-80 Hz be preserved, a requirement that is satisfied with re-sampling to 160 Hz. At this point, assumptions for exposure calculations are entered, to include duration of daily exposure, exposure days per year, age at which the subject starts a career, and the expected years of exposure. These assumptions affect the dose calculation and the outcome of the assessment.

Next, the software applies the two standards as follows. For assessment of WBV, the acceleration signal is weighted by applying the frequency factors given in ISO 2631-1. For assessment of multiple shocks, the acceleration signal is applied to the dynamic model specific to the signal direction. A typical signal (seat acceleration) and its two output signals (lumbar response to shocks and weighted WBV signal) are shown in Figure 3.

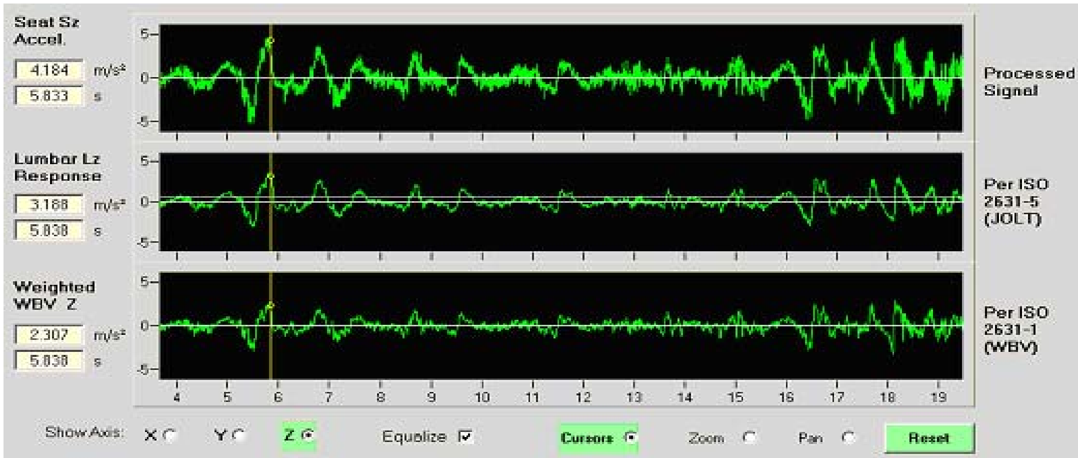

Figure 3: Display of three signals. Seat acceleration in the Z-direction (top), lumbar spine response in the Z-direction (middle), and acceleration signal after applying weight per ISO 231-1.

Given the spinal response, either as a result of applying weight or after passing through the dynamic model, the software extracts key parameters and saves them for subsequent assessment steps. By applying the recommended procedures of ISO 2631-1, parameters that are extracted include: the weighted root-mean squares (***Wrms***), peak acceleration and crest factor, vibration dose value (***VDV***), and maximum transient vibration value (***MTVV***). The ***Wrms*** then is used to determine the lower and upper boundaries of the caution zone, defined in ISO 2631-1, Annex B. An interactive window displays the caution zone and allows the user to determine the caution zone for any Wrms acceleration (Figure 4). Later in the process, the ***Wrms*** will be used to assign a "severity category" to the signature.

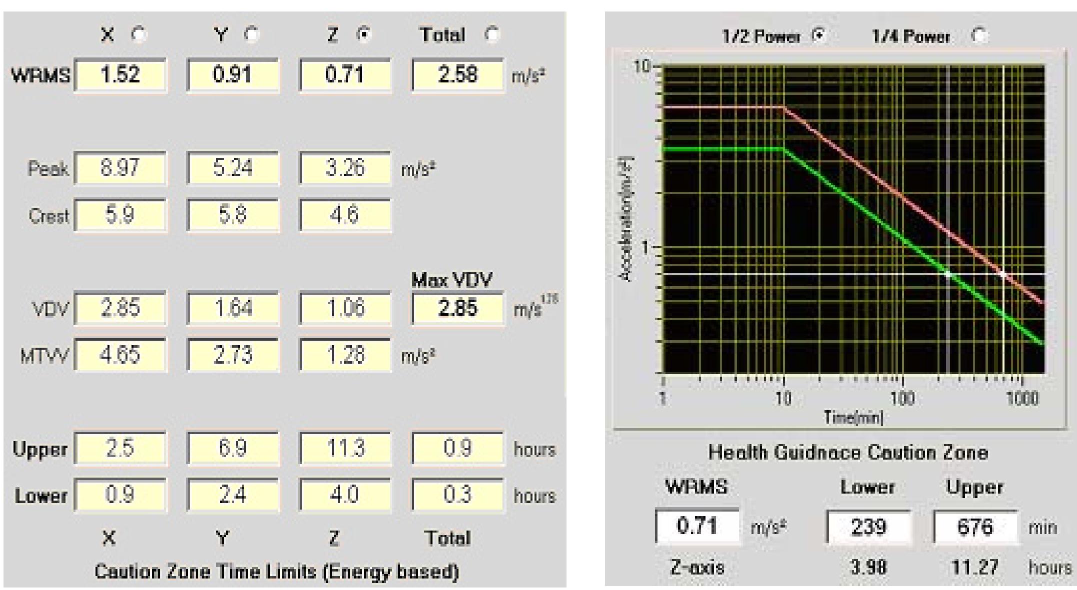

Figure 4: Key WBV evaluation parameters defined in ISO 2631-1 standard. (Note that the daily VDV(8) was used in the paper and not the Max VDV shown in this figure.)

For repeated shocks assessment, the spinal response signal that was produced by either the SDOF model or the RNN model is used to identify and count the number of peaks exceeding a certain threshold and calculate the acceleration dose for the measurement duration, then prorate it for the expected daily exposure duration.

The normative portion of the new ISO 2631-5 standard ends with the calculation of the average daily acceleration dose, described above. The standard provides guidance for the assessment of health effects of multiple shocks in Annex A, an informative part of the standard. In order to provide a useful tool for the HHA community, the ISO 2631-5 guidance was implemented. The outcome is a risk factor ***R*** that is a function of several factors, including exposure days per year, age at start of exposure, years of exposure, as well as the estimated average daily stress derived from the average acceleration exposure dose. The ***R***-factor is used to determine a severity category (per AR 40-10) as described in a later section.

4.1.3 Extensions to Meet HHA Requirements

The U.S. Army HHA program identifies a dozen health hazards, from shock and vibration to toxic gases, all of which must be evaluated before fielding any new system [U.S. Army 1992]. The evaluation process requires the medical assessor to classify the hazard according to its severity and probability of exposure. Given the probability and the severity, a risk assessment code (RAC) is assigned to the system that produced the hazard.

The severities of the WBV and jolt hazard are derived from the caution zone upper limit for WBV and from the risk factor ***R*** for repeated shock. Since the guidance of ISO does not fall along the definitions used in AR 40-10, the upper limit of the caution zone and the risk factor were used for the four severity categories defined in the regulation. Table 1 lists the conventions used by the USAARL.

Table 1: Convention used by USAARL to assign severity categories of WBV and repeated shock

Whole-Body Vibration per ISO 2631-1		Repeated Shocks per ISO 2531-5		Health Hazard Assessment per AR 40-10	
WBV Daily Exposure Limit	Daily Vibration Dose Value, VDV(8)	Equivalent daily stress, Sed	Risk factor, R	Severity Category	Descriptive Label
< 10 minutes	> 21.25	> 0.95	> 1.4	I	Catastrophic
10 – 30 minutes	12.75 – 21.25	0.65 – 0.95	1.4 – 1.0	II	Critical
30 min – 3 hours	4.25 – 12.75	0.35 – 0.65	1.0 – 0.6	III	Marginal
> 3 hours	< 4.25	< 0.35	< 0.6	IV	Negligible

Based on these definitions, the severity category is assigned automatically. The medical assessor then may accept the automatic recommendations or may reassign the severity, as shown in Figure 7.

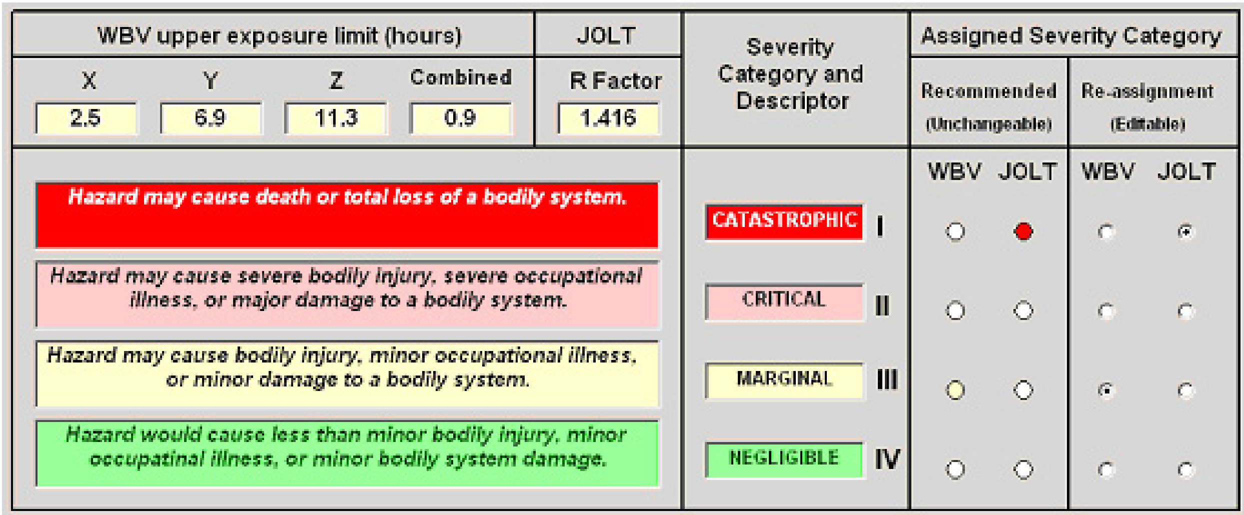

Figure 7: Assigning severity categories for WBV hazard (based on caution zone upper limit) and for repeated shock hazard (based on the R-factor).

In order to continue the HHA process, it is necessary to assign a hazard probability level for the WBV and repeated shock exposure. HHA experts agree that these levels must be based on the mission profile of the item (or its fleet) and the frequency of its usage. At this time, there are no set guidelines for this process, so that one must judiciously evaluate the mission and assign a probability of exposure, perhaps in consultation with the item user. The Jolt software displays the language that is used in the U.S. Army regulation 40-10 and requires that the user manually enter the probability level for WBV and multiple shocks. Figure 8 shows this interaction.

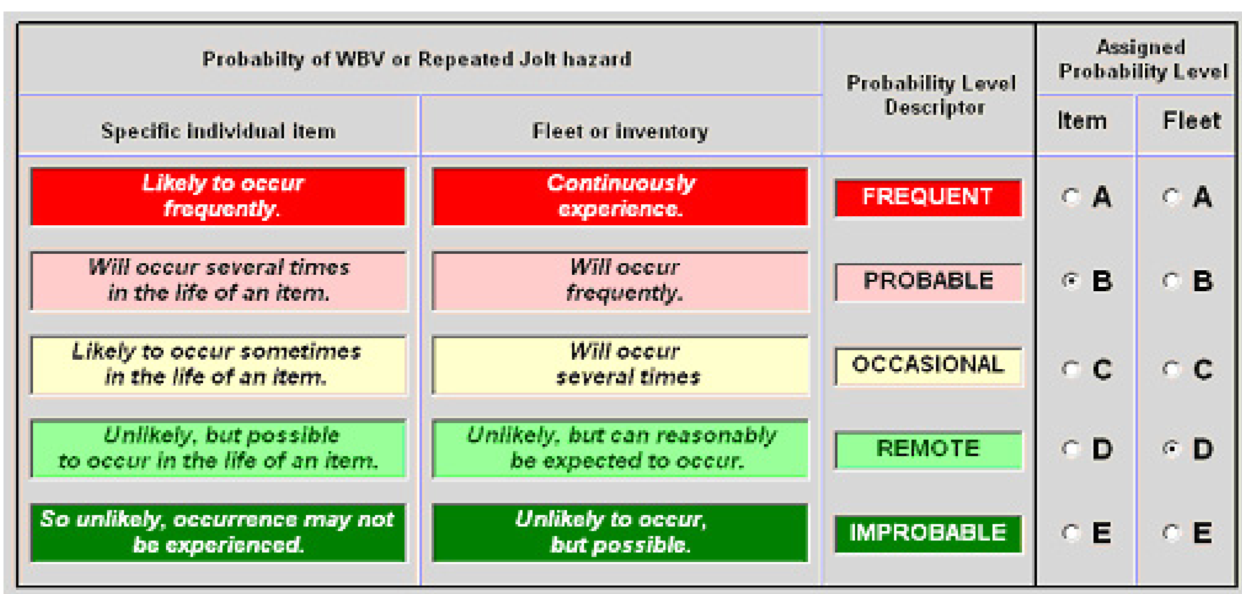

Figure 8: Assigning probability levels to the WBV and repeated shocks (jolt).

Finally, given the severity category and probability level of both WBV and repeated shock hazards, the risk assessment codes are then assigned for each hazard and for the item and fleet, as shown in Figure 9. In this example, it is clear that the assessment of WBV underestimated the severity of the repeated shocks that were embedded in the WBV signature.

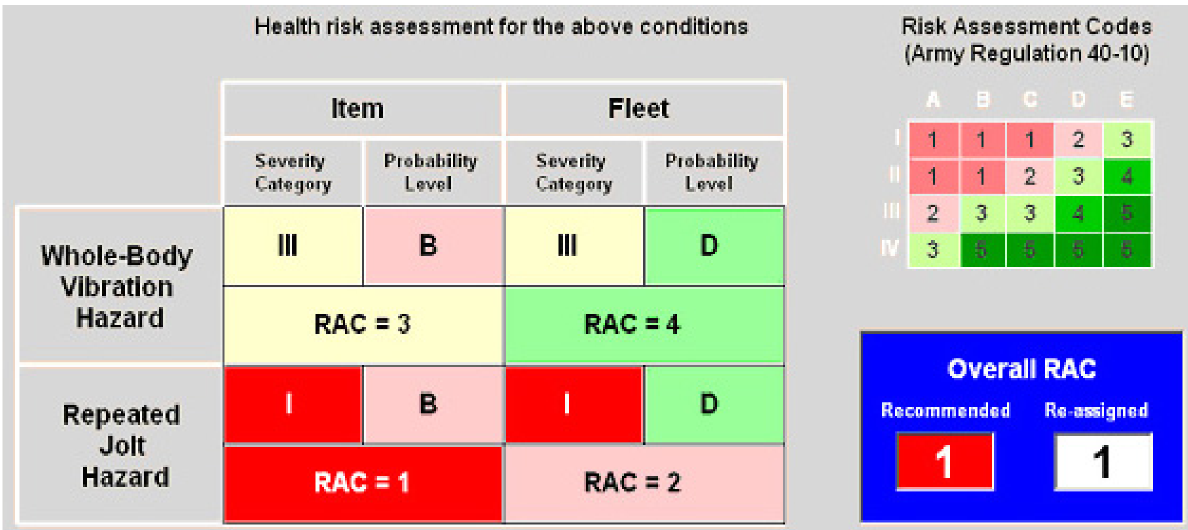

Figure 9: Assigning risk assessment codes (RACs).

4.2 Comparison of Parts 1 and 5 of ISO 2631

A study was undertaken at the USAARL to compare the outcome when three assessment methods are applied as prescribed in the existing ISO 2631-1 and the new ISO 2631-5 [ISO 1997, ISO 2004]. All three methods use the same ride pad signature as input to the data analysis but often produce different assessments, as will be demonstrated in this section.

4.2.1 Data Sources

The source of data was ride pad accelerations obtained from a dozen TGV's that were or are being developed by the U.S. Army. These included tracked and wheeled vehicles and water and land vehicles. All signatures were from seat cushion pads, that is, none of the data were from seat backs or from foot panels. Run conditions varied with terrain type, vehicle speed, and seat location. All vehicles were driven and occupied by healthy adult males who were seated upright.

4.2.2 Data Processing

The data were stored in a standardized format that was developed by BCRI and USAARL to facilitate data exchange. WBV-Jolt software (version 4.5) was run in batch mode on all available signals and summaries of results were saved in Microsoft Excel files. The summaries included, for each tri-axial ride pad signature, the vehicle and seating information, which is replaced in this paper by a code to avoid discussion of specific military vehicles. This should not detract from the goal in this paper, which is to compare repeated shock evaluation methods and not to evaluate the vehicles themselves. The terrain type and speed was also listed in the summaries to help explain any unusual outcome.

4.2.3 Evaluation Methods

Three evaluation methods were compared:

- **The RMS method**: the total root-mean square of the weighted acceleration a_w, (also referred to here as ***Wrms***) which is described in ISO 2631-1:1997 as the basic evaluation method.
- **The VDV method**: the daily vibration dose value, ***VDV(8),*** also described in ISO 2631-1:1997 as an additional method to use when the basic method is not sufficient to account for shocks that are embedded in the WBV signal.
- **The Jolt method**: the equivalent static compression dose, S_{ed}, which is derived from acceleration shocks dose and normalized to average daily exposure time, as described in the new ISO 2631-5:2004 standard (see section 3.4 above).

Normally, application of the **Jolt** method requires the calculation of the risk factor, ***R*** (discussed in section 3.4 of this paper), which takes into account the number of years and days per year of exposure and factors in the vertebral bone ultimate strength, which in turn depends on the age of the vehicle occupant at the time of exposure. Since the other two methods, ***Wrms*** and ***VDV(8)***, do not incorporate lifetime exposure, the basis of comparisons in this paper was restricted to the S_{ed} parameter.

4.2.4 Results and Discussion

A total of 1044 tri-axial signatures were processed and analyzed. However, a much smaller sample of signatures is included here for discussion.

It was reasonable to assume that, if the severity categories (SC) derived from the ***Wrms*** and from the S_{ed} for a given signature were both *negligible* (see definitions of Table 1), then the signature was not likely to contain significant levels of multiple shocks. The majority (over 90 percent) of signals available for analysis fell into this category and were excluded from further analysis and discussion.

There were about 70 runs whose ***Wrms***-based SC was different from the S_{ed}-based SC, indicating the presence of significant levels of shock. Nearly half of those runs had comparable SC's to the other half and were, therefore, not selected for further discussion. The remaining 40 runs, which were deemed appropriate and relevant for this paper, are listed in Table 2. Visual inspection of these signals confirmed the presence of multiple shocks, as indicated by severity categories equal to 1 or 2. The terrain type and speed are included to help explain unusual results. Although the tactical vehicle type and seat do affect the vibration and shock signature, their identification is not necessary for the purpose of this discussion. Again, the goal here is to compare different shock and vibration assessment methodologies and not to evaluate vehicles or seats.

A plot of the ***VDV(8)*** against the ***Wrms*** (Figure 10, left) shows some correlation between the two parameters. The ISO 2631-1 allows the use of an estimated vibration dose value (***eVDV***) and gives the values corresponding to the lower and upper boundaries of the caution zone as 8.5 (action level) and 17, (limit value) respectively (ISO 1997, clause B.3.1). The selected data set shows that the VDV(8) did not exceed the action level of 8.5 $m/s^{1.75}$, and only two exceeded the limit value of 17 $m/s^{1.75}$, as is clear in the left plot of Figure 10.

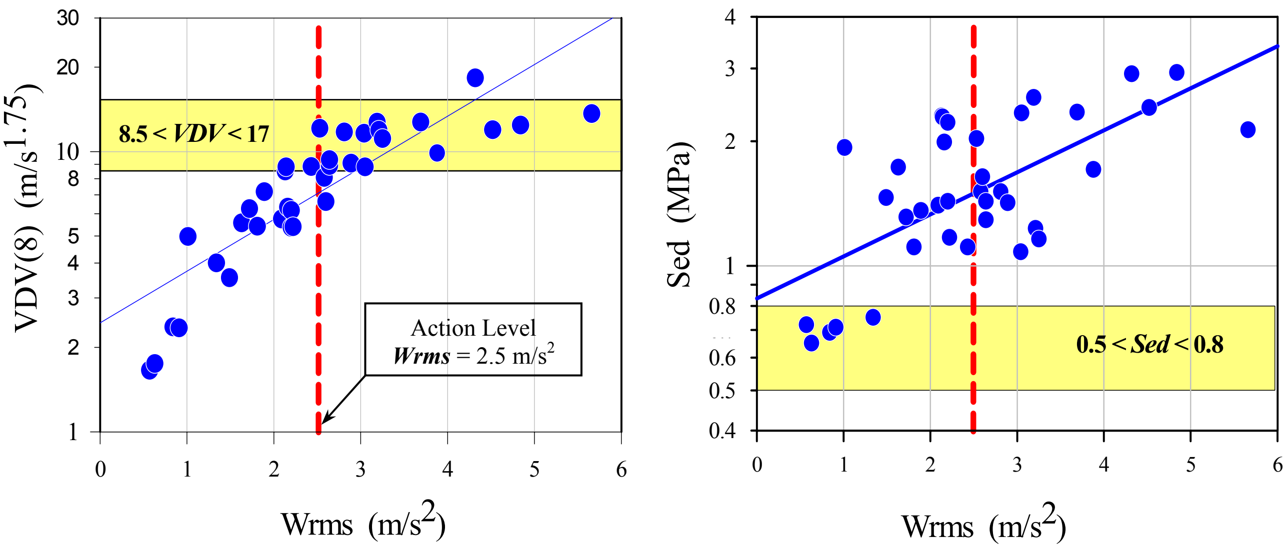

Figure 10: Plots of daily VDV(8) and Sed vs. Wrms, along with the corresponding caution zones

On the other hand, a plot of the S_{ed} against the ***Wrms*** placed all but a few of the cases above the caution zone defined in ISO 2631-5 (Figure 10, right), indicating that they may present a health risk. This was expected since the selection process of the sample of cases to discuss here virtually eliminated all "benign" signatures as determined from the ***Wrms*** and the S_{ed}, and included most cases where the new method detected a high content of repeated shocks. In other words, there was no point in selecting signatures for which the basic RMS method would be sufficient, and the use of the **Jolt** method is not indicated.

The ISO 2631-1 standard recommends the use of additional evaluation methods (beyond the basic RMS method) if the following two screening ratios are exceeded (ISO 1997, clause 6.3.3):

$$Q7 = MTVV / Wrms = 1.5 \quad \text{and} \quad Q8 = VDV / (Wrms * T^{1/4}) = 1.75$$

This is similar to the crest factor that was used unsuccessfully in the past to classify signals as ones containing shocks. The computed valued of Q7 and Q8 are included in Table 2 and plotted in Figure 11.

It is important to note that nearly all the selected tests produced Q7 ratios that were higher than the recommended threshold of 1.5, while nearly all Q8 ratios were below the threshold of 1.75 recommended as a flag for further analysis. The fact that Q8, which incorporates the VDV, does not trigger further analysis is consistent with the conclusion stated earlier in this section. The Q7 ratio for <u>most</u> of the cases was able to indicate that additional analysis is warranted. In fact, <u>all</u> the Q7 ratios would have exceeded a threshold value of Q7 = 1.25.

It is therefore proposed here that trigger threshold for the Q7 ratio be reduced to 1.25, and that Q8 not be used as a trigger for further evaluation of WBV signatures beyond the basic RMS method.

Table 2. Selected WBV and Jolt data and corresponding terrain conditions for selected TGV's.

Terrain Type	Vehicle, Seat Codes and Speed (mph)		Ratios for comparison		Method 1 (WBV method)		Method 2 (VDV method)		Method 3 (Jolt method)	
			Q7	Q8	**Wrms** (m/s^2)	S.C.	**VDV (8)** ($m/s^{1.75}$)	S.C.	**Sed** (MPa)	S.C.
Belgian Block	V4-A	25	1.72	0.66	2.43	3	8.83	3	1.11	1
	V4-E	35	1.46	0.70	2.81	3	11.74	3	1.51	1
	V7-A	20	1.53	0.62	2.89	3	9.08	3	1.42	1
	V4-E	45	1.45	0.70	4.32	2	18.28	2	2.91	1
	V7-A	25	1.57	0.64	4.78	2	15.96	2	5.20	1
Washboard	V2-G	5	1.38	0.57	2.22	3	5.38	3	1.17	1
	V3-A	10	2.68	0.61	2.64	3	8.91	3	1.29	1
	V3-D	10	4.40	0.64	2.64	3	9.34	3	1.43	1
	V9-F	25	5.17	0.62	3.25	3	11.11	3	1.16	1
	V3-A	5	1.61	0.61	3.69	2	12.73	3	2.35	1
Cross Country	V5-A	15	3.09	0.84	1.34	4	4.00	4	0.75	2
	V5-A	15	3.71	1.32	1.63	3	5.55	3	1.73	1
	V3-D	10	4.70	0.89	1.81	3	5.41	3	1.11	1
	V9-A	10	3.58	0.80	2.09	3	5.73	3	1.40	1
	V5-A	10	4.18	1.21	2.13	3	8.52	3	2.30	1
	V9-B	20	2.60	1.02	2.14	3	8.81	3	2.29	1
	V2-G	10	3.04	0.87	2.16	3	6.31	3	1.99	1
	V5-A	25	4.86	0.82	2.20	3	5.35	3	1.43	1
	V9-F	20	3.40	0.87	2.53	3	12.10	3	2.03	1
	V2-A	10	3.09	0.86	2.58	3	8.07	3	1.51	1
	V5-A	5	2.45	0.78	2.60	3	6.62	3	1.64	1
	V9-A	15	3.14	0.71	3.05	3	8.81	3	2.34	1
	V3-C	10	2.84	0.76	3.19	3	12.72	2	2.55	1
	V5-A	20	2.96	1.56	3.88	2	9.87	3	1.71	1
	V5-A	35	3.40	1.48	4.52	2	11.94	3	2.41	1
	V5-A	30	2.64	1.00	5.66	2	13.64	2	2.13	1
Paved	V3-A	22	20.7	0.70	0.57	4	1.66	4	0.72	2
	V3-A	20	19.4	0.70	0.63	4	1.75	4	0.65	2
	V3-C	20	19.6	0.68	1.72	3	6.25	3	1.31	1
	V3-C	22	26.9	0.78	1.89	3	7.19	3	1.36	1
	V3-C	16	7.87	0.70	3.04	3	11.59	3	1.08	1
	V3-C	12	10.5	0.67	3.21	3	11.91	3	1.23	1
Secondary	W3-C	18	4.13	0.82	0.91	4	2.35	4	0.71	2
	W3-C	15	3.49	0.71	1.49	3	3.54	4	1.46	1
	W2-B	7	3.06	0.75	2.20	3	6.16	3	2.22	1
	W3-C	7	4.20	1.10	3.55	2	10.05	3	3.94	1
	W2-D	25	2.83	0.62	4.84	2	12.42	3	2.93	1
Water	W1-D	---	3.20	0.51	0.84	4	2.36	4	0.69	2
	W1-B	---	5.91	0.91	1.01	4	4.97	3	1.93	1
	W1-A	---	11.2	1.11	3.01	3	13.25	2	6.91	1

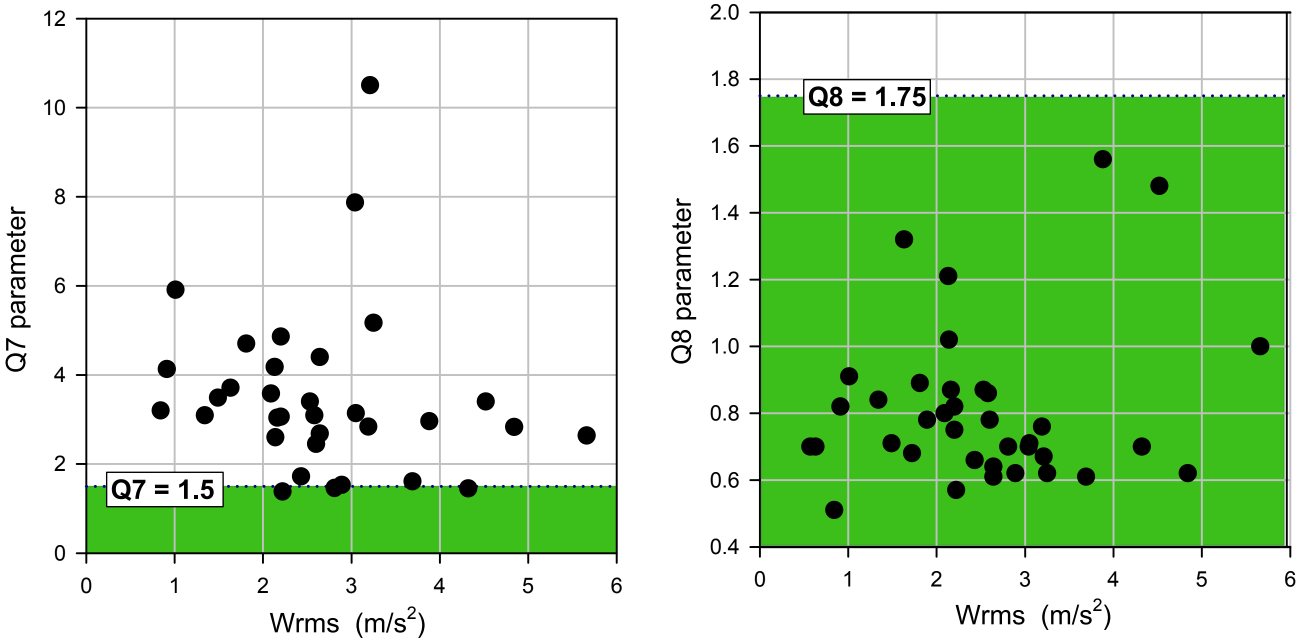

Figure 11: Scatter plots of Q7 and Q8 screening ratios. The green zones delineate values that would application of further evaluation methods, according to ISO 2531-1

One explanation for the failure of the ***VDV(8)*** to detect signatures with high shock contents is that the threshold currently recommended in the ISO 2631-1 may be too high. Figure 12 shows that there is some correlation (R^2 = 0.45) between the ***VDV(8)*** and the $\boldsymbol{S_{ed}}$:

$$VDV(8) = 4.1 \times S_{ed} + 1.5$$

In order for the ***VDV*** to be used for detecting high shock content in a vibration signature, the threshold should be lowered. If one accepts the correlation shown here, then the boundaries of a ***VDV(8)*** caution zone should be 3.5 $m/s^{1.75}$ for the lower boundary (action level) and 4.8 $m/s^{1.75}$ for the lupper boundary (limit value).

With these reduced caution zone boundaries, the majority of the cases would be detected as requiring further analysis, but some would still go undetected. This suggests that it is wise to use as many tools as available to decide on application of the new multiple shock method.

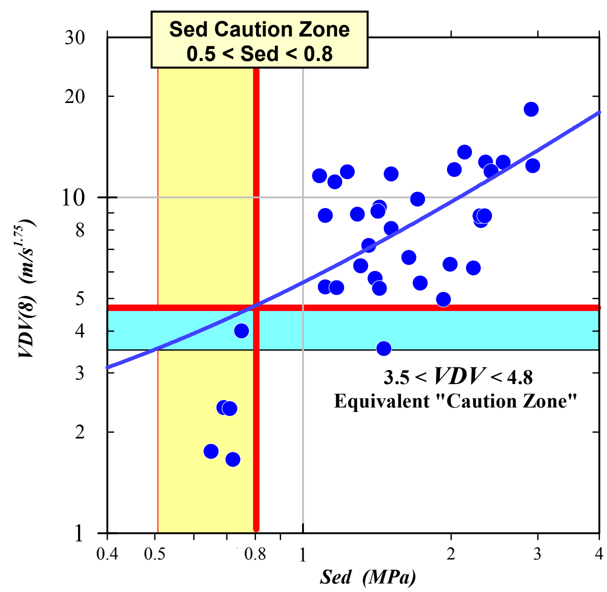

Figure 12: Proposed caution zone values for the VDV(8).

4.3 Health Hazard Assessment

The WBV and repeated shock evaluation methods that are given in the normative portions of the ISO 2631 standard do not set exposure limits. These are often suggested in "informative" annexes and guidelines. The rationale is that the setting and enforcement of exposure limits, which often are shrouded with controversy and not universally supported, should be a matter of choice for each country, and that an ISO standard should incorporate only methods and procedures that are universally accepted. This approach appears to have worked well for the European Parliament, which has issued a directive to set the daily exposure action value (standardised to an eight hour reference period) to 2.5 m/s^2 [EP 2002, Article 3]. An action value is a threshold that requires the user to take some administrative or engineering action to reduce the exposure.

In the United States, this function is the responsibility of government regulatory agencies, such as the Occupational Safety and Health Administration (OSHA). In practice, the guidelines given in the ISO 2631 normative and informative annexes are the primary (and often the only) reference for setting safe limits of WBV and repeated shock. For the U.S. Army, the limits are generally set by the U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM), which relies on the ISO standard for a source of this information.

The U.S. Army has a formal program for assessment of health hazards, which is required by Army Regulation 40-10 [U.S. Army 1992]. Unfortunately, the definitions and language of AR 40-10 do not match exactly those given in the ISO standard. For example, AR 40-10 requires that each hazard be assigned to one of four severity categories (catastrophic, critical, marginal, negligible – see Figure 7). On the other hand, the ISO 2631-1 standard defines exposure limit in terms of a caution zone, where the lower limit may be interpreted as an "action level" and the upper boundary as a "limit value" not to be exceeded, similar to the meaning of the European Parliament directive. To complicate the matter further, the ISO 2631-5 uses the risk factor $\boldsymbol{R}$, normalized to 8-hour exposure, to define the repeated shocks exposure to be low risk for $\boldsymbol{R} < 0.8$, high risk for $\boldsymbol{R} > 1.2$ and moderate risk for values intermediate values.

To apply the ISO standard while satisfying the Army regulation requirements, the USAARL adopted a conversion scheme that assigns severity categories for WBV exposure based on upper boundary of the caution zone for the weighted RMS as defined ISO 2631-1, and for repeated shocks based on the risk factor as defined in ISO 2631-5. This conversion scheme was given in Table 1.

Furthermore, AR 40-10 defines probabilities of exposure to hazard based on the mission profile of the item (vehicle) and the actual utilization rates of an individual item (vehicle) and of the entire fleet (see Figure 8). This separation between the severity category, which is an intrinsic characteristic of the vibration signature, and the probability of exposure is not all that distinct in the ISO standard. Since the mission requirement and utilization rates may vary from of user of one vehicle to another, assigning the probability of exposure (regardless of the severity of the hazard) must be done in cooperation with the user. As stated earlier when discussing Figure 8, the WBV-Jolt software displays the AR 40-10 language and requires the user to manually enter the probability level for WBV and repeated shocks.

Given the severity category and probability level, the final step in the HHA process is to assign a risk assessment code (RAC), as shown in Figure 9. RACs quantify risk to personnel (users and testers) operating or maintaining a system or conducting an operation. They also show the adverse effect on or possible loss of bodily systems described in categories of hazard severity and hazard probability.

5.0 SUMMARY OF CONCLUSIONS

A new methodology to evaluate whole-body vibration containing multiple shocks has been developed. Unlike existing repeated shocks evaluation methods, such as the VDV method or the crest factor that are based on mathematical properties of a WBV signal, the new method is based on biomechanical response of the lumbar spine. Application of the new method is limited to seated healthy adult males. The methodology includes (a) the new ISO 2631-5 standard; (b) the WBV-Jolt software, and (c) the HHA extensions that implement AR 40-10.

The ability of the new method to discriminate the presence of shocks in the WBV signature was compared to those of other methods (e.g., the VDV). Given a set of signals that were selected to have high shock content, the new method out-performed all other methods. This is not to say that the new method was able to predict injury from these signatures since these were test signatures and did not have injuries associated with them. The only way to verify the validity of the new method is prospective monitoring of the occupational health of vehicle operators over their careers. Although low- and high-risk thresholds were defined for the new method, these limits were based on the best biomechanical data available on lumbar spine vertebrae strength and failure. These threshold values should be monitored and, if necessary, revised based on credible new data that might be generated in the future.

6.0 RECOMMENDATIONS

- When screening WBV signatures for high shocks, use as many valid methods as possible.
- Use the ***Q7*** ratio (see text) but reduce the trigger threshold to ***Q7*** = 1.25. Do not use the ***Q8*** ratio.
- Use the ***VDV(8)*** as a screening tool but reduce the trigger threshold to ***VDV(8)*** = 3.5 $m/s^{1.75}$
- Do not use the ***VDV*** as method for assessment of repeated shocks.
- Conduct prospective surveys to monitor the lumbar spine health of vehicle drivers and review credible new data to confirm/amend the action values defined in the new method.
- Conduct further research to extend the new method to other postures.

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Detailed Analysis or Short Description of the AVT-110 contributions and Question/Reply

The Questions/Answers listed in the next paragraphs (table) are limited to the written discussion forms received by the Technical Evaluator. The answers were normally given by the first mentioned author-speaker.

P7 N. Alem, E. Hiltz,A. Breaux-Sims, B. Bumgardner 'Evaluation of New Methodology for Health Hazard Assessment of Repeated Shocks in Military Tactical Vehicles' (AARL, US)

This excellent paper compares the developed HHA (Health Hazard Assessment) method, and introduction of a new SED (Daily stress Dose) in the new standard ISO 2631-5, with the predictions by the current WBV (Whole Body Vibration) standard ISO 2631-1 , and demonstrates the applicability of this new ISO to tactical ground vehicles (TGV). A five-phase research program was designed to develop a standard method for HHA of mechanical shock and repeated impact in Army TGVs and conducted at the USAARL: after a survey of the existing biodynamic models that could be related to health problems, a procedure, a motion signature was created mathematically to realistically simulate the motion environment of TGVs by synthesizing two signals: one to characterize the shocks, and the other to characterize the near-continuous background vibration. Healthy people were then submitted to a series of short duration and long duration motion exposures at the MARS (multi-axis ride simulator) facilities, which was driven by the aforementioned standardized TGV signatures. A new ISO 2631-5 standard [ISO 2004] was then developed relying on the chosen dynamic models to generate acceleration response at the lumbar spine and caution and risk levels.

Discussor's name: R. Warwick
Q. Was the estimated or calculated VDV (Vibration Dose Value) used when comparing to the SED ?
R. The calculated VDV was in fact used in the comparison to the Sed. The estimated equivalent VDV (eVDV) was referenced on the graphs because it was one for which a 'caution zone' can be found in ISO 2631-1 and the EU directives. We assumed that the eVDV gives a reasonable approximation to the actual VDV so that its caution zone can be shown on the graph. In any case, the action level of VDV = 15 specified in the EU directive is within the caution zone (8.5-17) for the eVDV, both of which are well above the cluster of calculated VDV or WBV signatures that are known to contain significant levels of shocks.

Discussor's name: J. Vantomme
Q. The results of this analysis are of big importance as a screening tool. But should this information not be used by tank manufacturers as 'design targets'?
R. The ISO organisation does not define thresholds and limits that are acceptable. This is a regulatory function usually reserved to such enforcing agencies as the European Parliament (through directives) in Europe and the OSHA in the United States. However these regulatory agencies rely on experts who develop the standards to set limits and action levels. The caution zones given in the paper are those specified in an informative annex of the new Standard. At this time, these are the best estimates based on published literature, and therefore, can be considered 'design targets'. It is up the regulatory agency, or even the system developer to write them as design specifications.

Discussor's name: M. Celick
Q. What is the duration of each of the shock pulses? What about the magnitude that seems low?
R. The vibration platform was driven by signatures that contained mechanical shocks of 0.5 to 3.0g magnitude with wave forms of 2 to 11 Hz. This is equivalent to 45ms – 250 ms durations of shock pulses. A pulse is equivalent to one half of a full period. As to the seemingly low G's, these refer to the platform acceleration and not to the subject response as recorded by a ride pad. In some cases, the subject ride pad response to some of the shocks exceeded 10-15 G's and frequencies higher than 20 Hz were observed.