Comparative Analysis of
Timber and Steel Cross-ties
For
Light Density Secondary and Industrial Track

Report Submitted to
Railway Tie Association

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ZETA-TECH
A Harsco Track Technologies Business Unit
900 Kings Highway North
Cherry Hill, NJ 08034
(856) 779-7795
FAX (856) 779-7436
E-mail: palese@zetatech.com
Zarembski@zetatech.com

INTRODUCTION

The report presents the results of an analytical and economic investigation of the differences between 6”x8”, 7”x9” Timber Cross-Ties and Steel Cross-Ties as commonly used on light density secondary and industrial tracks. The tie sizes, types, and fastening systems investigated are those representative of these light density secondary and industrial tracks to include:

- Light density steel ties[1]
- 7”x9”x 8 ½’ standard and industrial grade ties
- 6”x8”x 8 ½’ standard grade ties

The specific focus of this activity is the effect of tie spacing on 6”x8” and 7”x9” timber cross-ties as compared to steel ties on a 24” spacing. Specifically, the capacity of each tie type to withstand typical loading on 25 mph track was evaluated with respect to the following:

- Analysis of ballast bearing stress at the bottom of the ties (which is also a function of track support- modulus and tie spacing)
- Analysis of the subgrade bearing stress (which is a function of ballast depth and track modulus).

The analysis results are then used to determine the costs associated with the timber and steel configurations to include the cost of initial tie installation as a function of tie size and number of ties inserted per mile (as a function of tie spacing). Note, this is also a function of installation (labor) cost.

[1] The economics of main line steel ties as compared to main line wood tie and fastener systems were addressed in previous RTA reports to include the RTA Report Development of Comparative Cross-Tie Unit Costs and Values, August 2006.

ANALYTICAL OVERVIEW: TIE LOAD DISTRIBUTION

The analytical approach used here-in is based on the beam on elastic foundation analysis approach which allows for the determination of the effect of such key track support variables as track modulus, tie type, tie spacing, and ballast depth. This approach forms the basis of the definition of the load transferred from the wheel/rail interface to the individual cross-tie, and down through the ballast..

Based on the defined vehicle loading of 36 Ton axle loading and 25 mph operating, the dynamic wheel/rail load can be determined from the AREMA impact load formula as follows:

$$P_d = P_{st}\left(1 + \frac{33V}{100D}\right)$$

where

P_d = Dynamic Wheel Load
P_{st} = Static Wheel Load
V = Speed in MPH
D = Wheel Diameter in inches

The resulting dynamic wheel load, Pd is 43,943 lbs. This is the load applied by the wheel to the top of the rail head.

This dynamic wheel load must, in turn, be distributed to the ties, which is a direct function of the track support, which is generally defined in terms of the vertical track modulus (lb/in/in). This is accomplished by the rail acting as a continuously supported beam, distributing the load across several ties. To determine the force on a tie under the dynamic wheel load, the rail is modeled as an infinite beam, continuously supported by an elastic foundation.

The response (deflection) of the rail (the "beam"), and the corresponding distribution of forces by the rail to the ties is defined by the governing equation for an infinite beam continuously supported by an elastic foundation. The resulting tie force (*F*), is defined as the maximum pressure multiplied by the tie spacing.

The resulting force at the rail tie interface can then be used to determine the percentage of total load carried by an individual tie (directly under the wheel) as a function of track modulus. This tie force is presented in Table 1 as a function of a range of track modulus values from 1000 to 8000 lb./in/in and tie spacing. Note that as the tie spacing increases, the force experienced by an individual tie (under the wheel) increases. In addition, as the support stiffens (track modulus increases), the force under the tie also increases.

TABLE 1: Determination of Force on Tie as Function of Track Modulus

Based on 286,000 lb. car with a 35,750 lb. static wheel load and an operating speed of 25 mph.

Track Modulus k, lb/in/in	Tie Force F, lb Tie Spacing (in)					
	19.5	20	21	22	23	24
1000	8,089	8,296	8,711	9,126	9,540	9,955
2000	9,619	9,866	10,359	10,852	11,345	11,839
3000	10,645	10,918	11,464	12,010	12,556	13,102
4000	11,439	11,732	12,319	12,905	13,492	14,079
5000	12,095	12,405	13,026	13,646	14,266	14,886
6000	12,659	12,984	13,633	14,282	14,931	15,581
8000	13,603	13,952	14,650	15,347	16,045	16,742

The tie force values presented in Table 1 are the same for all tie sizes considered as part of the analysis and as such will be used in the remainder of the analyses presented here.

ANALYSIS OF BALLAST/TIE STRESSES

One of the key functions of the cross-tie is to transfer the load from the rail seat to the tie/ballast interface, i.e. to the top of the ballast layer, for subsequent distribution through the ballast and into the subgrade. As already noted, the forces acting on the tie are distributed from the top of the rail through several ties. Likewise, the forces on the tie are distributed over the ballast at the bottom of the tie. Given that the pressure on the ballast is equal to the tie deflection multiplied by the track modulus, the corresponding rail seat loads presented in Table 1 can be used to define the ballast pressure distribution (maximum pressure). This distribution is illustrated in Figure 1.

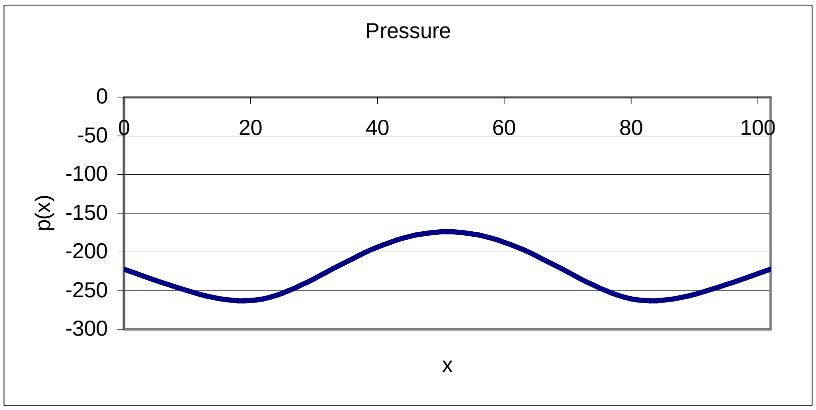

Figure 1. Tie/Ballast Pressure Distribution.

In order to analyze the stresses at the bottom of the cross-tie/top of the ballast layer, the AREMA design approach is used, where the tie distributes the load on to the ballast. This approach develops the stress on the ballast as a direct linear function of the bearing area of the tie on the ballast. For design purposes, AREMA suggests that one third of the tie's bearing area supports each of the two rail seat forces. Using this approach, and knowing that the forces on the tie vary with track modulus and tie spacing, the stress on the ballast can be determined for different size ties, different values of track modulus, and variations in tie spacing. These ballast stresses are presented in Table 2. In addition, since the steel tie is tamped over the entire length of the tie (not just under the rail seats), it is assumed the force on the tie is distributed over 41% of the tie (as opposed to 33% for wood), based on the field side of the rail of the tie and 2/3 of the gage portion (1/2 for each rail) of the tie.

TABLE 2: AREMA Tie-Ballast Stress

A) 6” x 8” Oak Ties

Track Modulus k, lb/in/in	AREMA Tie-Ballast Stress 6x8x8.5 Oak Tie Spacing (in)					
	19.5	20	21	22	23	24
1000	29.7	30.5	32.0	33.5	35.1	36.6
2000	35.4	36.3	38.1	39.9	41.7	43.5
3000	39.1	40.1	42.1	44.2	46.2	48.2
4000	42.1	43.1	45.3	47.4	49.6	51.8
5000	44.5	45.6	47.9	50.2	52.4	54.7
6000	46.5	47.7	50.1	52.5	54.9	57.3
8000	50.0	51.3	53.9	56.4	59.0	61.6

B) 7” x 9” Oak Ties

Track Modulus k, lb/in/in	AREMA Tie-Ballast Stress 7x9x8.5 Oak Tie Spacing (in)					
	19.5	20	21	22	23	24
1000	26.4	27.1	28.5	29.8	31.2	32.5
2000	31.4	32.2	33.9	35.5	37.1	38.7
3000	34.8	35.7	37.5	39.2	41.0	42.8
4000	37.4	38.3	40.3	42.2	44.1	46.0
5000	39.5	40.5	42.6	44.6	46.6	48.6
6000	41.4	42.4	44.6	46.7	48.8	50.9
8000	44.5	45.6	47.9	50.2	52.4	54.7

C) Steel Ties[2]

Track Modulus k, lb/in/in	Steel Tie Spacing					
	19.5	20	21	22	23	24
1000	31.6	32.4	34.1	35.7	37.3	38.9
2000	37.6	38.6	40.5	42.4	44.4	46.3
3000	41.6	42.7	44.8	47.0	49.1	51.2
4000	44.7	45.9	48.2	50.5	52.8	55.1
5000	47.3	48.5	50.9	53.4	55.8	58.2
6000	49.5	50.8	53.3	55.9	58.4	60.9
8000	53.2	54.6	57.3	60.0	62.8	65.5

Considering that the allowable stress for the ballast/subgrade interface is 65 psi, it can be seen from the above table that for all levels of track modulus and tie spacing, the applied loading results in acceptable levels of bottom of tie/ballast stress.

[2] This is based on the smaller Class 2 type steel tie with a bearing area (top of ballast) of 630 square inches.

ANALYSIS OF BALLAST/SUBGRADE STRESSES

As noted in the previous section, the stresses at the base of the tie, which are transmitted to the ballast, are then distributed through the ballast section, to the top of the subgrade. This distribution is a function of the parameters already noted together with the depth of the ballast layer. In this analysis, the ballast layer depths examined is 12" below bottom of the tie. (Note, ballast in the cribs and shoulders do not function to reduce the level of stress transmitted to the subgrade, so that the appropriate ballast depth is the depth of ballast below the bottom of the tie.)

Several analytical methods are available for determining the distribution of stresses transmitted through the ballast to the subgrade at a defined distance (ballast depth) below the bottom of tie. The most commonly used formula is the Talbot formula, which has been incorporated into the AREMA specifications. The results of this analysis are presented in Table 3.

TABLE 3: Subgrade Stresses (Simplified Analysis)

A) 6" x 8" Oak Ties

According to the Talbot Equation
AREMA Ballast-Subgrade Stress (psi)
6x8x8.5 Oak
Tie Spacing (in)

Track Modulus K, lb/in/in	19.5	20	21	22	23	24
1000	22.4	22.9	24.1	25.2	26.4	27.5
2000	26.6	27.3	28.6	30.0	31.4	32.7
3000	29.4	30.2	31.7	33.2	34.7	36.2
4000	31.6	32.4	34.1	35.7	37.3	38.9
5000	33.4	34.3	36.0	37.7	39.5	41.2
6000	35.0	35.9	37.7	39.5	41.3	43.1
8000	37.6	38.6	40.5	42.4	44.4	46.3

B) 7" x 9" Oak Ties

According to the Talbot Equation
AREMA Ballast-Subgrade Stress (psi)
7x9x8.5 Oak
Tie Spacing (in)

Track Modulus k, lb/in/in	19.5	20	21	22	23	24
1000	19.9	20.4	21.4	22.4	23.5	24.5
2000	23.6	24.3	25.5	26.7	27.9	29.1
3000	26.2	26.8	28.2	29.5	30.9	32.2
4000	28.1	28.8	30.3	31.7	33.2	34.6
5000	29.7	30.5	32.0	33.5	35.1	36.6
6000	31.1	31.9	33.5	35.1	36.7	38.3
8000	33.4	34.3	36.0	37.7	39.4	41.2

C) Steel Ties

According to the Talbot Equation
AREMA Ballast-Subgrade Stress (psi)
Steel

Track Modulus k, lb/in/in	Tie Spacing 19.5	20	21	22	23	24
1000	23.8	24.4	25.6	26.8	28.1	29.3
2000	28.3	29.0	30.5	31.9	33.4	34.8
3000	31.3	32.1	33.7	35.3	36.9	38.5
4000	33.7	34.5	36.2	38.0	39.7	41.4
5000	35.6	36.5	38.3	40.1	42.0	43.8
6000	37.2	38.2	40.1	42.0	43.9	45.8
8000	40.0	41.0	43.1	45.2	47.2	49.3

The above table shows shaded cells where the allowable ballast subgrade interface stress of 25 psi is not exceeded.

This suggests that use of steel ties on 24 inch spacing may generate higher subgrade stresses than 7” x 9” ties on 20 to 24 inch spacing under slow speed heavy axle load operations with a resulting increase in track geometry degradation. Likewise, that use of steel ties on 24 inch spacing may generate higher subgrade stresses than 6” x 8” ties on 20 to 22 inch spacing under slow speed heavy axle load operations with a resulting increase in track geometry degradation

COST ANALYSIS

The following section discusses the costs associated with each type of ties analyzed (6” x 8” Oak, 7” x 9” Oak, and Steel). This analysis focused on initial installation cost and includes the cost of the tie and fasteners, ballast, and labor to install. Table 4 below shows the cost breakdown

TABLE 4. Cost Breakdown for each Tie Type.

		Steel Tie[3]	Wood Tie	Wood Tie-IG	Wood Tie
Length (ft)		8.3	8.5	8.5	8.5
Height (in)		3.95	7	7	6
Width (in)		10.24	9	9	8
Spacing (in)		24	19.5	19.5	19.5
Ties/Mile		2640	3249	3249	3249
Ballast Depth (in)		12	12	12	12
Shoulder Width (in)		12	12	12	12
Ballast (CY/mile)	Total	2412	3784	3784	3619
	Cost/CY	$ 15	$ 15	$ 15	$ 15
	Cost/Mile	$ 36,178	$ 56,761	$ 56,761	$ 54,285
Tie[4]					
	Cost/Tie	$ 80.15	$ 65.00	$ 56.00	$ 49.00
	Cost/Mile	$211,596	$211,200	$181,957	$159,212
Labor					
	Installation savings[5]	5%			
	Cost/Tie	$18.00	$18.00	$18.00	$18.00
	Cost/Mile	$90,288	$ 95,040	$ 95,040	$ 95,040
Total Cost		$338,062	$363,001	$333,758	$308,538
			$ 24,939	$(4,304)	$(29,524)

[3] Light weight steel tie used for secondary and yard track. Economic of larger main line steel ties investigated previously (Development of Comparative Cross-Tie Unit Costs and Values, RTA Report, August 2006)

[4] Cost of wood cross-ties include new fastening systems commonly used on secondary and yard track; two 11” tie plates, 3 spikes per plate, box anchoring every third tie. If second hand plates and fasteners are used, a common practice in light density lines, then the costs will be reduced from those shown here.

[5] The 5% savings in installation costs for steel ties is based on reports from a major US Class 1 railroad. A sensitivity analyses to this savings is performed later in this report.

It can be seen from this table that the 7" x 9" standard ties on 19.5" spacing are more expensive on a first cost basis than for the steel ties on a 24" spacing. However, the 7" x 9" Industrial Grade (IG) ties on 19.5" and the 6" x 8" standard ties on 19.5" spacing are less expensive on a first cost basis than for steel ties on a 24" spacing. Note that these costs are based on the cost of the tie, variations in ballast required, and a 5% savings on labor costs for installation of steel ties. The remaining parameters are chosen based on the dimensions of the respective units and the engineering study presented in the previous sections.

In order to understand the effects of tie spacing presented previously, as well as cost variations in installation costs, a sensitivity analysis of these key parameters was performed. Specifically, tie spacing from 19.5" to 24" for wood ties (6" x 8" and 7" x 9") and steel installation costs (5% to 30%[6] savings over wood installation costs) were examined. Tables 5A through C show these results.

TABLE 5. Savings of Wood over Steel (24" OC) with 12" Ballast Depth .

Table 5A: Cost Savings of Steel Over 7"x9" x 8.5' Tie

Spacing	Steel Installation Savings					
	5%	10%	15%	20%	25%	30%
19.5	$ 24,939	$ 29,691	$ 34,443	$ 39,195	$ 43,947	$ 48,699
20	$ 19,827	$ 24,579	$ 29,331	$ 34,083	$ 38,835	$ 43,587
21	$ 10,333	$ 15,085	$ 19,837	$ 24,589	$ 29,341	$ 34,093
22	$ 1,702	$ 6,454	$ 11,206	$ 15,958	$ 20,710	$ 25,462
23	$ (6,178)	$ (1,426)	$ 3,326	$ 8,078	$ 12,830	$ 17,582
24	$(13,402)	$ (8,650)	$ (3,898)	$ 854	$ 5,606	$10,358

Table 5B: Cost Savings of Steel Over 7"x9" x 8.5' IG Tie

Spacing	Steel Installation Savings					
	5%	10%	15%	20%	25%	30%
19.5	$ (4,304)	$448	$5,200	$ 9,952	$ 14,704	$19,456
20	$ (8,685)	$ (3,933)	$ 819	$ 5,571	$ 10,323	$ 15,075
21	$(16,821)	$(12,069)	$ (7,317)	$ (2,565)	$ 2,187	$ 6,939
22	$(24,218)	$(19,466)	$14,714)	$ (9,962)	$ (5,210)	$ (458)
23	$(30,971)	$(26,219)	$(21,467)	$(16,715)	$(11,963)	$ (7,211)
24	$(37,162)	$(32,410)	$(27,658)	$(22,906)	$(18,154)	$(13,402)

[6] The range of savings is presented here to reflect reported differences in tie installation costs for steel ties. The 5% savings over wood is reflective of the experience of a major Class 1 railroad. The maximum value of 30% was selected to reflect a condition of large savings, which has been questioned but which is included here-in to illustrate a full range of potential savings.

Table 5C: Cost Savings of Steel Over 6"x8" x 8.5' Tie

Spacing	Steel Installation Savings					
	5%	10%	15%	20%	25%	30%
19.5	$(29,524)	$(24,772)	$(20,020)	$(15,268)	$(10,516)	$ (5,764)
20	$(33,376)	$(28,624)	$(23,872)	$(19,120)	$(14,368)	$ (9,616)
21	$(40,531)	$(35,779)	$(31,027)	$(26,275)	$(21,523)	$(16,771)
22	$(47,035)	$(42,283)	$(37,531)	$(32,779)	$(28,027)	$(23,275)
23	$(52,974)	$(48,222)	$(43,470)	$(38,718)	$(33,966)	$(29,214)
24	$(58,417)	$(53,665)	$(48,913)	$(44,161)	$(39,409)	$(34,657)

It can be seen from this table that 7”x9”standard ties do not offer a savings for the range of tie spacing and steel installation savings studied. However, the 7” x 9” Industrial Grade (IG) ties offer savings (depending on the actual savings in labor costs associated with steel tie installation) for most tie spacings. Likewise, the 6” x 8” standard ties offer significant savings (again depending on actual labor costs associated with steel ties) for a spacing of 21” or higher in all cases, and offer a savings at closer spacing, depending on the steel installation cost savings.

While the steel tie offers a significant reduction in ballast requirements (the single largest savings), there are cases where it is impractical to use less ballast, such as tracks adjacent to mainline track, requiring the same top of rail. In this case, the amount of ballast required increases, so that the top of tie is identical. The cost analysis results for this situation are shown in Table 6.

TABLE 6. Savings of Wood over Steel (24” OC) with Ballast Depth for Equal Top of Tie.

Cost Savings of Steel Over 7”x9” Oak Ties – Same Tie Height

	Steel Installation Savings					
Spacing	5%	10%	15%	20%	25%	30%
19.5	$19,840	$24,592	$29,344	$34,096	$38,848	$43,600
20	$14,250	$19,002	$23,754	$28,506	$33,258	$38,010
21	$3,869	$8,621	$13,373	$18,125	$22,877	$27,629
22	$(5,568)	$(816)	$3,936	$8,688	$13,440	$18,192
23	$(14,184)	$(9,432)	$(4,680)	$72	$4,824	$ 9,576
24	$(22,083)	$(17,331)	$(12,579)	$(7,827)	$(3,075)	$1,677

Cost Savings of Steel Over 6”x8” Oak Ties – Same Tie Height

	Steel Installation Savings					
Spacing	5%	10%	15%	20%	25%	30%
19.5	$(31,402)	$(26,650)	$(21,898)	$(17,146)	$(12,394)	$(7,642)
20	$(35,816)	$(31,064)	$(26,312)	$(21,560)	$(16,808)	$(12,056)
21	$(44,013)	$(39,261)	$(34,509)	$(29,757)	$(25,005)	$(20,253)
22	$(51,464)	$(46,712)	$(41,960)	$(37,208)	$(32,456)	$(27,704)
23	$(58,267)	$(53,515)	$(48,763)	$(44,011)	$(39,259)	$(34,507)
24	$(64,504)	$(59,752)	$(55,000)	$(50,248)	$(45,496)	$(40,744)

It can be seen from Table 6 that, when the in-track requirement is such that the top of tie of adjacent tracks (one with wood and one with steel) must be equal, there are instances when 7”x9” wood ties offer a benefit (22” to 24” spacing, depending on steel installation cost savings). In all cases, the 6”x8” wood ties offer a benefit. Note, the 7”x9” IG ties, which have a cost comparable to that of the 6” x8” ties gives similar savings to that shown for the 6”x8” standard tie (above).

CONCLUSIONS AND RECOMMENDATIONS

The study presented in this report presents the results of an analytical and economic investigation of the differences between 6”x8”, 7”x9” Timber Cross-Ties and Steel Cross-Ties as commonly used on light density secondary and industrial tracks. The tie sizes, types, and fastening systems investigated are those representative of these light density secondary and industrial tracks to include:

- Light density steel ties
- 7”x9”x 8 ½’ standard and industrial grade ties
- 6”x8”x 8 ½’ standard grade ties

The study analyzed the engineering comparison of 6”x8” and 7”x9” oak ties, along with a steel tie, in order to identify at which tie spacing the response of the track structure is similar. The distribution of forces to the remainder of the track structure is a function of the support conditions (track modulus) as well as the tie spacing. The tables presented in this report offer a mechanism for identifying an appropriate tie spacing at which timber ties can be installed in lower speed lighter tonnage lines, and offer adequate support.

The analysis of subgrade stresses under timber and steel ties suggests that use of steel ties on 24 inch spacing may generate higher subgrade stresses than 7” x 9” ties on 20 to 24 inch spacing under slow speed heavy axle load operations with a resulting increase in track geometry degradation. Likewise, that use of steel ties on 24 inch spacing may generate higher subgrade stresses than 6” x 8” ties on 20 to 22 inch spacing under slow speed heavy axle load operations with a resulting increase in track geometry degradation

Once an appropriate spacing is identified based on track conditions, the initial costing can be analyzed based on this tie spacing and various installation costs, including tie cost, ballast cost, and labor cost. While steel ties offer the ability to use less ballast and offer some savings in installation, the less expensive 7x9 Industrial Grade tie and the 6 x 8 wood tie, on a range of tie spacings, offers advantages in certain track locations. The exact savings is a function of the reduced labor costs for steel ties which has been a subject of significant discussion. Noting that one major Class 1 railroad indicates that only a modest 5% labor savings is achieved (based on that railroad’s experience with steel vs. wood ties), then the 7x9 Industrial Grade tie and the 6 x 8 wood tie, on a full range of tie spacings, offer net savings over the steel ties, with comparable load (and stress distributions to the ballast and subgrade).

In addition, steel ties, while less expensive from a material handling standpoint, require more time to surface, due to the need for surfacing in the center of the steel tie (as well as the rail seat areas)., as opposed to just under the rail seats for timber ties.

Note that this analysis was performed on a first-cost basis and no life cycle costing was taken into account. In addition, the engineering analysis for tie spacing considered the vertical load scenario only, and smaller spacing may be required in curves where lateral forces are higher and closer tie spacing is needed to maintain the lateral strength of the track structure..