

Influence of Thinning on Acoustic Velocity of Douglas-fir Trees in Western Washington and Western Oregon

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Abstract

Acoustic velocity was measured with a time-of-flight method on approximately 50 trees in each of five plots from four test sites of a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) thinning trial. The test sites reflect two age classes, 33 to 35 and 48 to 50 years, with 50-year site index ranging from 35 to 50 m. The acoustic velocity distribution in each plot formed the basis for selecting a stratified sample of 12 trees that were harvested for conversion into veneer or lumber. Using a resonance acoustic method, acoustic velocity was obtained for the delimbed and topped merchantable stem. The merchantable stem was bucked into long logs that were either mostly 35 ft (10.7 m) long for veneer conversion or 33 ft (10.1 m) long

for lumber conversion. After delivery to mill log yards, the long logs were measured with the resonance acoustic velocity method. The veneer long logs were bucked into 17 ft (5.1) short logs and the lumber long logs were bucked into 16 ft (4.9 m) short logs. The short logs were then tested with the resonance acoustic velocity method and cross-sectional discs were removed for measurement of density, moisture content, and other properties. Full and half sheets of veneer and 2 by 4 and 2 by 6 lumber recovered from the short logs were tested for stiffness and other properties. This paper presents two analyses. First, the 50 tree per plot sample is summarized and regression models are developed to examine the effects of thinning, stand age, stand density, and site index on tree acoustic velocity. Second, the six sample trees from each plot that were converted to lumber are summarized to examine relationships between time-of-flight acoustic velocity measured on the standing tree, the resonance acoustic velocity measured on the first woods log and first short log, and the modulus of elasticity (MOE) of lumber obtained from the first short log.

Introduction

When a forest stand is initiated or manipulated with a cultural treatment, managers often ask questions such as: What is the effect on growth, yield, and tree size? What is the effect on wood quality? Although forestry has many widely accepted field tools, sampling procedures, software, and models for gathering and summarizing data and making projections of growth, yield, and tree size, counterparts for wood quality assessment have lagged far behind. One of the reasons for this lag has been

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a lack of simple field tools permitting rapid collection of quality data from trees in a stand or sample plot. Lack of information about quality can lead to expensive misallocation of timber to processing facilities whereby products with desired characteristics and value are not obtainable. Furthermore, an inability to routinely collect information about quality as part of monitoring stand development may lead to choices of cultural practices that fail to maintain or improve quality or fail to meet expected future customer needs.

A second reason for the lag in wood quality assessment is the historical perception that nothing can be done about it because quality is a legacy of past growth that is present at harvest and all that one can do is sort and allocate according to visual grading rules that were set up for this purpose. Today this perception is inaccurate due to the intensive planning of forest development from choice of species to harvest and the shorter rotation now common on industrial forests. In addition, several factors are challenging traditional grading rules as a reasonable method for assessing quality and matching the resource to customer needs. Among these challenges are:

1. Continued dominance of construction as the primary use of wood, particularly coniferous species, in the U.S. construction applications require long, deep, straight members that are stiff and strong.
2. Trees, and the logs obtained from them, are smaller in diameter making it more difficult to obtain long, deep members.
3. Through genetic improvement and intensive silviculture trees are growing faster and reach harvestable size at a younger age. These young, fast-growing trees have a high proportion of juvenile wood of relatively low stiffness and strength compared to mature wood that would accumulate if rotations were longer. Furthermore, knots on fast-growing trees are often larger, further reducing strength and stiffness of products.
4. Visual log grading does not provide a precise, accurate assessment of the properties of wood products that can be recovered from logs. The peeler-sawlog grading system used in the Pacific Northwest for Douglas-fir places most logs in two grades, No.2 and No.3 Sawlog (H & W Saunders Ltd. 2001). These two log grades have no growth rate restriction, allow knot diameters up to 2.5 or 3.0 in., and have minimum small end diameter limits of 12 and 6 in. Logs of vastly different quality will be found in each of these grades and product recovery studies show no relationship between recovered product quality and these grades (Fahey et al. 1991) and in one case the relationship was inverted (Sonne et al. 2004).
5. To overcome these limitations, there has been a growing trend toward engineered wood products which combine small wood elements with adhesives and other materials. Engineered wood products fall into two classes: those that use stress-rated lumber or veneer elements in their construction, such as glulam beams, laminated veneerlumber, I-beams and joists, and trusses, and those that do not use stress-rated wood elements, such as oriented strandboard, oriented strand lumber, and wood-plastic composites.

These changes and factors raise new questions, such as what wood properties today's products need and how the match between the resource and product needs can be improved to increase value.

Technology using the speed of sound (often referred to as acoustic speed, ultrasonic speed, or stress wave speed; some replace the term speed with velocity) for assessing mechanical and physical properties of wood and wood-based materials is well known and documented (Pellerin and Ross 2002). In recent years, research in this field developed methods to assess the acoustic velocity in logs to predict stiffness of lumber or veneer they will yield (Ridoutt et al. 1999, Ross et al. 1997, Ross et al. 1999, Wang et al. 2004) and to assess acoustic velocity in standing trees to extend these predictions along the tree-to-product chain (Carter et al. 2005, Dickson et al. 2004, Knowles et al. 2004). This research has led to commercial field tools for assessing acoustic velocity of trees and logs and logs. Some of these tools (e.g., Fakopp TreeSonic, Fibre-gen ST-300)¹ use the time-of-flight method to measure acoustic velocity while other tools (e.g., Fibre-gen HM 200) use a resonance acoustic method (Wang et al. 2007). The time-of-flight tools are commonly used to obtain acoustic velocity near the base of trees while both types can be used to obtain acoustic velocity of logs. For further discussion of these methods relationships between tree and log acoustic velocity see Wang et al. (2007). The tree tools provide a means by which silviculturists, forest managers, and planners can predict stiffness potential of stands prior to harvest and could assist in valuation, stumpage purchase, and harvest scheduling decisions. The log tools provide a method for assessing potential product stiffness and can improve log marketing by matching log properties with veneer and lumber manufacturer needs.

Objectives

Although a number of studies have investigated the relationship between tree and log acoustic velocity and be-

¹ FAKOPP Enterprise Bt., H-9423 Agfalva, Fenyo u. 26, Hungary; Fibre-gen, 26 Tiffany Close, Manukau 2016, New Zealand. Neither the University of Washington nor the U.S. Forest Service recommends the equipment used in this study to the exclusion of others that may be suitable.

Table 1.—Mean values of plots from the installations of the Stand Management Cooperative.^a

Inst#	Owner	Location	Year planted	Year established	Age established	Age 2006	SI m (King)	QMD (cm)	HT40 (m)
803	Green Diamond	Shelton, WA	Jan 1955	1987	32	51	44	36	38
805	WADNR	Mt. Vernon, WA	Jan 1970	1988	18	36	47	30	32
807	Port Blakely	Estacada, OR	Jan 1974	1989	15	32	38	28	25
808	Weyerhaeuser	Dallas, OR	Dec 1960	1989	29	45	39	33	31

^a SI = site index at 50 years breast-height age; QMD = quadratic mean DBH; and HT40 = average height of the 40 largest trees by DBH.

tween log acoustic velocity and stiffness of lumber or veneer for a variety of species, relatively little is known about these relationships for Douglas-fir (*Pseudotsuga menziesii*, Mirb. Franco), which is renowned for its density and stiffness and is widely used in construction applications. Furthermore, less is known about how genetics and silvicultural practices affect acoustic velocity of trees in a stand; information that is important to managers wishing to make informed choices to enhance stiffness and value of Douglas-fir plantations. These issues led to a grant funded by the USFS Rocky Mountain Research Station as part of the AGENDA 2020² program with the following objectives.

1. What are the relationships between the average stiffness of lumber or veneer in a log, stiffness of the log, and stiffness of the parent tree and to what extent are these relationships influenced by stand, tree, or log variables?
2. What are the effects of cultural treatments and genetics on these stiffness relationships?
3. How can the natural variability of stiffness among trees within a stand be monitored and incorporated into decision support tools that assist managers in assessments if stands and stand treatments are within desired specifications and in making improved marketing decisions?

This paper summarizes results that are emerging for the tree to log to lumber aspect of Objective 1.

² This is a product of the Sustainable Forestry component of Agenda 2020, a joint effort of the USDA Forest Service Research & Development and the American Forest & Paper Association. Research partners include the Stand Management and Precision Forestry Cooperatives and Rural Technology Initiative Program at the University of Washington College of Forest Resources, USFS Pacific Northwest Research Station, and CHH FibreGen. Funds were provided by the USFS Rocky Mountain Research Station, the University of Washington, College of Forest Resources, the USFS Pacific Northwest Research Station, and the USFS Forest Products Laboratory.

³ A consortium of landowners and research institutions in the Pacific Northwest formed in 1985 to provide high-quality data on the long-term effects of silvicultural treatments on growth and yield, wood quality, and other forest services.

Experimental Procedure

Sample Material

Four Douglas-fir research installations of the Stand Management Cooperative (SMC)³ were chosen for this study (Table 1). They were established in 1987-1989 each with five plots; a control plus four plots following prescribed thinning regimes based on Curtis' relative density (Curtis 1982). Each plot is 1.15 acres (0.47 ha) and contains a square 0.5 acre (0.20 ha) measurement sample plot (MSP) surrounded by a treated buffer. In September 2006, a circular 0.25 acre (0.1 ha) plot was established in the geometric center of each MSP. Time-of-flight acoustic speed was obtained over a 1 m distance approximately centered at breast height (BH) on all of the trees within the circular plot with a TreeSonic timer. Three readings were obtained at each of three locations approximately 120° apart around the stem circumference, providing nine observations for each tree. All trees were mapped with respect to the center of the circular plot and the plot radius was increased if needed until a minimum of 50 trees were measured. One plot, on installation 808, was not used due to prior storm damage to the trees. In total 966 trees were measured.

In the office, the nine stress wave times were converted to mean acoustic velocity for each tree. Trees on each plot were listed in ascending order of acoustic velocity and a stratified random sample was selected. Two trees were randomly chosen from the lowest 10 percent, four from the next 11 to 50 percent, four from 51 to 90 percent, and two from the top 91 to 100 percent on each plot. One half of the trees in each stratum were randomly chosen for veneer conversion and the remainder for lumber conversion. Therefore, six trees from each of the 19 plots were selected for conversion to veneer and six for conversion to lumber; a total of 114 trees for each conversion process.

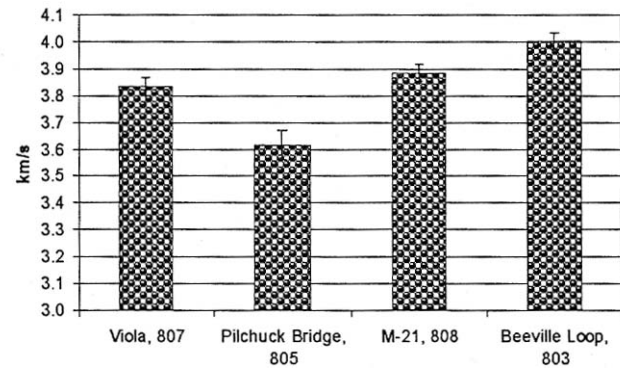
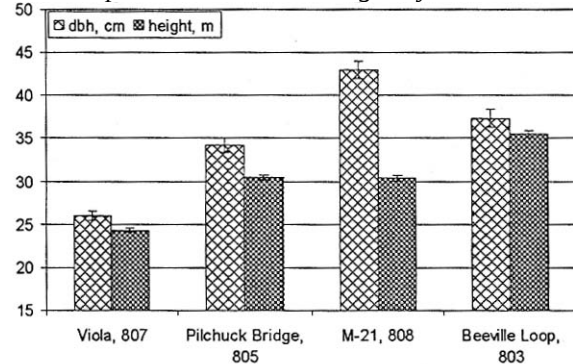
Harvesting was conducted between late October and early December 2006. Each sample tree was re-tested with the TreeSonic before felling. After felling, detailed measurements (Table 2) were obtained for the tree, merchantable stem, and long logs. The log preference for lumber process trees was to cut 33-ft- (10.1 m) long logs that were bucked into two 16-ft- (4.9 m) short logs for

Table 2.—*Treatment plot, tree, and log data.*

Variable	Description
Treatment plot	
AGE	Stand age, planting year to harvest year
STEMS	Number of stems ha ⁻¹ present at establishment and at harvest
HT40	Average height of the 40 largest trees by DBH, m
SIso	50 year breast-height age site index (King 1966) calculated from plot data
QMD	Quadratic mean DBH, cm
RD	Curtis' relative density at establishment and at harvest: plot basal area, m ² /QMD, cm ^{1/2}
PRD	Curtis' relative density at establishment after re-spacing each plot; plot basal area, m ² /QMD, cm ^{1/2}
Tree data	
DBH	Diameter at breast height, cm
HT	Total height, m
HCB	Height to crown base, m
HT/DBH	Ratio of total height to DBH, cm/cm
CL	Crown length = HT-HCB, m
CR	Crown ratio = 1-HT/HCB
V	Acoustic velocity, km/s, obtained from TreeSonic over 1 m distance
Long log and short log data	
Length	
Diameter at small and large ends	
Log scale, Scribner and cubic	
Acoustic velocity, km/s, obtained with the Director HM-200	
Diameter of the largest knot in each short log face	
Location and diameter of ramicorn branches in each log face	
Cross-section disc data (ends of each short log)	
Ring count	
Diameter outside bark, inside bark, at 10 rings, at 20 rings, at heart/sap boundary	
Green density (green weight/green volume)	
Ovendry weight (103°C) → Disk moisture content and specific gravity	
X-ray densitometer sample (pith to bark)	

sawing into lumber. The log preference for veneer process trees was to cut 35 ft (10.7 m) long logs that were bucked into two 17 ft (5.1 m) short logs each containing two peeler blocks. Cross-sectional discs were cut from the ends of the long logs and measured on-site. Detailed measurements of long logs were obtained at the mill log yards after which they were bucked to short (or mill) log lengths and re-measured. Resonant acoustic velocity of the merchantable bole, long logs, and short logs from each tree was obtained with the HM-200.

Sawing, drying, and planing of short logs from the lumber conversion trees was conducted at the South Union Sawmill in Elma, Washington during March and April 2007. Lumber was shipped to the U.S. Forest Products Laboratory where MOE was measured using the Metri-

a) *Mean sample tree acoustic velocity by installation***b)** *Mean sample tree DBH and height by installation***Figure 1.**—*Mean DBH (cm), total height (m), and acoustic velocity (km/s) for the four sample installations ($\pm$ se).*

guard E-computer. The 114 lumber conversion trees produced 246 long logs (26.1 MBF Scribner log scale) and 318 short logs; a number of long logs were not delivered from Installation 807 due to weather and many logs were not sawn; generally small diameter; crooked logs either from very small sample trees, or the upper stem of larger trees. In total 26.3 thousand board feet (MBF) of 2 by 4 and 2 by 6 lumber was obtained and tested.

Analysis

In effect, this study produced three distinct but inter-related data sets:

1. the 966 trees measured on the plots as the basis for the stratified sample chosen for product conversion,
2. the 114 lumber conversion trees from the stratified sample with corresponding log, disc, and lumber measurements, and
3. the 114 veneer conversion trees from the stratified sample with corresponding log, disc, and veneer measurements.

Since data checking and cleaning and development of an integrated database for the entire study is still underway, results presented in this paper, which is based on data sets 1 and 2, should be considered as preliminary.

Plot mean and individual tree statistics from data set 1 are presented graphically in Figures 1 through 4 to

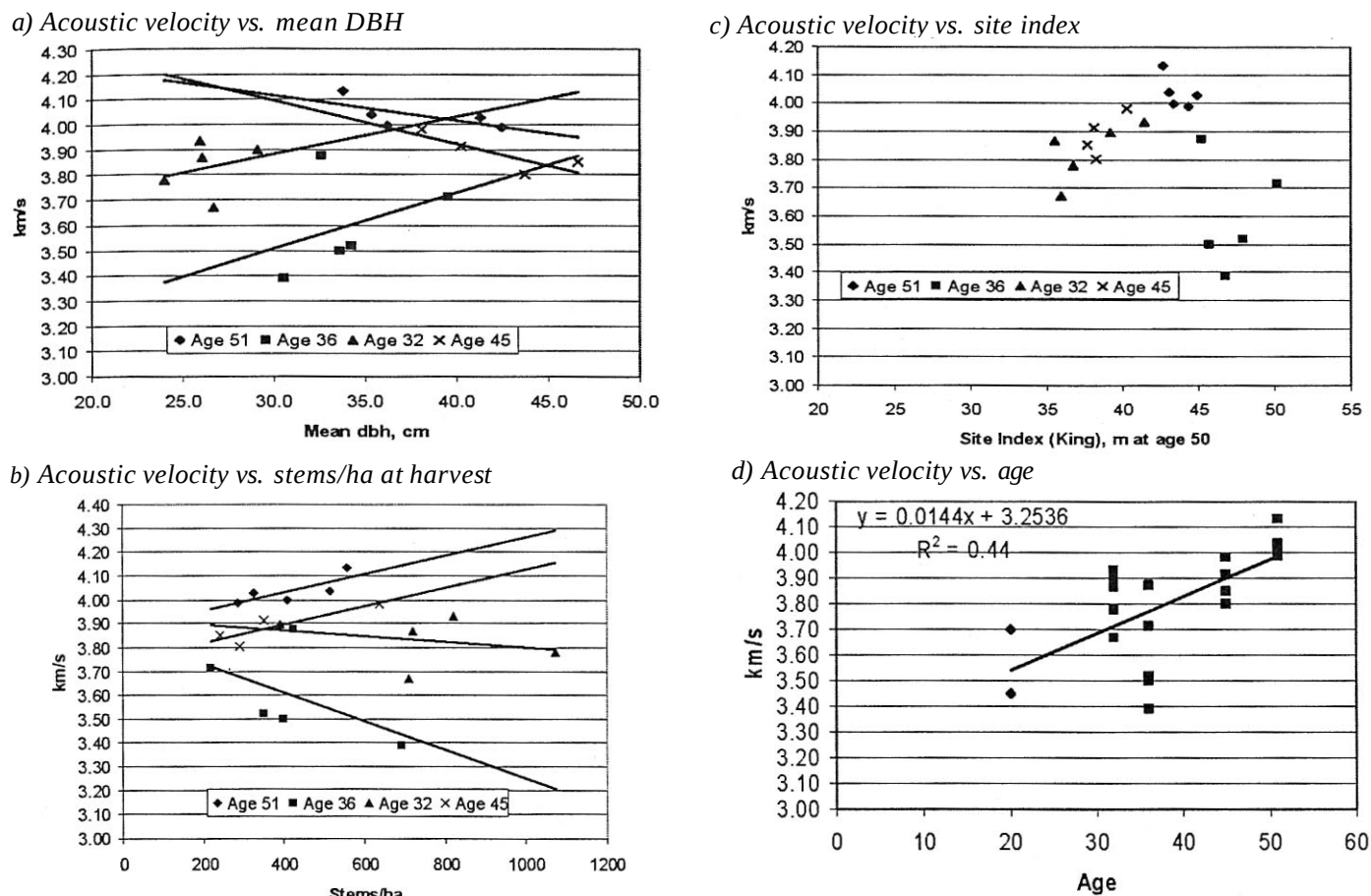


Figure 2.—Mean acoustic velocity (km/s) vs. (a) plot mean DBH (cm), (b) stems ha⁻¹, (c) site index (m), and (d) age for the 19 plots.

show the effects of installation and treatment plot conditions on acoustic velocity. Simple linear and multiple regression models were used to develop models that provide insights useful for forest management and silvicultural planning and which can be linked to growth models to predict acoustic velocity of trees in response to stand conditions and silvicultural treatments.

Data set 2 was used to calculate mean MOE of lumber for each short log and each long log position from each tree. Trees were sorted into five acoustic velocity classes (<3.33, 3.33 to 3.66, 3.67 to 3.99, 4.00 to 4.32, and ≥4.33 km/s). Mean tree and log position statistics were calculated for each of these tree classes and are presented graphically. Means were also calculated for each of the 19 treatment plots; simple linear regression models were developed for predicting plot mean first long log acoustic velocity, mean first short log acoustic velocity, and mean MOE of lumber from the first short logs from mean tree acoustic velocity. Simple linear regressions were also developed between first long log acoustic velocity and first short log acoustic velocity and between first short log mean lumber MOE and first short log acoustic velocity. Counterpart simple linear regression models were also

developed for the 85 lumber process trees from which logs were delivered and processed. Of the 114 trees sampled, 29 were either not delivered or logs from them were too small or crooked to saw. In developing the summaries, three extreme outlier short logs were removed.

Results and Discussion

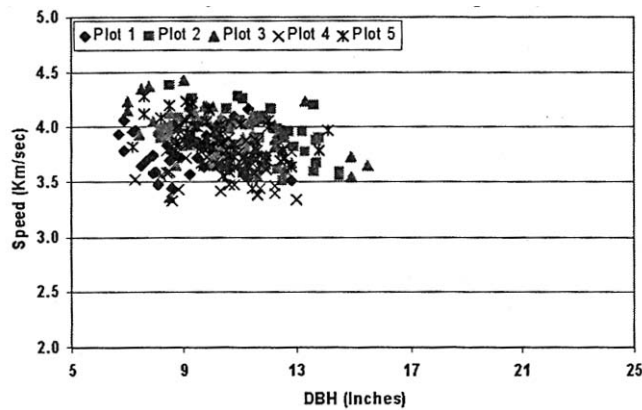
Effect of Stand and Treatment Variables on Tree Acoustic Velocity

The summaries in this section are based on acoustic velocity of 966 trees measured on the 19 treatment plots. **Figure 1** provides an overview of the mean statistics for all plots combined on each installation; **Figure 1a** shows mean tree acoustic velocity and **Figure 1b** shows mean tree DBH (cm) and height (m). The two left installations in these graphs were age 32 to 36 at harvest (15 to 18 at plot establishment) while the two on the right were age 46 to 51 at harvest (29 to 32 at plot establishment). Generally, the two younger installations had smaller trees and lower tree acoustic velocity.

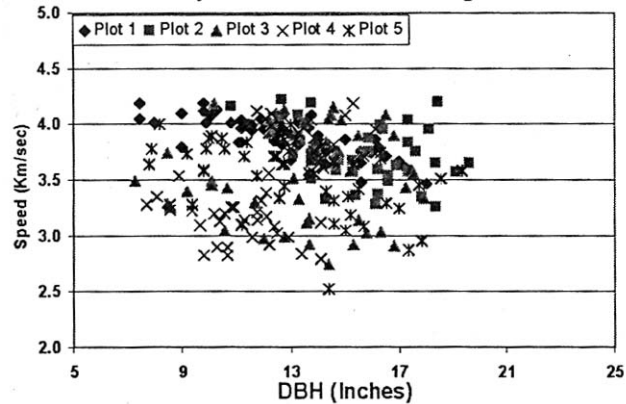
Figure 2 provides treatment plot details:

- mean tree acoustic velocity by mean DBH,

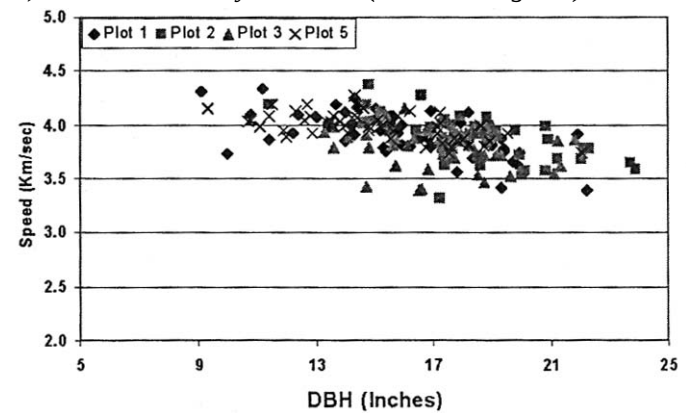
a) Acoustic velocity vs. DBH (Inst. 807, age 31)



b) Acoustic velocity vs. DBH (Inst. 805, age 36)



c) Acoustic velocity vs. DBH (Inst. 808, age 45)



d) Acoustic velocity vs. DBH (Inst. 803, age 51)

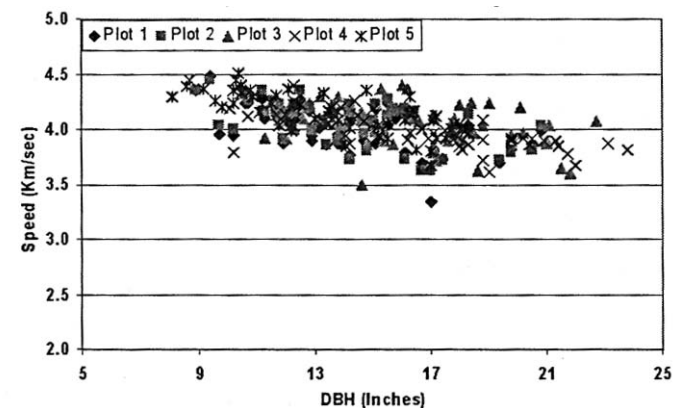


Figure 3.—Individual tree acoustic velocity (km/s) vs. DBH by plot on each sample installation, $n = 966$ trees, average 51 trees/plot.

- mean tree acoustic velocity by stand density in number of stems ha^{-1} ,
- mean tree acoustic velocity by 50-year BH age site index (King 1966), and
- mean tree acoustic velocity by stand age.

For acoustic velocity versus DBH (**Fig. 2a**) and versus the number of stems ha^{-1} (**Fig. 2b**), the two younger installations show increasing acoustic velocity with increasing DBH and decreasing stems ha^{-1} while the two older installations show opposite trends. This is perplexing but the difference in age when these installations were established and treatments began may explain some of these differences. When the plots were established, the two older stands were 29 to 32 years old, well beyond the 20 year age of transition from juvenile wood to mature wood is commonly used for Douglas-fir (Fahey et al. 1991). Many studies have found a 5 to 10 percent decrease of wood specific gravity following thinning although thinning may increase specific gravity on sites with late season moisture deficits (Briggs and Smith 1986). Since lower specific gravity is associated with lower strength and stiffness, reduced acoustic velocity would be expected in sites without the moisture deficit conditions. The lower acoustic velocity with increased

DBH associated with the thinning in the two older installations is in agreement with others (Wang et al. 2001); Carter et al. (2005) found that thinning increased acoustic velocity in a stand with a late season moisture deficit. In contrast, the younger stands were 15 to 18 years old, close to the age of transition from juvenile wood to mature wood in Douglas-fir. Since mature wood is stronger and stiffer than juvenile wood (Bendtsen 1978), one would expect acoustic velocity of trees to increase as mature wood is added. Thinning, which was more frequent in these young stands, reduced stand density, increased DBH, and added mature wood more rapidly. Consequently, these young stands exhibit increasing acoustic velocity with decreasing stand density and with increasing DBH. At the juvenile-to-mature wood transition stage of stand development, the trend of increasing wood stiffness combined with the generally negative effect of thinning. Apparently, the net effect in these two installations is positive, i.e., the gain due to the shift to mature wood production offset the growth effect produced by thinning. This agrees with Bendtsen (1978) who pointed out that the effect of accelerated growth alone on wood properties is minor compared with the difference between juvenile wood and mature wood properties.

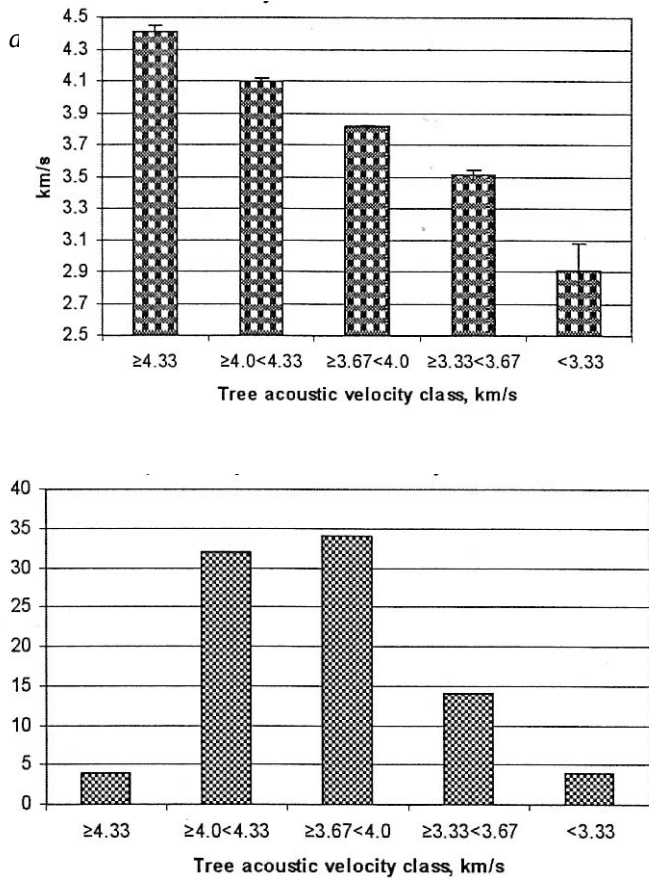


Figure 4.—Mean acoustic velocity ($\pm se$) and frequency of trees in each tree acoustic velocity class.

Branches in the lower stem may also be involved in these differences. The trees in the young stands had many branches within the region of the stem tested for acoustic velocity, making it difficult to obtain a time-of-flight measurement that was not affected by knot wood. Since stress wave transmission time is much faster parallel to the grain than perpendicular to the grain (Pellerin and Ross 2002), knot wood and distorted stem wood around knots will slow wave time along the stem lowering the acoustic velocity. Given the geometry of branches radiating from the stem center, there is a higher chance that distortions associated with knots will affect acoustic velocity when stem diameter is small. Reduced stand density, which increases stem diameter growth, likely reduced the effect of knots on acoustic velocity. Future research will be needed to examine the trade-off between the positive effect of the accumulation of mature wood and the negative effect of knots. The trend with site index (Fig. 2c) is unclear; there is a pattern of increasing acoustic velocity with increasing site index for plots from three of the installations but this is not consistent with the fourth. There is a pattern of increasing acoustic velocity with increasing age (Fig. 2d); in this figure, data has been added from two younger installations. Increasing acoustic velocity with increasing age would be expected as trees age

and accumulate strong, stiff mature wood over a core of less strong and stiff juvenile wood.

Although the patterns for plot mean acoustic velocity versus plot mean DBH are contradictory in **Figure 2a**, **Figure 3** shows a trend of decreasing acoustic velocity versus DBH at the individual tree level for all of the plots on all of the installations. This is consistent with previous reports (Carter et al. 2005). Reasons for higher variability exhibited by trees on the younger installations, however, are not clear. Observations in the field noted that trees in these younger installations had a much higher density of branches over the 1 m distance measured for acoustic velocity than the older installations. The knot effect on acoustic velocity noted above, combined with the higher branch density may be contributing to higher variability within and between trees from the younger installations. Future research will be needed to determine if knottiness or other factors are responsible for higher variability of acoustic velocity in younger stands.

A regression model to predict the mean plot acoustic velocity from these stand variables found that only age and stand density; stems ha^{-1} , at establishment were significant ($r^2_{adj} = 0.77$, RMSE = 0.68, $n = 19$).

$$\frac{V_{km/s}}{1.558} = 2.871 + 0.2261 \text{ AGE} + 0.00682 \frac{SPHA_{estab}}{0.00125}$$

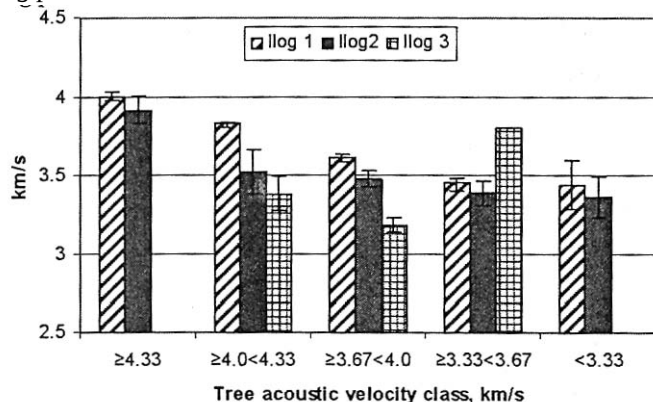
Mean acoustic velocity of trees in a stand increases with its age and with denser stem count.

A counterpart model was developed at the individual tree level ($r^2_{adj} = 0.42$, RMSE = 0.23, $n = 966$).

$$\begin{aligned} \frac{V_{km/s}}{0.324} = & 3.090 + 0.0252 \frac{RD_{estab}}{0.0054} + 0.0113 \frac{AGE}{0.0033} - \\ & 0.0259 \frac{DBH_{cm}}{0.0045} - 2.792 \left(\frac{SPHA_{end}}{SPHA_{estab}} \right) \frac{0.415}{0.0033} + 0.0187 \frac{RD_{harv}}{0.0033} + \\ & 0.942 \frac{THIN}{0.226} - 0.0320 \frac{RD_{destab}}{0.0055} THIN + \\ & 0.0143 \frac{AGE}{0.0038} THIN + 0.0279 \frac{DBH_{cm}}{0.0082} \left(\frac{SPHA_{end}}{SPHA_{estab}} \right) \end{aligned}$$

Tree acoustic velocity increases with increasing age and decreases with increased DBH as would be expected from **Figures 2d** and **3**. The effect of stocking and stocking change, however, is also important as can be seen by the complex of terms involving relative density at establishment and at harvest, the fraction of number of stems ha^{-1} that remain, and whether or not the stand was thinned. The significant effect of thinning has been reported by others (Carter et al. 2005, Wang et al. 2001), but one found that thinning led to an increase in acoustic ve-

a) Long (33 ft) log mean acoustic velocity by tree class and log position



b) Number of long (33 ft) logs by tree class and log position

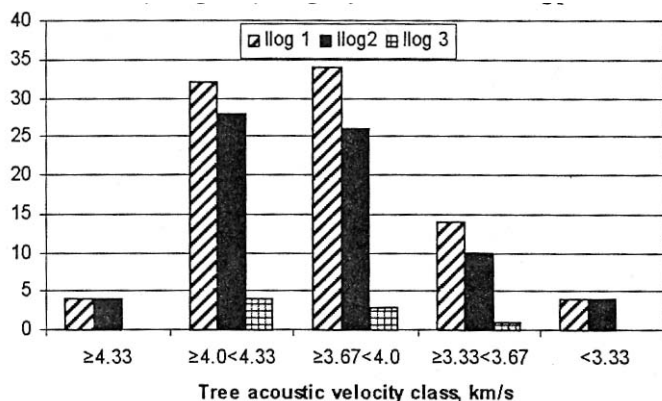


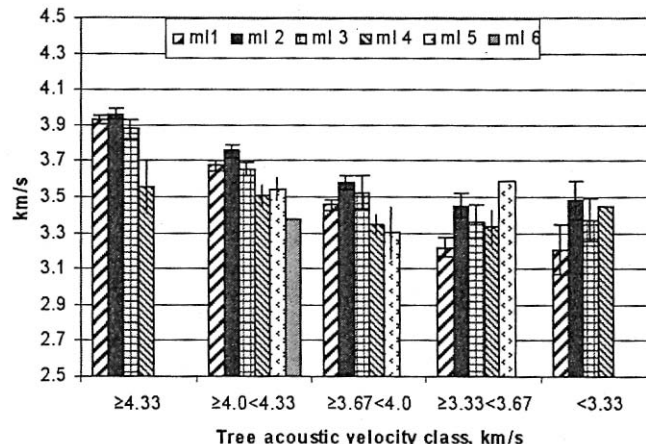
Figure 5.—Mean acoustic velocity ($\pm$ se) and frequency count of long-logs by height position within each tree acoustic velocity class.

locity while the other found a decrease. Differences in species, site conditions, and type of thinning may produce seemingly contradictory effects of thinning. For example, referring to **Figure 3**, it should be apparent that a thinning that removes smaller DBH trees from these Douglas-fir plots is removing the stems with higher acoustic velocity so the mean acoustic velocity of the residual stand will be immediately lowered. Since the scope of the study installations and treatment plots within them is somewhat limited, we caution against wide use of our equation. But, it points out the need for more comprehensive studies of how stand and treatment variables affect acoustic velocity; a topic of importance for management of silvicultural operations and potential integration with growth models.

Relationships Among Tree and Log Acoustic Velocities and Recovered Lumber MOE

Figure 4 presents mean and standard errors of acoustic velocity and frequency of trees within the five tree acoustic velocity classes. Approximately 75 percent of the trees were nearly equally split between the 3.67 to 4.00

a) Mill (16 ft) log acoustic velocity by tree class and log position



b) Number of mill (16 ft) logs by tree class and log position

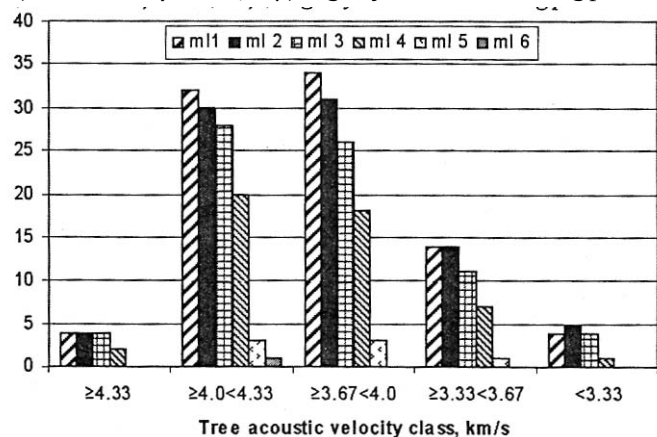
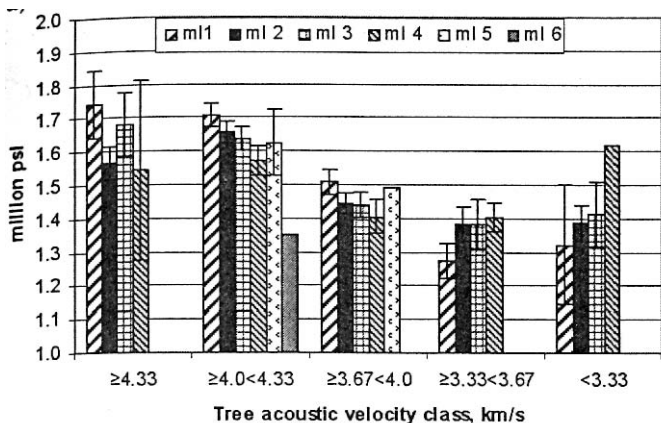


Figure 6.—Mean acoustic velocity ($\pm$ se) and frequency count of short-logs by height position within each tree acoustic velocity class.

and 4.00 to 4.33 classes. **Figure 5** shows mean and standard errors of acoustic velocity and frequency of long logs by height position for the trees in each of these classes. The three higher tree acoustic velocity classes indicate a decrease in long log acoustic velocity with higher height position in the tree but this pattern is not as distinct in the lower two acoustic velocity classes. The very high acoustic velocity for the log 3 position in the 3.33 to 3.67 class is due to a single log.

Figure 6 shows mean and standard errors of acoustic velocity and frequency of short logs by height position for the trees in each of the classes. Short log acoustic velocity is always lower for log position 1 (butt) compared to position 2 which is consistent with other data for Douglas-fir (Carter et al. 2005). Megraw et al. (1999) found lower stiffness of clear wood in the lower end of Douglas-fir trees and attribute this to a combination of high microfibril angle and low wood density. **Figure 7** shows mean and standard errors of acoustic velocity and frequency of MOE of lumber from short logs by height position for the

a) Lumber MOE by tree class and mill (16 ft) log position



b) Number of mill (16 ft) logs by tree class and log position: MOE

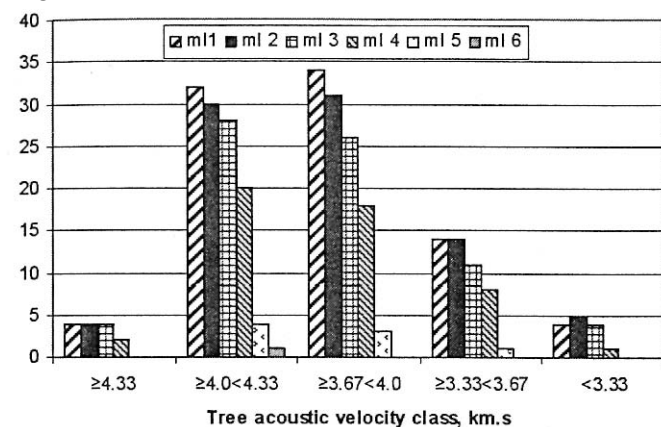


Figure 7.—Mean lumber MOE ($\pm$ se) and frequency count of short-logs by height position within each tree acoustic velocity class.

trees in each of the classes. The pattern of mean MOE with log position is similar to that of acoustic velocity but the log 1 position does not exhibit lower mean MOE compared to position 2. The lack of consistency with **Figure 6**, especially in the three higher acoustic velocity classes, may be associated with differences in knots, juvenile wood percent, or other factors. Although the patterns of the three higher tree acoustic velocity classes are similar and seem consistent, the two lower tree classes seem to have a tendency for either no change or perhaps higher log acoustic velocity and MOE higher in the stem. It should be noted that these two lower classes contain relatively few trees and have high standard errors; however, further investigation of low acoustic velocity trees and logs to understand this behavior seems warranted.

Figure 8 presents regressions between treatment plot ($n = 19$) trends of first long log ($r^2 = 0.55$) and first short log ($r^2 = 0.58$) mean acoustic velocity and first short log MOE ($r^2 = 0.58$) versus mean tree acoustic velocity. **Figure 9** presents regressions between the first short log versus first long log acoustic velocity ($r^2 = 0.88$) and be-

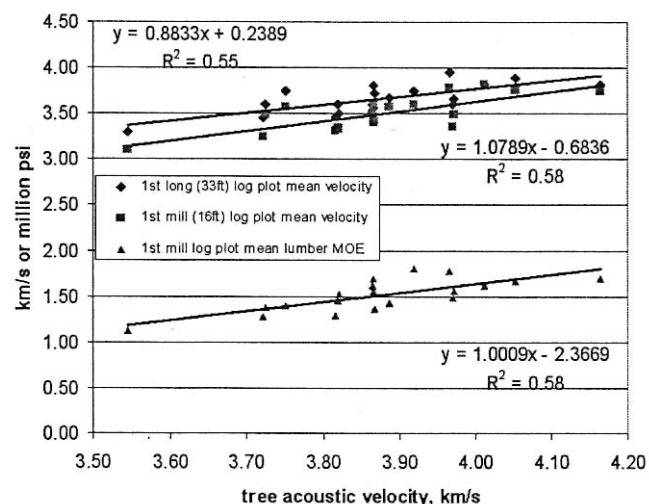
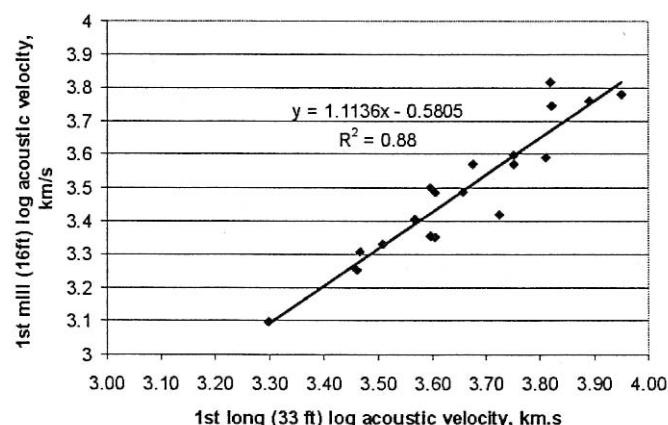


Figure 8.—Linear regression of mean acoustic velocity of the first (butt) long-log and short-log and first short-log mean lumber MOE vs. mean tree acoustic velocity for the 19 treatment plots.

a) 1st mill log velocity vs. 1st long-log velocity



b) 1st mill (16 ft) log: MOE vs. acoustic velocity

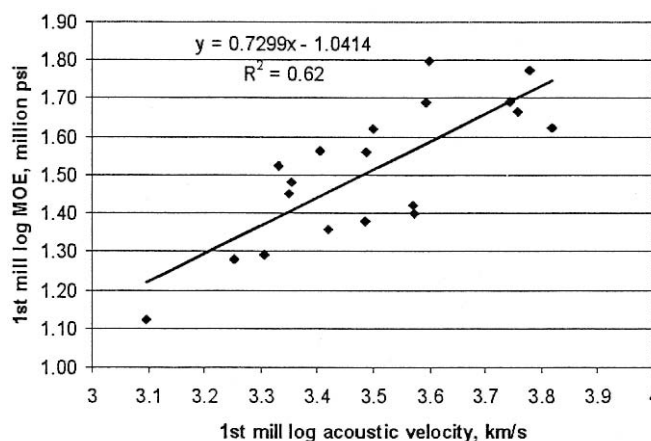


Figure 9.—Linear regression of (a) mean acoustic velocity of the first (butt) short-log vs. mean acoustic velocity of the first long-log and (b) mean MOE of lumber from the first short-logs and first short-log mean acoustic velocity for the 19 treatment plots.

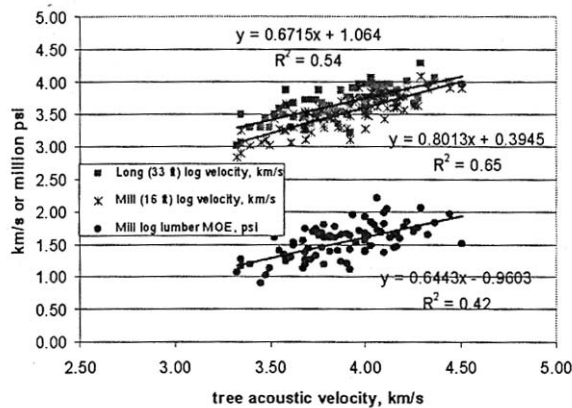


Figure 10.—Linear regressions of the acoustic velocity of the first (butt) long-log and short-log and first short-log lumber MOE vs. tree acoustic velocity for 85 sample trees.

tween first short log lumber MOE versus first short log acoustic velocity ($r^2 = 0.73$) These mean trends are consistent with previous studies (Dickson et al. 2004, Ross et al. 1997, Wang et al. 2004).

Figure 10 presents regressions between individual tree ($n = 85$) trends of first long log ($r^2 = 0.54$) and first short log ($r^2 = 0.65$) mean acoustic velocity and first short log MOE ($r^2 = 0.42$) versus mean tree acoustic velocity. **Figure 11** presents regressions between the first short log and first long log acoustic velocity ($r^2 = 0.90$) and between the first short log lumber MOE and first short log acoustic velocity ($r^2 = 0.59$).

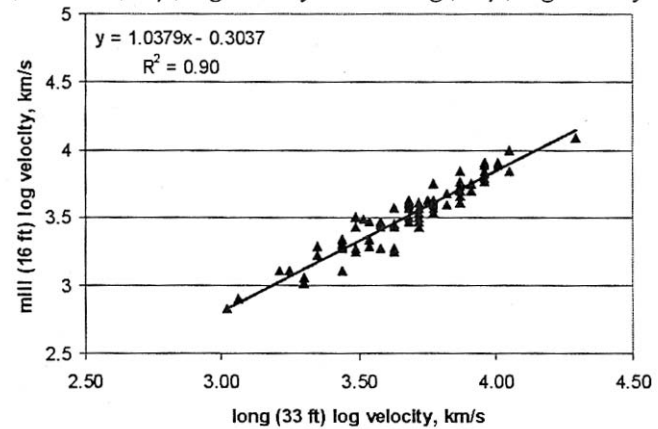
These preliminary analyses suggest that individual tree models for acoustic velocity are as good as plot mean models but that the model for individual tree MOE is somewhat poorer than its plot mean counterpart. Further understanding of the patterns and differences and resolution of some of the questions these models raise may emerge when the analysis is expanded to consider other data that is being edited and incorporated into the database. This includes the effect of knots (Ridoutt et al 1999) and ramicorn branches; log diameter (Wang et al. 2007); and wood density; ring count, percent juvenile wood, etc. obtained from the discs from the ends of each log.

Conclusions

This study developed relationships between time-of-flight acoustic velocity of standing trees, resonance acoustic velocity of logs, and MOE of lumber using a sample of six trees from 19 treatment plots on four installation sites of a Douglas-fir thinning trial. Preliminary findings are:

1. Tree acoustic velocity increases with age, decreases with DBH, and is affected by initial stand density conditions, (relative density and stems ha^{-1}) and change in density produced by thinning.

a) 1st mill (16 ft) log velocity vs. 1st long (33ft) log velocity



b) 1st mill (16 ft) log lumber MOE vs. log velocity

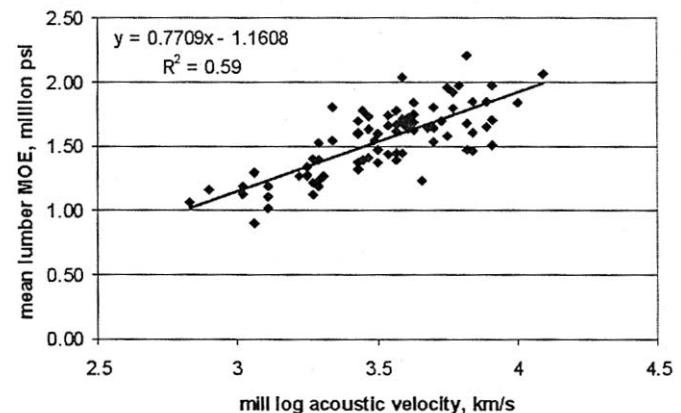


Figure 11.—Linear regression of (a) acoustic velocity of the first (butt) short-log vs. acoustic velocity of the first long-log and (b) MOE of lumber from the first short-log and first short-log acoustic velocity for the 85 sample trees.

2. Treatment plot mean and individual tree acoustic velocity, first (butt) long log velocity, first short log acoustic velocity, and first short log lumber MOE exhibit relationships similar to those reported by others.

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Proceedings of the 15th International Symposium on Nondestructive Testing of Wood

*September 10-12, 2007
Duluth, Minnesota, USA*

**Natural Resources Research Institute
University of Minnesota Duluth
Duluth, Minnesota, USA**

**USDA Forest Products Laboratory
Madison, Wisconsin, USA**



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ISBN-13: 978-1-892529-52-7

Publication No. 7221

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Printed in the United States of America.

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