Acoustic Velocity of Rail Ties with Free and Fixed Boundary Conditions

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Abstract

Nondestructive evaluation (NDE) is an effective technology that has been used for many decades to assess wood properties. However, NDE has not been well developed for in-service assessment of railroad ties of various wood species, grades, and boundary conditions. Acoustic velocity (AV) of railroad ties in free (on ballast) and fixed (packed with ballast and under static weight) boundary conditions was investigated herein. Overall, 60 new on-grade, 40 new off-grade, and 55 Grade-one (1) legacy ties were investigated. Ties were either oak/hickory or mixed hardwood. All ties were first measured in the free boundary condition and then packed with ballast, weighted, and measured in the fixed boundary condition. Ties were placed on ballast with approximately 10- to 11-cm (4- to 4.5-in.)-wide gaps between each. The AV that was measured after each tie was placed on the ballast (AV_{free}). Next, the ties were packed with ballast. Then a static weight, mimicking the load of rails, was placed on each tie and the AV was measured (AV_{fixed}) with a Hitman HM220. All data were analyzed using three-way analysis of variance. The AV was higher for new on-grade versus new off-grade and legacy ties. The AV was higher for fixed versus free boundary condition. These results indicate that AV could be used to separate on-versus off-grade ties during production and that laboratory-scale AV technology could develop into an in-service technique.

Wood is a preferred material for rail ties, also known as sleepers. However, it has challenges including long-term mechanical stress and degradation by organisms such as fungi and termites. Railroad safety is of critical importance at the national level. Railroad tie integrity is one key to maintaining gauge, i.e., the distance between the rails. Several materials have been used for railroad ties, including concrete, steel, synthetic polymers, fiberglass, and wood. Among those, >90 percent of rail ties are wood (Smith 2019). Wood's advantages include favorable processing, availability, elasticity, insulation, and installation. Tie strength and stiffness can vary among species (Lutch 2009, Rocha et al. 2021). The annual wood tie market is on the order of 20 million. These ties service the approximately 140 thousand miles of rail line in the United States. In the track, ties are spaced approximately 46 to 51 cm (18 to 20 in) apart in the center. Most wood ties are approximately 18 cm (7 in) thick by 23 cm (9 in) wide. As such, there are approximately 3,150 to 3,520 railroad ties per mile of track. By multiplying the miles of track times the number of ties per mile, one can estimate that there are approximately 441 to 493 million ties in service in the United States. With approximately 20 million ties going into service each year, one can estimate that the annual overall replacement rate is approximately 4 to 4.5 percent and that average service life is on the order of 22.5 to 25 years. To maintain rail safety, ties must be replaced before they lose functionality. Nondestructive evaluation (NDE) technology to assess ties in track is needed. In many cases NDE is used on wood products and structures. NDE makes possible the assessment of internal and nonvisible degradation in wood materials (Ross 2015, Abadi et al. 2019, Zielińska and Rucka 2021). The use of NDE to determine the biological degradation of several wood species has been widely investigated (De Groot et al. 1994, 1998; Ross et al. 1994a, 1994b, 1996, 1997, 2022; Ross and De Groot 1998); however, its functionality has not been tested on railroad ties when

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Table 1.—Experimental layout indicating replicates and type of railroad ties used in this study and summary statistics of acoustic velocity in different railroad ties including two boundaries, two sets of wood species, and three grade conditions.

	New on ties				Legacy ties	
	Oak/hickory		Mixed wood		Oak/hickory	
	AV_{free} ft/s (m/s)	AV_{fixed} ft/s (m/s)	AV_{free} ft/s (m/s)	AV_{fixed} ft/s (m/s)	AV_{free} ft/s (m/s)	AV_{fixed} ft/s (m/s)
Mean	11,814 (3,601)	12,220 (3,725)	11,245 (3,428)	11,836 (3,608)	10,590 (3,228)	11,077 (3,376)
Median	12,091	12,238	11,264	11,841	10,845	11,276
StDev	1,315	1,268	786	736	1,363	1,442
COV (%)[a]	11	10	7	6	13	13
Minimum	8,399	8,481	9,913	10,044	6,928	6,325
Maximum	14,165	14,602	12,731	13,133	12,429	13,519
Replicates	38	38	22	22	43	43

[a] COV = coefficient of variation.

different wood species combined with free and fixed boundary states as well as with new on-, new off-, and old-grade-conditions ties. A higher acoustic velocity (AV) value is often associated with a higher density, indicating greater strength (Hassani et al. 2021, Datta et al. 2023). It is well documented that AV is correlated with strength and stiffness in various wood products, including lumber, timber, cross-laminated timber, and others. Acoustic velocity has shown strong correlation with destructive testing results for modulus of elasticity (MOE) and modulus of rupture (MOR; Ross 2015). It is well documented that the AV-to-MOE correlation is relatively strong (e.g., 90%), whereas its correlation to MOR is moderate (e.g., 50%; Ross 2015, Correa et al. 2022). These results indicate that AV can potentially be used to evaluate nondestructively the mechanical performance of wooden railroad ties.

The use of AV for NDE of concrete ties showed promising results for determination of inner damages as well as their durability (Shafiei et al. 2016, Fisk 2018, Henderson and Sherrock 2018). Currently there is no standard method for evaluating the structural integrity of wood structures using NDE technologies. There are, however, a variety of techniques for use in varying situations. AV is a demonstrated NDE technology. It has been used on wood members and structures both in the laboratory and in service. The effect of boundary conditions on AV in wood has not, however, been studied. In the case of rail ties, this factor is critically important with respect to transitioning technology from the laboratory scale to the in-track/in-service scale.

This work investigates the use of AV as a means of evaluating tie integrity in a simulated track condition. The objectives of this work were:

1. Evaluate the AV response between ties of two wood species groups (oak/hickory and mixed hardwood).
2. Evaluate the AV response in new on-grade versus new off-grade versus legacy ties.
3. Evaluate the AV response of ties in free boundary state (sitting on ballast rock) versus fixed boundary state (packed with ballast rock and under simulated rail load).

Moreover, influences of boundary condition on AV response and its changes among species groups, between new on- versus off-grade ties or between new versus legacy ties, were investigated.

Materials and Methods

Experimental layout

Several types of wood ties were investigated. These included new freshly sawn green ties that were either new on-grade versus new off-grade or old ties that were taken out of service (legacy). The number of each category was 60 new on-grade, 40 new off-grade, and 55 legacy ties. The species groups of these ties were oak/hickory or mixed hardwoods including ash, beech, sweet gum, and sycamore. The sample replication for each combination is presented in Table 1. All new ties were selected from a tie concentration yard. To test the new ties in the green condition, and reduce or eliminate the effects of moisture, each tie was set onto the simulated rail bed within approximately 4 weeks of sawing. Legacy ties were procured from class 1 railroad ties.

Tie procurement and installation

This process was performed in different phases that are illustrated in Figure 1 (a to d). To simulate in-track conditions, a 12.7-cm (5-in)-thick ballast rock bed was installed on concrete. Ballast rocks were approximately 5.0 to 12.7 cm (2 to 5 in) in size (Fig. 1a). The ballast rock bed was approximately 6.7 m (22 ft) wide and 21 m (70 ft) long. It was designed to support two rows of ties, each containing 60 pieces. Ties were placed with an approximate 10- to 11-cm (4- to 4.5-in)-wide gap between each. Figure 1b illustrates 60 freshly cut green ties installed on the ballast. The species of every tie was recorded. Among the new on-grade ties, 38 were oak/hickory and 22 were mixed hardwood. This ratio of oak/hickory to mixed hardwood was similar to that seen in commercial use. Ties were labeled sequentially 1 to 60 for reference identification throughout evaluation. Legacy ties were selected from a stockpile of ties in varying states of decomposition. Legacy ties were taken directly from a cooperating railroad company (Fig. 2). In addition to freshly sawn ties, the legacy ties that had been taken out of service were placed on the ballast (Fig. 1c). Once all ties were placed on the ballast, tie dimensions (thickness, width, and length) were measured and recorded to the nearest one-quarter inch (0.63 cm). After initial AV evaluation (described below), ties were packed with ballast rock (Fig. 1d) for the fixed boundary evaluation.

Table 1.—Extended.

Legacy ties		New off ties			
Mixed wood		Oak/hickory		Mixed wood	
AV_{free} ft/s (m/s)	AV_{fixed} ft/s (m/s)	AV_{free} ft/s (m/s)	AV_{fixed} ft/s (m/s)	AV_{free} ft/s (m/s)	AV_{fixed} ft/s (m/s)
10,993 (3,351)	11,100 (3,383)	10,950 (3,338)	11,148 (3,398)	10,847 (3,306)	10,670 (3,252)
10,982	11,191	10,979	11,164	11,005	10,749
1,651	1,428	622	686	1,068	1,109
15	13	6	6	10	10
6,904	7,501	8,998	9,233	8,688	8,186
12,854	13,275	11,990	12,501	12,764	12,607
12	12	20	20	20	20

For fixed boundary evaluation, ballast-packed ties were loaded with a static weight intended to simulate that imparted by rails in track. With a known rail weight of 202.4 kg/m (136 lb/ft) and a known tie spacing of 45.7 to 50.8 cm (18 to 20 in), it was calculated that each rail imparts 92.5 to 103 kg (204 to 227 lb) on the face of the tie. Additionally, each tie plate (approximately 6.8 to 8.2 kg [15 to 18 lb]) imparts weight. In sum, for the two rail tie plates on each tie, the estimated imparted weight ranges from 197 to 210 kg (434 to 463 lb). To simulate this loading, a 200-kg (443-lb) assembly of a 5-cm (2-in)-thick steel plate welded to two tie plates was constructed (Fig. 1e). The tie plate spacing was fixed to simulate that seen in service. While under the load and packed with ballast, the AV of each tie was measured.

Nondestructive evaluation

The AV was measured with a Hitman HM220 device. For measurement, the device was pressed into the one end of the tie in longitudinal direction. A hammer was used to hit the same end of the tie beside the Hitman device. The Hitman device then calculates the time it takes for the wave to travel to the far end and back. First, AV was measured after each tie was placed on the ballast, which was considered as AV_{free}, indicating AV in the "free" or unrestricted boundary condition. Next, the AV was also measured after the ties were packed with ballast and with a static weight installed atop each tie. This value was considered the AV_{fixed}, that is, AV in the "fixed" or restricted boundary condition as developed in track. Figure 1e illustrates the AV measurement of a tie while in the fixed condition. AV_{free} and AV_{fixed} were measured within approximately 1 week of each other. In this manner, moisture content changes were minimized. This period was required to coordinate data measurement and collection along with the ballast packing operation.

Statistical analysis

A completely randomized design was used where each tie served as an experimental unit. A three-way analysis of variance with 2 by 3 by 2 factorial arrangement of treatments to test for the main and interactive effects of the two wood species treatments (oak/hickory and mixed hardwood), three grade condition treatments (new on-grade, new off-grade, and legacy), and two boundary condition (free and fixed) treatments was used. The normal distribution of the data was verified using the Shapiro–Wilk test at $\alpha = 0.05$. The power analysis used is based on a standard error of 0.8, an $\alpha = 0.05$, and a standard deviation of 4. This analysis indicated that to achieve statistically relevant results with a minimal error rate, eight replicate groups per treatment combination and a minimum of 20 ties per each replicate group were needed. All data were analyzed using a general linear mixed models (PROC GLIMMIX) of SAS 9.4© (SAS Institute Inc, Cary, NC) and $P \leq 0.05$ was considered for treatment differences. Additionally, noticeable trends were deemed at $P < 0.1$. Furthermore, mean separation was determined using Fisher's protected least significant difference (Steel and Torrie 1980). The following statistical model was used for all data.

$$Y_{ijk} = \mu + S_i + G_j + (SG)_{ij} + B_k + (SB)_{ik} + (GB)_{jk} + (SGB)_{ijk} + E_{ijk} \tag{1}$$

where μ is the population mean, S_i is the effect of wood species treatment ($i = 1$ to 2); G_j is the effect of grade condition treatments ($j = 1$ to 3), $(SG)_{ij}$ is the interaction of each wood species treatment with grade condition treatment, B_k is the effect of boundary state treatments ($B = 1$ to 2); $(SB)_{ik}$ is the interaction of each wood species treatment with boundary state treatment, $(GB)_{jk}$ is the interaction of each grade condition treatment with boundary state treatment, $(SGB)_{ijk}$ is the interaction of each wood species treatment with each grade condition and boundary state treatments, and E_{ijk} is the residual error.

Results and Discussion

The summary statistics of AV for different ties in the combination of boundary state, wood species, and grade condition are presented in Table 1.

There were no significant interactive effects on AV among boundary state, wood species, and grade condition (Table 2). Also, no significant main effect on AV was observed between oak/hickory and mixed wood species (Fig. 3). Greater AV was observed in the new one as compared with the new off and legacy ties (Fig. 4). This information suggests that AV technology could be used for differentiating new on-grade ties versus off-grade ties or

Figure 1.—(a) Ballast rock bed, (b) freshly cut green ties installed on the ballast, (c) installation of legacy ties on the ballast, (d) installation of ballast between each of the ties, (e) 200-kg (434-lb) weight constructed and used to simulate the load of the rails on each tie, and (f) measurement of acoustic velocity of a given tie (identification number 11) while in the fixed boundary condition.

new on-grade ties versus in-service ties that need replacement. The free boundary ties exhibited lower AV than those that belonged to fixed boundary (Fig. 5). This relationship was generally consistent across all ties (Fig. 6). As such, one can surmise that the use of AV at the bench or pilot scale can be adapted to an in-track NDE technology.

The aim of the current study was to use AV as a NDE technology for wood ties. Oak/hickory versus mixed wood species, free versus fixed boundary states, and new on-grade

Figure 2.—Collection of legacy ties at a commercial railroad stockpile.

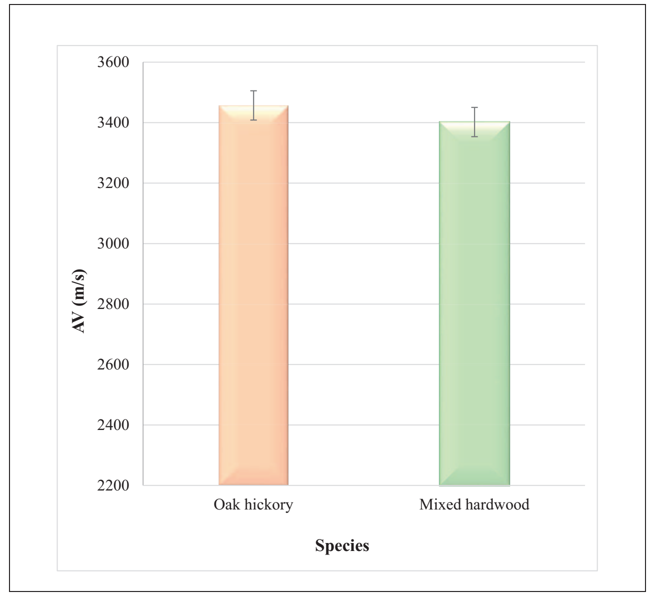

Figure 3.—Main effect of oak/hickory species and mixed hardwoods species on acoustic velocity (AV) of railroad ties. The number of replications per treatment combination is 81; SEM = 48.4.

versus new off-grade and legacy ties were investigated. The findings herein showed that there were no interactive effects of AV from combinations of boundary, grade, and wood species (Table 2). Also, it was observed that main effects of grade and boundary state were significant. Greater AV was observed for new on-grade ties in comparison with new off-grade and legacy ties. Also, with respect to boundary condition, AV was higher for fixed as compared with free. It is interesting to note that there was no significant difference between new off and legacy ties, indicating that the AV of an off-grade new tie is not different from that of a legacy tie that has been taken out of service. Although the removal of old ties that were in service for 20 years can be used for exterior structural applications, their mechanical performances were significantly deteriorated as compared with new ties, regardless of wood type (Lin et al. 2007). The study conducted by Lin et al. (2007) showed that destructive (MOE and MOR) and NDE (dynamic MOE) responses were significantly lower for old versus new ties. Ties used in this study belonged to Grade one; however, grade specification was not determined (Lin et al. 2007), which may negatively affect the results. These results indicate that further research is needed to determine the durability of wooden in-service ties belonging to different species using NDE technology.

In the study described herein no significant difference was observed between the ties of two different species groups. This finding may be because the overall characteristics and density of the two species groups were similar. Comparatively, when woods with greater density differences are evaluated, AV differences become more pronounced. For instance, in past research, when AV was tested for musical instruments, linden wood and sapwood exhibited higher AV responses and the lowest values belonged to ebony and walnut wood species; oak wood remined intermediate (Stanciu et al. 2022). Additionally, a greater AV response was observed for beech wood in comparison with pine wood before and after thermal treatment timber (Mania et al., 2023). No significant difference between hardwood species (oak vs. beech) was detected in that previous research. Herein, the wood species-to-grade interaction was statistically significant. Potentially a reason for not observing treatment differences for AV value when combined effects were considered could be linked to the unequal number of specimens in each treatment combination. Further research that compares these treatment combinations with destructive bending tests is advised.

Table 2.—Effects of different species, grade conditions, and boundary states of railroad ties on acoustic velocity (AV).

	Species		Grade			Boundary	
	Oak/hickory	Mixed hardwood	New on	New off	Legacy	Free	Fixed
AV (ft/s)	11,343	11,163	11,842[a]	10,909[b]	10,876[b]	11,116[b]	11,440[a]
SEM	106.3	128.5	109.9	141.9	120.4	107.1	104.9
AV (m/s)	3,457	3,402	3,609[a]	3,325[b]	3,315[b]	3,388[b]	3,487[a]
SEM	32.4	39.2	34.5	43.3	36.7	32.6	32

	Species	Grade	Boundary	Species × grade	Species × boundary	Grade × boundary	Species × grade × boundary
P-values	0.261	**<0.001**[c]	**0.034**	0.168	0.539	0.404	0.651

[a,b] Treatment means within the same column within effect without common superscripts are significantly different ($P \leq 0.05$).

[c] Bolded numbers are statistically significant ($P < 0.05$).

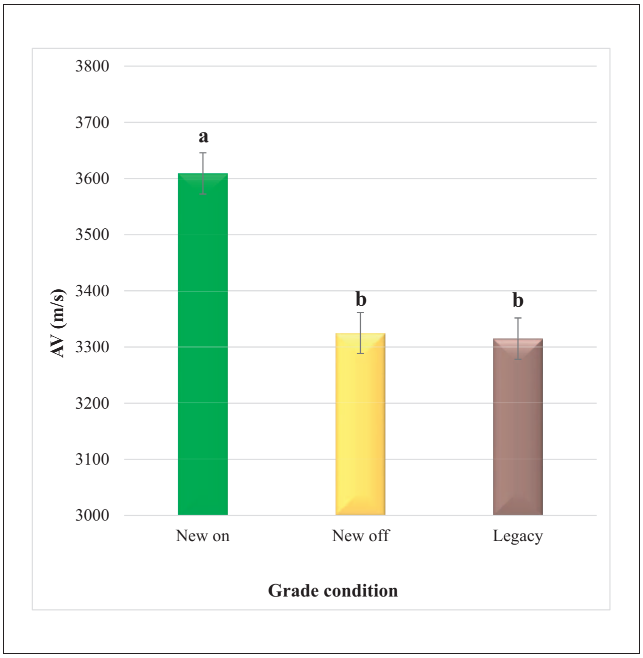

Figure 4.—Main effect of new freshly sawn green ties (new on) that were either on grade versus off grade (new off) or legacy that was taken out of service on acoustic velocity (AV) of railroad ties. Treatment means within the same column within effect without common superscripts are significantly different ($P \leq 0.05$). The number of replications per treatment combination is 104; SEM = 36.7.

Conclusions

In conclusion, the impact of new on-grade, new off-grade, and in-service (legacy) grade condition ties, free and fixed boundary conditions, and either oak/hickory or mixed wood species on AV were investigated. Findings revealed that AV was only individually affected by boundary states and grade condition. New on-grade ties showed a higher AV when compared with new off-grade or legacy ties. These results indicate that AV could be used as a means of quality assessment during production and for in-track tie condition assessment. In addition, AV was higher for fixed versus free boundary conditions. These results indicate that AV at the bench or pilot scale can be adapted to in-track conditions. The incorporation of equal specimen numbers across treatment combinations may increase the ability to detect differences.

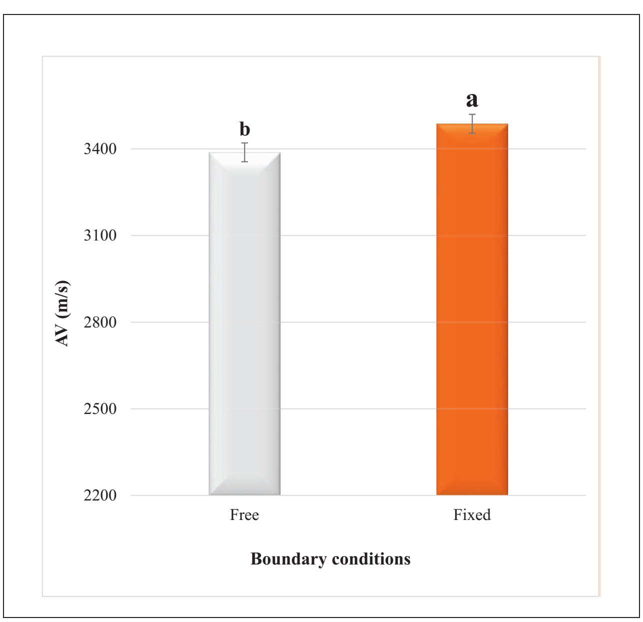

Figure 5.—Main effect of free and fixed boundary state on acoustic velocity (AV) of railroad ties. Treatment means within the same column within effect without common superscripts are significantly different ($P \leq 0.05$). The number of replications per treatment combination is 82; SEM = 32.6.

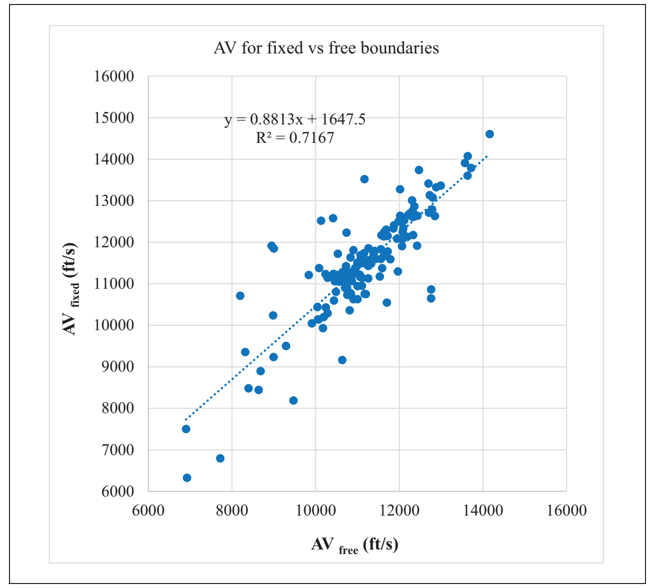

Figure 6.—Regressed relationship of acoustic velocity (AV) between free versus fixed boundary conditions for all ties.

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