Subjective Characterization of Snowmobile and ATV Vibration

Justin D. Keske, **Jason R. Blough**, and **Brandon J. Dilworth**
Michigan Technological University, Houghton, Michigan

Comfort and quality have been an increasing concern for manufacturers of recreational vehicles. Advances in technology have given rise to more sophisticated and luxurious machines. Operator vibration exposure is one area of concern. This study utilizes sensory jury testing to characterize vibration levels perceived by the operator with respect to levels measured using instrumentation.

Based on feedback from the current snowmobile and ATV market, vibration levels at the operator interfaces for some machines are too high with regard to customer expectations. This fact begs the question: How high is too high? This question was the driving motivation for this research. The goal of this work was to develop a model with which to evaluate the vibration via subjective and objective characterization.

Human Vibration Response

In this study of snowmobile and ATV vibration, precautions were taken to be very specific in assessing human vibration exposure. This study considered only vibration effects on operator comfort. It omitted characterizing the vibration induced from ground input while operating the snowmobiles and ATVs. Thus, any vibration originating from input due to the terrain was not considered. This was controlled through the use of a smooth test track and jury instruction. Specifically, only vibration induced by the engine and drive-train components was considered. In effect, this eliminated analysis of frequencies below about 15 Hz.

Several locations on snowmobiles and ATVs where vibration was transmitted to the operator were considered. Basicentric coordinate systems were established for each of these locations for the measurement of translational vibration. These coordinate systems are defined in published ISO standards.[1-3]

This study did not consider the effects of rotational vibration and made no attempt to quantify the way in which vibration discomfort is affected with respect to exposure time. These effects were controlled so that variability due to exposure time was eliminated.

Vibration Rating Jury

Frequency weighting curves for comfort have been formed for some applications of human vibration exposure. With a weighting function, the magnitude of every frequency component can be adjusted to reflect an appropriate comfort level. Thus, weighted acceleration magnitudes can be used as a measure of comfort.

A jury test was performed to characterize the vibration to which operators of snowmobiles and ATVs are exposed. Jurors were instructed to evaluate the vibration with respect to overall comfort. The goal of the testing was to subjectively characterize the vibration felt by an operator at the three interfaces of the machine – handlebars, seat, and running boards/foot wells.

The jury was composed mostly of employees working in the snowmobile and ATV industry. This provided a jury that was educated in the goals of the project and ensured proper motivation of the jury to yield good results. At the same time, this jury was very representative of typical snowmobile and ATV consumers, since many of them own their own machines. The jury consisted of 26 members for snowmobile testing done in the winter on snow-covered ground. The jury consisted of 32 members for ATV testing done in the summer.

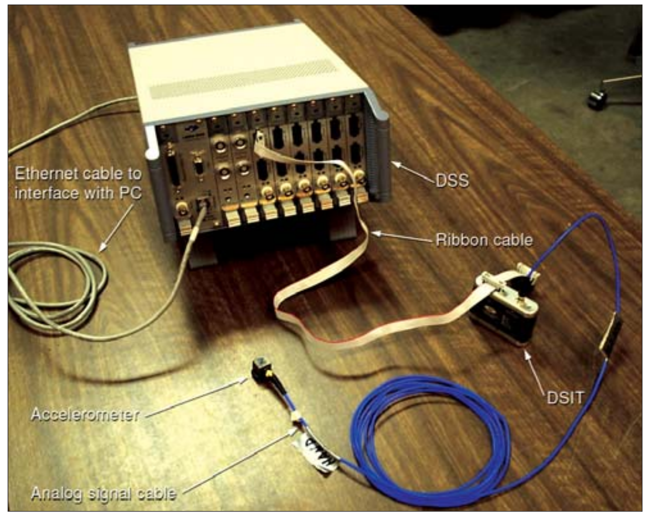

Figure 1. Larson Davis DSS.

Before any testing took place, the jury was taken through an orientation explaining the details of jury testing. A 1-to-10 rating scale was used. This method provided a simple, effective way of evaluating vibration felt by the jurors while avoiding confusion and additional jury education. In this study, a rating of 1 was attributed to very significant, uncomfortable vibration. A rating of 10 was attributed to very insignificant, smooth vibration or a lack of vibration altogether. Jurors were instructed to assign a rating to the vibration felt at each location based on their overall impression regarding comfort.

Machines and Operating Conditions

The two jury testing studies each used five operating conditions per machine – one stationary idling condition, three constant-speed moving conditions, and one acceleration condition. Nine snowmobiles and 10 ATVs were tested; all were numbered for unbiased reference. All measurements were performed in a straight path; no turning or maneuvering was involved. All steady-state conditions were maintained for at least 20 seconds to allow the operator enough time to assess and properly rate the vibration.

Snowmobile and ATV vibration was measured on every machine for all corresponding operating conditions noted previously. The vibration was measured with the machines operating on the same test track used for jury testing.

Vibration Data Acquisition

The system used for data collection was a digital sensing system (DSS) from Larson Davis. The DSS uses digital sensor interface transmitters (DSITs) connected to cables carrying the analog signals from the transducers. Using a 24-bit analog-to-digital converter, a DSIT samples the analog signal received from a transducer at a desired sample rate. The digital data are then carried by an economical ribbon cable, to which several DSITs can be attached, to the DSS. Several ribbon cables from different locations attached to several DSITs can be attached to the DSS.

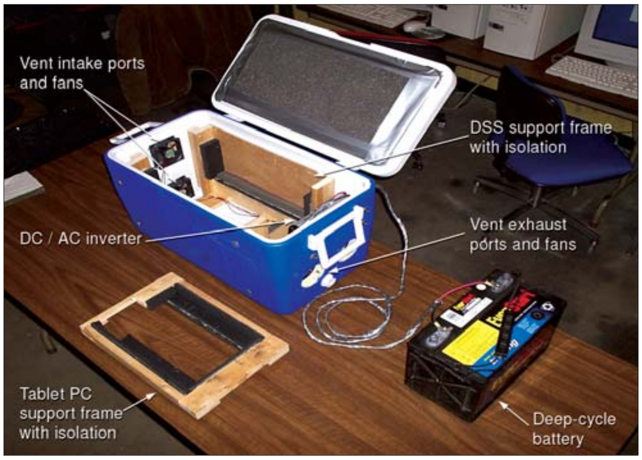

Figure 2. DSS containment.

The versatility provided by the DSS was very helpful for this application, allowing for shorter analog transducer cables and customized lengths of ribbon cable. Shorter analog transducer cables not only simplified the test setup, but also minimized signal noise since the data are digitized at the DSIT. In addition, the quick disconnect clips that secure the DSITs to the ribbon cable made decoupling the rider from the acquisition system a simple task when moving from one machine to the next. The DSS assembled with a single ribbon cable, a single 3-channel DSIT, and one tri-axial accelerometer is shown in Figure 1.

During snowmobile tests, the DSS was packed inside an ordinary cooler isolated by foam. The cooler offered an effective means of containing the DSS and associated hardware and keeping out snow. Contained inside the cooler were the DSS, a tablet PC, power supplies for both, and a DC–to-AC power inverter. The tablet PC was interfaced directly to the DSS via an Ethernet cable. The tablet PC and DSS were both powered by the inverter, which was powered by a deep-cycle battery outside the cooler. The DSS was controlled using the Larson Davis free-support WaveFront software. A full LabVIEW implementation has also been recently developed and includes a real-time, order-tracking application.

Maximum ambient temperatures during snowmobile testing never exceeded –15° F (–26° C), eliminating the need for any ventilation for the cooler. The cooler was modified for ATV testing to allow ventilation for cooling. Internal support frames were constructed to hold the DSS and tablet PC suspended inside the cooler to allow air to pass over the external surfaces of the DSS and tablet PC. Intake and exhaust ventilation ports were created and cooling fans installed. An air-intake box was also constructed and outfitted with a filter to keep out dust. A picture of the modified cooler and its internals is shown in Figure 2. The DSS support frame was mounted inside the cooler, and the tablet PC support frame was placed on top of the DSS within the support frame of the DSS. Figure 3 shows the DSS contained by the cooler, and Figure 4 shows the entire acquisition assembly.

Ribbon cables were run from the DSS, out of the cooler, and through an access hole to the DSITs, which were contained in a backpack worn by the operator. For snowmobile testing, the cooler and battery were pulled behind the snowmobile in a sled (see Figures 5 and 6). For ATV testing, the cooler and battery were strapped down to the cargo rack (see Figure 7). The DSS demonstrated excellent reliability during testing, even while bouncing around violently over rough terrain during some preliminary tests.

Vibration Data Processing

Each juror provided a vibration rating for each test. These data were normalized for equivalence among jurors and rescaled to fit the original rating scale. From the sample population of ratings for each test, a statistical analysis was performed with outliers removed. A jury verdict for each test was taken as the mean of each test's sample population.

Acceleration time traces were acquired for each of the three orthogonal axes at the hand, seat, and foot locations for every machine and operating condition. These data were processed in a couple of different ways to understand the characteristics

Figure 3. DSS in cooler.

Figure 4. Data acquisition assembly.

Figure 5. Snowmobile test setup.

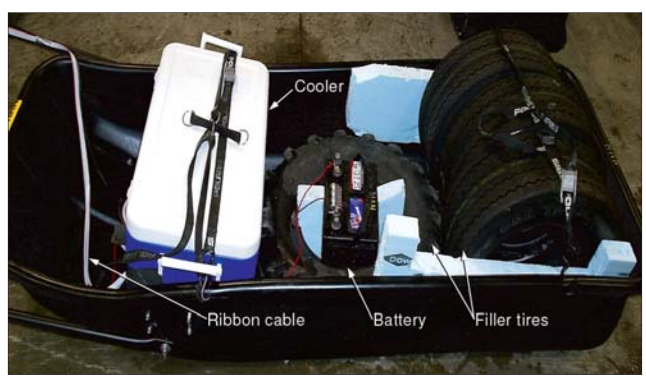

Figure 6. Towing sled for snowmobile test.

Figure 7. ATV test setup.

of the vibration and how best to quantify it.

Based on preliminary investigation of the data, we decided to use the overall RMS acceleration as the metric to evaluate vibration values. Since one number is desired per location (hand, seat, and foot), we decided to use the vector sum overall RMS acceleration, A_{RMS} , at each location calculated from the vector sum time trace, $A(t)$, as described by Equations 1 and 2, where k_x, k_y, and k_z are multiplying factors for each of the three axes. These allow more or less relative emphasis to be placed on one or two of the axes should the case arise where the axes differ in importance. For this study, k_x, k_y, and k_z and were taken as unity. The vector sum overall RMS acceleration may also be calculated alternatively by Equation 3 where a_x^2, a_y^2, and a_z^2 are the squares of the X, Y, and Z axes RMS accelerations. Equations 2 and 3 are equivalent.

$$A(t) = \sqrt{(k_x a(t))^2 + (k_y a_y(t))^2 + (k_z a_z(t))^2} \quad (1)$$

$$A_{\text{RMS}} = \sqrt{\frac{1}{T}\int_0^T A^2(t)dt} \quad (2)$$

$$A_{\text{RMS}} = \sqrt{k_x^2 a_x^2 + k_y^2 a_y^2 + k_z^2 a_z^2} \quad (3)$$

Subjective to Objective Data Correlation

Correlations were run between the jury verdicts for each test and the vibration metric A_{RMS}. The jury verdicts were plotted versus A_{RMS} considering the different locations separately; these plots included all operating conditions and all machines. The idling condition had significantly different trends than for those conditions where the machine was moving. This operating condition can be observed from the correlation plot in Figure 8.

The data were then segregated into plots that included only moving operating conditions, or all conditions except idling. These data were further segregated into plots containing only one specific operating condition, where each data point represented a different machine. This was done first for snowmobiles and then for ATVs. It was repeated for all the different frequency weighting functions used for calculating A_{RMS}. An investigation of the many correlation plots suggested using a linear model to characterize the relationship between A_{RMS} values and the verdicts of the jury. The model takes the simple linear form of Equation 4, where β_0 and β_1 are the parameters to be determined from data points in the correlation plot:

$$\text{Subjective Vibration Rating} = \beta_0 \times \beta_1 - A_{\text{RMS}} \quad (4)$$

For each correlation plot, an ordinary least-squares problem was posed. Based on the linear regressions determined from ordinary least-squares analysis, all plots were investigated to determine those that correlated the best.

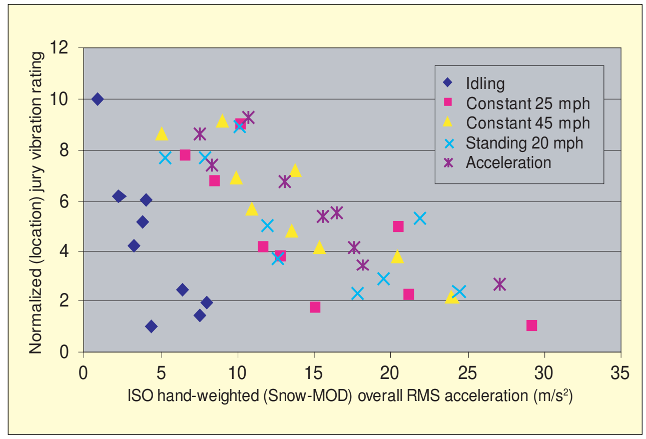

Figure 8. Correlation Plot 1 – hand regression, all conditions.

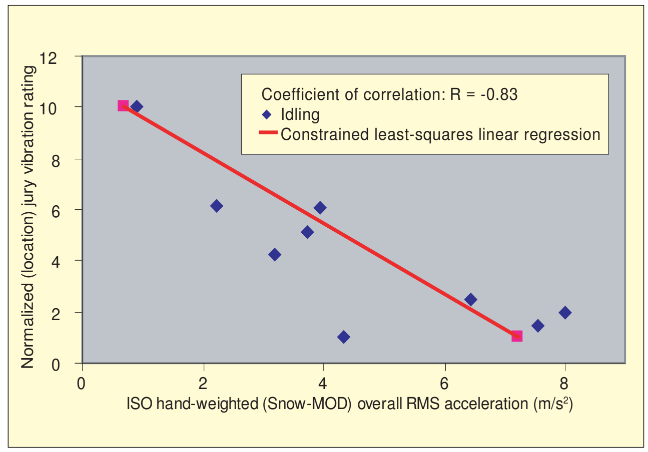

Figure 9. Correlation Plot 2 – hand regression, idling.

After inspecting all regressions, the best combinations were chosen to develop recommended human vibration evaluation models. A constrained least-squares linear regression analysis was performed for these combinations. The minimum A_{RMS} value that would correspond to a rating of 10 in the obtained regression line was constrained to be 75% of the smallest reported real data point in the particular data set.

The constrained, least-squares, linear-regression lines for the data in Figure 8 were segregated into idling, all moving conditions, and one standing condition. These are plotted in Figures 9, 10, and 11, respectively. In Figure 11, the ordinary least-squares-regression line has also been included to show that it would intercept the vertical axis at a value of less than 10. This illustrates the need for a constrained, least-squares regression line.

Vibration Exposure Evaluation Model

Human vibration exposure evaluation models were developed for the hand, seat, and foot locations of snowmobiles and ATVs for various operating conditions using the constrained, least-squares, linear-regression lines. These models essentially allow a subjective assessment of the vibration levels on the vehicles from objective vibration measurements. The simple linear form of the model, Equation 5, is the same for all cases. This equation is the same as Equation 4 used in the model development with the parameters β_0 and β_1 renamed as B and M, respectively:

$$\text{Subjective Vibration Rating} = M \times A_{\text{RMS}} + B \quad (5)$$

As developed from this study, the recommended values for the parameters M and B were provided to the sponsor for the various locations, machine types, and operating conditions studied. The frequency weighting functions to be used on the vi-

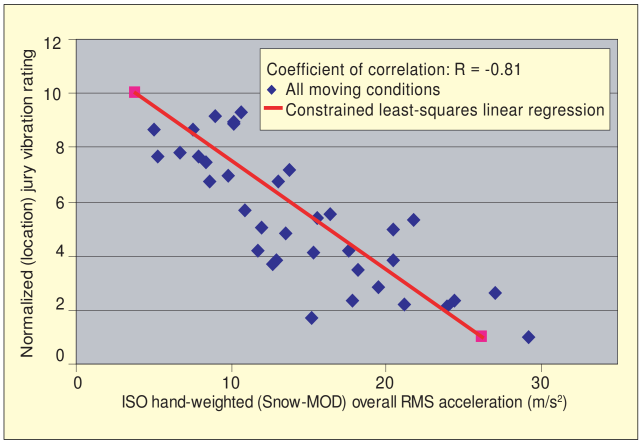

Figure 10. Correlation Plot 3 – hand regression, all moving conditions.

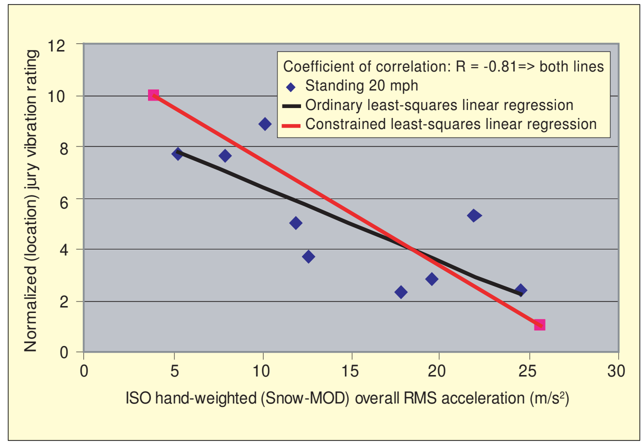

Figure 11. Correlation Plot 4 – hand regression, standing 20 mph.

bration data for the calculation of the vibration metric A_{RMS} were included. The complete set of correlation plots containing the constrained least-squares linear regressions used to develop these parameters were provided to the sponsor as well.

This study resulted in the development of a model and associated parameters with which to evaluate the subjective response to the vibration of snowmobiles and ATVs. This model can be used in place of the subjective jury testing that was performed during this study. Use of the models simply requires measuring vibration, applying a specified frequency weighting function, and computing A_{RMS}. From this, a prediction of the subjective vibration rating on a 1-10 scale can be generated from the model.

Conclusions

Model parameters have been developed for evaluating human vibration exposure from the operator interfaces of snowmobiles and ATVs for several common operating conditions. The parameters used in the model have been shown to correlate well to the research conducted in the study. The model can be used in conjunction with other analyses for future design of snowmobiles and ATVs to better suit the comfort demands of the consumer with respect to vibration exposure.

References

1. ISO 2631-1: 1997, Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part 1: General Requirements.
2. ISO 5349-1: 2001, Mechanical Vibration – Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration – Part 1: General Requirements.
3. ISO 5349-2: 2001, Mechanical Vibration – Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration – Part 2: Practical Guidance for Measurement at the Workplace.

The author may be reached at: jdkeske@mtu.edu.