February 14, 2005

Mr. James C. Gauntt
Executive Director
The Railway Tie Association
115 Commerce Drive, Suite C
Fayetteville, GA 30214

Dear Mr. Gauntt:

Enclosed here-in is ZETA-TECH Associates, Inc.'s report "Comparative Analysis of 6"x8" vs. 7"x9" Timber Cross-ties".

If you have any questions please give me a call.

Sincerely,

Allan M. Zarembski, Ph.D., P.E.
President

# Comparative Analysis of
# 6"x8" vs. 7"x9" Timber Cross-ties

Report Submitted to
Railway Tie Association

February 14, 2005

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# EXECUTIVE SUMMARY

The report presents the results of an analytical investigation of the differences between 6"x8" vs. 7"x9" Timber Cross-Ties. The specific focus of this activity is the analysis of the difference in life cycle costs for tracks with tie replacement (of between 200 and 2000 ties/mile) with 6"x 8" vs. 7"x 9" timber cross-ties of similar quality wood. This life cycle analysis includes the effect of the different tie sizes on tie and subgrade stresses (and corresponding surfacing cycles) as well as on tie bending and tie bearing stresses (and corresponding tie life).

Based on the analyses presented, the engineering life of the 6"x 8" tie is between 14% and 20% less than the 7"x 9" tie based on both tie bending and tie plate bearing stresses effects. Thus for a branch line application, where an industry average life for the 7"x9" tie is 32 years, the 6"x8" tie will have a life of between 26 and 28 years.

In a similar analysis, the surfacing cycle for 6"x 8" tie is approximately 10% to 11% shorter than the 7"x 9" tie based on tie bearing stresses to include tie to ballast and ballast to subgrade stresses. Thus for a branch line application, where an industry average surfacing cycle for the 7"x 9" tie is 6 years, the 6"x 8" tie will have a surfacing cycle of between 5.3 and 5.4 years.

Note that there is a significant cost different between the two sizes of ties in material with the 6"x8" tie having a material cost of about $24 a tie and an installed cost (including material and labor) of $74. This is compared to the 7"x 9" tie with a material cost of about $35 a tie and an installed cost (including material and labor) of $85.

Thus, on a life cycle cost basis, the first cost savings associated with the less expensive 6"x 8" tie is offset by the shorter tie life and the reduced surfacing cycle (requiring more frequent surfacing). Noting that a mile of track has to be surfaced even if only a small percentage of the ties are replaced, the life cycle analysis shows that for large scale tie replacement on a branch or secondary line, the 6"x 8" tie is less expensive but for a limited tie replacement, the 6"x 8" tie life cycle costs are greater than those for the 7"x 9" tie. The cross-over point varies with the cost of money used, the damage factors assumed, and the component lives but ranges from 400 ties at 6"x 8" tie life of 28 years to 1500 ties at 6"x 8" tie life of 26 years.

Similarly, sensitivity to such key factors as interest rate, surfacing cycle, and tie life all affect the overall economics. In general, however, large-scale tie applications on light density track appear to have an economic life cycle justification, while smaller scale installations do not always provide a net economic benefit over the life cycle of the ties.

## INTRODUCTION

The report presents the results of an analytical investigation of the differences between 6”x8” vs. 7”x9” Timber Cross-Ties. The specific focus of this activity is the analysis of the difference in life cycle costs for tracks with tie replacement (of between 200 and 2000 ties/mile) with 6”x8” vs. 7”x9” timber cross-ties of similar quality wood. This life cycle analysis includes the effect of the different tie sizes on tie and subgrade stresses (and corresponding surfacing cycles) as well as on tie bending and tie bearing stresses (and corresponding tie life). Note, the focus of this analysis will be on branch line track where 6”x8” ties are candidates for large scale usage.

For comparison of wood tie size (6”x8” vs. 7”x9”) this includes the following:

- Analysis of the bending stress of the tie as a function of the track support (modulus)
- Analysis of ballast bearing stress at the bottom of the ties (which is also a function of track support- modulus)
- Analysis of the subgrade bearing stress (which is a function of ballast depth and track modulus).
- Determination of the comparative tie life of 6”x8” vs. 7”x9” timber cross-ties as a function of:
  - Tie bending stress
  - Tie plate bearing stress
- Determination of the comparative surfacing cycles for 6”x8” vs. 7”x9” timber cross-ties as a function of:
  - Tie-ballast bearing stress
  - Ballast-subgrade bearing stress

The resulting analysis results will be used to determine the life cycle costs associated with the two tie sizes to include

- Cost of initial tie replacement as a function of tie size and number of ties inserted per mile
- Cost of future tie replacement, as a function of tie size
- Cost of future surfacing cycles as a function of tie size

The result will be a life cycle cost analysis for tie replacement with 6”x8” vs. 7”x9”ties as a function of the number of ties replaced per mile.

## ANALYTICAL OVERVIEW: TIE LOAD DISTRIBUTION

The analytical approach used here-in is based on the beam on elastic foundation analysis approach [1,2] which allows for the determination of the effect of such key track support variables as track modulus, wood type, and ballast depth. This approach is used in the tie size analysis, and forms the basis of the definition of the load transferred from the wheel/rail interface to the individual cross-tie. For a more detailed and in depth description of the analysis approach, refer to Appendix A.

Based on the defined vehicle loading of 36 Ton axle loading and 25 mph operating speed (which is a speed appropriate for branch line track that can be considered for 6"x8" ties), 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, as illustrated in Figure A.1 of the Appendix.

The response (deflection) of the rail (the "beam"), and the corresponding distribution of forces by the rail to the ties is defined by the differential equation and boundary/regularity conditions defined in Appendix A. This resulting tie force ($F$), which is defined as the maximum pressure multiplied by the tie spacing ($a$), is presented in Appendix A and is consistent with those equations presented by Hay [1] and AREMA [2]. Appendix A presents a detailed description of the derivation of these equations and their application.

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. For a complete description of the input values and analysis, refer to the Appendix.

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 lb | Percentage Load carried by tie under wheel % |
|---|---|---|
| 1000 | 8089 | 18.4% |
| 2000 | 9619 | 21.9% |
| 3000 | 10645 | 24.2% |
| 4000 | 11439 | 26.0% |
| 5000 | 12095 | 27.5% |
| 6000 | 12659 | 28.8% |
| 8000 | 13603 | 31.0% |

The tie force values presented in Table 1 are the same for both tie sizes (6"x8" vs. 7"x9") and as such will be used in the remainder of the analyses presented here.

COMPARISON OF 6”x8” AND 7”x9” CROSS-TIES
ANALYSIS OF TIE BENDING STRESS

Using the rail seat forces defined in Table 1 as a function of track modulus, it is possible to calculate the bending stress within the tie. Note, this bending stress is also a function of tie type, since the wood species affects both the modulus of elasticity (E) of the wood as well as the allowable bending stress. Table 2 presents the five different wood types used, together with their modulus of elasticity (E) and allowable bending stress.

TABLE 2: Wood Species Properties

| | Oak | Doug Fir | GUM | Hemlock | Pine |
|---|---|---|---|---|---|
| Modulus of Elasticity | 1,060,000 | 1,440,000 | 1,090,000 | 970,000 | 1,280,000 |
| Allowable Stress (psi) | 1025 | 1175 | 1075 | 950 | 1000 |

Since the tie itself can be considered as a “beam” on an elastic foundation (the ballast and subgrade) it is necessary to analyze the tie as a function of the way it is supported on the ballast. Traditional tie analysis defines the tie as being supported under the outside thirds of its length, i.e. under the rail seats. This leaves the middle third “open”, a condition which is not normally found in track. In order to more realistically analyze the tie support, the tie has been analyzed as a finite beam on a continuous elastic foundation, and is presented in detail in Appendix A.

Figures 1 present the tie bending moment distributions ( and corresponding tie bending stresses) for this analysis.

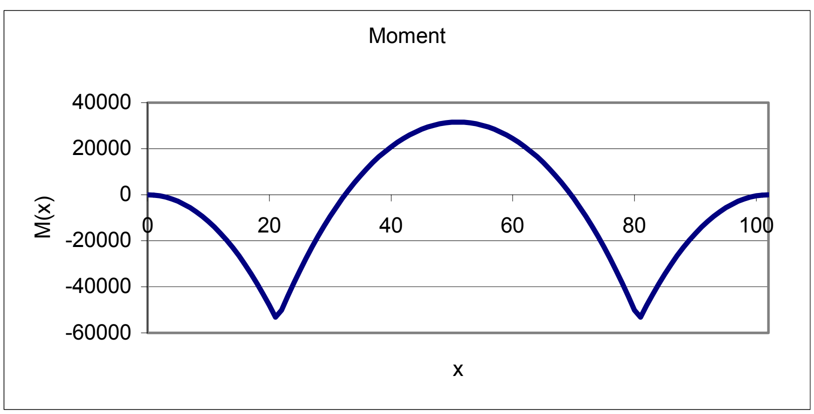



Figure 1: Tie Moment Distribution; Continuously Supported Tie

This analysis can be considered to be a “bound” and as such can be used to examine the effect of tie size. This comparison is presented in Table 3 for this analysis approach. As can be seen in this tables, the bending stress of the 6”x8” tie is, as expected, greater than that of the 7”x9” tie, because of the decreased section modulus due to the smaller tie dimensions. As can be seen in Tables, for poor support (low modulus) the tie bending stresses are of the order of 16% to 21% greater for the 6”x8” ties.

Table 3: Tie Bending Stress Comparison

| Track Modulus k, lb/in/in | Oak 6x8 | Oak 7x9 | Oak Ratio | Douglas Fir 6x8 | Douglas Fir 7x9 | Douglas Fir Ratio | GUM 6x8 | GUM 7x9 | GUM Ratio |
|---|---|---|---|---|---|---|---|---|---|
| 1000 | 774.8 | 646.3 | 1.20 | 772.1 | 635.8 | 1.21 | 774.6 | 645.4 | 1.20 |
| 2000 | 915.2 | 791.7 | 1.16 | 920.7 | 782.9 | 1.18 | 915.9 | 791.0 | 1.16 |
| 3000 | 995.1 | 882.8 | 1.13 | 1009.5 | 878.5 | 1.15 | 996.7 | 882.6 | 1.13 |
| 4000 | 1047.5 | 947.6 | 1.11 | 1070.4 | 948.5 | 1.13 | 1049.9 | 948.0 | 1.11 |
| 5000 | 1084.3 | 997.1 | 1.09 | 1115.0 | 1002.9 | 1.11 | 1087.5 | 997.9 | 1.09 |
| 6000 | 1111.1 | 1036.5 | 1.07 | 1149.0 | 1046.9 | 1.10 | 1114.9 | 1037.8 | 1.07 |
| 8000 | 1146.2 | 1095.9 | 1.05 | 1196.7 | 1114.7 | 1.07 | 1151.2 | 1097.9 | 1.05 |

| Track Modulus k, lb/in/in | Hemlock 6x8 | Hemlock 7x9 | Hemlock Ratio | Pine 6x8 | Pine 7x9 | Pine Ratio |
|---|---|---|---|---|---|---|
| 1000 | 775.1 | 649.2 | 1.19 | 773.4 | 639.9 | 1.21 |
| 2000 | 912.6 | 793.6 | 1.15 | 919.2 | 786.7 | 1.17 |
| 3000 | 989.5 | 883.0 | 1.12 | 1004.8 | 880.7 | 1.14 |
| 4000 | 1039.3 | 946.2 | 1.10 | 1062.6 | 948.9 | 1.12 |
| 5000 | 1073.6 | 994.1 | 1.08 | 1104.3 | 1001.5 | 1.10 |
| 6000 | 1098.3 | 1032.1 | 1.06 | 1135.6 | 1043.8 | 1.09 |
| 8000 | 1129.8 | 1088.9 | 1.04 | 1178.5 | 1108.4 | 1.06 |

Noting the allowable stress values from Table 2 it can be seen that for low and moderate modulus values (1000 to 3000 lb/in/in), the stress levels even for the smaller 6”x8” ties, are within the allowable limits for all of the tie materials [Note: However, that Hemlock, the tie material with the lowest allowable stress is marginal at 3000 lb/in/in.] However for high modulus values (4000 lb/in/in and greater), the stress levels for the 6”x8” ties begin to exceed allowable limits, with a potential for premature failure. In general, however, track where 6”x8” ties are to be used is usually low to moderate modulus track and only rarely exceeds 4000 lb/in/in in track modulus.

Note, that the tie bending stress analysis presented in Table 3 does not account for the effect of the abrading away of the base of the tie (due to the pressure at the bottom of tie/ top of ballast interface).

COMPARISON OF 6”x8” AND 7”x9” CROSS-TIES
ANALYSIS OF TIE BEARING STRESS

While the load applied to each tie is the same, regardless of tie size (assuming comparable modulus values), the 6”x8” tie, with its 8” wide face may not be able to accommodate the more standard 12” AREMA tie plate with a width of 7 ¾”. That is because the tie plate tolerances and potential for less than exact application in the field increases the possibility that one of the tie plate edges will go past the end of the tie. This condition can cause problems during tamping operations when the tamping tools impact the tie plate, causing loosening of the spikes and potential increased degradation of the ties ( not to mention increased potential forces applied to the tamper itself).

Thus for this analysis, it is assumed that the smaller 10” AREMA tie plate, with a width of 7 ½” will be used. This allows for greater margin of error in installation.

The resulting tie plate bearing areas are therefore:

- 6”x8” tie with a 10” AREMA tie plate (7 ½” x 10”) has a bearing area of 75 square inches
- 7”x9” tie with a 12” AREMA tie plate (7 ¾” x 12”) has a bearing area of 93 square inches

The resulting ratio of bearing area for the 7”x9” tie with a 12” AREMA tie plate vs. the 6” x8” tie with a 10” AREMA tie plate is 1.24.

Since bearing stress is linear with bearing area, the bearing stresses on the 6”x8” tie can be taken to be 24% greater than that for the 7”x9” tie.

COMPARISON OF 6”x8” AND 7”x9” CROSS-TIES
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 2.

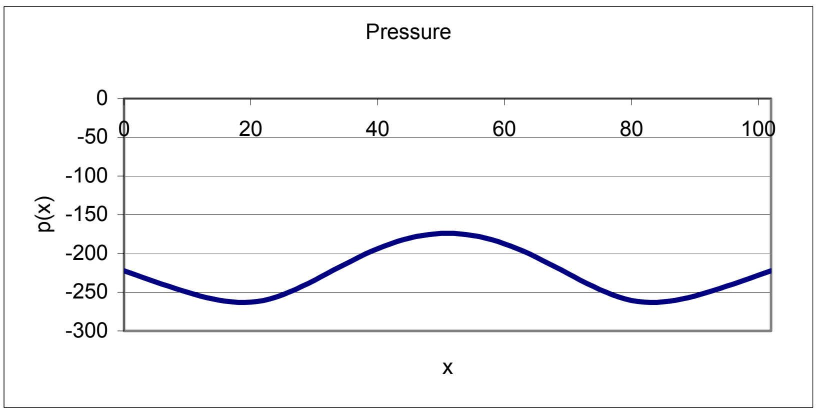



Figure 2. Tie/Ballast Pressure Distribution.

In order to analyze the stresses at the bottom of the cross-tie/top of the ballast layer, the AREMA design approach [2] 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, as presented in Appendix A, and knowing that the forces on the tie vary with track modulus, the stress on the ballast can be determined for different size ties and different values of track modulus. These ballast stresses are presented in Table 4. (Note, these stresses are independent of wood species).

These pressures are important in that they are directly related to the rate of track geometry degradation and the corresponding need for track surfacing. In particular, the higher stresses resulting from the smaller footprint of the 6”x8” tie, results in a higher rate of track geometry degradation and a corresponding increased need fro track surfacing, than for the 7”x9” tie.

TABLE 4: AREMA Tie-Ballast Stress

| Track Modulus | Tie Force | 6x8 | 7x9 | |
|---|---|---|---|---|
| k, lb/in/in | F, lb | psi | psi | Ratio |
| 1000 | 8089 | 29.7 | 26.4 | 1.125 |
| 2000 | 9619 | 35.4 | 31.4 | 1.125 |
| 3000 | 10645 | 39.1 | 34.8 | 1.125 |
| 4000 | 11439 | 42.1 | 37.4 | 1.125 |
| 5000 | 12095 | 44.5 | 39.5 | 1.125 |
| 6000 | 12659 | 46.5 | 41.4 | 1.125 |

Note: The 6”x8” tie provides a ballast bearing stress level that is 12.5% higher than the 7”x9” ties. Thus, while all stresses are below the AREMA design (allowable) level of 65 psi, it is expected that the surfacing cycle under the 6”x8” ties will be approximately 11% shorter than that for the 7”x9” ties, this requiring more frequent surfacing over the long term.

COMPARISON OF 6”x8” AND 7”x9” CROSS-TIES
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, three ballast layer depths will be examined; 6”, 9” and 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 5.

TABLE 5: Subgrade Stresses (Simplified Analysis)

| Track Modulus | Ballast Depth = 6” | | | Ballast Depth = 9” | | | Ballast Depth =12” | | |
|---|---|---|---|---|---|---|---|---|---|
| k, lb/in/in | 6X8 | 7X9 | Ratio | 6X8 | 7X9 | Ratio | 6X8 | 7X9 | Ratio |
| 1000 | 53.2 | 47.3 | 1.1 | 32.0 | 28.5 | 1.1 | 22.4 | 19.9 | 1.1 |
| 2000 | 63.3 | 56.2 | 1.1 | 38.1 | 33.9 | 1.1 | 26.6 | 23.6 | 1.1 |
| 3000 | 70.0 | 62.2 | 1.1 | 42.2 | 37.5 | 1.1 | 29.4 | 26.2 | 1.1 |
| 4000 | 75.2 | 66.9 | 1.1 | 45.3 | 40.3 | 1.1 | 31.6 | 28.1 | 1.1 |
| 5000 | 79.6 | 70.7 | 1.1 | 47.9 | 42.6 | 1.1 | 33.4 | 29.7 | 1.1 |
| 6000 | 83.3 | 74.0 | 1.1 | 50.2 | 44.6 | 1.1 | 35.0 | 31.1 | 1.1 |
| 8000 | 89.5 | 79.5 | 1.1 | 53.9 | 47.9 | 1.1 | 37.6 | 33.4 | 1.1 |

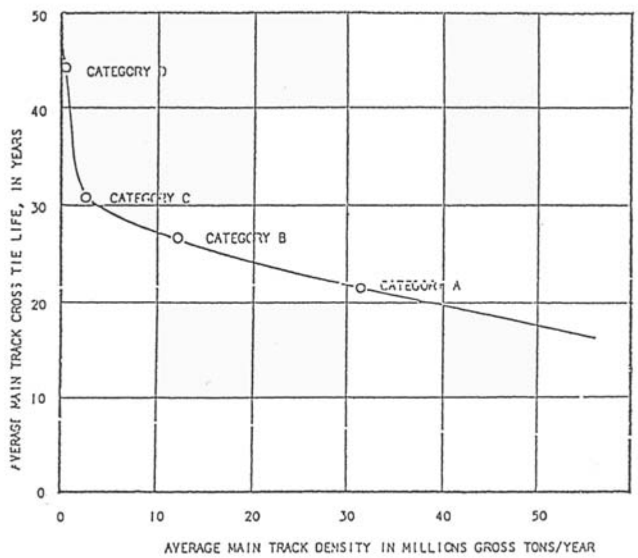
As can be seen in this table, the stress level generated by the 6”x8” tie is approximately 10% greater than that generated by the 7”x9” tie.

Furthermore, noting the high stress levels generated at the 6” and 9” ballast depths (including ballast and subballast), it can be clearly seen that a 12” ballast layer (ballast plus subballast) should be used for either tie size, 6”x8” or 7’x9”.

It should also be noted that the stress levels begin to exceed the AREMA recommended subgrade levels (25 psi) at higher track modulus values. Thus, in a manner analogous to that discussed earlier for the tie bending stresses, the subgrade stresses begin to exceed the AREMA recommended limits for higher track modulus support conditions. However for the range of modulus support conditions most typical for branch lines where 6”x8” ties will be used, the stresses are within the general range of that specified by AREMA.

## TIE LIFE

While tie life varies significantly as a function of such key parameters as curvature, annual tonnage (MGT), and environmental conditions, for most branch line and secondary track applications, with limited traffic levels, a more composite tie life value can be used. Looking at generalized STB replacement statistics [3] shown in Figure 3, it appears that an average tie life of 32 years can be used for low density secondary and branch lines and 45 years can be used for very low density track.




Tie Life vs Tonnage for Four Different Density Categories

Fig 3. US System Average Tie Life

Noting that tie life can be assumed to be proportional to the stress levels applied to the tie in track, the effect of tie size on stresses has been shown to be as follows:

- Ratio of tie bending stresses of 6”x8” tie vs. 7”x9” tie: 1.16 to 1.21
- Ratio of tie bearing stresses of 6”x8” tie vs. 7”x9” tie: 1.24*

* Based on a 7” x9” tie with a 12” AREMA tie plate vs. the 6”x8” tie with a 10” AREMA tie plate. If the same size tie plate is used, this ratio is reduced dramatically (and in fact approaches 1.0)

However, for those categories of tie degradation that are independent of either bending or bearing stress, such a spike killed ties, ties that have experienced derailment (wheel) damage or damage form mechanical equipment, there is no degradation of tie life due to tie size and the resulting ratio of tie stresses is 1.0.

Research studies [4] have indicated the following tie failure distribution:

- Plate cutting (associated directly with bearing stresses): 18 to 20% of ties removed from track
- Decay/Deterioration and (in many cases) associated tie plate area crushing (associated with bearing stresses): 43 to 44% of ties removed from track
- Splitting (associated directly with bending stresses): 16 to 18% of ties removed from track
- Spike Killing (not associated with bearing or bending stresses): 14 to 16% of ties removed from track
- Miscellaneous causes (generally not associated with bearing or bending stresses): 2 to 9% of ties removed from track

Based on the above distribution of failures, a composite stress damage ratio can obtained based on the following distribution of stresses:

| | | |
|---|---|---|
| Tie Life ratio based on non-size related parameters | 1.00 | 20.00% |
| Tie Life based on bending stress | 1.16 | 25.00% |
| Tie Life based on bearing stress | 1.24 | 55.00% |
| Tie Life based on composite of bearing and bending | | 1.17 |

The effect of these stresses on tie life is shown in Table 6

TABLE 6: TIE LIFE (Years)

| | Tie Life 7x9 STB Average | Tie Life 6x8 Reduction due to bending stresses | Tie Life 6x8 Reduction due to bearing stresses | Tie Life 6x8 Reduction due to composite stresses |
|---|---|---|---|---|
| Moderate to Low density track | 32 | 27.6 | 25.8 | 27.3 |
| Low density track | 45 | 38.8 | 36.3 | 38.4 |

In addition, in typical North American maintenance practice, ties are replaced on a cyclic basis generally using production gangs. These tie cycles can range from 40 to 1200+ ties per mile (less than 400 ties per mile becomes uneconomical for large scale production gangs and ties are then installed using more limited gangs at higher per tie costs). The number of cycles is directly related to the ratio of total ties per mile (approximately 3200 for wood tie track) and the number of ties installed per cycle. Thus for a installation of 800 ties per mile, there would be four complete tie cycles during the lifespan of the tie (3200/800 = 4).

SURFACING CYCLE

Surfacing cycle, or item between surfacing operations to correct track geometry deviations, varies significantly as a function of such key parameters as soil and ballast condition, annual tonnage (MGT), and environmental conditions. For most branch line and secondary track applications, with limited traffic levels, a more composite surfacing cycle value can be used. Looking at generalized surfacing cycle models, such as the one presented in Figure 4 [5], it appears that an average surfacing cycle of 6 years can be used for low density secondary and branch lines and 8 years can be used for very low density track and yards. As traffic increases, the surfacing decreases accordingly.

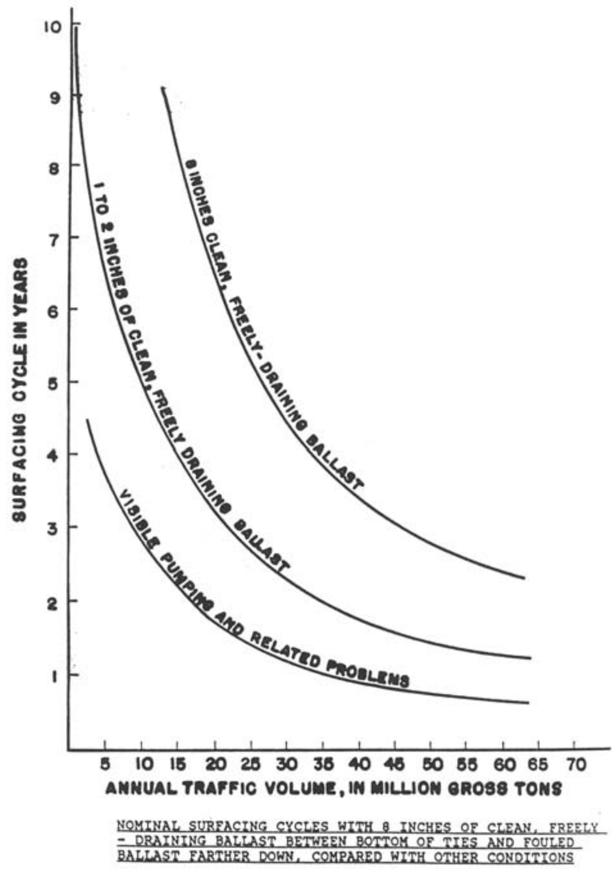



Figure 4: Surfacing cycle vs. Annual Traffic Volume (MGT)

Noting that surfacing cycle can be assumed to be proportional to the stress levels applied to the ballast or subgrade layers in track,  the effect of tie size on stresses has been shown to be as follows:

- Ratio of tie-ballast bearing stresses of 6”x8” tie vs. 7”x9” tie: 1.125
- Ratio of ballast-subgrade bearing stresses of 6”x8” tie vs. 7”x9” tie: 1.1

Noting the tie-ballast interface stress as being more conservative, the effect of these stresses on surfacing cycle is shown in Table 7A.

TABLE 7A: Surfacing Cycle (Years)

| | 7x9 | 6x8 |
|---|---|---|
| Low density track | 6 | 5.3 |
| Very low density track | 8 | 7.1 |

It should be noted however that surfacing cycle is very much dependant on level of traffic as well as allowable track geometry variations (corresponding to FRA Track Class). Thus a broader range of surfacing cycles is shown in Table 7B as follows:

TABLE 7B: Surfacing Cycle (Years)

| | 7x9 | 6x8 |
|---|---|---|
| Moderate density track | 4 | 3.6 |
| Lower density track | 6 | 5.3 |
| Low density track | 8 | 7.1 |
| Very low density track | 10 | 8.9 |

LIFE CYCLE COST ANALYSIS

Using the above differences in tie life and surfacing cycle, together with appropriate tie and surfacing costs, it is possible to compare life cycle costs for tracks with conventional tie replacement (of between 400 and 1600 ties/mile) with 6"x8" vs. 7"x9" timber cross-ties of similar quality wood, specifically grade ties[1].

The analysis approach taken is to examine the costs, over a significantly long life cycle (of the order of 50+ years), associated with tie replacement and surfacing. The comparison will be that of renewing the track by inserting new 6" x8" ties at year zero and then on a regular maintenance cycle corresponding to the percentage of total ties installed. This will be compared to the same type of renewal using 7"x9" ties. The respective tie lives (and thus tie cycles) and surfacing cycles will be adjusted to reflect the difference in expected component lives and maintenance cycles, as described previously.

Thus if 800 ties per mile were being replaced on a cyclic basis, and using the 32 year tie life for 7"x9" ties under moderate to low density traffic, then based on 3200 ties per mile, the following tie insertion schedule would be followed over a 50+ year time horizon. (Note: The 8-year cycle is based on 800/3200 ties inserted with a tie life of 32 years)

| | | |
|---|---|---|
| Cycle 1 | Year 0 | 800 ties |
| Cycle 2 | Year 8 | 800 ties |
| Cycle 3 | Year 16 | 800 ties |
| Cycle 4 | Year 24 | 800 ties |
| Cycle 5 | Year 32 | 800 ties |
| Cycle 6 | Year 40 | 800 ties |
| Cycle 7 | Year 48 | 800 ties |
| Cycle 8 | Year 56 | 800 ties |
| Cycle 9 | Year 64 | 800 ties |

If 7"x9" ties would be used, then their reduced life would follow the following insertion schedule: (note the 8 year cycle is based on 800/3200 ties inserted with a tie life of 27.3 years- corresponding to the more composite tie stress ratio)

| | | |
|---|---|---|
| Cycle 1 | Year 0 | 800 ties |
| Cycle 2 | Year 6.8 | 800 ties |
| Cycle 3 | Year 13.6 | 800 ties |
| Cycle 4 | Year 20.4 | 800 ties |
| Cycle 5 | Year 26.2 | 800 ties |
| Cycle 6 | Year 33 | 800 ties |
| Cycle 7 | Year 39.8 | 800 ties |
| Cycle 8 | Year 47.6 | 800 ties |
| Cycle 9 | Year 54.4 | 800 ties |

[1] Industrial grade ties have a significantly different tie life and as such much be examined separately.

Usually by the time you go out 50 years, the time value of money makes the benefits of anything past 50 years to be very small.

In a similar manner the surfacing cycles must be compared noting the differences in surfacing cycles due to the increased ballast bearing pressure defined previously.

Thus based on a surfacing cycle of 6 years for 7"x9" ties and 5.3 years for 6.8" ties, the following surfacing cycles would take place

| | 7"x9" | 6"x8" |
|---|---|---|
| Cycle 1 | Year 0 | Year 0 |
| Cycle 2 | Year 6 | Year 5.3 |
| Cycle 3 | Year 12 | Year 10.6 |
| Cycle 4 | Year 18 | Year 15.9 |
| Cycle 5 | Year 24 | Year 21.2 |
| Cycle 6 | Year 30 | Year 26.5 |
| Cycle 7 | Year 36 | Year 31.8 |
| Cycle 8 | Year 42 | Year 37.1 |
| Cycle 9 | Year 48 | Year 42.4 |
| Cycle 10 | | Year 49.7 |

Note: The extra cycle required to reach 50 years.

In order to calculate life cycle costs it is necessary to assume an interest rate. In today's economy, a rate of between 6% and 10% is appropriate, with an "average rate of 8%".

The costs for track surfacing is of the order of $10,000 a mile, to include a small ballast lift (2 to 4 inches) typical of lower density track.

The cost for the cross-ties is given in Table 8.

Table 8: Timber Tie Costs

| Costs | Material | Labor | Total |
|---|---|---|---|
| 6x8 | $24 | $50 | $74 |
| 7x9 | $35 | $50 | $85 |

Using the above sample case of 800 ties per mile, together with the above costs, the life cycle costs can be calculated as follows:

| | 7"x9" ties | 6"x8" ties | Savings (use of 6"x8" ties) |
|---|---|---|---|
| Initial tie installation costs* | $68,000 | $59,200 | $ 8,800 |
| Present value of 10 future tie cycles* | $79,743 | $85,223 | -$ 5,479 |
| Present value of surfacing cycles | $16,616 | $19,214 | -$ 2,598 |
| Net Savings of 6"x8" ties | | | $ 723 |

* based on 800 ties per mile per cycle

Thus in this case, the use of 6”x8” ties is economically justified on a life cycle cost basis.

If a more limited tie installation is required, requiring 500 ties per mile, the life cycle costs are calculated as follows:

| | 7”x9” ties | 6”x8” ties | Savings (use of 6”x8” ties) |
|---|---|---|---|
| Initial tie installation costs* | $42,500 | $37,000 | $ 5,500 |
| Present value of 10 future tie cycles* | $88,624 | $91,631 | -$ 3,007 |
| Present value of surfacing cycles | $16,616 | $19,214 | -$ 2,598 |
| Net Savings of 6”x8” ties | | | -$ 105 |

* Based on 800 ties per mile per cycle

Thus in this case, the use of 6”x8” ties is not economically justified (marginally) on a life cycle cost basis.

If however, a major renovation is required, thus needing 1200 ties per mile, the life cycle analysis can be calculated as follows;

| | 7”x9” ties | 6”x8” ties | Savings (use of 6”x8” ties) |
|---|---|---|---|
| Initial tie installation costs* | $102,000 | $ 88,800 | $ 13,200 |
| Present value of 10 future tie cycles* | $ 67,180 | $ 74,034 | -$ 6,855 |
| Present value of surfacing cycles | $ 16,616 | $ 19,214 | -$ 2,598 |
| Net Savings of 6”x8” ties | | | $ 3,747 |

*based on 1200 ties per mile per cycle. Note: Because so many ties are being put in, the future tie cycles are also spread out further, corresponding to a 12 year tie cycle and 10.2 year tie cycle for 7x9 and 6x8 ties respectively.

Thus in the case of this larger tie application, the use of 6”x8” ties is economically justified.

For the case of an 8% interest rate, the composite stress based reduction in tie life, 7”x9” tie life of 32 years and 6 year surfacing cycle, the results for the full range of tie gang sizes is presented in Table 9 and Figure 5.

Figure 5: 8% Interest; Composite Life and Damage Values

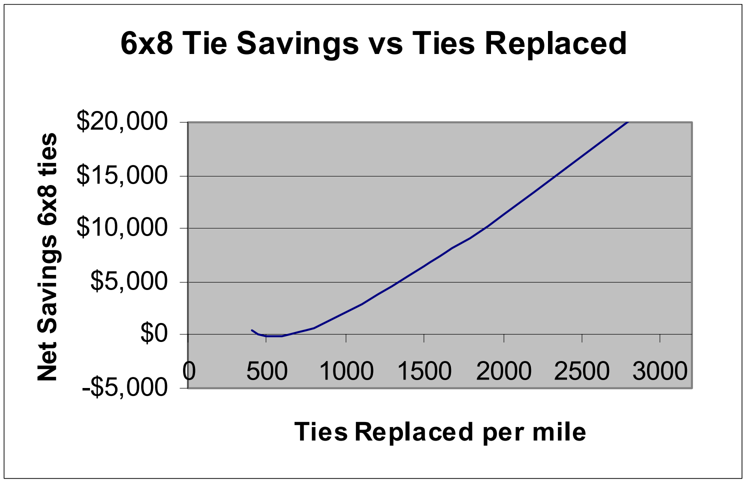



Table 9: 8% Interest; Composite Tie Life and Damage Values

| Ties Install Installed | Cost 7x9 | Cost 6x8 | Initial Cost Difference | 10 Cycle Cost 7x9 | 10 Cycle Cost 6x8 | 10 cycle Cost Difference | Net savings With Surfacing 6x8 Ties |
|---|---|---|---|---|---|---|---|
| 400 | $34,000 | $29,600 | $4,400 | $89,975 | $91,412 | -$1,437 | $365 |
| 500 | $42,500 | $37,000 | $5,500 | $88,624 | $91,631 | -$3,007 | -$105 |
| 600 | $51,000 | $44,400 | $6,600 | $86,043 | $90,157 | -$4,114 | -$112 |
| 700 | $59,500 | $51,800 | $7,700 | $82,973 | $87,873 | -$4,900 | $201 |
| 800 | $68,000 | $59,200 | $8,800 | $79,743 | $85,223 | -$5,479 | $722 |
| 900 | $76,500 | $66,600 | $9,900 | $76,501 | $82,428 | -$5,927 | $1,375 |
| 1000 | $85,000 | $74,000 | $11,000 | $73,310 | $79,599 | -$6,289 | $2,113 |
| 1100 | $93,500 | $81,400 | $12,100 | $70,199 | $76,792 | -$6,593 | $2,909 |
| 1200 | $102,000 | $88,800 | $13,200 | $67,180 | $74,034 | -$6,855 | $3,747 |
| 1300 | $110,500 | $96,200 | $14,300 | $64,255 | $71,339 | -$7,083 | $4,618 |
| 1400 | $119,000 | $103,600 | $15,400 | $61,428 | $68,711 | -$7,283 | $5,518 |
| 1500 | $127,500 | $111,000 | $16,500 | $58,697 | $66,155 | -$7,458 | $6,444 |
| 1600 | $136,000 | $118,400 | $17,600 | $56,060 | $63,670 | -$7,609 | $7,392 |
| 2000 | $170,000 | $148,000 | $22,000 | $46,436 | $54,441 | -$8,005 | $11,396 |
| 2400 | $204,000 | $177,600 | $26,400 | $38,194 | $46,304 | -$8,110 | $15,692 |
| 2800 | $238,000 | $207,200 | $30,800 | $31,204 | $39,182 | -$7,978 | $20,224 |
| 3200 | $272,000 | $236,800 | $35,200 | $25,333 | $32,994 | -$7,662 | $24,940 |

As can be seen in Table 9 and Figure 5, for this tie damage effect, the 6"x8" ties are economically justified over the 50 year life cycle for those cases where 650 or more ties per mile are installed on a regular tie gang cycle basis.

Appendix B presents the complete detailed analysis.

## SENSITIVITY ANALYSIS

Sensitivity analyses were performed for several key variables to show the effect on the life cycle economics. These included sensitivities to:

- Tie Life Reduction
- Interest Rate
- Tie Life
- Surfacing Cycle

Sensitivity to tie life reduction is a key effect and can have a major impact on the overall economics. In the previous section, the composite tie life reduction was used, a reduction of the order of slightly more than 15%, corresponding to the distribution of tie failures as reported in the literature. In order to show the sensitivity of the results to this important factor, two additional analyses will be presented:

- The more conservative tie life reduction of almost 20% (corresponding to a damage factor of 1.24)
- Less conservative tie life reduction of 14% (corresponding to a damage factor of 1.16)

Figures 6A, and 6B and Table 10 A and 10B present the sensitivity to tie insertions as a function of tie life reduction of 20% and 14% respectively.

Figure 6A: 8% Interest; Conservative Life and Damage Values

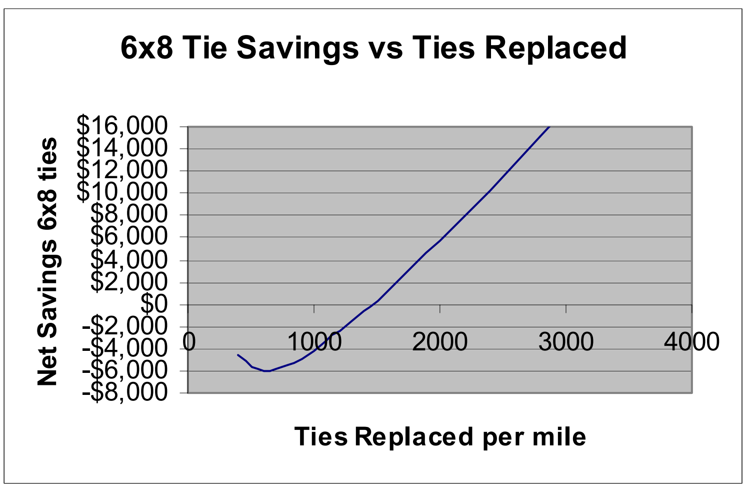


Table 10A: 8% Interest; Conservative Life and Damage Values

| Ties Install Installed | Cost 7x9 | Cost 6x8 | Initial Cost Difference | 10 Cycle Cost 7x9 | 10 Cycle Cost 6x8 | 10 Cycle Cost Difference | Net Savings Including Surfacing 6x8 Ties |
|---|---|---|---|---|---|---|---|
| 400 | $34,000 | $29,600 | $4,400 | $89,975 | $96,267 | -$6,293 | -$4,491 |
| 500 | $42,500 | $37,000 | $5,500 | $88,624 | $97,119 | -$8,494 | -$5,593 |
| 600 | $51,000 | $44,400 | $6,600 | $86,043 | $96,028 | -$9,986 | -$5,984 |
| 700 | $59,500 | $51,800 | $7,700 | $82,973 | $93,963 | -$10,991 | -$5,889 |
| 800 | $68,000 | $59,200 | $8,800 | $79,743 | $91,426 | -$11,683 | -$5,482 |
| 900 | $76,500 | $66,600 | $9,900 | $76,501 | $88,679 | -$12,178 | -$4,877 |
| 1000 | $85,000 | $74,000 | $11,000 | $73,310 | $85,859 | -$12,548 | -$4,147 |
| 1100 | $93,500 | $81,400 | $12,100 | $70,199 | $83,035 | -$12,835 | -$3,334 |
| 1200 | $102,000 | $88,800 | $13,200 | $67,180 | $80,243 | -$13,064 | -$2,462 |
| 1300 | $110,500 | $96,200 | $14,300 | $64,255 | $77,504 | -$13,249 | -$1,547 |
| 1400 | $119,000 | $103,600 | $15,400 | $61,428 | $74,825 | -$13,398 | -$596 |
| 1500 | $127,500 | $111,000 | $16,500 | $58,697 | $72,212 | -$13,516 | $386 |
| 1600 | $136,000 | $118,400 | $17,600 | $56,060 | $69,666 | -$13,606 | $1,396 |
| 2000 | $170,000 | $148,000 | $22,000 | $46,436 | $60,159 | -$13,723 | $5,678 |
| 2400 | $204,000 | $177,600 | $26,400 | $38,194 | $51,700 | -$13,507 | $10,295 |
| 2800 | $238,000 | $207,200 | $30,800 | $31,204 | $44,226 | -$13,022 | $15,180 |
| 3200 | $272,000 | $236,800 | $35,200 | $25,333 | $37,665 | -$12,332 | $20,269 |

Thus for this case, 6”x8” ties show an economic life cycle advantage only for large-scale insertions of the order of 1500 ties or greater. However, this is based on a severe penalty for the 6”x8” ties in service. If a less conservative effect is consider, specifically, the 1.16 damage factor associated with the tie bending stresses, then the results are as follows:

Figure 6B: 8% Interest; Less Conservative Tie Damage Effect

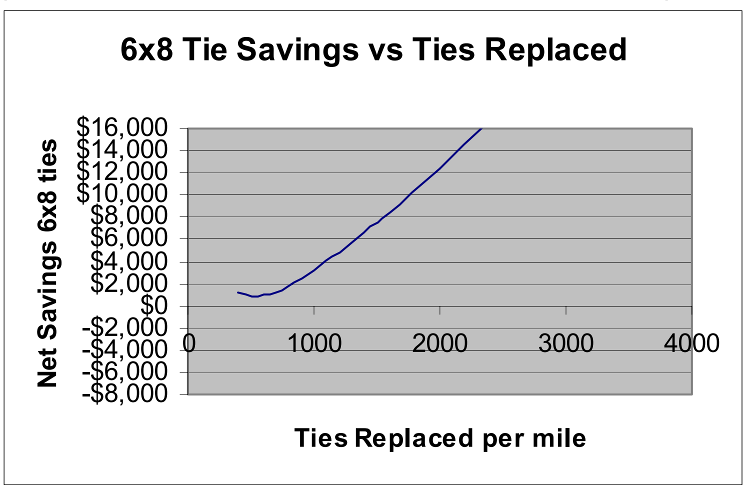


Table 10B: 8% Interest; Less Conservative Tie Damage Effect

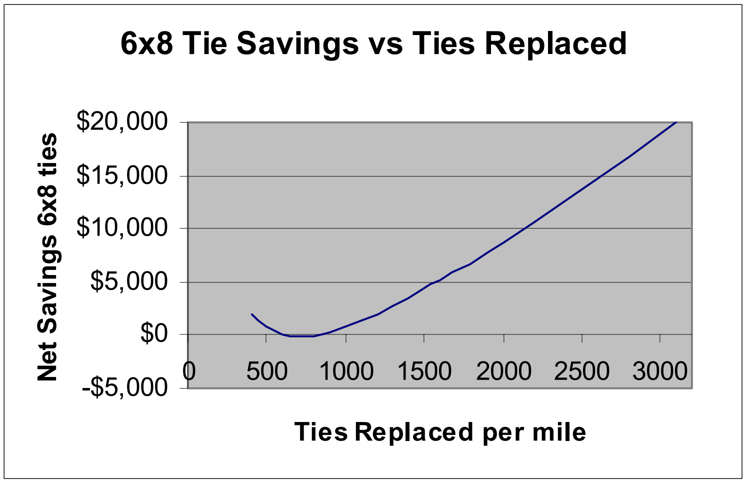
| Ties Install Installed | Cost 7x9 | Cost 6x8 | Initial Cost Difference | 10 Cycle Cost 7x9 | 10 Cycle Cost 6x8 | 10 Cycle Cost Difference | Net Savings With Surfacing 6x8 Ties |
|---|---|---|---|---|---|---|---|
| 400 | $34,000 | $29,600 | $4,400 | $89,975 | $90,536 | -$561 | $1,240 |
| 500 | $42,500 | $37,000 | $5,500 | $88,624 | $90,648 | -$2,024 | $878 |
| 600 | $51,000 | $44,400 | $6,600 | $86,043 | $89,110 | -$3,068 | $934 |
| 700 | $59,500 | $51,800 | $7,700 | $82,973 | $86,792 | -$3,819 | $1,282 |
| 800 | $68,000 | $59,200 | $8,800 | $79,743 | $84,124 | -$4,381 | $1,820 |
| 900 | $76,500 | $66,600 | $9,900 | $76,501 | $81,323 | -$4,822 | $2,479 |
| 1000 | $85,000 | $74,000 | $11,000 | $73,310 | $78,495 | -$5,185 | $3,217 |
| 1100 | $93,500 | $81,400 | $12,100 | $70,199 | $75,693 | -$5,493 | $4,008 |
| 1200 | $102,000 | $88,800 | $13,200 | $67,180 | $72,942 | -$5,762 | $4,840 |
| 1300 | $110,500 | $96,200 | $14,300 | $64,255 | $70,254 | -$5,999 | $5,703 |
| 1400 | $119,000 | $103,600 | $15,400 | $61,428 | $67,637 | -$6,209 | $6,593 |
| 1500 | $127,500 | $111,000 | $16,500 | $58,697 | $65,091 | -$6,394 | $7,507 |
| 1600 | $136,000 | $118,400 | $17,600 | $56,060 | $62,618 | -$6,557 | $8,444 |
| 2000 | $170,000 | $148,000 | $22,000 | $46,436 | $53,441 | -$7,005 | $12,396 |
| 2400 | $204,000 | $177,600 | $26,400 | $38,194 | $45,364 | -$7,170 | $16,632 |
| 2800 | $238,000 | $207,200 | $30,800 | $31,204 | $38,308 | -$7,103 | $21,099 |
| 3200 | $272,000 | $236,800 | $35,200 | $25,333 | $32,188 | -$6,856 | $25,746 |

As can be seen in Table 10 and Figure 6, for this tie damage effect, which is less conservative but still significant, the 6"x8" ties are economically justified over the 50 year life cycle for all cases shown (400 ties and above).

Interest rate can be a major factor in any life cycle cost analysis. The range of interest rates used in this analysis is between 6% and 10%.

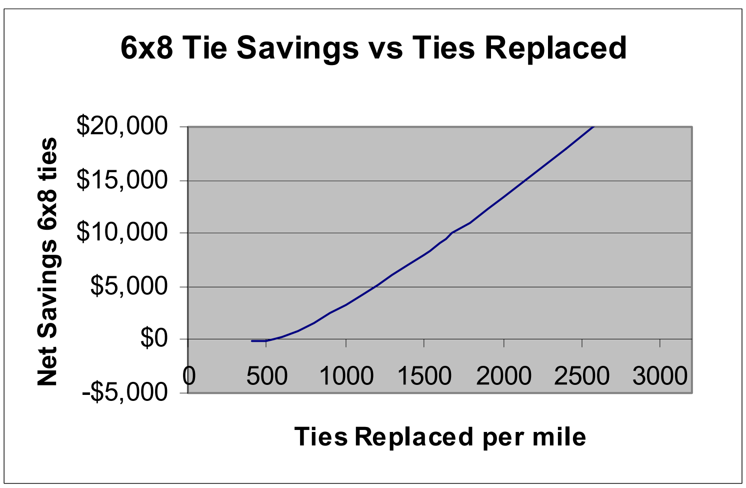
Figures 7A, and 7B present the sensitivity to tie insertions as a function of interest rates of 6% and 10% respectively (8% is shown in Figure 5 and 6) for the composite tie life damage effect.

Figures 7A 6% interest, Composite Tie Damage




Note: The cross-over point is approximately 700 ties.

Figures 7B 10% interest, Composite Tie Damage



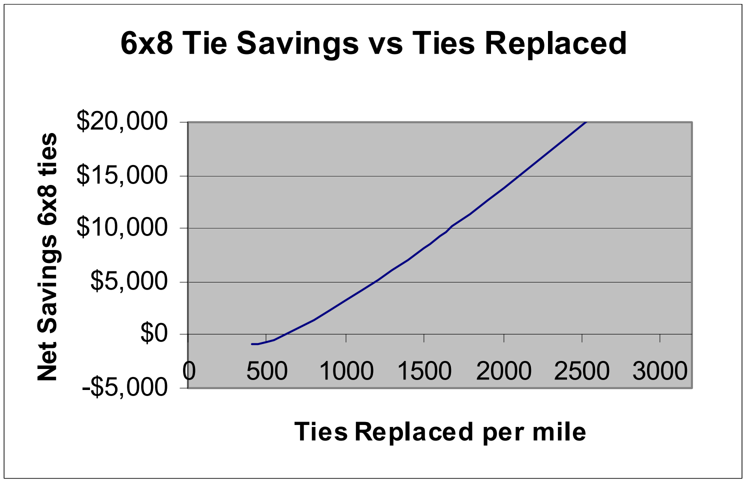

Note: The cross-over point is approximately 500 ties.

Both tie life and surfacing cycles can likewise be important factors in this life cycle cost analysis. They will be addressed below.

If the track is a very low density track, then the average tie life would increase to 45 years for the 7"x9" ties and the resulting 6"x8" tie life would be 38.4 years in the composite stress based case.

Figure 8 present the sensitivity to tie insertions as a function tie life (at an interest rate of 8%). Note, surfacing cycle is maintained at 6 years for the 7"x9" tie case.

Figures 8: 8% interest, Composite Tie Damage, 45 year tie life for 7x9 ties

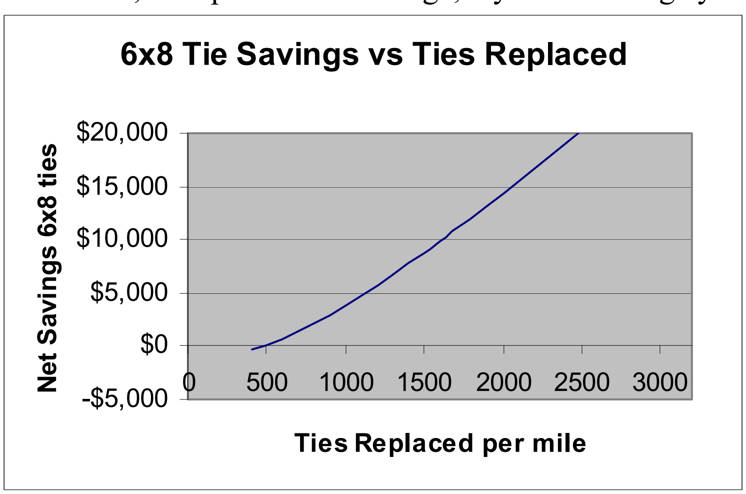



Note: The cross-over point is approximately 600 ties.

Likewise, for very low density track, the average surfacing cycle would increase to 8 years for the 7"x9" ties and the resulting 6"x8" surfacing cycle would be 7.1 years.

Figure 9 presents the sensitivity to tie insertions as a function of surfacing cycles (at an interest rate of 8%) based on the longer tie life of 45 years ( 7"x9" ties)

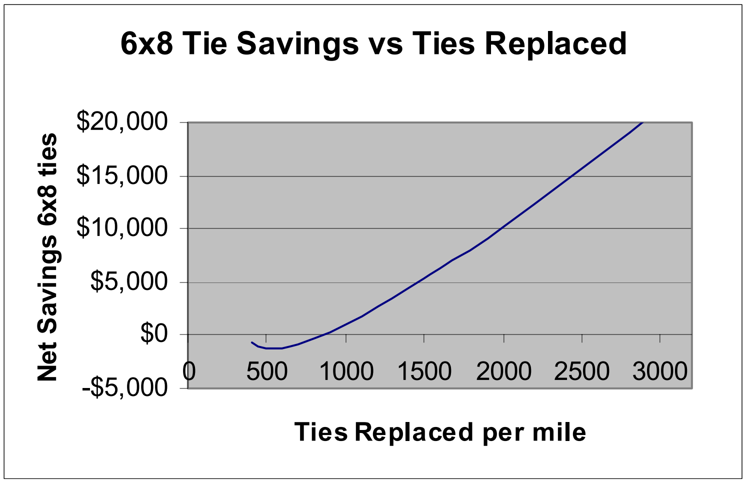
Figures 9: 8% interest, Composite Tie Damage, 8 year surfacing cycle for 7x9 ties




Note: The cross-over point is approximately 400 ties.

Finally, the question arises as to what level of density of traffic requires the use of the larger 7"x9" ties. While a detailed analysis of this question is beyond the scope of this report, the effect of increased tonnage can be approximately be reducing the surfacing cycle, which is the first (and shortest term) effect that will occur in the case of increasing traffic density. Figure 10 illustrates this effect with a surfacing cycle of 4 years and a 32-year tie life (7”x9” ties).

Figures 10 8% interest, Composite Tie Damage, 4 year surfacing cycle for 7x9 ties




As can be seen in this Figure, the 6”x8” ties are economical only for tie gang insertions of 850 ties per mile or greater. If the effect of the increased traffic density on the reduction in tie life was added, the effects would be accelerated. In general, as traffic density increases and surfacing cycles and tie lives are decreased, the economic case for the 6”x8” ties will be diminished.

Appendix C presents the detailed analysis for this case of reduced surfacing cycle.

## CONCLUSIONS AND RECOMMENDATIONS

Based on the analyses presented, the engineering life of the 6”x8” tie is between 14% and 20% less than the 7”x9” tie based on both tie bending and tie plate bearing stresses effects. Thus for a branch line application, where an industry average life for the 7”x9” tie is 32 years, the 6”x8” tie will have a life of between 26 and 28 years.

In a similar analysis, the surfacing cycle for 6”x8” tie is approximately 10% to 11% shorter than the 7”x9” tie based on tie bearing stresses to include tie to ballast and ballast to subgrade stresses. Thus for a branch line application, where an industry average surfacing cycle for the 7”x9” tie is 6 years, the 6”x8” tie will have a surfacing cycle of between 5.3 and 5.4 years.

Note that there is a significant cost different between the two sizes of ties in material with the 6”x8” tie having a material cost of about $24 a tie and an installed cost ( including material and labor) of $74. This is compared to the 7”x9” tie with a material cost of about $35 a tie and an installed cost (including material and labor) of $85.

Thus, on a life cycle cost basis, the first cost savings associated with the less expensive 6”x8” tie is offset by the shorter tie life and the reduced surfacing cycle (requiring more frequent surfacing). Noting that a mile of track has to be surfaced even if only a small percentage of the ties are replaced, the life cycle analysis shows that for large scale tie replacement on a branch or secondary line, the 6”x8” tie is less expensive but for a limited tie replacement, the 6”x8” tie life cycle costs are greater than those for the 7”x9” tie. The cross-over point varies with the cost of money used, the damage factors assumed, and the component lives but ranges from 400 ties at 6”x8” tie life of 28 years to 1500 ties at 6”x8” tie life of 26 years.

Similarly, sensitivity to such key factors as interest rate, surfacing cycle, and tie life all affect the overall economics. In general, however, large scale tie applications on light density track appear to have an economic life cycle justification, while smaller scale installations do not always provide a net economic benefit over the life cycle of the ties.

As track densities increase however, the economics start to move away from the 6”x8” ties, even for large scale installations.

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[1] Hay W. W., Railroad Engineering, Second Edition, John Wiley and Sons, New York, 1982

[2] AREMA, Manual for Railway Engineering, 1999

[3] Zarembski, A. M., “Wood Tie Life: Part I; Average Tie Life”, Tracking R&D, Simmons Boardman Books, 1992

[4] Zarembski, A. M., “Examining Wood Tie Failure”, Tracking R&D, Simmons Boardman Books, 1992

[5] Ahlf, R.E., The Behavior of Railroad Track and the Economical Practices of its Maintenance and Rehabilitation, Course notes presented at Roadbed and Rails: Fundamentals Maintenance and Economics, Wilmington DE, 1994.

# APPENDIX A: Tie and Ballast Stresses Analysis

## Analysis of Alternate Tie Types

Railway Tie Association

**General Inputs**

| | | | |
|---|---|---|---|
| Moment of Inertia, I = | 65.6 | in^4 | for 115 RE rail section |
| Tie Spacing, a = | 19.5 | in | |
| Wheel Diameter, D = | 36 | in | |
| Speed, V | 25 | mph | |
| Static Axle Load = | 35.75 | tons | |
| Static Wheel Load, Pst = | 35750 | lbs | |
| Dynamic Wheel Load, Pd = | 43942.71 | lbs | according to AREMA formula Pd = Pst*(1+33V/100D) |
| Track Modulus, k = | 2000 | lb/in/in | |
| Modulus of Elasticity, E = | 3.00E+07 | lb/in^2 | |

**Determination of Force on Tie**

| | | |
|---|---|---|
| Deflection under tie, w(0) = | 0.247 | in |
| Pressure under tie, p(0) = k*w(0) = | 493 | lb/in |
| Force under tie, F(0) = a*p(0) = | 9619 | lbs |
| Percent of Dynamic Wheel Load | 22% | |

| Track Modulus k, lb/in/in | Tie Force F, lb | |
|---|---|---|
| | 9619 | |
| 1000 | 8089 | 18.4% |
| 2000 | 9619 | 21.9% |
| 3000 | 10645 | 24.2% |
| 4000 | 11439 | 26.0% |
| 5000 | 12095 | 27.5% |
| 6000 | 12659 | 28.8% |
| 8000 | 13603 | 31.0% |

**Determination of Tie Bending Stress**

*need to compare to allowable stress by species*

Tie Bending Stress (psi)

| Track Modulus | Oak | | | Douglas Fir | | | GUM | | | Hemlock | | | Pine | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| k, lb/in/in | 6x8 | 7x9 | Ratio | 6x8 | 7x9 | Ratio | 6x8 | 7x9 | Ratio | 6x8 | 7x9 | Ratio | 6x8 | 7x9 | Ratio |
| 1000 | 774.8 | 646.3 | 1.20 | 772.1 | 635.8 | 1.21 | 774.6 | 645.4 | 1.20 | 775.1 | 649.2 | 1.19 | 773.4 | 639.9 | 1.21 |
| 2000 | 915.2 | 791.7 | 1.16 | 920.7 | 782.9 | 1.18 | 915.9 | 791.0 | 1.16 | 912.6 | 793.6 | 1.15 | 919.2 | 786.7 | 1.17 |
| 3000 | 995.1 | 882.8 | 1.13 | 1009.5 | 878.5 | 1.15 | 996.7 | 882.6 | 1.13 | 989.5 | 883.0 | 1.12 | 1004.8 | 880.7 | 1.14 |
| 4000 | 1047.5 | 947.6 | 1.11 | 1070.4 | 948.5 | 1.13 | 1049.9 | 948.0 | 1.11 | 1039.3 | 946.2 | 1.10 | 1062.6 | 948.9 | 1.12 |
| 5000 | 1084.3 | 997.1 | 1.09 | 1115.0 | 1002.9 | 1.11 | 1087.5 | 997.9 | 1.09 | 1073.6 | 994.1 | 1.08 | 1104.3 | 1001.5 | 1.10 |
| 6000 | 1111.1 | 1036.5 | 1.07 | 1149.0 | 1046.9 | 1.10 | 1114.9 | 1037.8 | 1.07 | 1098.3 | 1032.1 | 1.06 | 1135.6 | 1043.8 | 1.09 |
| 8000 | 1146.2 | 1095.9 | 1.05 | 1196.7 | 1114.7 | 1.07 | 1151.2 | 1097.9 | 1.05 | 1129.8 | 1088.9 | 1.04 | 1178.5 | 1108.4 | 1.06 |

**Determination of Tie-Ballast Stress**

Factor of Safety = 1.0

| Track Modulus | Tie Force | AREMA Tie-Ballast Stress | | |
|---|---|---|---|---|
| | | 8 | 9 | |
| k, lb/in/in | F, lb | psi | psi | Ratio |
| 1000 | 8089 | 29.7 | 26.4 | 1.125 |
| 2000 | 9619 | 35.4 | 31.4 | 1.125 |
| 3000 | 10645 | 39.1 | 34.8 | 1.125 |
| 4000 | 11439 | 42.1 | 37.4 | 1.125 |
| 5000 | 12095 | 44.5 | 39.5 | 1.125 |
| 6000 | 12659 | 46.5 | 41.4 | 1.125 |
| 8000 | 13603 | 50.0 | 44.5 | 1.125 |

**Determination of Ballast-Subgrade Stress**

According to the Talbot Equation

AREMA Ballast-Subgrade Stress (psi)

| Track Modulus | 6 | | | 9 | | | 12 | | |
|---|---|---|---|---|---|---|---|---|---|
| k, lb/in/in | 6X8 | 7X9 | Ratio | 6X8 | 7X9 | Ratio | 6X8 | 7X9 | Ratio |
| 1000 | 53.2 | 47.3 | 1.1 | 32.0 | 28.5 | 1.1 | 22.4 | 19.9 | 1.1 |
| 2000 | 63.3 | 56.2 | 1.1 | 38.1 | 33.9 | 1.1 | 26.6 | 23.6 | 1.1 |
| 3000 | 70.0 | 62.2 | 1.1 | 42.2 | 37.5 | 1.1 | 29.4 | 26.2 | 1.1 |
| 4000 | 75.2 | 66.9 | 1.1 | 45.3 | 40.3 | 1.1 | 31.6 | 28.1 | 1.1 |
| 5000 | 79.6 | 70.7 | 1.1 | 47.9 | 42.6 | 1.1 | 33.4 | 29.7 | 1.1 |
| 6000 | 83.3 | 74.0 | 1.1 | 50.2 | 44.6 | 1.1 | 35.0 | 31.1 | 1.1 |
| 8000 | 89.5 | 79.5 | 1.1 | 53.9 | 47.9 | 1.1 | 37.6 | 33.4 | 1.1 |

# APPENDIX B: Life Cycle Analysis Based on Composite Tie Life

Surfacing Cycle And Economics

| Surfacing cycles | | | Ties/mile = 3200 | | | Composite | |
|---|---|---|---|---|---|---|---|
| MGT | Cycle | | Tie Life | Tie Life | Tie Life | Tie Life | |
| | 7x9 | 6x8 | 7x9 | 6x8 | 6x8 | 6x8 | |
| Low Density | 6 | 5.3 | 32 | 27.6 | 25.8 | 27.3 | Use this line |
| Very Low density | 8 | 7.1 | 45 | 38.8 | 36.3 | 38.4 | |
| | | | | Bending | Bearing | | |

| Costs | Material | Labor | Total | | |
|---|---|---|---|---|---|
| 6x8 | $24 | $50 | $74 | | Equal Quality |
| 7x9 | $35 | $50 | $85 | | |
| Surfacing | | | $10,000 | per mile | |
| Interest rate | | 8% | | | |

| | | | |
|---|---|---|---|
| Surfacing effect based on tie-ballast stresses | 1.125 | | |
| Tie Life ratio based on non-size related parameters | 1.00 | 20.00% | For modulus of 2000 |
| Tie Life based on bending stress | 1.16 | 25.00% | |
| Tie Life based on bearing stress 10" vs 12" plate | 1.24 | 55.00% | |
| Tie Life based on composite of bearing and bending | 1.172 | | |

Based on a mile of track

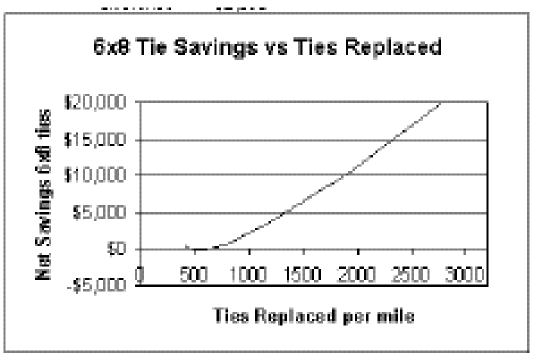
| Ties Install Installed | Tie Cycle 7x9 | Tie Cycle 6x8 | Cost 7x9 | Cost 6x8 | Initial Cost Difference | 7x9 Premium 10 Cycle Cost 7x9 | 10 Cycle Cost 6x8 | 7x9 Premium 10 Cycle Cost Difference | Tie Cost Difference | 7x9 Premium Ties Install Installed | Net Savings 6x8 Ties |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 400 | 4.0 | 3.4 | $34,000 | $29,600 | $4,400 | $89,975 | $91,412 | -$1,437 | $2,963 | 400 | $365 |
| 500 | 5.0 | 4.3 | $42,500 | $37,000 | $5,500 | $88,624 | $91,631 | -$3,007 | $2,493 | 500 | -$105 |
| 600 | 6.0 | 5.1 | $51,000 | $44,400 | $6,600 | $86,043 | $90,157 | -$4,114 | $2,486 | 600 | -$112 |
| 700 | 7.0 | 6.0 | $59,500 | $51,800 | $7,700 | $82,973 | $87,873 | -$4,900 | $2,800 | 700 | $201 |
| 800 | 8.0 | 6.8 | $68,000 | $59,200 | $8,800 | $79,743 | $85,223 | -$5,479 | $3,321 | 800 | $722 |
| 900 | 9.0 | 7.7 | $76,500 | $66,600 | $9,900 | $76,501 | $82,428 | -$5,927 | $3,973 | 900 | $1,375 |
| 1000 | 10.0 | 8.5 | $85,000 | $74,000 | $11,000 | $73,310 | $79,599 | -$6,289 | $4,711 | 1000 | $2,113 |
| 1100 | 11.0 | 9.4 | $93,500 | $81,400 | $12,100 | $70,199 | $76,792 | -$6,593 | $5,507 | 1100 | $2,909 |
| 1200 | 12.0 | 10.2 | $102,000 | $88,800 | $13,200 | $67,180 | $74,034 | -$6,855 | $6,345 | 1200 | $3,747 |
| 1300 | 13.0 | 11.1 | $110,500 | $96,200 | $14,300 | $64,255 | $71,339 | -$7,083 | $7,217 | 1300 | $4,618 |
| 1400 | 14.0 | 11.9 | $119,000 | $103,600 | $15,400 | $61,428 | $68,711 | -$7,283 | $8,117 | 1400 | $5,518 |
| 1500 | 15.0 | 12.8 | $127,500 | $111,000 | $16,500 | $58,697 | $66,155 | -$7,458 | $9,042 | 1500 | $6,444 |
| 1600 | 16.0 | 13.7 | $136,000 | $118,400 | $17,600 | $56,060 | $63,670 | -$7,609 | $9,991 | 1600 | $7,392 |
| 2000 | 20.0 | 17.1 | $170,000 | $148,000 | $22,000 | $46,436 | $54,441 | -$8,005 | $13,995 | 2000 | $11,396 |
| 2400 | 24.0 | 20.5 | $204,000 | $177,600 | $26,400 | $38,194 | $46,304 | -$8,110 | $18,290 | 2400 | $15,692 |
| 2800 | 28.0 | 23.9 | $238,000 | $207,200 | $30,800 | $31,204 | $39,182 | -$7,978 | $22,822 | 2800 | $20,224 |
| 3200 | 32.0 | 27.3 | $272,000 | $236,800 | $35,200 | $25,333 | $39,994 | -$7,662 | $27,538 | 3200 | $24,940 |

Surfacing cycle costs — Note, surfacing cost is same in cycle 1

7x9 Premium

| 2nd Cycle 7x9 | 2nd Cycle 6x8 | 2nd Cycle Difference | 3rd Cycle 7x9 | 3rd Cycle 6x8 | 3rd Cycle Difference | 4th Cycle 7x9 | 4th Cycle 6x8 | 4th Cycle Difference | 5th Cycle 7x9 | 5th Cycle 6x8 | 5th Cycle Difference | | Total Cost Difference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $6,302 | $6,633 | -$332 | $3,971 | $4,400 | -$429 | $2,502 | $2,919 | -$416 | $1,577 | $1,936 | -$359 | | -$1,537 |

| 6th Cycle 7x9 | 6th Cycle 6x8 | 6th Cycle Difference | 7th Cycle 7x9 | 7th Cycle 6x8 | 7th Cycle Difference | 8th Cycle 7x9 | 8th Cycle 6x8 | 8th Cycle Difference | 9th Cycle 7x9 | 9th Cycle 6x8 | 9th Cycle Difference | 10th Cycle 6x8 (Extra) | Total Cost Difference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $994 | $1,284 | -$291 | $626 | $852 | -$226 | $395 | $565 | -$171 | $249 | $375 | -$126 | $249 | -$2,598 |



# APPENDIX C: Life Cycle Analysis Based on Reduced Surfacing Cycle

Surfacing cycle and economics

| Surfacing cycles | | | | | Ties/mile=3200 | | Composite | |
|---|---|---|---|---|---|---|---|---|
| MGT | Cycle | | | Tie Life | Tie Life | Tie Life | Tie Life | |
| | 7x9 | 6x8 | | 7x9 | 6x8 | 6x8 | 6x8 | |
| Low Density | 8 | 7.1 | | 45 | 45.0 | 36.3 | 38.4 | Use this line |
| Very Low density | 10 | 8.9 | | 45 | 45.0 | 36.3 | 38.4 | |
| | | | | | Bending | Bearing | | |

| Costs | Material | Labor | Total | |
|---|---|---|---|---|
| 6x8 | $24 | $50 | $74 | Equal quality |
| 7x9 | $35 | $50 | $85 | |
| Surfacing | | | $10,000 per mile | |
| Interest rate | | 8% | | |

| | | | |
|---|---|---|---|
| Surfacing effect based on tie-ballast stresses | 1.125 | | |
| Tie Life ratio based on non-size related parameters | 1.00 | 20.00% | For modulus of 2000 |
| Tie Life based on bending stress | 1.16 | 25.00% | |
| Tie Life based on bearing stress 10" vs 12" plate | 1.24 | 55.00% | |
| Tie Life based on composite of bearing and bending | 1.172 | | |

Based on a mile of track

| Tie Install Installed | Tie Cycle 7x9 | Tie Cycle 6x8 | Cost 7x9 | Cost 6x8 | Initial Cost Difference | 7x9 Premium 10 Cycle Cost 7x9 | 10 Cycle Cost 6x8 | 7x9 Premium 10 Cycle Cost Difference | Tie Cost Difference | 7x9 Premium Tie Install Installed | Net savings 6x8 Ties |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 400 | 5.6 | 4.5 | $34,000 | $29,600 | $4,400 | $61,935 | $68,667 | -$6,732 | -$2,332 | 400 | -$4,292 |
| 500 | 7.0 | 5.7 | $42,500 | $37,000 | $5,500 | $58,932 | $66,745 | -$7,813 | -$2,313 | 500 | -$4,273 |
| 600 | 8.4 | 6.8 | $51,000 | $44,400 | $6,600 | $55,695 | $64,149 | -$8,454 | -$1,854 | 600 | -$3,814 |
| 700 | 9.8 | 7.9 | $59,500 | $51,800 | $7,700 | $52,483 | $61,348 | -$8,865 | -$1,165 | 700 | -$3,125 |
| 800 | 11.3 | 9.1 | $68,000 | $59,200 | $8,800 | $49,376 | $58,526 | -$9,150 | -$350 | 800 | -$2,310 |
| 900 | 12.7 | 10.2 | $76,500 | $66,600 | $9,900 | $46,400 | $55,758 | -$9,358 | $542 | 900 | -$1,418 |
| 1000 | 14.1 | 11.3 | $85,000 | $74,000 | $11,000 | $43,559 | $53,070 | -$9,512 | $1,488 | 1000 | -$472 |
| 1100 | 15.5 | 12.5 | $93,500 | $81,400 | $12,100 | $40,853 | $50,475 | -$9,623 | $2,477 | 1100 | $517 |
| 1200 | 16.9 | 13.6 | $102,000 | $88,800 | $13,200 | $38,280 | $47,975 | -$9,696 | $3,504 | 1200 | $1,544 |
| 1300 | 18.3 | 14.7 | $110,500 | $96,200 | $14,300 | $35,836 | $45,571 | -$9,735 | $4,565 | 1300 | $2,606 |
| 1400 | 19.7 | 15.9 | $119,000 | $103,600 | $15,400 | $33,519 | $43,261 | -$9,741 | $5,659 | 1400 | $3,699 |
| 1500 | 21.1 | 17.0 | $127,500 | $111,000 | $16,500 | $31,325 | $41,043 | -$9,718 | $6,782 | 1500 | $4,822 |
| 1600 | 22.5 | 18.2 | $136,000 | $118,400 | $17,600 | $29,248 | $38,916 | -$9,668 | $7,932 | 1600 | $5,972 |
| 2000 | 28.1 | 22.7 | $170,000 | $148,000 | $22,000 | $22,048 | $31,277 | -$9,229 | $12,771 | 2000 | $10,811 |
| 2400 | 33.8 | 27.2 | $204,000 | $177,600 | $26,400 | $16,413 | $24,917 | -$8,504 | $17,896 | 2400 | $15,936 |
| 2800 | 39.4 | 31.8 | $238,000 | $207,200 | $30,800 | $12,079 | $19,687 | -$7,609 | $23,191 | 2800 | $21,231 |
| 3200 | 45.0 | 36.3 | $272,000 | $236,800 | $35,200 | $8,797 | $15,436 | -$6,639 | $28,561 | 3200 | $26,601 |

Surfacing Cycle costs — Note, surfacing cost is same in Cycle 1

| 2nd Cycle 7x9 | 2nd Cycle 6x8 | 7x9 Premium 2nd Cycle Difference | 3rd Cycle 7x9 | 3rd Cycle 6x8 | 3rd Cycle Difference | 4th Cycle 7x9 | 4th Cycle 6x8 | 4th Cycle Difference | 5th Cycle 7x9 | 5th Cycle 6x8 | 5th Cycle Difference | | Total cost Difference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $5,403 | $5,785 | -$383 | $2,919 | $3,347 | -$428 | $1,577 | $1,936 | -$359 | $852 | $1,120 | -$268 | | -$1,438 |

| 6th Cycle 7x9 | 6th Cycle 6x8 | 6th Cycle Difference | 7th Cycle 7x9 | 7th Cycle 6x8 | 7th Cycle Difference | 8th Cycle 7x9 | 8th Cycle 6x8 | 8th Cycle Difference | 9th Cycle 7x9 | 9th Cycle 6x8 | 9th Cycle Difference | 10th Cycle 6x8 (extra) | Total cost Difference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $460 | $648 | -$188 | $249 | $375 | -$126 | $134 | $217 | -$83 | $73 | $125 | -$53 | $73 | -$1,960 |