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# Speed and whole body vibration in a sample of grapple skidders from the US South

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**ABSTRACT.** *Whole body vibration (WBV) is a risk factor for the development of musculoskeletal disorders among logging equipment operators. In 2014 we sampled operator exposure to WBV in logging equipment common in the southern United States. The average weighted acceleration anticipated over an eight-hour day (A(8)) was 0.64 ms$^{-2}$ (sd 0.32) for trailer mounted loaders, 1.04 ms$^{-2}$ (sd 0.42) for wheeled feller-bunchers, and 1.58 ms$^{-2}$ (sd 0.34) for skidders. All were above the European Union (EU) action value of 0.51 ms$^{-2}$, but skidders were consistently above the limit value of 1.15 ms$^{-2}$. Because travel speed is important for skidder productivity, we explored the relationship between WBV and speed. We accumulated data over 52 second intervals (0.0006 day) generating more than 2900 intervals from 11 sites. A regression analysis by site revealed significant positive relationships between speed and vibration for 9 of 11 skidders ($R^2$ from 0.02 to 0.62). Speed distributions revealed three operational styles and mean speeds ranging from 1.15 to 1.54 ms$^{-1}$. A stepwise regression with speed, and speed$^2$ for all skidders was significant (F 125.51, MSE 39.77, $R^2$ 0.34 and df 12, 2898) and included speed, speed$^2$, operational style, locations (trail or landing), and all but one of the two-way interactions. When A(8) was estimated for other skidders, the model generated important differences in A(8) for speed and operational styles. Operational planning and training about tradeoffs between speed and productivity could be an important administrative control for reducing exposure to WBV.*

***Keywords.*** *logging, skidder, ergonomics, whole-body vibration, speed, productivity*

## Introduction

Chronic exposure to whole body vibration (WBV) during machine and vehicle operation has been linked epidemiologically to negative health outcomes, especially low back pain and related musculo-skeletal disorders (MSDs) (Bovenzi et al., 2006; Tiemessen et al., 2008). Action values and limit values for the average weighted acceleration anticipated over an eight-hour work shift, A(8), provide guidelines to minimize the health impacts of WBV exposure. The European Union (EU) directive 2002/44/EC describes a daily exposure action value of 0.5 ms$^{-2}$ and a daily exposure limit value of 1.15 ms$^{-2}$. The three dominant machines used in logging in the southern US are the knuckleboom loader, wheeled feller-buncher, and wheeled grapple skidder. Lynch (2017) recorded A(8) averages for knuckleboom loaders of 0.64 ms$^{-2}$, wheeled feller bunchers of 1.05 ms$^{-2}$, and wheeled grapple skidders of 1.58 ms$^{-2}$. In Brazil daily exposures for tracked feller bunchers, processors, harvesters and forwarders were less than the limit value but wheeled skidders recorded A(8) values of 1.62 and 1.23 ms$^{-2}$ for day and night shifts, respectively (Oliveira et al., 2021).

While the operational differences in WBV between forest machines have not been specifically attributed, skidders travel at relatively high speeds across rough terrain when compared to forest machines that may be stationary (loaders and processors) or move at relatively slow speeds (forwarders, harvesters, feller-bunchers, dozers). For forwarders Rehn et al. (2005) found that factors important to vibration changed as a function of load status, loaded or empty. Significant factors that influenced WBV during forwarder operation included the machine model, the operator, and the terrain. Wegscheid (1994) indicated that operators' driving behaviors were important in the measured exposure for skidder operators. In wheeled loaders operating styles resulted in significant variation in vibration exposures for the same tasks (Cocheo, 2013). During unloaded elements skidder operators were exposed to significantly higher WBV than during loaded elements (Cation et al., 2008). The difference was attributed to the dampening effect of the load and the difference in speed. In other off-road equipment, it seems likely that vibration is positively correlated with machine speed (Eger et al., 2011; Marin et al., 2016). For a skidder in controlled terrain conditions acceleration increased with speed (Golsse, 1990). We hypothesize that machine speed is important factor in determining skidder operator WBV exposure. While factors related to the operator and trail roughness might be important too, there may be more potential for administrative control of WBV exposure by monitoring and adjusting skidder speed distribution.

# Methods

Whole body vibration data were collected for 11 skidders and other logging machines in the Coastal Plain and Piedmont of Alabama and Georgia in the summer of 2014 as indicated in Lynch (2017). A Larson Davis HVM 100 seat pad accelerometer was placed under the ischial tuberosities (sit bones) of the operators according to ISO 2631.1:1997 (ISO, 1997). The acceleration was summed in 5-second intervals for each of the x, y, and z axes and by the weighted root mean square (rms) with a weight of 1.4 for the x and y axes and a weight of 1 for the z axis. The vibration data were typically recorded for one half of a typical shift for unique machine and operator combinations. Basic data on the machine (seat type) and operator (age, experience, and body mass index (BMI)) and trails were collected (Table 1). Nine of the eleven skidders had seats with air suspension.

*Table 1. Site and operator data for skidders in the study.*

| | Operator | | | | Obstacles | | | Air suspension seat (Yes/No) | Max trail distance (m) |
|---|---|---|---|---|---|---|---|---|---|
| Site | Age (years) | Height (m) | Weight (kg) | BMI (kg/m$^2$) | Frequency (#/m) | Frequency (> 20 cm) (#/m) | Height (m/m) | | |
| A | 46 | 1.80 | 84.1 | 25.8 | 0.58 | 0.09 | 0.78 | Yes | 130 |
| B | 38 | 1.88 | 100.0 | 28.2 | 1.55 | 0.15 | 0.19 | No | 360 |
| C | - | - | - | - | 0.20 | 0.05 | 0.03 | Yes | 200 |
| D | 28 | 1.83 | 77.3 | 23.1 | 0.20 | 0.05 | 0.03 | Yes | 150 |
| E | 49 | 1.83 | 112.7 | 33.6 | 0.79 | 0.24 | 0.16 | Yes | 240 |
| F | 20 | 1.80 | 63.6 | 19.5 | 0.89 | 0.09 | 0.11 | Yes | 140 |
| G | 40 | 1.78 | 93.2 | 29.4 | 0.89 | 0.09 | 0.11 | Yes | 190 |
| H | 39 | 1.73 | 68.2 | 22.8 | 0.79 | 0.24 | 0.13 | Yes | 200 |
| I | 62 | 1.80 | 105.9 | 32.5 | 1.60 | 0.22 | 0.22 | Yes | 250 |
| J | 30 | 1.83 | 74.5 | 22.2 | 1.60 | 0.22 | 0.22 | Yes | 330 |
| K | 25 | 1.75 | 61.4 | 19.9 | 1.83 | 0.13 | 0.21 | No | 190 |

Location data were collected using Trackstick global positioning system (GPS) devices set to record a location (latitude and longitude coordinate pair) every 10 seconds. The combination of machine speed and GPS location fix resulted in a position fix or coordinate location recording on average every 16 seconds. The clock on the data collector for the accelerometer was not precisely synchronized with the GPS during data collection and adjustments were made to the accelerometer time to match the GPS time by manually synchronizing machine starts and stops identified by both the GPS and the accelerometer. Solutions for time adjustments that satisfy the start and end requirements from both devices typically had a potential error of approximately 10 seconds.

The Microsoft Excel index function and time information was used to assign a GPS location to each accelerometer data point (5-second interval). We estimated the weighted rms acceleration for each interval between subsequent locations according to equation B.3 in ISO 2631.1:1997. For each location fix, except for the first location, the data included the acceleration rms in the x, y, and z axes, the weighted sum of the axes, the time elapsed on the accelerometer (in 5- second increments), the time elapsed between GPS location fixes, and the distance between the two sets of coordinates. The distance between GPS locations was estimated with the GEODIST function in SAS (SAS-Institute, 2016).

We rounded the excel format time to the nearest 0.0006 day (or 52 seconds) and summed the data into those increments for each position. The summation of data in longer time intervals was intended to reduce the impact of imprecise synchronization of the GPS and the accelerometer and the impact of erroneous coordinate locations due to poor satellite reception by the GPS. We imported locations into Google Earth and manually categorized each location as occurring on the landing (landing) or on a recognizable trail (trail). The remaining points were classified as other. Skidder production cycles are typically split into at least three types of elements. In landing elements, the skidder drops the trees for processing and loading and occasionally does other support tasks. In travel elements, the skidder drives back and forth from a pile of trees to the landing. Some portion of travel is completed on relatively well worn primary skid trails. In grapple/loading elements, the skidder finds the piles of trees and picks them up. Sometimes the operators must locate and pick up more than one pile. In our case, the points where grapple/loading elements occurred were likely to be classified as other.

After the harvest, we identified a primary skid trail with the GPS locations and estimated terrain roughness on trail sections 400 to 600 meters long. Every five meters, an observer counted the obstacles in 20-cm height classes (0 to 20, 21 to 40, 41 to 60, and 61 to 80) in a one meter wide swath or sample perpendicular to the trail and across the full extent of the machine wheel tracks. We developed three parameters, obstacle frequency (obstacles), obstacle frequency for those greater than 20 cm (obstacles > 20), and the total obstacle height (height). For the frequencies, the value was estimated as the total count divided by the number of samples. For the height, we summed the number of obstacles times the height class midpoint (10, 30, 50, and 70 cm) and divided by the number of samples. Obstacle frequency ranged from 0.2 $m^{-1}$ to 1.8 $m^{-1}$. Between 10 and 20% of obstacles were greater than 0.2 m high with a frequency between 0.05 $m^{-1}$ to 0.24 $m^{-1}$.

# Results and Discussion

The speed distributions for all sites after rounding to the nearest 52 seconds are presented in Figure 1. Before rounding, there were almost 12,000 position fixes and less than 3,000 after rounding. Extreme speeds were possible with occasional large errors in position fixes. In the rounded data, only 2 positions had extreme speeds (more than 7 $ms^{-1}$) while the unrounded data set had more than 150 positions with speeds this high. After rounding, the median time per position was 50 seconds, the mean was 60 seconds and 10th and 90th percentile values were 40 and 65 seconds, respectively. Longer times could be due to time between positions longer than 52 seconds. Shorter times could be due to missing vibration data, missing position fixes or both.

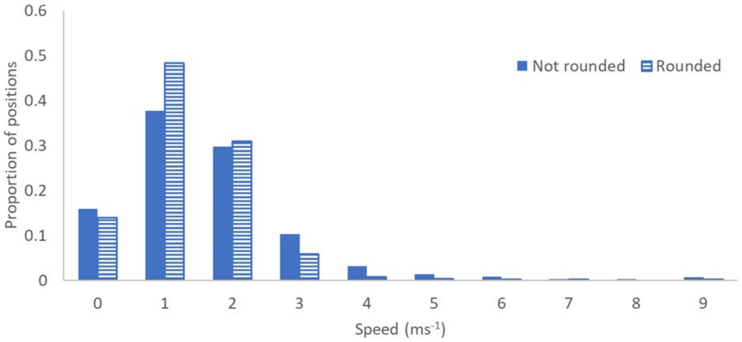

*Figure 1. Proportion of position fixes by speed class (1 ms$^{-1}$) for data rounded to the nearest 52 seconds (Rounded) and all position fixes with acceleration data (Not rounded).*

The speed distribution by site and by 0.5 $ms^{-1}$ speed classes are in Figure 2. We grouped the skidders by Operational Style (OS) based on the speed distribution. Two of the sites (F and H) were classified as OS-1 and had a mode speed of 0 $ms^{-1}$. Another 3 sites (C, I, and K) were classified as OS-2. The modes for those distributions were less pronounced and had proportions of time in speeds from 0 to 1.5 $ms^{-1}$ at about 20% for each speed class. The remainder of sites were classified as OS-0 and had less than 20% of time at 0 $ms^{-1}$ with a distinct mode between 0.5 and 2 $ms^{-1}$. Nonproductive delay was determined by idle times with speed of 0 $ms^{-1}$ (rather than rounded to 0) and a duration of 9 minutes or more. Fourteen instances of nonproductive delay were identified with a weighted rms acceleration ($A_{wxyz}$) of 0.35 $ms^{-2}$, a median of 0.21 $ms^{-2}$ and only 3 values greater than 0.47 $ms^{-2}$.

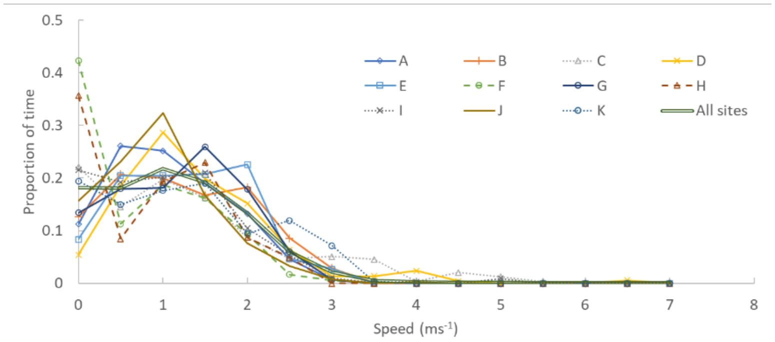

*Figure 2. Speed distribution for all sites combined (solid double line) and each site (sites A through K) in 0.5 $ms^{-1}$ speed classes. Operational styles (OS) are indicated as a solid line for OS-0, a dashed line for OS-1, and a dotted line for OS-2.*

Mean speed ranged from 1.13 to 1.54 $ms^{-1}$ among the 11 sites (Table 2). Speeds on landings averaged 1.01 $ms^{-1}$ compared to mean trail speeds of 1.42 $ms^{-1}$. The acceleration was similar for the landing, trail, and other locations. The operational styles also were similar with respect to both speed and acceleration. The relationship between mean acceleration ($A_{wxyz}$, $A_{wx}$, $A_{wy}$, and $A_{wz}$) and speed (using 0.5 $ms^{-1}$ speed classes) are displayed in Figure 3. Acceleration increased steadily as speeds increased from 0 to 2 $ms^{-1}$. At speeds greater than 2 $ms^{-1}$, acceleration remained the same or declined with greater speeds. Based on this general relationship we tested a quadratic regression equation with speed and speed squared and a series of dummy variables for operational style (OS-0, OS-1, and OS-2) and location (landing or trail) with the two-way interactions to identify significant relationships. Golsse & Hope (1987) found acceleration differences by skidder element and attributed the differences mostly to speed.

*Table 2. Mean and standard deviation (sd) for speed, weighted acceleration and time interval for each site, the locations (Other, Trail, and Landing), Operational Style (OS-0, OS-1, and OS-2) and for All sites. Time is the total duration of accelerometer data.*

| | Speed | Weighted acceleration (rms) | | | | Interval | Time |
|---|---|---|---|---|---|---|---|
| Site | $ms^{-1}$ | $A_{wxyz}$ | $A_{wx}$ | $A_{wy}$ | $A_{wz}$ | s | hr |
| A | 1.15 (0.69) | 2.23 (0.77) | 1.18 (0.5) | 0.94 (0.3) | 0.63 (0.19) | 57 (28) | 3.2 |
| B | 1.38 (0.79) | 2.09 (0.88) | 0.88 (0.35) | 0.96 (0.44) | 0.97 (0.51) | 57 (38) | 10.3 |
| C | 1.54 (1.22) | 2.3 (0.58) | 0.96 (0.21) | 1.15 (0.38) | 0.88 (0.3) | 63 (128) | 3.6 |
| D | 1.42 (0.93) | 2.76 (1.23) | 0.98 (0.25) | 1.51 (0.93) | 0.93 (0.34) | 52 (16) | 3.3 |
| E | 1.36 (0.69) | 2.33 (0.9) | 0.89 (0.28) | 1.23 (0.62) | 0.84 (0.34) | 57 (31) | 3.0 |
| F | 1.16 (0.64) | 2.24 (1.38) | 0.9 (0.56) | 1.17 (0.78) | 0.82 (0.42) | 81 (124) | 3.1 |
| G | 1.36 (0.66) | 2.01 (0.75) | 0.84 (0.32) | 0.85 (0.31) | 1.09 (0.51) | 57 (45) | 4.3 |
| H | 1.3 (0.62) | 2.05 (0.96) | 2.05 (0.96) | 1.15 (0.63) | 0.7 (0.32) | 74 (140) | 4.4 |
| I | 1.18 (0.86) | 2.1 (0.57) | 0.85 (0.26) | 1.09 (0.32) | 0.77 (0.26) | 59 (37) | 4.3 |
| J | 1.13 (0.68) | 1.58 (0.48) | 0.55 (0.15) | 0.76 (0.22) | 0.84 (0.37) | 60 (68) | 5.1 |
| K | 1.49 (0.85) | 2.01 (0.69) | 0.91 (0.32) | 0.86 (0.3) | 0.95 (0.42) | 60 (73) | 4.0 |
| Other | 1.46 (0.83) | 2.19 (0.85) | 1 (0.6) | 1.08 (0.52) | 0.9 (0.4) | 58 (61) | 22.5 |
| Trail | 1.42 (0.82) | 2.02 (0.82) | 0.88 (0.44) | 0.97 (0.47) | 0.9 (0.44) | 54 (27) | 10.3 |
| Landing | 1.01 (0.72) | 2.08 (0.98) | 0.95 (0.5) | 0.99 (0.58) | 0.83 (0.41) | 69 (103) | 15.9 |
| OS-0 | 1.31 (0.76) | 2.11 (0.92) | 0.86 (0.37) | 1 (0.55) | 0.91 (0.44) | 57 (42) | 29.2 |
| OS-1 | 1.24 (0.63) | 2.12 (1.15) | 1.59 (1) | 1.16 (0.69) | 0.75 (0.37) | 77 (133) | 7.5 |
| OS-2 | 1.39 (0.99) | 2.13 (0.63) | 0.9 (0.27) | 1.03 (0.36) | 0.87 (0.34) | 60 (84) | 11.9 |
| All | 1.32 (0.81) | 2.11 (0.89) | 0.96 (0.53) | 1.03 (0.53) | 0.88 (0.41) | 60 (71) | 48.7 |

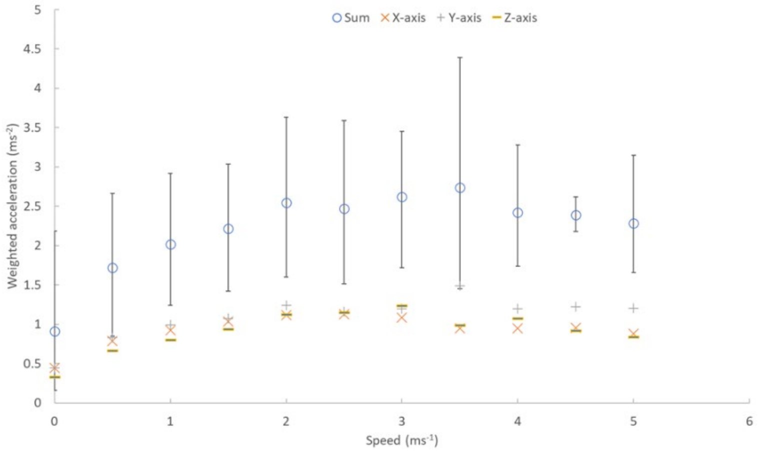

*Figure 3. Mean weighted rms acceleration ($A_{wxyz}$, $A_{wx}$, $A_{wy}$, and $A_{wz}$) by speed class (0.5 $ms^{-1}$). Error bars indicate the 90% confidence interval for $A_{wxyz}$.*

Results of the regressions with stepwise selection for $A_{wxyz}$ for all sites together and individual sites are presented in Table 3. All of the site models were statistically significant at when considering $\alpha = 0.05$, and all but two (C and G) are were significant when considering $\alpha$ = at 0.001. Nine of the 11 models fit the quadratic model and most of the models (8 of 11) included at least one location variable. In general, there was little similarity among the models considering which location values were included. Regression models of acceleration ($A_{wxyz}$, $A_{wx}$, $A_{wy}$, and $A_{wz}$) with dummy variables for operational style, location, and the two-way interactions are presented in Table 4. All of these models fit the quadratic model and included the dummy variables for both operational styles. In general, OS-1 had a lower intercept and higher slopes compared to OS-0 and OS-2. The four models were similar in fit and significance while the model for $A_{wz}$ had the greatest $R^2$ and lowest MSE.

We predicted the weighted acceleration rms ($A_{wxyz}$) using the model in Table 4. The predicted and observed acceleration rms ($A_{wxyz}$) were summed for each site and location. In total, there were 33 observed and predicted values for $A_{wxyz}$. In Figure 4 the predicted and observed data are grouped by location (landing, trail, and other) and projected by speed. The general relationship was similar to that in Figure 3 and the single data point with speed greater than 2 $ms^{-1}$ had lower observed and predicted acceleration. Mean speeds for landing locations were lower than other and trail locations. The data identified by Operational Style shows more obvious relationships with speed and acceleration. The highest slope as indicated for OS-1 by the model in Table 4 is evident in Figure 5. The very low apparent slope for OS-2 values was also indicated by the model.

To determine if differences indicated by the model yielded important differences in acceleration, we developed estimates from a skidder production study by Klepac & Mitchell (2016). All of the skidding cycles were observed under very similar site conditions with one operator on each of two skidders. The two samples for each skidder were completed with different sizes of tree piles or bunches resulting in different load sizes. The observed speed equaled the average round trip distance per cycle multiplied by the number of observed cycles per hour converted from meters per hour to meters per second. The estimated speed was the weighted mean of speed and element time using the observed trail speed from Klepac and Mitchell (2016) and landing and other speeds from Table 2. For the Cat 525B, the speed estimates are very close. The estimated speeds for the TC 630B are 0.16 and 0.19 $ms^{-1}$ lower than the observed speed or less than 8% different. The differences might be related to the study estimates for landing and other speeds, but the total distance traveled per hour estimated from study data may also be subject to error. The range in observed trail speed (1.74 to 2.77) was greater than the median value from this data set, but within the range of observed data.

For A(8), we estimated $A_{wxyz}$ for each element and operational style using the trail, landing and other speeds. We weighted $A_{wxyz}$ with the proportion of time by element in Table 5 and estimated A(8) with six hours operating time in an eight-hour shift. As expected, when the OS-1 model was applied, A(8) was the most sensitive to speed. With the OS-2 model, only the extreme speeds are noticeably different. We also estimated the number of operating hours in an 8- hour shift which result in an A(8) of 1.5 $ms^{-2}$. The range in these observed speeds would produce a 30 to 50% change in operating hours. There was not much difference in estimated hours comparing OS-0 and OS-1, but the application of OS-2 reduced the impact of speed and increased hours by 15 to 35% across the range in speed.

*Table 3. Results of stepwise selection of regression of acceleration ($A_{wxyz}$) for all sites combined (all) and each site (A through K) versus the independent variables: speed (s), speed squared ($s^2$), landing (l) and trail (t) locations and the interaction of location with speed and speed squared, $t*s$, $l*s$, $t*s^2$, and $l*s^2$.*

| Sites | Model | | Error | | $R^2$ | F | P |
|---|---|---|---|---|---|---|---|
| | df | MS | df | MS | | | |
| All | 5 | 10532 | 2905 | 42.17 | 0.301 | 249.76 | <0.0001 |
| A | 4 | 2429 | 196 | 23.13 | 0.349 | 26.25 | <0.0001 |
| B | 2 | 19775 | 645 | 22.95 | 0.572 | 430.86 | <0.0001 |
| C | 4 | 1627 | 224 | 68.68 | 0.096 | 5.92 | 0.0002 |
| D | 3 | 2202 | 202 | 33.08 | 0.248 | 22.18 | <0.0001 |
| E | 2 | 3757 | 188 | 33.33 | 0.375 | 56.37 | <0.0001 |
| F | 2 | 9803 | 141 | 113.87 | 0.379 | 43.04 | <0.0001 |
| G | 7 | 1536 | 259 | 29.40 | 0.168 | 7.46 | <0.0001 |
| H | 4 | 10686 | 207 | 37.98 | 0.576 | 70.34 | <0.0001 |
| I | 1 | 153 | 262 | 30.32 | 0.019 | 5.03 | 0.0257 |
| J | 4 | 4365 | 303 | 8.33 | 0.634 | 130.94 | <0.0001 |
| K | 5 | 5125 | 234 | 22.56 | 0.493 | 45.43 | <0.0001 |

| | Intercept | Speed | $Speed^2$ | Location |
|---|---|---|---|---|
| All | 0.974 | 1.227 | -0.2049 | $0.243(t)-0.521(t*s)+0.1311(t*s^2)$ |
| A | 1.369 | 0.888 | -0.1620 | $-0.292(t)-0.402(l*s)$ |
| B | 0.672 | 1.230 | -0.1195 | |
| C | 1.803 | 0.811 | -0.1076 | $0.645(l)-0.1216(l*s^2)$ |
| D | 1.441 | 0.708 | -0.1176 | $0.352(t)$ |
| E | 0.842 | 0.926 | | $0.408(l)$ |
| F | 0.511 | 1.886 | -0.3440 | |
| G | 0.801 | 1.671 | -0.5128 | $1.538(t)+0.657(l)-1.733(t*s)-0.335(l*s)-0.4558(t*s^2)$ |
| H | 0.546 | 1.768 | -0.3192 | $-0.383(t)-0.1829(l*s^2)$ |
| I | 1.926 | 0.115 | | |
| J | 0.541 | 1.133 | -0.1770 | $0.496(l*s)-0.3005(l*s^2)$ |
| K | 2.253 | | | $-0.856(t)-1.776(l)+2.999(l*s)+0.0759(t*s^2)-1.3014(l*s^2)$ |

Machine speed is an important factor in determining the WBV exposure received by skidder operators. Since the operating conditions are so varied across a site, the speed in response to specific operating conditions and during specific tasks would have been more valuable data. Operational style may indicate to some degree how operators respond to terrain conditions and tasks as well as the planning and execution of skidding cycles. Unfortunately, each operational style is difficult to generalize and could indicate a range of different operating behaviors or site conditions. However, it seems logical that if speeds are evenly distributed by time from 0 to the likely trail speed, the weight of reduced acceleration at lower speeds would reduce acceleration overall. The type of operating behavior and planning that would lead to even time distributions can be addressed. Those behaviors and attributes include slower speeds while grappling and loading trees, planning travel where most of the path is on primary trails, and avoiding excessive speeds when the machine is unloaded. Longer skid distances increase the proportion of cycle time at higher speeds, but may not increase WBV since the tradeoff is proportionally less travel in rough terrain off the main trails. For example, the A(8) for the site data had a correlation with maximum skid distance of -0.55 (Table 1).

Over time, operational levels of WBV have not decreased substantially with technological improvements in skidders, leaving administrative controls as a primary strategy for managing WBV exposure. As a result, managers need a suite of more accessible tools including handheld device-based tools to measure WBV (Mayton & Kim, 2021) and speed. Tools and devices for collecting location and speed data are widely available and might be directly accessible from telematics offered with many modern machines. Integrating the data into useful information and decision criteria is a final important step.

*Table 4. Results of stepwise selection of regression of weighted acceleration ($A_{wxyz}$, $A_{wx}$, $A_{wy}$, and $A_{wz}$) with independent variables speed (s), speed squared ($s^2$), Operational style (OS-1 and OS-2), landing (l) and trail (t) locations and the interaction of operational style and location and with speed and speed squared, t*s, l*s, t*$s^2$, and l*$s^2$. The location (other) and operational style (OS-0) are included in the base model.*

| | | $A_{wxyz}$ | $A_{wx}$ | $A_{wy}$ | $A_{wz}$ |
|---|---|---|---|---|---|
| Model | df | 12 | 8 | 11 | 9 |
| | MS | 4992 | 2403 | 1288 | 1657 |
| Error | df | 2898 | 2902 | 2899 | 2901 |
| | MS | 39.77 | 11.52 | 14.18 | 7.22 |
| $R^2$ | | 0.342 | 0.365 | 0.366 | 0.416 |
| F | | 125.51 | 208.48 | 90.84 | 229.38 |
| Parameters | | | | | |
| Intercept | | 1.046 | 0.487 | 0.452 | 0.318 |
| Speed (s) | | 1.066 | 0.383 | 0.575 | 0.559 |
| Speed$^2$ ($s^2$) | | -0.1449 | -0.0486 | -0.0847 | -0.0692 |
| Operating Style | OS-1 | -0.340 | -0.089 | -0.182 | -0.151 |
| | OS-2 | 0.567 | 0.173 | 0.279 | 0.220 |
| OS*s | OS-1 | 0.242 | 0.857 | 0.354 | |
| | OS-2 | -0.559 | -0.113 | -0.258 | -0.2140 |
| OS*$s^2$ | OS-1 | | -0.1440 | -0.0661 | |
| | OS-2 | 0.0612 | | 0.0264 | |
| Location | Landing | -0.207 | | | |
| | Trail | | -0.097 | 0.098 | 0.0722 |
| | Landing*s | 0.392 | | | 0.032 |
| | Trail*s | -0.201 | | -0.210 | -0.107 |
| | Landing*$s^2$ | -0.1038 | | | |
| | Trail*$s^2$ | 0.0592 | | 0.0506 | 0.0345 |

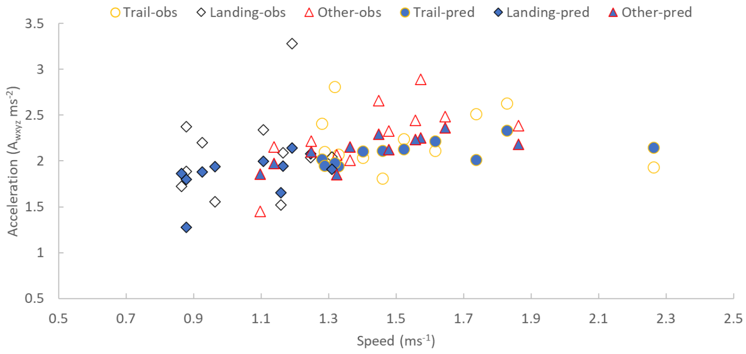

*Figure 4. Observed and predicted weighted rms acceleration ($A_{wxyz}$) for each value of site (A - K) and location (landing, trail, other) compared to the mean speed.*

*Figure 5. Observed (obs) and predicted (pred) weighted rms acceleration ($A_{wxyz}$) for each value of site (A - K) and location (landing, trail, and other) and grouped by Operational Style (OS-0, OS-1, and OS-2) compared to the mean speed.*

*Table 5. Operations data and estimated acceleration from skidders in Klepac and Mitchell (2016) using the model for $A_{wxyz}$. Weighted acceleration (A(8)) was estimated with 6 hours of operating time in an 8 hour shift.*

| | | Skidder | | | |
|---|---|---|---|---|---|
| | | Cat 525B | Cat 525B | TC 630D | TC 630D |
| Load size | Tons per cycle | 3.2 | 3.8 | 5.9 | 6.8 |
| Proportion of operating time | Trail | 0.52 | 0.70 | 0.67 | 0.68 |
| | Landing | 0.27 | 0.10 | 0.20 | 0.18 |
| | Other | 0.21 | 0.25 | 0.28 | 0.21 |
| Speed ($ms^{-1}$) | Trail | 1.74 | 2.55 | 2.77 | 2.19 |
| | Landing | 1.01 | 1.01 | 1.01 | 1.01 |
| | Other | 1.46 | 1.46 | 1.46 | 1.46 |
| | Observed | 1.44 | 2.30 | 2.65 | 2.14 |
| | Estimated | 1.48 | 2.25 | 2.46 | 1.98 |
| Weighted acceleration A(8) ($ms^{-2}$) | OS-0 | 1.93 | 2.26 | 2.37 | 2.16 |
| | OS-1 | 1.95 | 2.43 | 2.56 | 2.27 |
| | OS-2 | 1.82 | 1.96 | 2.06 | 1.94 |
| Operating hours to 1.5 $ms^{-2}$ | OS-0 | 3.6 | 2.6 | 2.4 | 2.9 |
| | OS-1 | 3.5 | 2.3 | 2.1 | 2.6 |
| | OS-2 | 4.1 | 3.5 | 3.2 | 3.6 |

# References

Bovenzi, M., Rui, F., Negro, C., D'Agostin, F., Angotzi, G., Bianchi, S., . . . Stacchini, N. (2006). An epidemiological study of low back pain in professional drivers. Journal of Sound and Vibration, 298(3), 514-539. doi:10.1016/j.jsv.2006.06.001

Cation, S., Jack, R., Oliver, M., Dickey, J., & Lee-Shee, N. (2008). Six degree of freedom whole-body vibration during forestry skidder operations. International Journal of Industrial Ergonomics, 38(9-10), 739-757. doi:10.1016/j.ergon.2007.10.003

Cocheo, C. (2013). The influence of the operator driving style in whole-body vibration exposure from wheel loaders in a limestone quarry. Italian Journal of Occupational and Environmental Hygiene, 4(1), 6-11.

Eger, T. R., Contratto, M. S., & Dickey, J. P. (2011). Influence of driving speed, terrain, seat performance, and ride control on predicted health risk based on ISO 2631-1 and EU directive 2002/44/EC. Journal of Low Frequency Noise, Vibration and Active Control, 30(4), 291-312.

Golsse, J.-M. (1990). Evaluation of skidder seats for reducing whole-body vibration. Technical Report TR-99, FERIC.

Golsse, J.-M., & Hope, P. A. (1987). Analysis of whole-body vibration levels during skidding. Technical Report TR-77, FERIC.

ISO Standard. (1997). 2631-1: Mechanical vibration and shock - evaluation of human exposure to whole body vibration.

Klepac, J., & Mitchell, D. (2016). Comparison of four harvesting systems in a loblolly pine plantation. Professional Agricultural Workers Journal, 4(1), 1-14.

Lynch, S. (2017). Quantification of ergonomic risk factors in southeastern logging operations. (PhD). Auburn University,

Marin, S., L., Rodriguez, A., Rey, E., Barrero, L. H., Dennerlein, J., & Johnson, P. W. (2016). Influence of speed in whole body vibration exposure in heavy equipment mining vehicles. Paper presented at the Human Factors and Ergonomics Society Annual Meeting.

Mayton, A., & Kim, B. (2021). Using a mobile app to estimate whole-body vibration and seat isolation performance in surface mining. International Journal of Heavy Vehicle Systems, 28(4), 487-502. doi:10.1504/IJHVS.2021.118239

Oliveira, F., Lopes, E., Koehler, H., & Behling, A. (2021). Application of an Integrated Ergonomic Indicator (IEI) in evaluating forest machines. International Journal of Forest Engineering, 32(3), 256-265. doi:10.1080/14942119.2021.1937773

Rehn, B., Lundstrom, R., Nilsson, L., Liljelind, I., & Jarvholm, B. (2005). Variation in exposure to whole-body vibration for operators of forwarder vehicles - aspects on measurement strategies and prevention. International Journal of Industrial

Ergonomics, 35(9), 831-842. doi:10.1016/j.ergon.2005.03.001

SAS-Institute. (2016). SAS (Version 9.4).

Tiemessen, I. J., Hulshof, C. T., & Frings-Dresen, M. H. (2008). Low back pain in drivers exposed to whole body vibration: analysis of a dose-response pattern. Occup Environ Med, 65(10), 667-675. doi:10.1136/oem.2007.035147

Wegscheid, E. (1994). Another look and skidder ride vibration. Journal of Forest Engineering, 5(2), 21-32.