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January 12, 2000

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

Dear Mr. Gauntt:

Per Dr. Zarembski, enclosed is a copy of "Cost-benefit Analysis of Sleeper Replacement Strategies: Simulation Model", from the annual TRB meeting, which was held this week. If you have any questions, please do not hesitate to call.

Sincerely,

Marjorie P. Wellman

Marjorie P. Wellman
Receptionist

ACKNOWLEDGEMENTS

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1 INTRODUCTION

In Australian freight operations, 25-35 percent of total train operating expenses are track maintenance related *(1)*. Exclusive of rail costs, sleeper replacement represents the most significant maintenance cost for the railways *(2)*. Traditionally, the replacement of sleepers has been via spot replacement to hold or tie the track until cyclic maintenance is undertaken by a large gang, when approximately one third of the sleepers is replaced. This maintenance policy does not necessarily optimise resource allocation *(3)*. The need exists for a comparison between sleeper replacement policies, to allow the most effective and economic policy to be implemented.

It was estimated in 1991 that seventy-five percent of the world's railway consists of timber sleepers *(3)*. Despite the increasing reliability and effectiveness of alternatives such as steel and concrete, Sonti, et al *(4)* concluded in 1995 that timber has been and will continue to be the most popular material for railway sleepers in the United States. The reasons given for this included the availability of timber, the knowledge of timber sleepers that exists within the industry, the ease of manufacturing and handling and their cost effectiveness compared to alternatives. In 1998 Gruber *(5)* states that well over 90% of maintenance and construction of railway tracks utilise timber sleepers, with the market dominance warranted due to the costs versus the benefits of timber sleepers. Therefore, timber sleepers should be a focus in an investigation of replacement strategies, as these represent the majority of sleepers currently existing in track and used for replacement. Timber sleepers also require more maintenance than alternate sleeper types such as steel or concrete. Extensions of the research to include alternative sleeper types could, however, test the validity of such statements that the costs versus the benefits merit the marketplace dominance of timber sleepers.

One critical aspect in determining the condition of track with respect to sleepers is the dispersion of defective sleepers in the railway track. A section of railway track with 50 percent defective sleepers may still be safe to operate if each failed sleeper lies between two sound ones, yet the same section of track with only 1% defective sleepers all adjacent to one another would be unusable. The Association of American Railways (AAR) has conducted research into multiple sleeper failures *(6)*. The study has shown that the maintenance policy is a key factor in the occurrence of multiple sleeper failure. A further conclusion was that the numbers of clusters of defective sleepers of various sizes provides a more relevant basis for replacement decisions than just the percent of failed sleepers in the section of track. Therefore, in comparing replacement strategies for the sleepers in a section of railway track, the clustering patterns of the defective sleepers should be taken into account.

The objective of the research reported here is to develop a simulation model to predict the distribution of clusters in a section of timber sleepered track, enabling comparison of different replacement strategies. Goodall *(7)* discussed the development of clusters of failed sleepers, or multiple failures, and the effect of these on the timing of resleepering. It was reported that a model was developed which calculated the likely occurrence of various sized clusters for different replacement strategies, though due to limitations this was still a theoretical model.

Statistical analysis of the distribution of the life of sleepers has been conducted and used for determination of the strategy for sleeper replacement *(8)*. Assuming sleeper lives have a Normal Distribution, the percentage of sleepers requiring replacement is inversely proportional to the percentage of average life remaining. The assumption that the sleeper lives are represented by a Normal Distribution has been questioned by an Australian study *(9)*, as the early and later years of a sleeper's life may not be accurately represented by the Normal Distribution. A Weibull Distribution is considered an appropriate distribution for the time to failure of railway sleepers because:

(a) It is applicable when a number of flaws exist in an item and the item fails due to the severest flaw;

(b) The hazard rate can increase over time;

(c) The Weibull Distribution can include a guarantee period in which no failures occur. *(9)*

2 THE SIMULATION MODEL

The model, which is designed to simulate the condition of sleepers on a section of railway track, is written in Visual Basic within Microsoft Excel 97.

The following assumptions apply to the model:

(a) The simulation is for a track consisting solely of timber sleepers.

(b) A sleeper's condition is assessed as being the number of years of life remaining.

(c) A sleeper is considered failed if the years of life remaining are less than the failure criterion.

(d) The life remaining of a sleeper reduces by one year annually, except when an adjacent sleeper has failed.

(e) Any replacement of sleepers occurs only at the end of a given year.

(f) Sleepers are replaced with new timber sleepers.

(g) The years of life remaining for a sleeper are initially generated from the Weibull Distribution. The Weibull Distribution has been extensively used in situations where identical components subjected to identical environmental conditions will fail at different and unpredictable times *(10)*.

The Weibull Distribution used in this research has two parameters, α and β. β is approximately equal to the mean of the distribution. α is the shape parameter, which will give distinctly different shapes to the probability density function. The Probability Density Function is given by *(11)*:

$$f(x) = \frac{\alpha}{\beta^{\alpha}} x^{\alpha-1} e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \qquad (1)$$

where $x >= 0$, $\beta > 0$, $\alpha > 0$

The distribution is used to determine the length of life of the timber sleepers, which models the effects of the large number of factors that influence the life, including environmental factors such as humidity, temperature and rainfall, and traffic characteristics such as load frequency and tonnage. Altering the two parameters for the Weibull distribution changes the type of track that is being considered, for example, a low curvature track with high frequency traffic in a dry climate to a high curvature track with infrequent heavily loaded traffic in a humid climate. An investigation would need to be conducted on the expected life of sleepers for the particular region the model is applied to.

The following inputs are defined by the user: the number of years for which the sleepers in the section of track should be simulated; the number of sleepers in the section of track to be simulated; the failure criterion - the number of years of life remaining at which a sleeper is considered to be failed; the increase in the decay rate for a sleeper due to an adjacent sleeper failing; the cost per sleeper replaced and the parameters for the Weibull distribution.

In addition, the operator must select, from the options available: the replacement strategy, that is the policy according to which the sleepers are replaced; the intervention frequency, that is the frequency at which intervention occurs according to the selected policy; the definition of a cluster of defective or failed sleepers, as the cluster considered may be more complex than an uninterrupted row of defective sleepers, and the initial track condition, that is the age of the sleepers at the beginning of the simulation, with the options of new or mature track. There are four available options for the replacement strategy: no replacement of sleepers at all; replacement of all the failed sleepers at the end of the year; replacement of two adjacent sleepers when they have both failed at the end of the year; and patterned replacement, that is replacement of sleepers regardless of whether they have failed in a specific pattern. The options available for the intervention frequency include replacement every year; replacement every set number of years; and replacement in years with above a certain level of failed sleepers. The intervention frequency can be combined with any of the replacement polices to give a different replacement strategy. For example, the replacement of all failed sleepers at the end of every second year or the replacement of all failed sleepers at the end of years with more than 20% failed sleepers are different replacement strategies. The main steps of the simulation are shown in Figure 1. The

3 MODEL RESULTS

A sample simulation is illustrated with ten thousand sleepers for a period of twenty years. The inputs used for the simulation are given in Table 1, with the cost of replacing a sleeper dependent on the percent of the sleepers in the track that are being replaced. The model generates two outputs, one of which is the full simulation, which includes the years of life remaining for each sleeper at the end of each year, prior to the replacement and after the replacement that occurs according to the selected policy at the end of the year. A summary of the simulation is the second output and can be seen in Table 2. This includes the initially generated track conditions at the end of each year prior to replacement occurring and the final track conditions after replacement for the last year. The first two values given are the average life remaining and the percent defective sleepers, which are an overall measure of the track condition. The numbers of clusters of defective sleepers of different sizes, from two sleepers to ten or more sleepers, indicate the dispersion of the defective sleepers in the track section. The number of sleepers replaced and the cost of replacement are also displayed, which allows the condition of the track to be compared to the cost of maintaining it.

As the track simulated is mature track, at the start of the first year it has an average of 8.9 years of life remaining and 13% failed sleepers. In the final track condition, which is at end of the 20th year after replacement, there is 12% sleepers failed with an average of 10.3 years of life remaining. Compared to the first ten years of the simulation, in the second ten years the number of sleepers replaced is lower and fewer clusters exist. As the final track condition is after replacement that year, there are no clusters present as all failed sleepers that are adjacent to another failed sleeper have been replaced.

The input parameters used in the previous simulation were varied to test the sensitivity of the model, the correct functioning and reliability of the simulation using multiple simulations, as the effects of input variations can be compared to actual track behaviour. The standard inputs used were those given in Table 1, which were held constant while the input parameter being tested was given a range of values. The number of sleepers and the different replacement strategies are discussed below, with sensitivity analysis of the other input parameters producing results consistent with expectations.

3.1 Reliability of the Model

The number of sleepers chosen for the simulations depends on the required reliability of the model with that number of sleepers: repeated simulations must produce consistently repeatable results. Ten simulations were conducted for each of seven test sections with different numbers of sleepers in each section, from one hundred to ten thousand sleepers. The variations between the results of ten separate simulations with the same inputs, decreased as the number of sleepers in the simulation increases. Therefore, the higher the number of sleepers simulated, the more repeatable the results.

For ten thousand sleepers, the relative percent difference between the minimum and maximum values for the outputs of ten simulations is given in Table 3. For the average years of life remaining and the percent of failed sleepers, the relative percent is calculated as the minimum predicted number of years remaining subtracted from the maximum number of years predicted, divided by the maximum. For the clusters, the relative percent in Table 3 is calculated by the minimum predicted number of clusters of a given type subtracted from the maximum predicted number divided by the total average number of clusters. The variations in the relative percent differences for both the average life remaining and percent of failed sleepers are small for the simulations of ten thousand sleepers. The relative percent difference between maximum and minimum for the total cost each year is generally between 10% and 20%, however the total cost for the 20 year period differs by less than $13,000 ($701,360 to $714,250) and therefore has a relative percent of 1.8. The relative percentages for the number of sleepers replaced and the total cost are identical except for years 13 and 16, as in these two years the minimum number replaced is just below 500, which is less than 5% of the sleepers in the track. The replacement cost per sleeper, as given in Table 1, is therefore higher in comparison to replacing 5-10% of the sleepers in the track, which is the case in every other instance.

The relative percentage for clusters of 2 is also generally between 10% and 20% because the majority of the clusters are clusters of two, which can be seen in the sample results in Table 2. Nevertheless, the relative percentages for the majority of the clusters are all less than 10%, therefore, ten thousand sleepers is acceptable as the results are reliably repeatable.

3.2 Cost Benefit Analysis of Replacement Strategies

Replacement strategies were simulated for all the possible available combinations of replacement policies and intervention frequencies, which resulted in 37 different strategies.

For patterned replacement, one sleeper was replaced in every 5, 10, 15 and 20 sleepers. The levels of defective sleepers before intervention of >10%, >15%, >20% and >25% were used, while replacement every 1, 2, 3, 4 and 5 years was also simulated.

A large volume of data is obtained from this because for each of the 37 replacement strategies a results table, like Table 2, is produced. Due to space restrictions, the three figures following give a summarised version of the results. For each of the replacement strategies over the 20 year simulated period, the average years of life, the average percent of failed sleepers, the total number of sleepers replaced (in thousands) and the total cost (in hundreds of thousands) are given. Excluding the no replacement strategy, Figure 2 gives the twelve most expensive replacement strategies, Figure 3 gives the middle twelve replacement strategies by total expense and the most expensive twelve strategies are in Figure 4.

Generally, as the total cost of replacement increases, the track condition worsens, however, there are definite differences between the strategies. The worst performances generally appear to be from the *patterned-replacement* policies, however, these strategies are replacing sleepers that are not necessarily the defective ones until the cycle is established. As the condition of the track is steadily improving over time for the patterned replacement policies, to judge the long-term effects, a longer simulation would need to be conducted. The simulation does indicate, however, that commencing a patterned replacement policy on track with a random dispersion of failed sleepers is not initially very effective.

The *replace-when-failed* policy was, as would be expected, the best performing policy with respect to track condition because this policy is replacing every failed sleeper. The *replace-when-failed* policy was also quite cost effective when the intervention frequency was not each year, for example in Figure 2 the best strategy of that twelve appears to be the *replace-when-failed* policy, combined with the intervention level of >25% failed sleepers.

For the *replace-when-failed* policy, the defective sleeper intervention levels of >10%, >15%, >20% and >25% resulted in replacement approximately every 2, 3, 4 and 5 years respectively. Therefore, approximately 5% of sleepers are failing each year. This is different, however, for policies other than *replace-when-failed*, as the failed sleepers affect the rate of decay of adjacent sleepers.

Replacement every year was very consistent after the first few years for all the replacement policies, excluding the *no-replacement* policy, with the sleepers replaced and the resulting track condition each year fairly constant for each different policy. The intervention every year, however, tended to be more expensive as the costs increased as the number of sleepers replaced at one time decreased.

For *patterned-replacement*, the cycle length is the number of years between intervention multiplied by the number of sleepers in which one is replaced, which is the number of years it will take to replace every sleeper position once. For example, replacing one sleeper in 5 every second year has a cycle length of 10, as does replacing one sleeper in 10 every year. If the cycle length is greater than the average life of the sleepers, the defects will tend to increase over time as each sleeper position is not being replaced within the average sleeper life. *Patterned-Replacement* replaces one sleeper every set number of sleepers, *x*. The higher the *x* value, the higher the number of large clusters.

Replace-when-two-adjacent-both-failed resulted in replacing approximately the same total number of sleepers (12,000 – 13,000) for all the intervention frequencies. The total cost was, however, significantly different for the different intervention frequencies. The strategies that were replacing every year, including replacing at >10% and >15% defective sleepers, were more expensive. These strategies had a fairly constant value of defective sleepers of around 20% at the end of each year prior to replacement.

4 CONCLUSIONS

A simulation model has been developed which allows a method of comparison for different sleeper replacement strategies in railway track. The percent failed sleepers, the average life remaining, numbers of clusters of various sizes, the number of sleepers replaced and the cost of replacement are generated as a basis for comparing the replacement policies on a section of timber sleepered track. The life of a timber sleeper is assumed to be represented by the Weibull Distribution. The simulation model has a number of user controlled inputs, which allows flexibility for the operator.

The length of track that is simulated is dependent on the required reliability of the model. As the number of sleepers simulated increases, the reliability of the results also increases. The track length accepted for testing purposes was ten thousand sleepers, which produced sufficiently repeatable results. Sensitivity analysis was conducted on each of the input parameters and a number of replacement strategies were simulated.

The comparison of the replacement strategies indicates that commencing a *patterned-replacement* policy on track with a random dispersion of failed sleepers is not initially very effective. The *replace-when-failed* policy was generally the best performing policy with respect to the track condition. This policy was also quite cost effective when the intervention frequency was greater than each year.

The model, in its current state of development, can be used by track maintenance planning engineers to compare replacement strategies on the basis of whole-of-life costs. The latter includes the initial cost of implementing a specific strategy and its effects over the long-term in terms of total sleeper maintenance requirements over the track segment being analysed.

Future research should expand the developed model to include other replacement strategies and alternative sleeper types such as concrete and steel. The simulation would then provide a full economic cost-benefit analysis of sleeper replacement strategies applicable to a range of different railway tracks. The model, when fully developed, has the following potential applications:

(a) Evaluation of sleeper replacement strategies in terms of: direct monetary cost of undertaking each strategy; risk of delays to trains (speed restrictions), of derailments and of accidents related to each strategy; and full economic cost-benefit analysis of a strategy compared with a no replacement base-case to highlight the economic benefit of intervention.

(b) Evaluation of the impacts of deferred maintenance, ie deferring sleeper replacement. The effects of changing the timing for implementation of a given strategy could be assessed using the model.

(c) Assessment of strategies based on interspersing steel sleepers into existing timber sleepered track in various ratios, for a given section of track.

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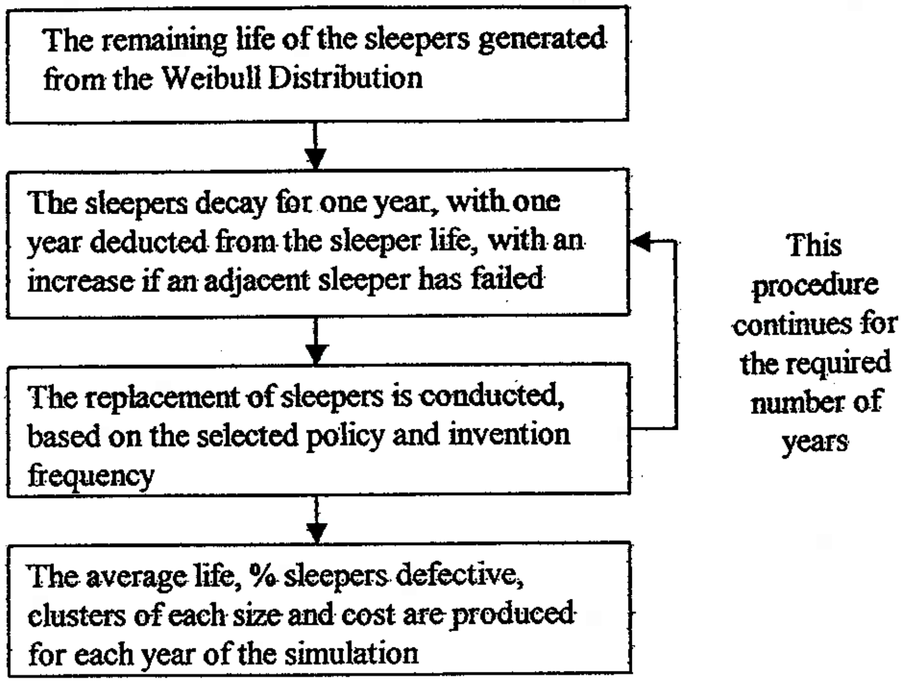

Figure 1: The Process of the Simulation

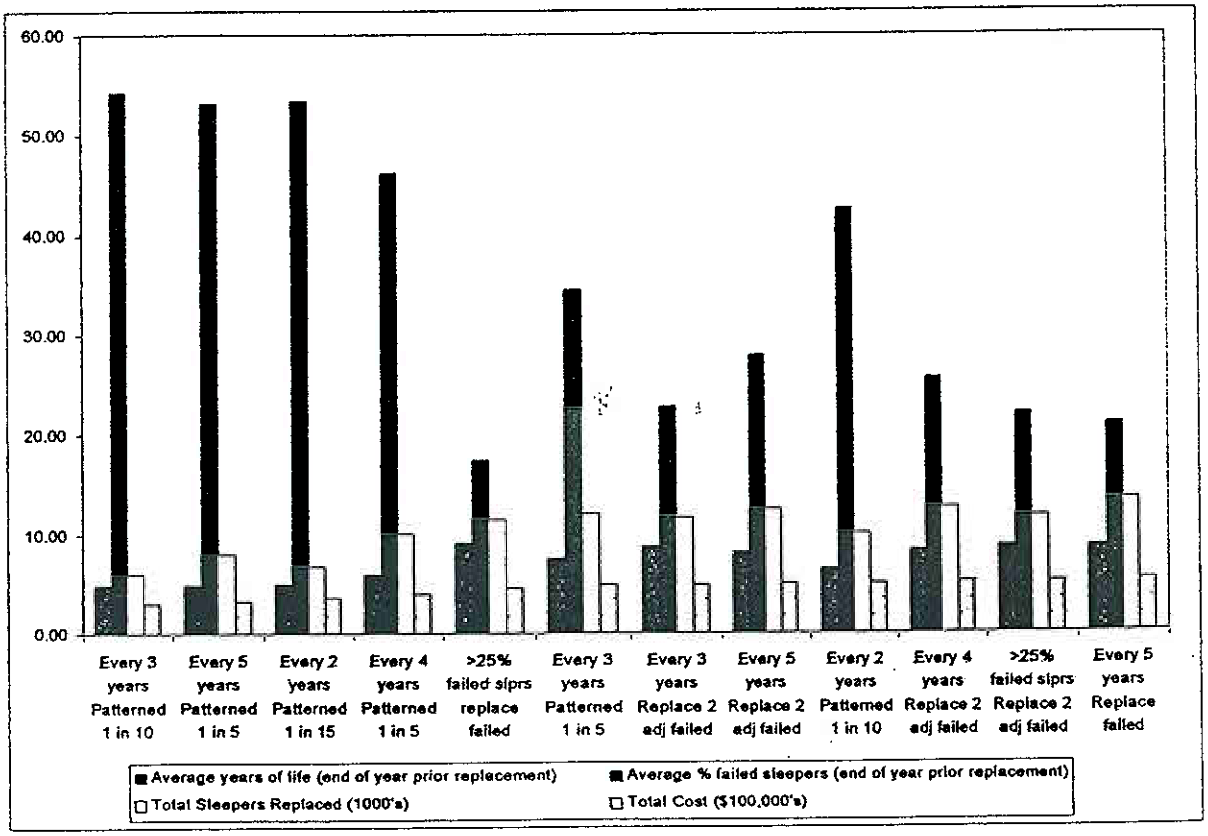

Figure 2: The Results for the Twelve Least Expensive Replacement Strategies

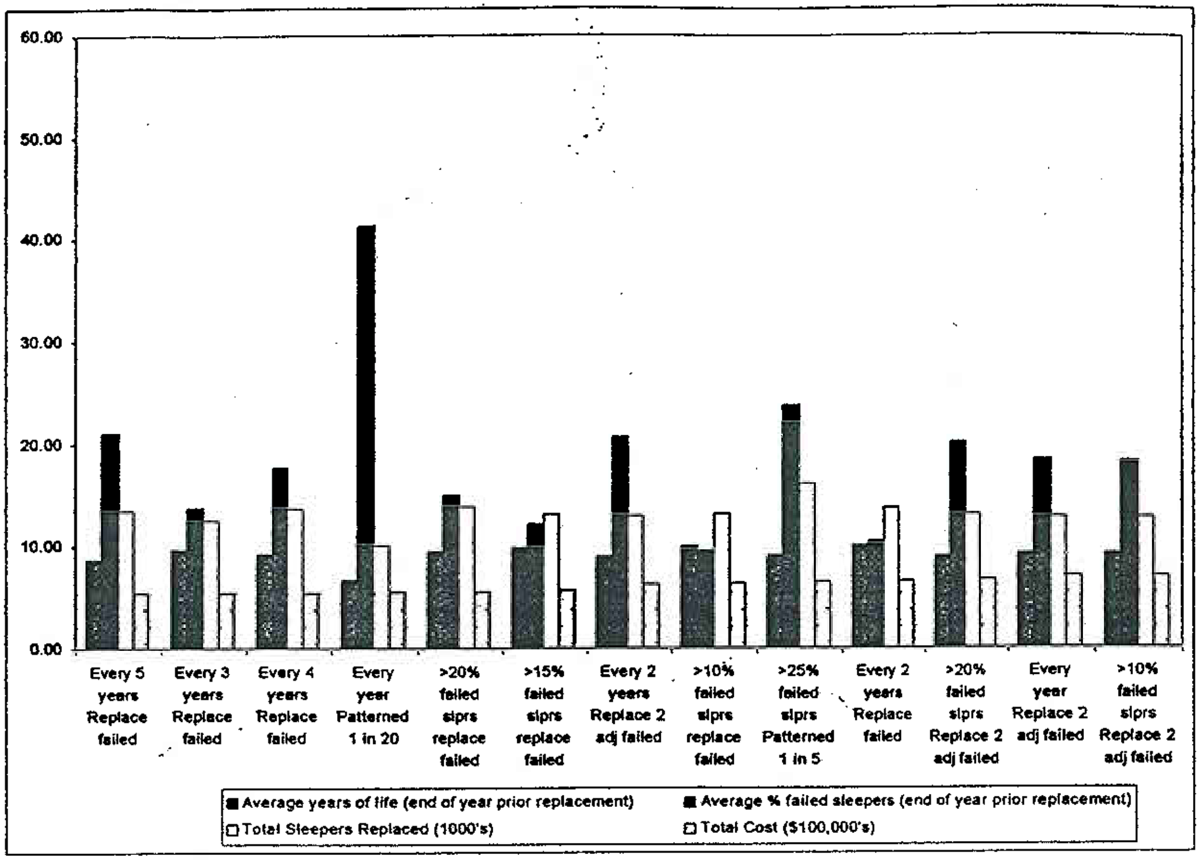

Figure 3: The Results for the Middle Twelve Replacement Strategies by Total Expense

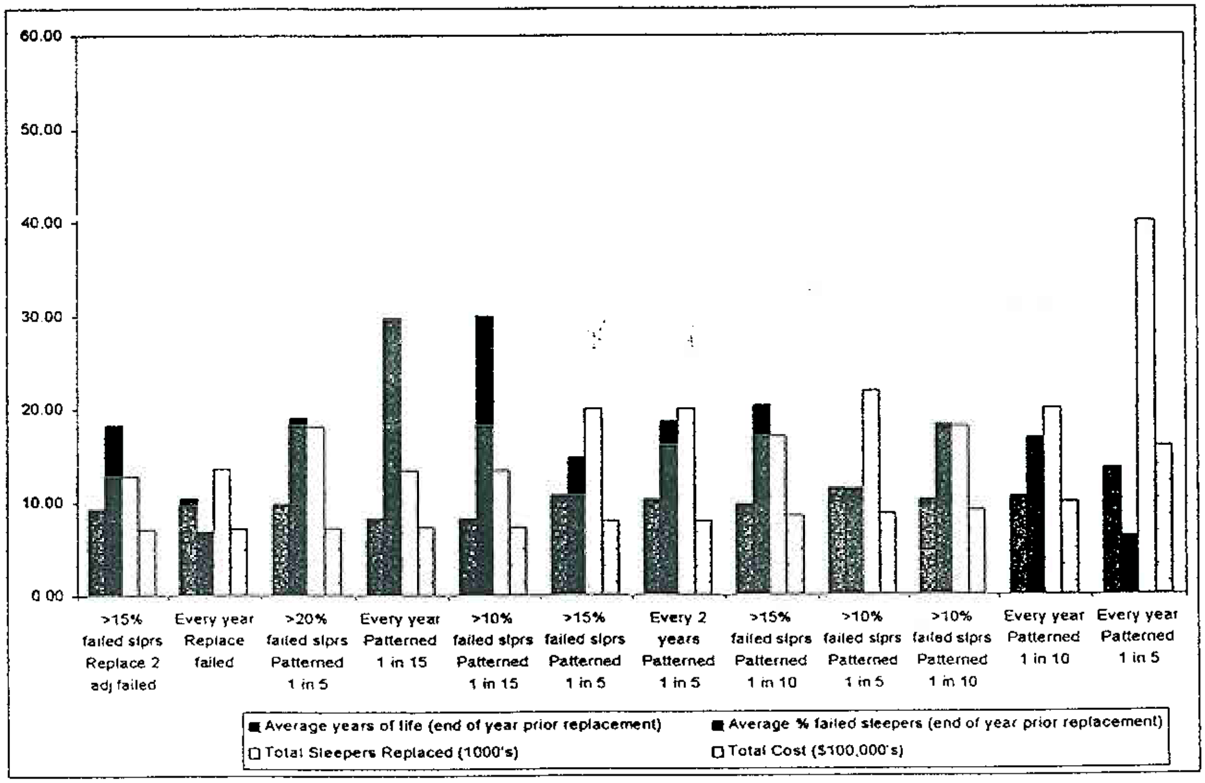

Figure 4: The Results for the Twelve Most Expensive Replacement Strategies

Table 1: Inputs for the Simulation

Input	Value
Intervention Frequency	Option 1: Every year
Replacement Policy	Option 3: Replace 2 adjacent sleepers both failed
Initial Conditions	Option 1: Mature Track
Cluster Definition	Option 3: Sleepers between clusters <= small cluster to be one cluster
Number of Years	20
Number of Sleepers	10000
Alpha (Weibull Shape Parameter)	3
Beta (Weibull Approximate Mean)	20
Failure Criterion (years)	2
% Increase in Decay if Adjacent Sleeper Failed	50
Cost per Sleeper Replaced	Replacing <5%: Installation cost $38 + cost of sleeper: $22 Replacing 5-10%: Installation cost $33 + cost of sleeper: $22 Replacing 10-15%: Installation cost $28 + cost of sleeper: $22 Replacing 15-20%: Installation cost $23 + cost of sleeper: $22 Replacing ≥20%: Installation cost $18 + cost of sleeper: $22

Table 2: The Results of the Simulation

	Initial	End Yr 1	End Yr 2	End Yr 3	End Yr 4	End Yr 5	End Yr 6	End Yr 7	End Yr 8	End Yr 9	End Yr 10	End Yr 11	End Yr 12	End Yr 13	End Yr 14	End Yr 15	End Yr 16	End Yr 17	End Yr 18	End Yr 19	End Yr 20	Final
Av Years of Life Left	8.9	7.8	8.3	8.4	8.7	8.8	9.1	9.3	9.5	9.6	9.6	9.7	9.7	9.7	9.5	9.3	9.2	9.3	9.2	9.2	9.3	10.3
% Failed Sleepers	13	21	20	21	20	20	19	18	18	18	18	17	17	17	17	18	18	17	17	18	17	12
Clusters of 2	129	268	203	238	194	209	221	194	201	194	211	185	179	176	157	178	188	187	178	217	186	0
Clusters of 3	15	53	57	38	60	68	48	49	35	36	54	50	41	31	38	33	35	39	36	31	29	0
Clusters of 4	3	11	9	8	10	8	9	10	13	9	12	8	11	1	10	10	6	8	6	9	8	0
Clusters of 5	1	11	8	10	10	10	5	5	7	4	3	5	7	8	4	5	8	5	7	8	6	0
Clusters of 6	2	7	2	10	6	9	9	6	3	5	4	4	3	1	3	6	12	5	7	9	7	0
Clusters of 7	0	6	1	5	2	2	4	6	1	4	2	1	2	1	3	4	3	2	3	3	0	0
Clusters of 8	1	4	0	4	1	2	2	2	2	0	0	0	1	1	0	1	0	0	1	0	0	0
Clusters of 9	0	1	1	1	0	0	1	0	1	2	0	0	0	0	0	3	1	0	0	1	0	0
Clusters of >=10	0	3	1	1	0	2	0	3	1	1	1	0	0	0	0	0	1	1	1	0	0	0
Sleepers Replaced		901	676	776	696	777	725	700	635	612	681	597	583	499	512	585	621	586	575	657	547	
Total Cost ($)		49,555	37,180	42,680	38,280	42,735	39,875	38,500	34,925	33,660	37,455	32,835	32,065	29,940	28,160	32,175	34,155	32,230	31,625	36,135	30,085	

Table 3: The Relative Percent Difference between Minimum and Maximum for 10 Simulations

	Initial	End Yr1	End Yr2	End Yr3	End Yr4	End Yr5	End Yr6	End Yr7	End Yr8	End Yr9	End Yr 10	End Yr 11	End Yr 12	End Yr 13	End Yr 14	End Yr 15	End Yr 16	End Yr 17	End Yr 18	End Yr 19	End Yr 20	Final
Av Years of Life Left	1.6	1.9	2.5	3.1	3.0	3.1	3.3	1.9	2.5	2.5	3.4	2.5	2.5	1.9	1.5	2.0	2.2	2.1	3.6	3.1	3.0	2.2
% Failed Sleepers	8.6	5.7	6.8	3.6	4.1	4.7	8.2	7.4	6.2	6.1	6.9	6.4	8.1	9.2	5.6	5.3	5.8	5.8	5.1	8.3	7.7	6.0
Clusters of 2	17.4	8.9	22.5	20.4	13.8	10.9	16.1	12.3	15.9	13.2	20.4	11.3	17.6	19.2	15.0	11.0	24.8	13.8	11.6	15.9	17.4	0.0
Clusters of 3	14.1	6.9	11.4	7.6	7.2	9.0	8.2	7.7	11.9	8.7	10.8	7.1	4.6	6.1	5.6	5.5	9.3	8.8	5.2	7.6	5.2	0.0
Clusters of 4	2.6	2.3	2.9	3.1	2.3	1.7	3.0	3.2	3.2	2.6	3.2	2.9	2.9	5.2	2.6	3.4	3.8	2.9	2.0	4.0	2.8	0.0
Clusters of 5	5.1	1.4	1.5	2.8	3.3	2.0	3.6	3.5	2.2	2.6	2.4	3.8	3.8	3.1	1.7	2.5	1.7	3.3	2.4	2.8	3.6	0.0
Clusters of 6	1.9	3.4	4.4	2.8	2.6	2.7	3.0	2.5	1.8	2.6	3.6	3.4	3.3	2.2	3.0	2.5	4.6	2.9	3.2	3.6	2.0	0.0
Clusters of 7	1.3	2.0	1.5	1.4	1.0	1.7	1.6	1.1	1.1	2.3	1.2	3.4	1.7	1.3	1.3	2.1	2.1	0.8	1.2	1.2	1.6	0.0
Clusters of 8	0.6	1.1	0.7	1.7	1.0	0.7	1.0	1.8	0.7	1.5	0.8	1.3	0.4	1.3	0.4	0.8	0.4	0.8	1.2	0.8	1.2	0.0
Clusters of 9	0.6	1.1	0.7	0.7	1.0	1.0	1.3	1.4	1.1	0.8	0.4	1.3	0.4	0.9	0.9	1.3	0.4	0.4	0.4	0.8	1.2	0.0
Clusters of >=10	0.6	0.9	0.7	0.7	0.7	1.0	0.7	1.1	0.4	1.9	0.8	0.8	0.4	0.9	0.9	1.3	0.8	0.4	0.8	0.4	1.2	0.0
Sleepers Replaced		14.5	21.2	14.9	13.4	15.8	11.6	13.3	19.4	15.1	18.1	15.3	9.7	16.0	12.6	9.3	20.3	13.2	13.4	18.1	19.2	
Total Cost		14.5	21.2	14.9	13.4	15.8	11.6	13.3	19.4	15.1	18.1	15.3	9.7	13.3	12.6	9.3	17.4	13.2	13.4	18.1	19.2	