"Economics of Increased Axle Loads: FAST/HAL Phase II Results,"

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Summary

Based upon the cases analyzed to date, the use of heavier cars, with attendant increased axle loads, may be a viable tool for achieving significant total savings in cost for specific rail operations. The potential net benefits for operations with 286,000 gross vehicle weight (GVW) cars are in the range of 2 to 6 percent. For 315,000 GVW vehicles, the net benefit is in the range of -1 to 1.3 percent; no significant improvement from 263,000 GVW operations.

Overall the Facility for Accelerated Service Testing and heavy axle load (HAL) research and subsequent economic evaluations performed through the end of Phase II confirm the basic conclusions and recommendations reached at the end of Phase I.

The economic results are highly route and service specific. Thus, individual railroads should analyze their particular service alternatives.

BACKGROUND

Phase I of the Heavy Axle Load (HAL) Tests at the Facility for Accelerated Service Testing (FAST) was designed to determine if operations with axle loads above the 33 tons allowed in interchange service (263K pounds gross vehicle weight — GVW — for four axle cars) were technically feasible and economically desirable. Results of Phase I testing were reported to the industry at the *Workshop on Heavy Axle Loads* held in Pueblo, Colorado, in the fall of 1990. Shortly afterward in 1991, a Phase I economic report to the industry was made. This study concluded (1) operation with increased axle loads was technically feasible, (2) economically desirable under favorable conditions, and (3) certain areas of concern must be addressed to resolve the uncertainties of HAL operations and improve their economics.

Phase II of the FAST/HAL testing was designed to (1) evaluate improved components and maintenance practices that offer cost reductions in areas where the Phase I tests suggested potential improvements and (2) allow the determination of the life of longer-lived track components, such as ballast and rail.

In addition to testing new components at FAST, additional data has been collected from revenue operations with HAL traffic. Also new models for analyzing the performance of steel bridges and track components, such as turnouts, ballast, and ties have been developed.

The purpose of this FAST/HAL Phase II Economic Study is to update the Phase I analysis and conclusions based on the additional information available from the FAST/HAL Phase II tests. The new information includes new component designs and maintenance procedures tested, the revenue experience on member roads, and the new theoretical models available concerning the performance of critical track components and steel bridges.

OVERVIEW OF ANALYSIS

Phase I

The Phase I study considered the direct operating costs of providing unit-train transportation of coal over four generic routes: (1) an "eastern" route characterized by moderate grades and significant curvature, (2) a "western" route characterized by moderate grades and less curvature, (3) a "mountain route" with extreme grades and curvature, and (4) a "level route" with very little curvature or grades. Trains traveling each route were (1) weight (drawbar force) limited or (2) length limited by considerations, such as siding lengths, loading or unloading loops, or other length limitations. Operations that were length limited were shown to gain a greater advantage from increased axle loads than those that were weight limited since the greater capacity per unit of train length of the HAL cars could be used to increase the lading in the train. The economics of two HAL cars were evaluated (1) the 315K GVW cars as tested at FAST, and (2) the 286K GVW cars as evaluated based on interpolations with the deterioration models calibrated to 263K GVW and the 315K GVW operations at FAST. This resulted in 16 evaluations of HAL equipment alternatives in two operating environments over four different route characteristics. In all cases, the 286K HAL traffic cost advantage was superior to the standard 263K with the advantage varying from 7.0 percent to 1.6 percent. The 315K HAL traffic had mixed results varying from 5.2 percent advantage over the 263K to a 3.0 percent disadvantage. In no case did the 315K traffic cost out perform the 286K option.

Beyond the generic studies, the Phase I report contained the results of two case studies where the AAR and the industry *Ad Hoc* FAST /HAL Economic Committee worked closely with two member roads to analyze specific proposed HAL services on those roads. The effects of HAL traffic on bridges on these case study routes were developed by the individual road's bridge departments. These more detailed analyses reached the same conclusions and provided additional validation to the generic studies.

Phase II

The Phase II economic studies use the same basic methodologies and many of the same tools employed in Phase I; however, there are some changes in the details of the analysis.

Changes in Scope — First, only the eastern and western generic studies are performed in Phase II. The extreme mountain and level routes did not produce the extremes of either relative advantage or disadvantage of either HAL equipment option, and they were not comparable to either of the actual routes used in case studies in Phase I. Thus, the Committee and staff did not feel the data collected from these routes added anything to the understanding of the economics of increasing axle loads. Given severe limits on both funding and time for Phase II, these routes were eliminated. Second, no case studies were conducted in Phase II, since the overhead to work with a new set of roads was beyond the time and resource constraints of the current study.

Changes in Analytic Tools — During the five years since the Phase I study, there have been several improvements in the analytic tools available to conduct this economic assessment. These changes involve both upgrades in existing tools and the development of new tools. First, the Train Energy Model that simulates the physical operation of the train consists over the route has undergone two major updates providing both better train handling and an aerodynamic subroutine that allows a more accurate computation of the aerodynamic component of train resistance. Second, the Total Right of Way Maintenance Analysis and Costing System has been upgraded with new models for turnout degradation, wood tie life, and ballast life. Third, a new model for the fatigue life of steel bridges has been developed that allows bridge impacts to be evaluated in our generic studies.

Changes in Relative Prices of Resources — Although the early 1990's have been characterized by lower average inflation rates than the previous decade, there have been some changes in both the absolute and relative prices of the resources required to provide rail transportation, and the relative price changes have had some impact on the relative advantage of HAL economics.

It is the total predicted advantage that determines the conclusions about the optimum choice of axle loads, but as the results of the current study are presented, the primary sources of any changes from the Phase I HAL study will be identified.

HAL ECONOMIC IMPACT ON BRIDGES

In the analysis of Phase I, the impact on bridges was included only in two railroad specific case studies. Since then the AAR has developed a steel bridge fatigue life assessment model that can assess the impact of HAL traffic on bridge component life. This model has been calibrated using data collected at HAL revenue sites through instrumentation of bridges. This bridge fatigue model coupled with the AAR's Steel Bridge Cost Model now permits bridge and route specific analysis of the impact of HAL traffic on steel bridges. The impact on timber bridges is included using expert opinion.

Steel Bridges — This analysis shows a decrease in the fatigue life of specific steel bridge components from HAL traffic. Detailed fatigue analyses were conducted on 34 bridges selected from more than 70 submitted by member roads as representative of the bridges on routes likely to be used for HAL traffic. These bridges were then used to represent the actual bridges on six specific routes that currently carry or are expected to carry HAL traffic. For 263K base traffic and the 286K and 315K HAL alternatives, the annual percent of total fatigue life consumed was calculated for each component of each bridge. The percent consumption was then multiplied by the replacement cost for each component to calculate steady-state annual component renewal costs. These component costs were summed for all critical components of each bridge to obtain the total annual steady-state renewal costs for the bridge. To calculate the cost for a generic route, the four routes typical of eastern coal routes (and similarly for the western routes) were assumed to be placed end-to-end, and a steel bridge cost per 1000 net-ton-miles was calculated.

Timber Bridges —The timber bridge analysis is based on expert opinion of selected AREA bridge committee members who form the HAL Bridge Evaluation Working Group. The major effect of HAL traffic is to accelerate timber cap or bridge replacement. The Bridge Working Group agreed on the following cap/bridge replacement rates for timber bridges:

- For 263 kip traffic, caps/bridges will be replaced beginning immediately and all caps/bridges will be replaced uniformly over a 20-year period. Two replacement scenarios were examined, replacing 25 percent of the timber bridges and 75 percent of the caps (Base Case) and replacing 75 percent of bridges and 25 percent of the caps (Pessimistic Case).
- For 286 kip traffic, caps/bridges will be replaced beginning immediately and all caps/bridges will be replaced uniformly over a 10-year period. Two replacement scenarios were examined, replacing 25 percent of the timber bridges and 75 percent of the caps (Base Case) and replacing 75 percent of bridges and 25 percent of the caps (Pessimistic Case).
- For 315 kip traffic on the 30 MGT eastern route, caps/bridges will be replaced beginning immediately and all caps/bridges will be replaced uniformly over a 5-year period. Two replacement scenarios were examined, replacing 25 percent of the timber bridges and 75 percent of the caps (Base Case) and replacing 75 percent of bridges and 25 percent of the caps (Pessimistic Case).
- For 315 kip traffic on the 80 MGT western route, all bridges will be replaced beginning immediately and all bridges will be replaced uniformly over a 5-year period.

This conservative approach was taken due to the lack of a deterioration model addressing specific timber bridge components. Costs for both cap and bridge replacements were obtained from member railroads. Estimates were also provided on the train delay times and costs resulting from the replacement or repair work. Relative amounts of cap replacement versus bridge replacement provide insight to cost sensitivity.

Results — Costs for the steel and timber bridges were added yielding a total cost per 1000 net-ton-miles for each of the routes. These costs are presented in Exhibits 1 and 2 as a percent of the cost of the base, 263K GVW traffic. Although the percent increases are large for HAL traffic, the impact on the total analysis is small because bridge maintenance and renewal is a small percent of the total cost (2-3%) of HAL traffic. However, for the six individual railroad routes evaluated, the total bridge costs varied by nearly an order of magnitude; therefore a specific route analysis is preferable when assessing the impact of HAL traffic on any route involving major steel structures or a significant number of timber structures.

Cost Changes Phase I (1991) to Phase II (1995)

The estimated cost elements have changed in the current study due to (1) changes in the models used to predict component life cycle costs, (2) changes in the component designs, maintenance practices, and materials used in the Phase II tests, (3) changes in the relative costs of certain resources, and (4) for turnouts, a correction in the calculation of routine maintenance costs that caused turnout costs to be overstated in Phase I. Exhibits 3, 4, 5, and 6 show the relative cost changes for the estimated direct operating and track cost elements in Phase II compared to the estimated Phase I costs including the correction to the turnout costs for Phase I. To gain a better understanding of these changes, let us consider each cost component individually.

Operating Costs

Crew— Although the cost per crew member has increased, the use of two-man crews in 1995 compared to the three-man crews assumed in 1991 along with the increase in the base miles from 108 to 130 have decreased the crew cost per net-ton-mile in all scenarios.

Car and Locomotive Ownership — Both car and locomotive ownership costs have increased over the period due primarily to a strengthening of the market for both types of equipment. The equipment prices in 1991 were influenced by a preceding decade of weak equipment demand.

Car and Locomotive Maintenance — Both car and locomotive maintenance have remained essentially constant during the 1991 - 1995 period. This is due to improvements in component performance such as the new specification wheels and the elimination of certain unnecessary regulations such as the discolored wheel removal rule.

Fuel — Fuel costs have decreased slightly from 1991 to 1995.

Since crew and fuel are reduced by increasing axle loads and these components have become relatively cheaper, the advantage of increasing axle loads has been slightly decreased since the 1991 study.

Track Costs

Rail — The performance of rail has remained as expected from Phase I testing. The cost of new rail has increased since 1991 due to a general increase in the demand for rail and a reduction in the domestic suppliers. The routine maintenance associated with the rail has been reduced by the development of improved field weld kits and procedures. Field weld performance was one of the key areas needing improvement noted during Phase I. Phase II has met this objective.

Ties — The estimated cost of ties has substantially increased since the 1991 study. This is primarily due to further development and calibration of the AAR tie life model leading to an increase in the expected life-cycle tie costs for all axle loads. In addition, the cost of ties and their installation cost in track have increased. For the increased axle loads, the Phase II testing has shown that premium fasteners are desirable for improving gage retention on curves of 3 degrees or greater. The cost of fasteners do not affect significantly the increased costs for HAL traffic. Ties remain a small part of the total costs and do not significantly increase with increasing axle loads.

Ballast — Additional tests of ballast during Phase II and model development by the AAR have suggested that ballast maintenance costs will be substantially lower than estimated during Phase I. The "good" ballast materials at FAST have shown little or no effects due to increased axle loads. Service testing and member road experience suggest that both surfacing requirements and eventual ballast renewal activities will be less than estimated during Phase I.

Turnouts — Phase II at FAST and revenue service tests have shown that turnouts of both conventional and improved design and improved materials can substantially extend life and reduce life-cycle costs for turnouts under all three traffic scenarios. The cost penalty for increasing axle loads has been reduced by improved turnouts, a major objective of Phase II.

Overall Phase II's investigation to determine ways to reduce the adverse impacts of increased axle load traffic on the track structure and to improve the economics of increasing axle loads has been successful.

SUMMARY OF THE ECONOMIC IMPACTS OF INCREASING AXLE LOADS

Track — After correcting the error in turnout maintenance costs, the Phase I study showed a 7.9 percent and 22.8 percent increase for track costs in the west for 286K and 315K traffic respectively and 10.9 percent and 23.1 percent respectively in the east. Exhibit 7 shows that for the west the increases are now 5.9 and 21 percent for 286K and 315K traffic respectively. In the east the increases are 11 percent and 24.2 percent respectively as shown in Exhibit 8. The estimates include the impact of increased axle load traffic on bridges in the Phase II results, while they were not included in the Phase I results. Without the additional impact of increased axle loads on bridges, the cost penalty for increased axle loads would be decreased in all cases. Certainly the areas targeted for improvement in Phase II — field welds (routine rail maintenance) and turnouts — have shown significant improvement as have ballast and surfacing.

Overall — Exhibits 9, 10, 11 and 12 show the total impact of increasing axle loads on direct transportation costs in the west and east for both length and weight limited operating scenarios. Overall, the 286K traffic is shown to be economically effective in all four scenarios evaluated while 315K traffic is better than 263K only in the length limited, western scenario. No scenario shows 315K traffic to be more economic than 286K traffic.

The degree of reduction in direct transportation cost due to increasing axle loads in this Phase II analysis is slightly less than estimated in the Phase I report. This slight decrease is due primarily to changes in the relative costs of resources. For example, crew and fuel benefited by increasing axle loads have decreased in cost, while track components deteriorated by increased axle loads have become relatively more expensive. In addition, the costs of bridges that are affected adversely by increased axle loads are included in Phase II results, while they were not in Phase I. Without the bridge impacts, the improved track components and maintenance procedures in Phase II would have resulted in increased advantages for increased axle loads.

CONCLUSIONS/RECOMMENDATIONS

Phase II test results show specific cost element estimates have changed in their absolute and/or relative importance and certain problem areas, such as turnouts and field welds, have been improved. Overall, the FAST/HAL research and subsequent economic evaluations performed through the end of Phase II confirm the basic conclusions and recommendations reached at the end of Phase I.

TECHNICAL FEASIBILITY OF 315,000-POUND BULK COMMODITY EQUIPMENT

Based on the physical and engineering test results at FAST through the end of Phase II in 1995, as well as the reported operational experiences of select North American and foreign railroads, there do not appear to be any unmanageable barriers to the operation of heavier (i.e. 39-ton) axle loads over well-maintained track that has good quality components and over bridges of sufficient strength.

Based upon the cases analyzed, track maintenance costs under HAL operations can be expected to increase by anywhere from about 5 to 20 percent under 286,000-pound cars and 20 to 40 percent under 315,000-pound cars. Capital programs can be expected to increase 2 to 10 percent under 286K cars and 9 to 22 percent under 315K cars, while routine maintenance may increase by 15-30 percent under 286K and 45-65 percent under 315K cars. Although the routine maintenance is a smaller dollar item than program maintenance, it is important to recognize that this maintenance cannot be deferred without immediate, severe consequences.

ECONOMICS OF HAL OPERATIONS

Based on the analyses to date, the use of heavier cars, with attendant increased axle loads, may be a viable tool for achieving potentially significant total savings in cost for certain rail operations. For the cases analyzed, potential net benefits in the range of 2-6 percent (including bridge costs, see Exhibit 13) would seem to warrant serious investigation as a means to increase the productivity of specific routes and services. Results are highly route and service specific. Following are critical variables:

(1) Bridge characteristics (extent of renewal/reinforcement required)

(2) Rail characteristics/maintenance (quality, i.e. metallurgy/condition of rail, and extent of lubrication and grinding) on running tracks

(3) Other running track support characteristics (quality of ties, ballast, and subgrade)

(4) Equipment characteristics and utilization (loading) policies (initial cost, net-to-tare ratio, load cycles and horsepower utilization)

(5) Operating constraints (train length or train weight limitations)

(6) The capability of support (yard and industry) tracks to handle heavier cars

While the 286,000-pound car was not the subject of the FAST/HAL tests, the design specified and analyzed offered significant net benefits when compared to the 315,000-pound cars used in the FAST/HAL tests or the conventional 263K cars extensively tested at FAST before 1986.

Exhibit 1. Bridge Cost in Percent of Cost for Base Case - 263K GVW Traffic
Typical Western Coal Route
With 80 MGT Per Year

Bridge Type	Scenario - 5.9 Feet/Mile of Timber Bridges 26.0 Feet/Mile of Steel Bridges	Car Gross Vehicle Weight (Pounds)		
Base Case		**263,000**	**286,000**	**315,000**
Timber	Replace 75% of caps and 25% of bridges for timber bridges, Replace all timber bridges for 315,000 pound case	100%	144%	584%
Steel	Fatigue Life Consumption of Components	100%	112%	155%
Total	**75% / 25% Caps Vs. Replace**	**100%**	**113%**	**173%**
Pessimistic Case				
Timber	Replace 25% of caps and 75% of bridges for timber bridges, Replace all timber bridges for 315,000 pound case	251%	362%	584%
Steel	Fatigue Life Consumption of Components	100%	112%	155%
Total	**25% / 75% Caps Vs. Replace**	**106%**	**123%**	**173%**

Exhibit 2. Bridge Cost in Percent of Cost for Base Case - 263K GVW Traffic
Typical Eastern Coal Route
With 30 MGT Per Year

Bridge Type	Scenario - 4.5 Feet/Mile of Timber Bridges 52.4 Feet/Mile of Steel Bridges	Car Gross Vehicle Weight (Pounds)		
Base Case		**263,000**	**286,000**	**315,000**
Timber	Replace 75% of caps and 25% of bridges for timber bridges.	100%	144%	177%
Steel	Fatigue Life Consumption of Components	100%	113%	156%
Total	**75% / 25% Caps Vs. Replace**	**100%**	**115%**	**157%**
Pessimistic Case				
Timber	Replace 25% of caps and 75% of bridges for timber bridges	252%	364%	448%
Steel	Fatigue Life Consumption of Components	100%	113%	156%
Total	**25% / 75% Caps Vs. Replace**	**110%**	**129%**	**174%**

Exhibit 3

Phase II Costs Compared to Phase I

Generic Western Route, Length Limited

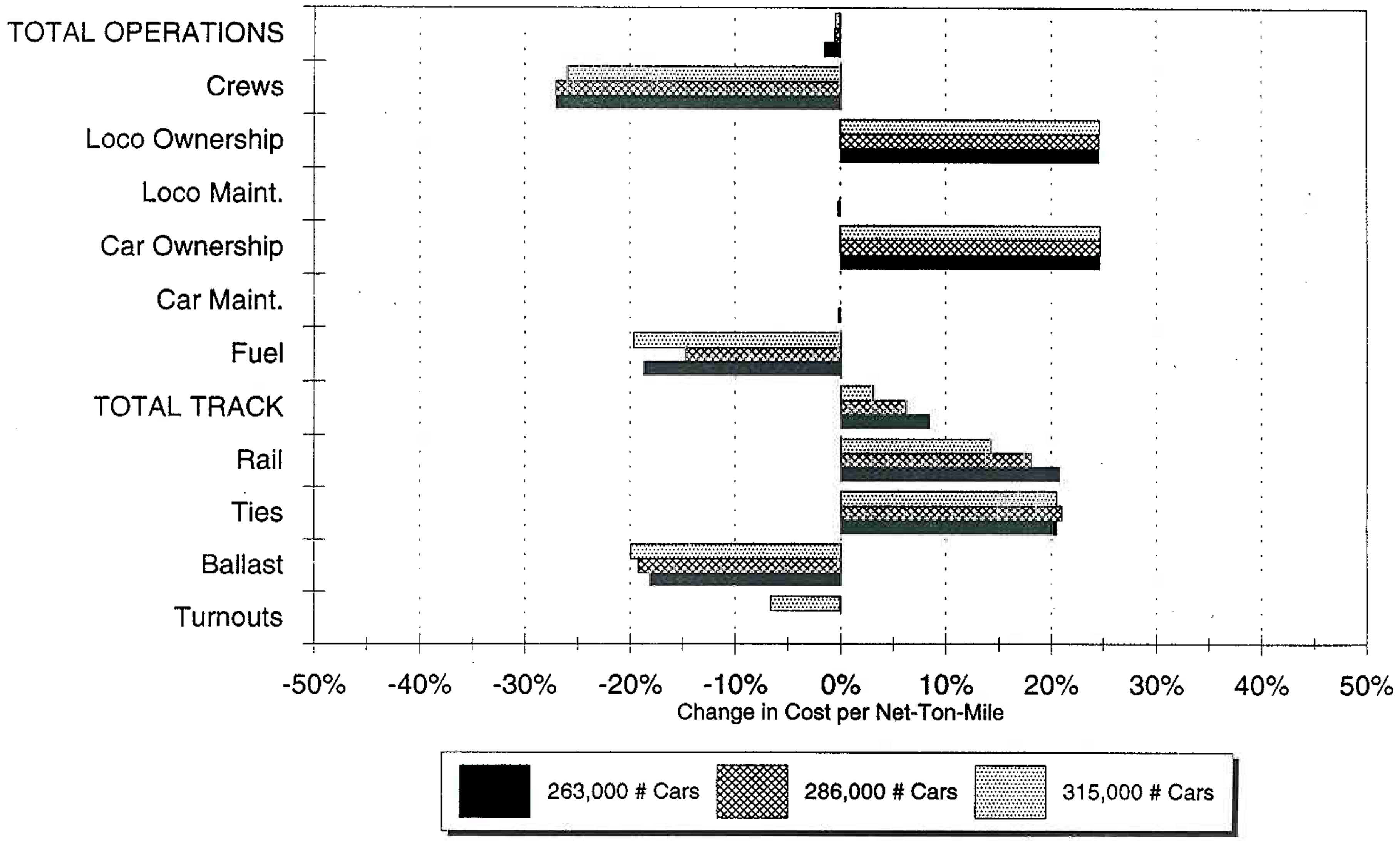


Exhibit 4

Phase II Costs Compared to Phase I

Generic Western Route, Weight Limited

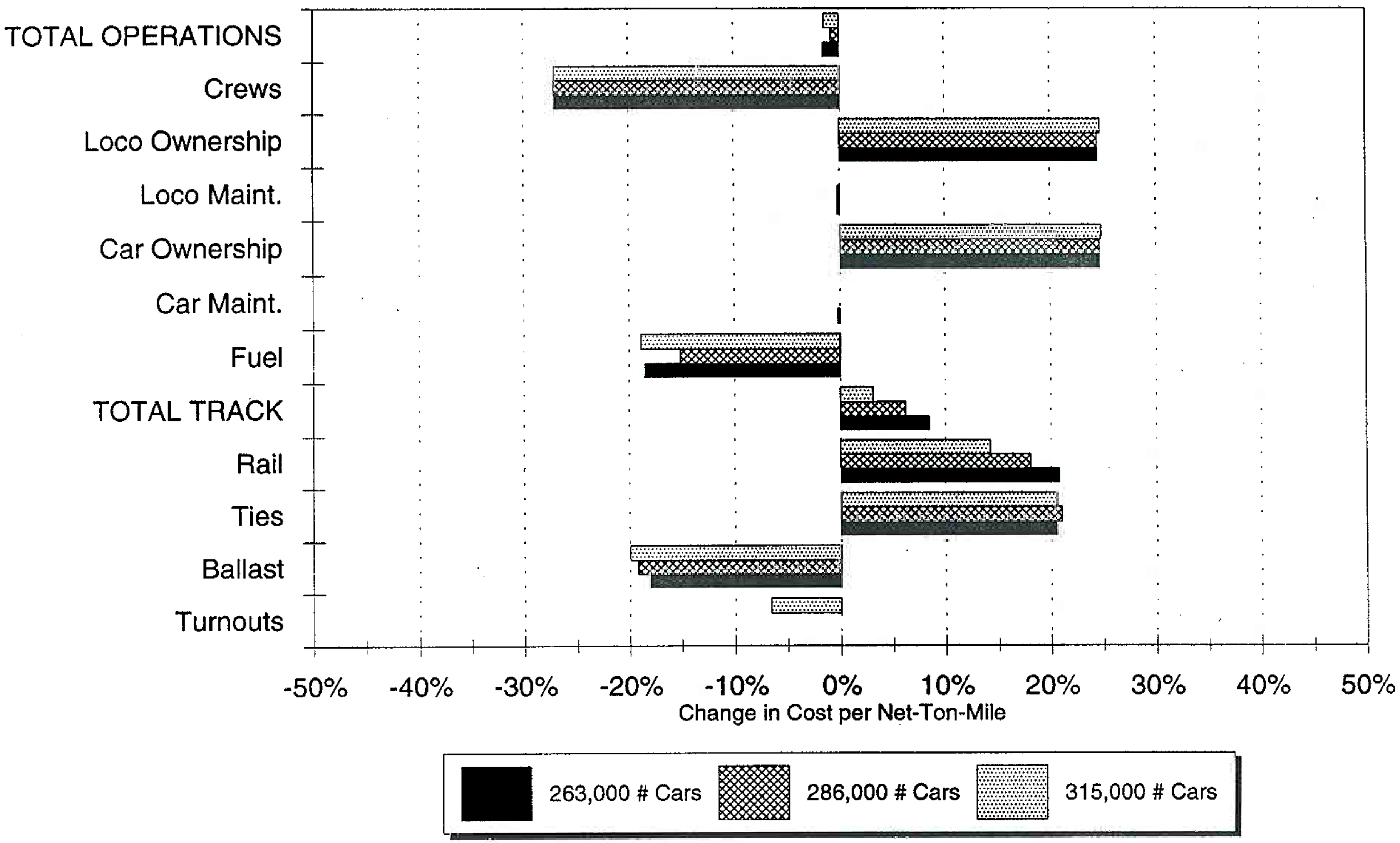


Exhibit 5

Phase II Costs Compared to Phase I

Generic Eastern Route, Length Limited

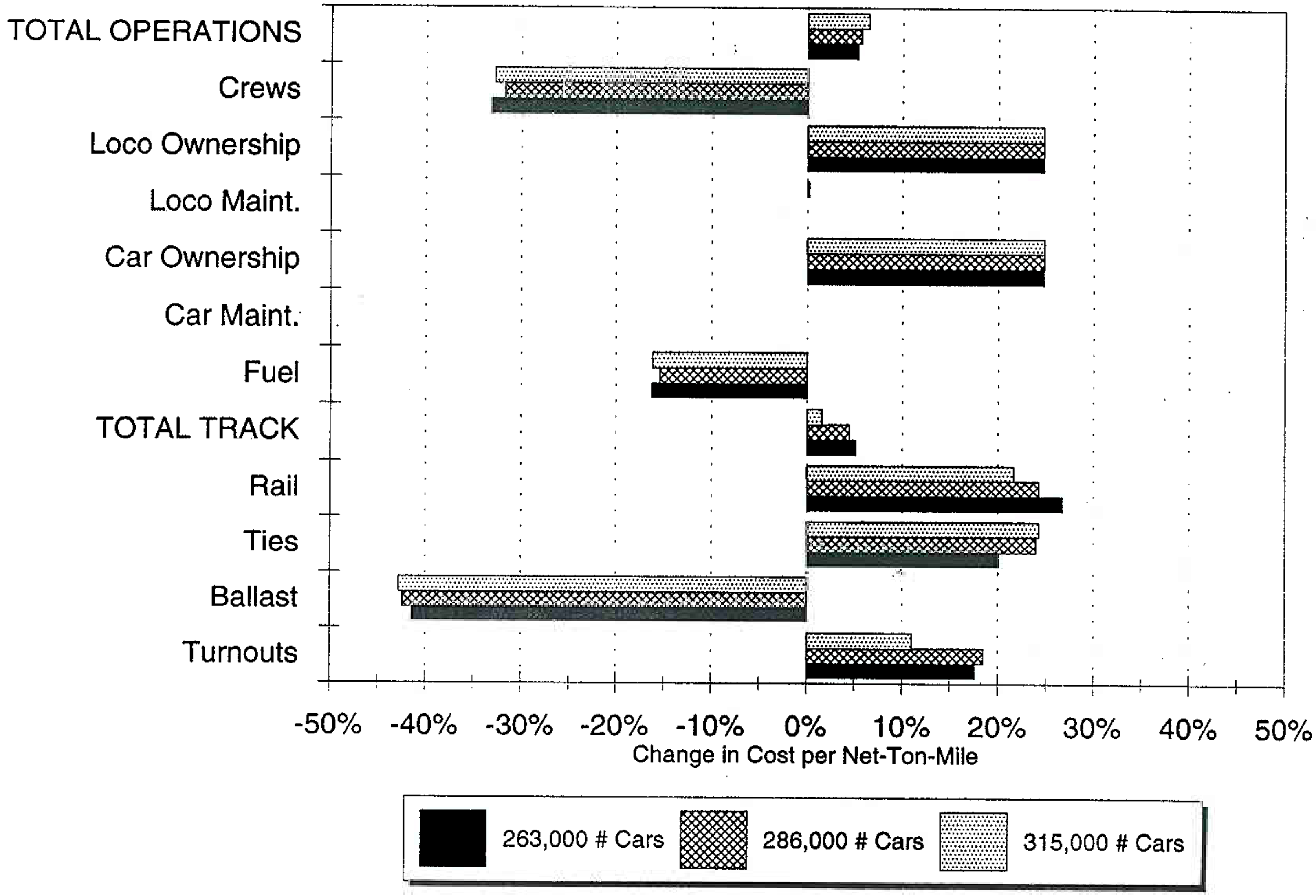


Exhibit 6

Phase II Costs Compared to Phase I

Generic Eastern Route, Weight Limited

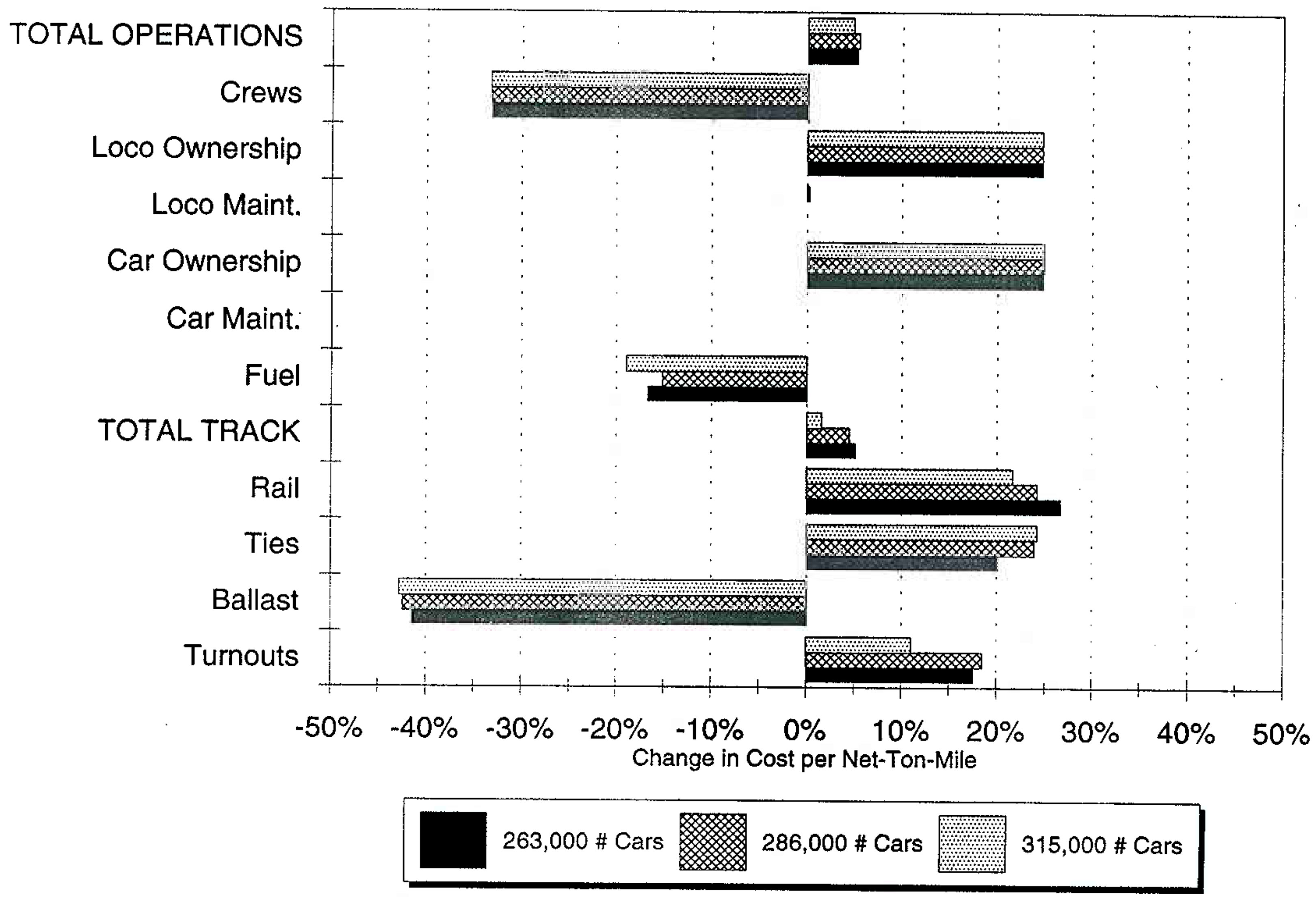
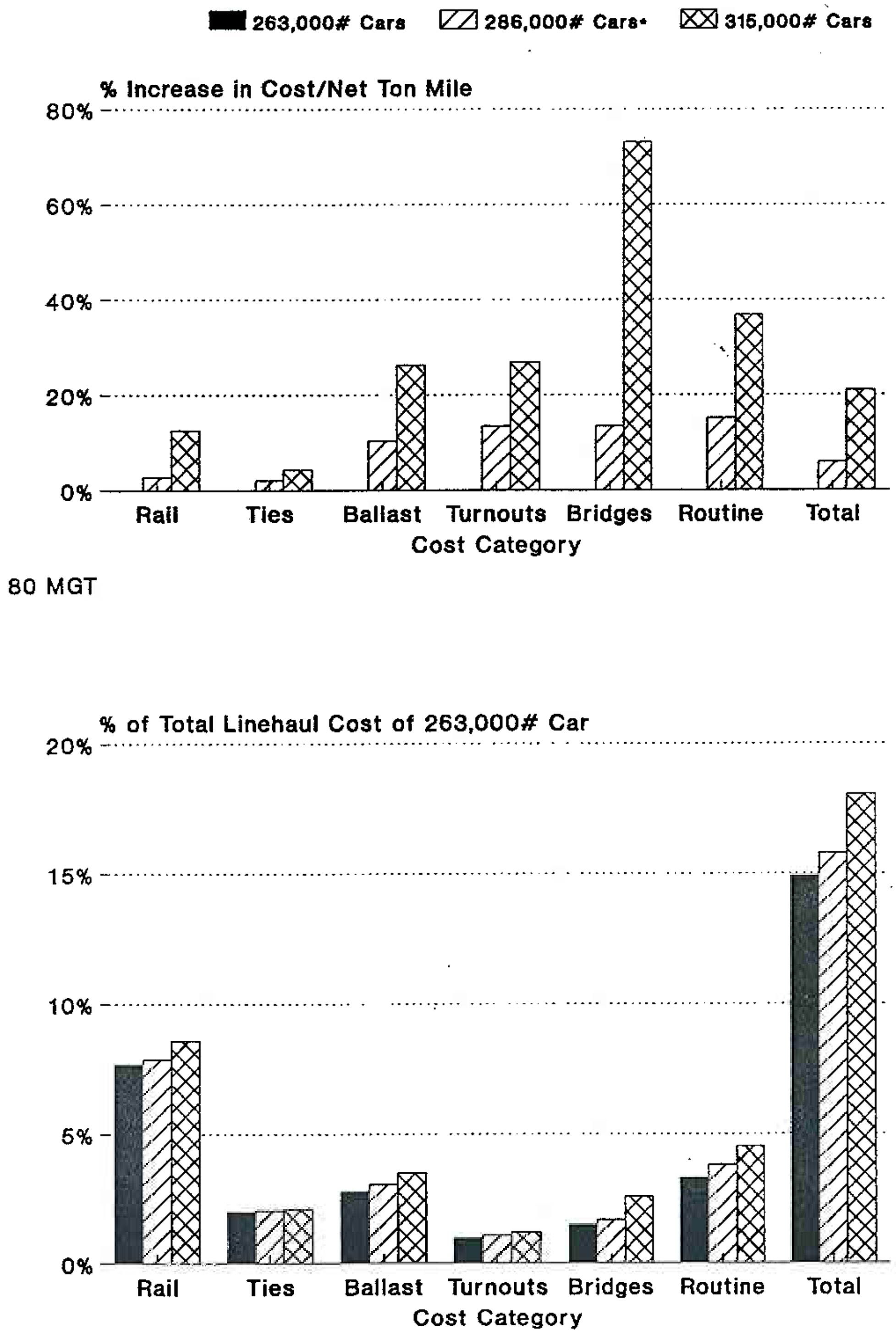


Exhibit 7

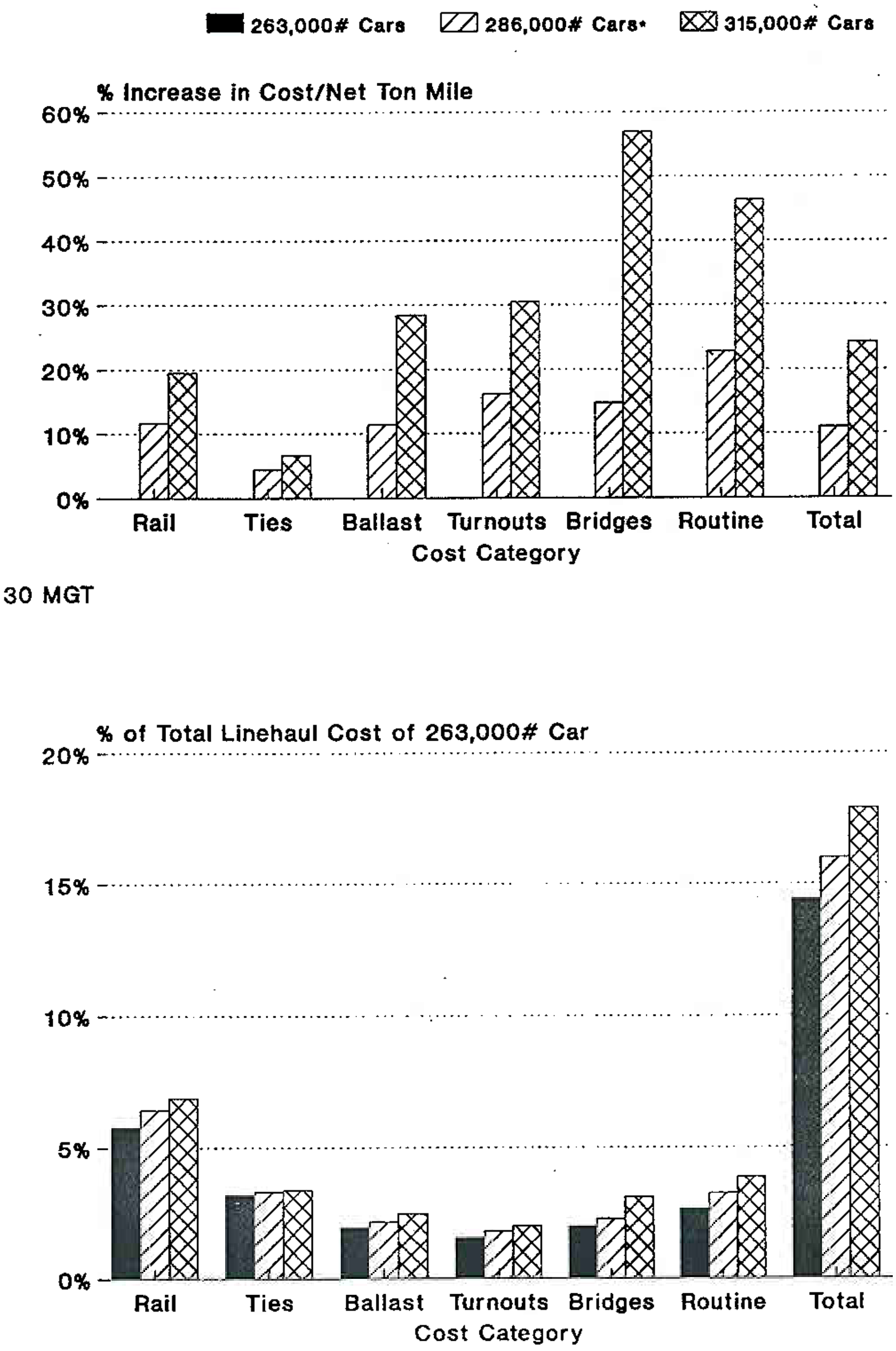
HAL Track Maintenance Cost
Comparisons vs 263,000# Cars
Generic Western Route, Length Limited



* Intermediate projection, not measured directly at FAST

Exhibit 8

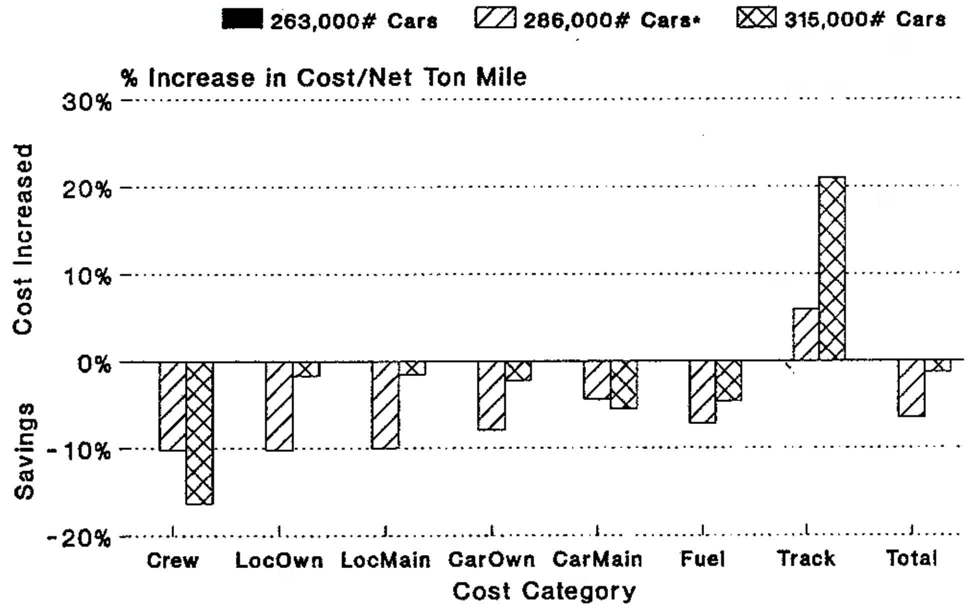
HAL Track Maintenance Cost
Comparisons vs 263,000# Cars
Generic Eastern Route, Length Limited



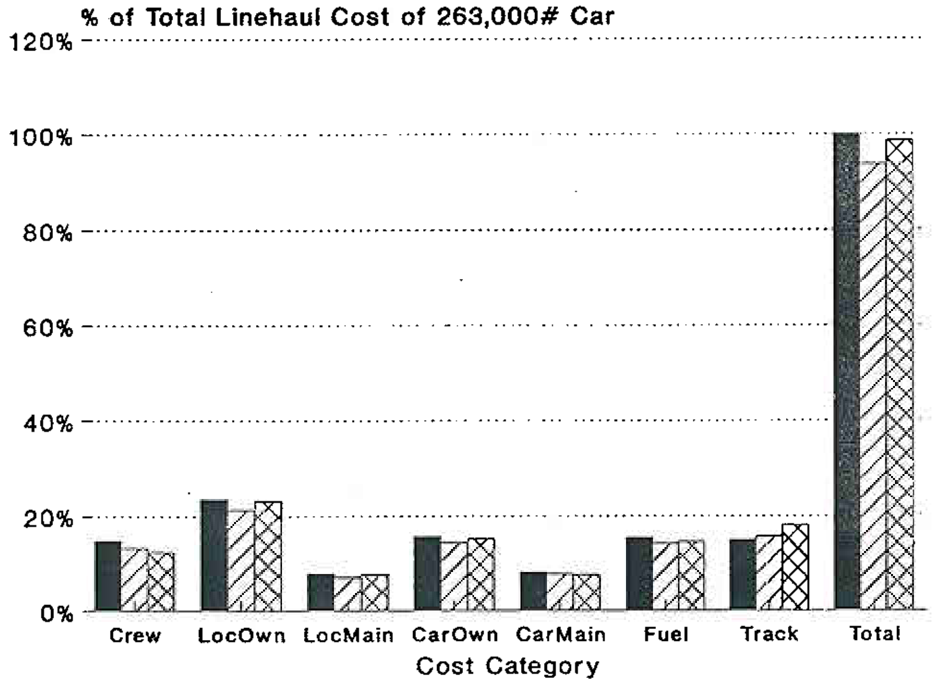
* Intermediate projection, not measured directly at FAST

Exhibit 9

Linehaul Cost Comparisons
vs 263,000# Cars
Generic Western Route, Length Limited



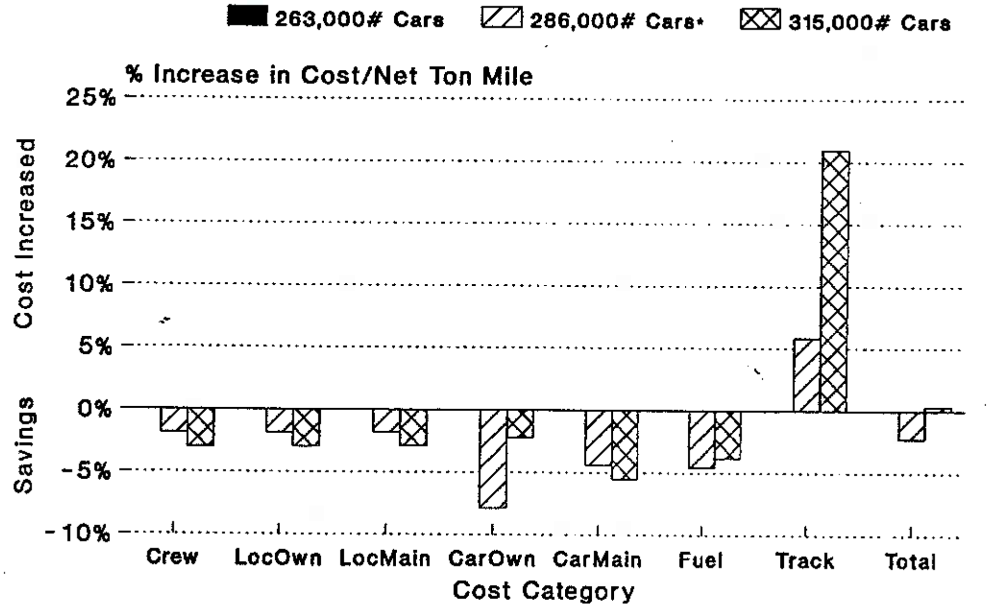
80 MGT



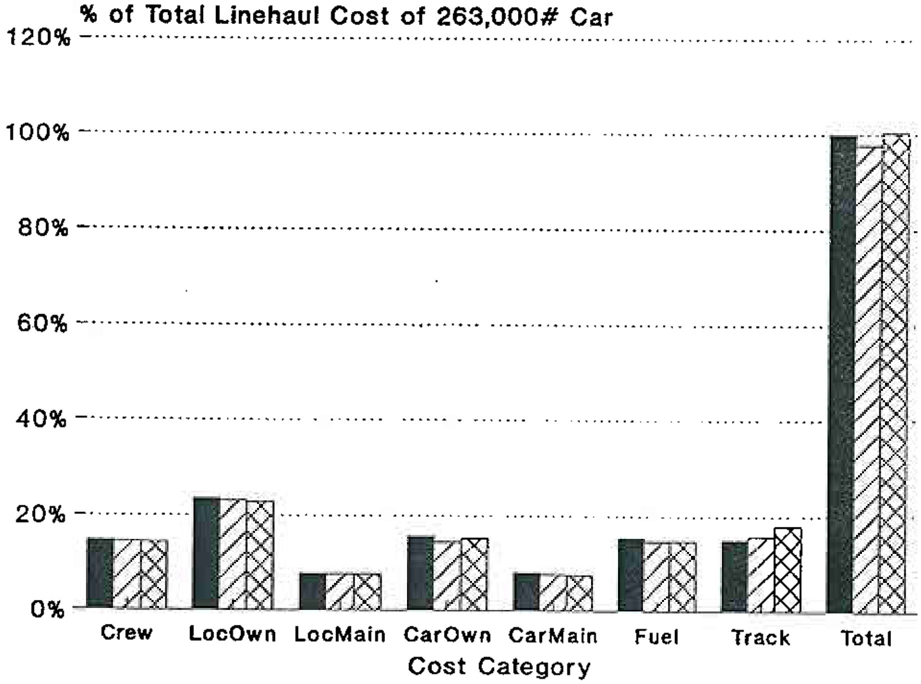
* Intermediate projection, not measured directly at FAST

Exhibit 10

Linehaul Cost Comparisons
vs 263,000# Cars
Generic Western Route
Equal Trailing Weight



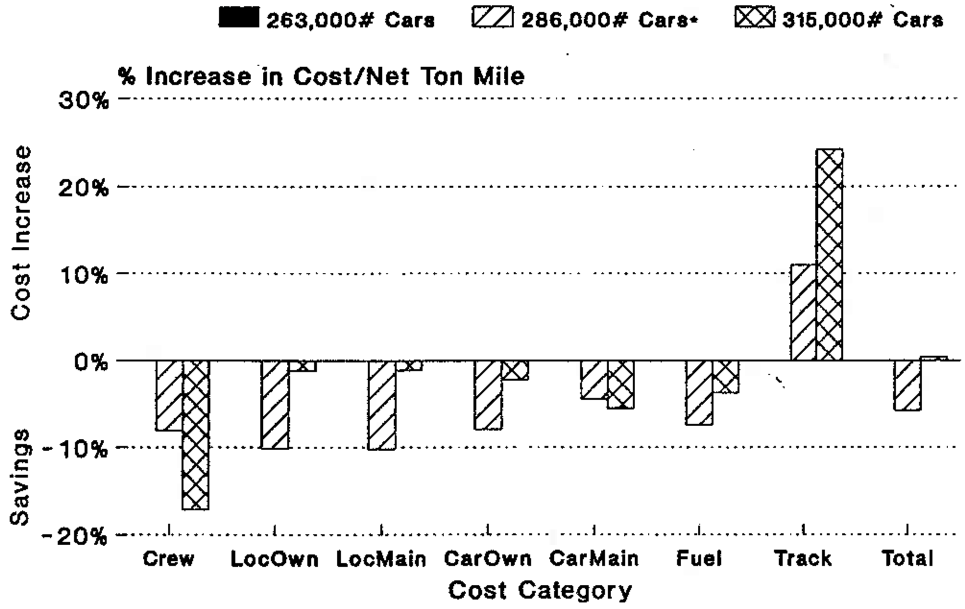
80 MGT



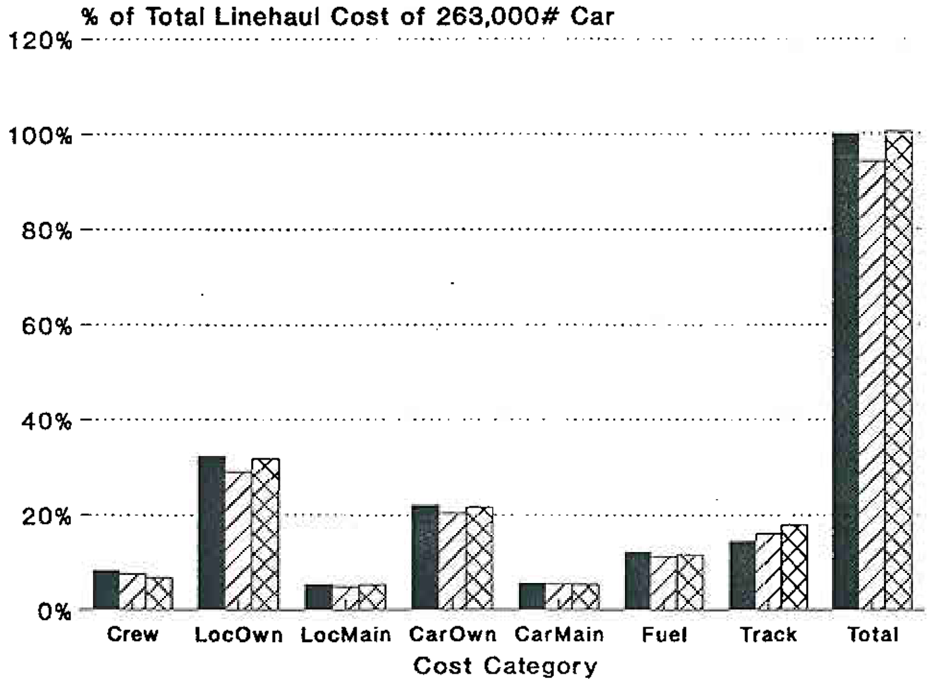
* Intermediate projection, not measured directly at FAST

Exhibit 11

Linehaul Cost Comparisons
vs 263,000# Cars
Generic Eastern Route, Length Limited



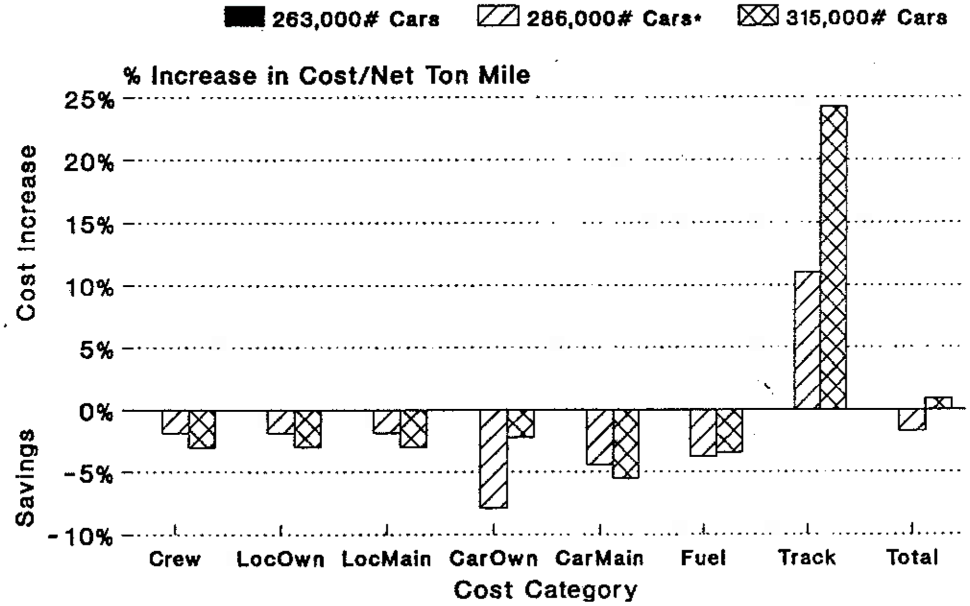
30 MGT



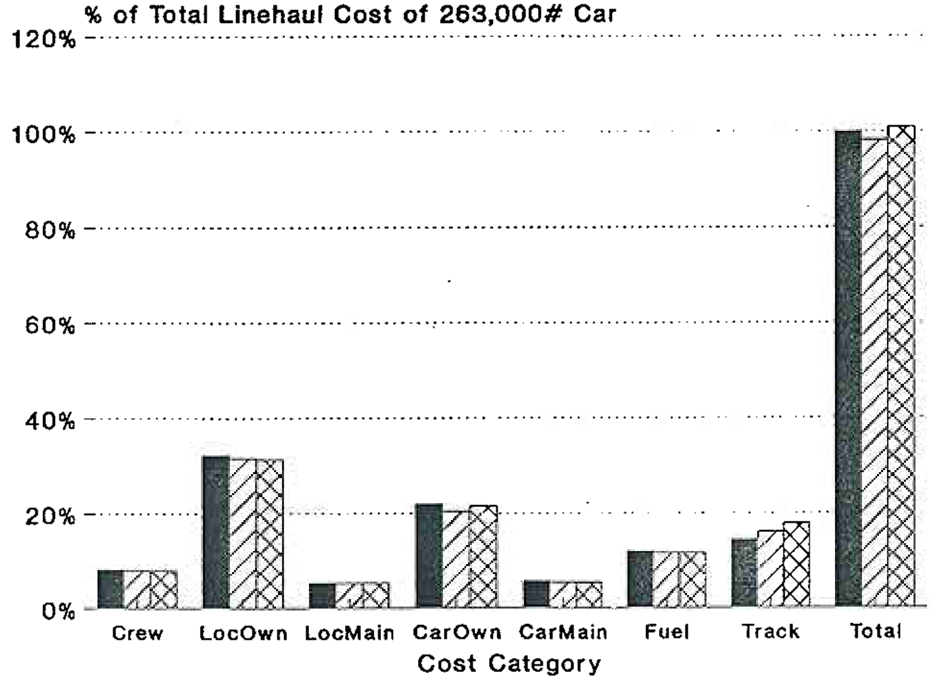
* Intermediate projection, not measured directly at FAST

Exhibit 12

Linehaul Cost Comparisons
vs 263,000# Cars
Generic Eastern Route
Equal Trailing Weight



30 MGT



* Intermediate projection, not measured directly at FAST

Exhibit 13. Line Haul Cost Comparison Versus 263,000 GVW Operations

Cost Category	286,000 GVW Operations				315,000 GVW Operations			
	Western Route		Eastern Route		Western Route		Eastern Route	
	Length Limited	Weight Limited	Length Limited	Weight Limited	Length Limited	Weight Limited	Length Limited	Weight Limited
Operations	-8.7%	-3.65%	-8.6%	-3.84%	-5.2%	-3.2%	-3.6%	-3.0%
Track & Bridges	5.9%	5.9%	11.0%	11.0%	21.0%	21.0%	24.2%	+24.2%
Total Savings	6.50%	2.3%	5.8%	1.7%	1.3%	-.4%	-0.4%	-0.9%

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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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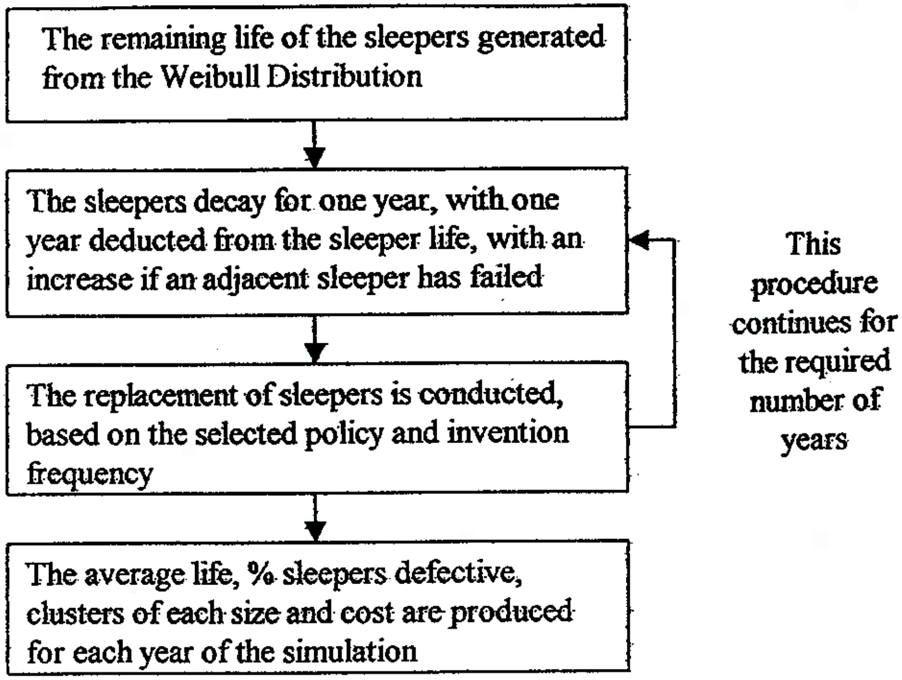

Figure 1: The Process of the Simulation

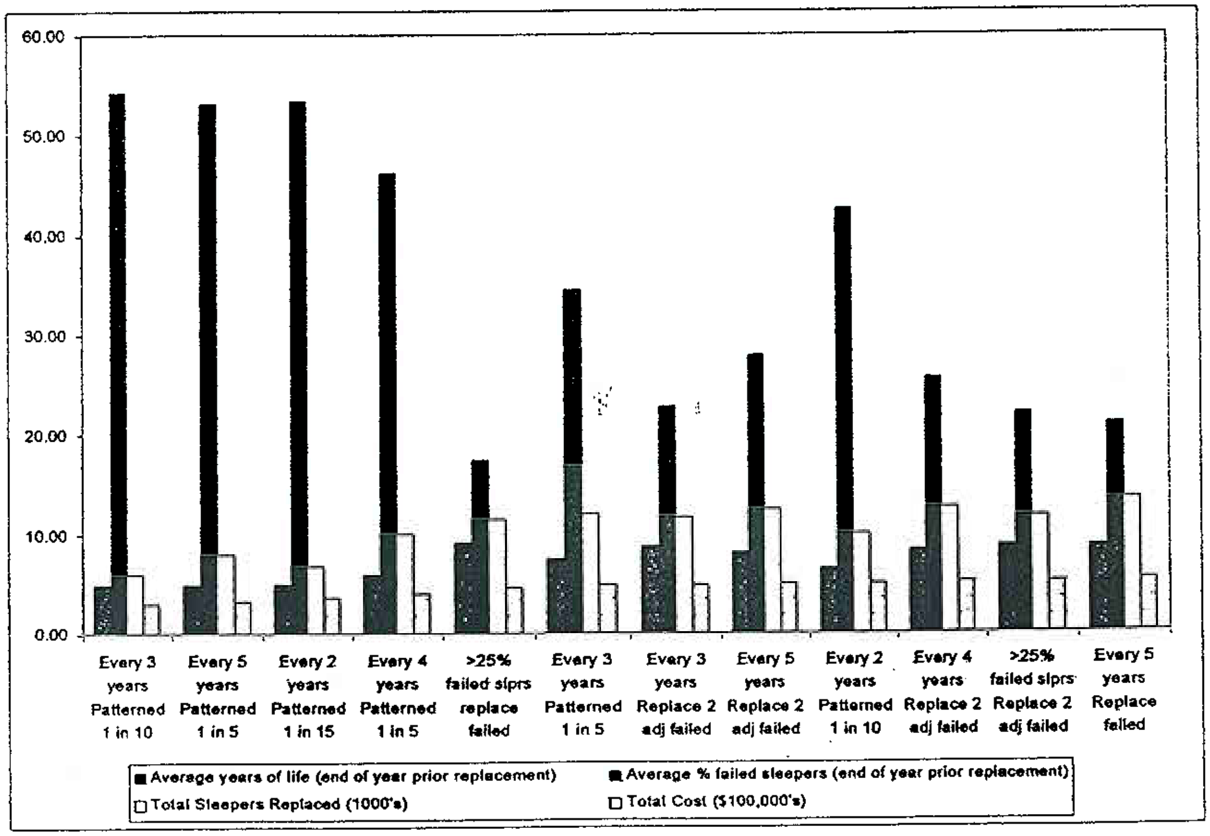

Figure 2: The Results for the Twelve Least Expensive Replacement Strategies

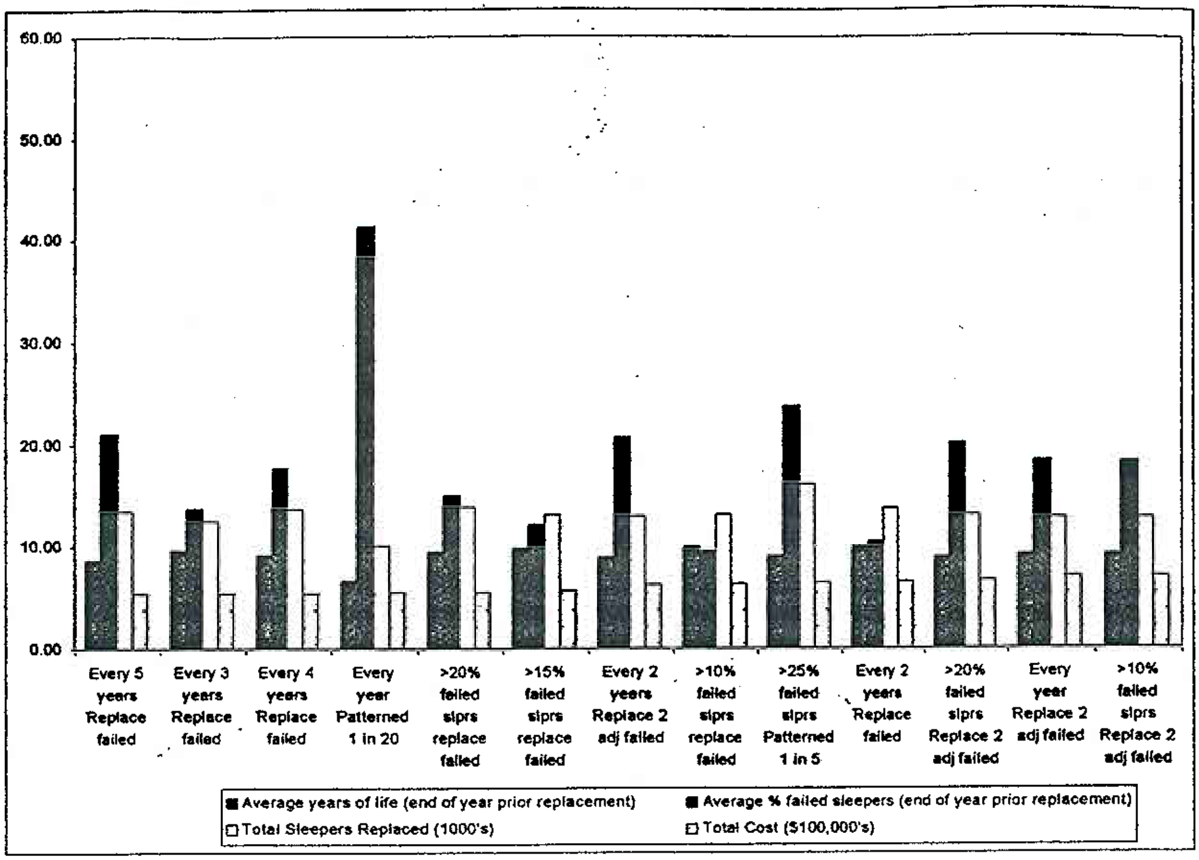

Figure 3: The Results for the Middle Twelve Replacement Strategies by Total Expense

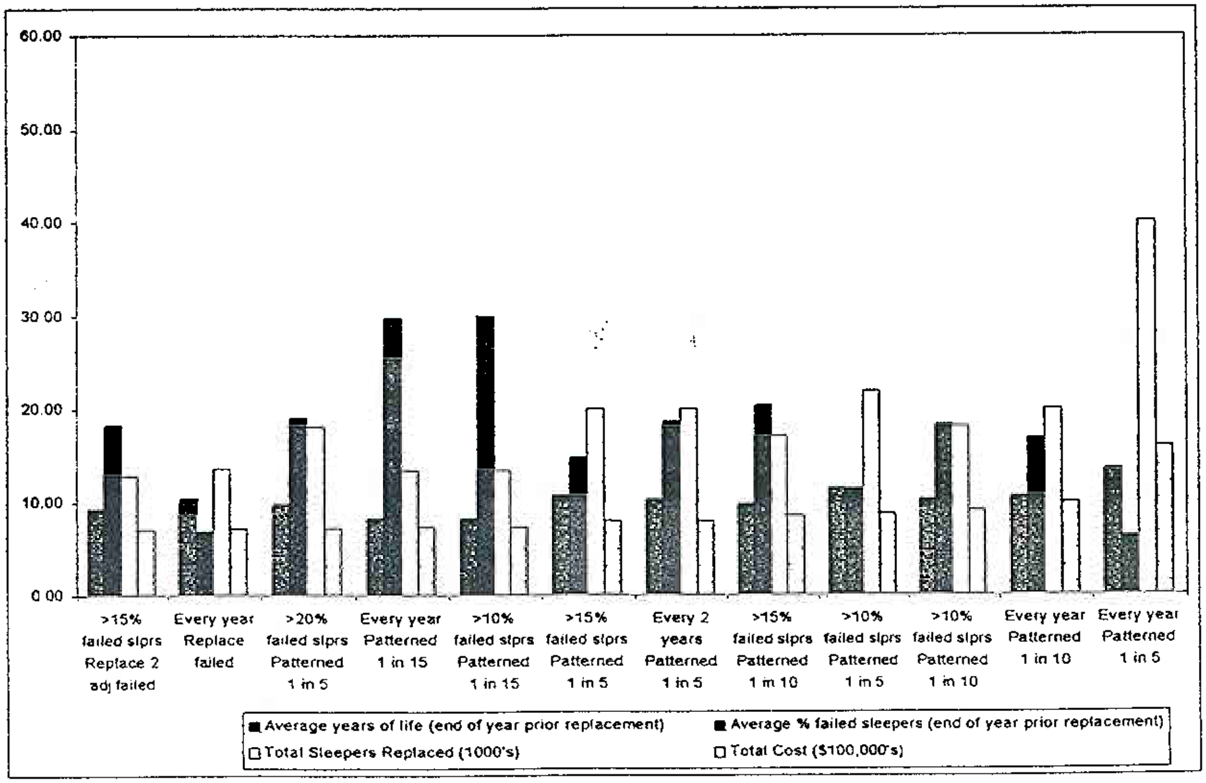

Figure 4: The Results for the Twelve Most Expensive Replacement Strategies

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 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	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	