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ECONOMICS OF HEAVY AXLE LOADS: PREDICTED AND ACTUAL BENEFITS OF HAL OPERATIONS

REPORT NO. R-943

by

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Transportation Technology Center, Inc.,
a subsidiary of the Association of American Railroads
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13. Abstract

Over the past 15 years, Transportation Technology Center, Inc. (formerly Research and Test Department of the Association of American Railroads) has devoted a great deal of research to technical and economic issues related to increasing axle loads under a program jointly funded by the Association of American Railroads and the Federal Railroad Administration. Much of this research has been based upon the various phases of the Heavy Axle Load Test (HAL) Program conducted at the FRA's Transportation Test Center in Pueblo, Colorado. Phase I of the HAL Program compared the operation of 315,000-pound cars to the operation of 263,000-pound cars over test track at the Facility for Accelerated Service Testing (FAST). Phase I confirmed the feasibility of operating safely with 315,000-pound cars, but it also identified various technical problems that were exacerbated by the heavier cars. In Phase II, additional tests were conducted using premium track components and improved maintenance techniques. In Phase III, another series of tests was completed using 315,000-pound cars equipped with improved suspension trucks.

The analyses consistently recommended 286,000-pound cars as opposed to either 263,000-pound car or 315,000-pound car operations. However, both costs and benefits of HAL operations are highly site specific. Therefore, it is recommended that individual railroads carefully analyze their specific service alternatives.

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Executive Summary

Over the past 15 years, Transportation Technology Center, Inc. (formerly Research and Test Department of the Association of American Railroads) has devoted a great deal of research to technical and economic issues related to increasing axle loads under a program jointly funded by the Association of American Railroads (AAR) and the Federal Railroad Administration (FRA). Much of this research has been based upon the various phases of the Heavy Axle Load Test (HAL) Program conducted at the FRA's Transportation Test Center in Pueblo, Colorado. Phase I of the HAL Program compared the operation of 315,000-pound cars to the operation of 263,000-pound cars over test track at the Facility for Accelerated Service Testing (FAST). Phase I confirmed the feasibility of operating safely with 315,000-pound cars, but it also identified various technical problems that were exacerbated by the heavier cars. In Phase II, additional tests were conducted using premium track components and improved maintenance techniques. In Phase III, another series of tests was completed using 315,000-pound cars equipped with improved suspension trucks.

The analyses consistently recommended 286,000-pound cars as opposed to either 263,000-pound car or 315,000-pound car operations. However, both costs and benefits of HAL operations are highly site specific. Therefore, it is recommended that individual railroads carefully analyze their specific service alternatives.

Summary of Conclusions from the HAL Implementation, Operations, and Economic Considerations

1. The analyses consistently recommended 286,000-pound cars as opposed to either 263,000-pound car or 315,000-pound car operations.
2. The railroads adopted the 286,000-pound car for coal operations; implementation has been beneficial to the industry, with annual savings over $200 million and cumulative savings well over $1 billion.
3. Advances in technology reduced track costs significantly; the industry today could handle 315,000-pound cars at equivalent or lower track costs ($/1000 Net Ton Miles) than were achievable with 263,000-pound cars at the outset of the HAL tests in the mid-1980s.

4. Improved suspension trucks are clearly justified, but implementation has been hindered because the costs and benefits are dispersed among equipment owners and the railroad or railroads moving the cars.
5. The need for capacity enhancement is more critical today than when the tests began, as capacity bottlenecks are emerging throughout the system.
6. Shorter 286,000-pound cars can provide many of the operating and capacity savings of a shift to 315-pound cars without incurring additional track costs (although the increase in bridge costs might be comparable or higher in some cases to the increase for 315,000-pound cars).
7. The transition to 286,000-pound cars has been very smooth, possibly because it was a much smaller step than the prior increase from 220,000-pound to 263,000-pound cars. Now it may be time to take another step aimed at capacity improvement (either the 315,000-lb car or shorter 286,000-lb cars), taking advantage of the improvements in the track structure and in bridges that have been accomplished since the beginning of the tests.

List of Tables

1.0 INTRODUCTION

Increasing the capacity and gross weight of freight cars above the current 263,000-pound design car is one way to improve the productivity of rail freight operations. If more net tons can be carried by each train, then productivity gains will be achieved by reducing the number of train crews required to haul a given tonnage. If the ratio of net to gross tons can be increased, additional savings can be achieved in fuel, track costs, and equipment costs. With fewer trains to move any given tonnage, there will be an improvement in capacity and a reduction in meet-pass delays. Offsetting some or all of these benefits will be an increase in track and bridge costs if axle loads are increased.

Over the past 15 years, TTCI (formerly Research and Test Department of the Association of American Railroads) has devoted a great deal of research to technical and economic issues related to increasing axle loads under a program jointly funded by the Association of American Railroads (AAR) and the Federal Railroad Administration (FRA). Much of this research has been based upon the various phases of the Heavy Axle Load Test (HAL) Program conducted at the Transportation Test Center in Pueblo, Colorado. Phase I of the HAL Program compared the operation of 315,000-pound cars to the operation of 263,000-pound cars over test track at the Facility for Accelerated Service Testing (FAST). Phase I confirmed the feasibility of operating safely with 315,000-pound cars, but it also identified various technical problems that were exacerbated by the heavier cars. In Phase II, additional tests were conducted using premium track components and improved maintenance techniques. In Phase III, another series of tests was completed using 315,000-pound cars equipped with improved suspension trucks. A detailed description of the FAST Program and its various phases are described in the appendices.

Following the completion of each testing phase, an economic analysis compared the costs and benefits of going to heavier cars. The effects of HAL operations on track costs were estimated through the use of deterioration models calibrated to the FAST results, information from other research, and experience. The track models were used to estimate track costs for three possibilities:

1. 263,000-pound base case
2. 286,000-pound cars
3. 315,000-pound cars

Operating costs were estimated by identifying specific consists that could be used for unit coal train operations on a typical 30-MGT line in the east and a typical 80-MGT line in the west. The unit costs, track components, maintenance practices, and track deterioration parameters were first developed for the Phase I Economic Analysis in cooperation with the HAL Economics Task Force. Case studies of actual coal lines were also conducted in Phase I in cooperation with an eastern and a western railroad in order to validate the methodology. The case studies of the eastern and western coal lines were updated at the end of Phase II and Phase III, taking into account changes in track components and unit costs, as well as improved knowledge of the effects of HAL operations on the track structure. Additional case studies were conducted for a broader set of possible car designs and operating conditions.

In general, heavier axle loads will increase track and facility costs, but decrease operating and equipment costs. Since track costs are much smaller than operating plus equipment costs, HAL operations can be economically beneficial even if the percentage increase in track costs is far greater than the percentage decrease in operating plus equipment costs.

Both costs and benefits are highly route and site specific. The most promising opportunities are for high density, bulk unit train operations over good track, especially where train lengths and line capacity are limited. The situations that are least likely to be justified on a benefit/cost basis are HAL operations over light density lines where the track structure is weak and there are no problems with train length or line capacity.

2.0 OVERVIEW OF THE FAST/HAL TESTS

This section, organized by track component, provides an overview of the conclusions from the FAST/HAL tests. The purpose of this section is to identify the key factors that affect track costs as axle loads increase, because these are the factors that eventually limit the productivity gains that can be achieved. Summaries of the test results are included in the appendix of this report.

2.1 Rail Grinding and Fatigue

Rail defects can be a major concern under HAL loads. For standard 300 Bhn rail (and lower hardness rails), increasing axle loads above 33-tons can cause a greater increase in rail surface and internal defect rates, especially on medium to heavy density lines.

Under 263,000-pound cars at FAST, corrugations were a relatively minor problem. During the first 160 MGT operations under 315,000-pound car operation, corrugations in rail became noticeable and grew faster for standard rail with the same hardness in nearly the same location. In fact, corrugations became so severe (0.1 inch deep) that the rail had to be ground after about 85 MGT of HAL traffic. This finding suggested that, if softer rail is used, extensive grinding and rail inspection may be required to eliminate corrugations and to reduce the number of service failures under 39-ton axle loads. The increased costs for grinding and defect repair of standard metallurgy rail can be one of the constraints on higher axle loads.

A number of new rail grinding experiments followed over the next 300 MGT operations to examine the effect of different rail grinding strategies on the rolling contact fatigue of rail with different metallurgies. Rail surface defects, shells, and detail fractures occurred on both the standard and premium rails available at that time, regardless of the grinding strategy. Results of these tests were inconclusive as they varied as a function of rail cleanliness, rail lubrication, and track curvature.

These tests indicated the need to use continuous-cast, premium head- hardened rail under heavy axle loads as a way to reduce internal rail defects and surface problems. Further tests are being conducted to determine the effects of rail grinding in fatigue life of premium head-hardened rail. After about 25 MGT of operation, no internal defects have been detected in any of the rails, ground or non-ground, in any of the test zones in either curve. In this respect, continuous-cast premium rail — whether ground or not — appears highly resistant to internal head defects. Non-ground rails have less metal loss than ground rails. Assuming a combined gage/head wear limit of 7/8 inch, predictions for the lives of the various rails are (1) ground rail in 6-degree curve — 1,000 MGT (2) ground rail in 5-degree curve — 1,700 MGT (3) non-ground rail in 5-degree curve — over 5,000 MGT. These figures assume rail failure only by wear.

Surface conditions of the ground and non-ground rail are comparable, with the exception of high rail gage corner checking on some of the non-ground rails. The non-ground rails are performing at least as well as the ground rails. The only gage corner spalls/shells that have developed are on the high rails in the 6-degree curve ground every 75 MGT (0.040-inch metal removal).

There has been no significant difference in performance between the dry-worn and control rails in the 5-degree curve. That is, a period of dry wear prior to normal curve lubrication has had no effect on rail performance.

In various test sections of the High Tonnage Loop at FAST where the wheel and rail profile did not match (due to excessive high rail, gage face grinding tests), the premium suspension trucks did not show any improvements in curving performance compared to standard three-piece trucks. As a result from these findings, railroads should closely monitor and evaluate their current wheel/rail profile maintenance practices in order to realize the full benefits offered by improved suspension trucks.

2.2 Rail Wear

Under laboratory conditions, rail wear has been shown to increase as a function of contact stress times creepage (slip at the wheel rail interface), hence is proportional to approximately the cube root of axle load. It would then be expected that increasing axle loads from 33 to 39 tons would not lead to substantial increases in rail wear (about 6 percent). Therefore, on a net-ton basis, higher axle loads would not increase, and might slightly reduce wear rates because of improvements in the net-to-tare ratio of the cars. About 1,000 MGT of operation of heavy axle load cars at FAST indicate that rail wear is more affected by rail lubrication, truck suspension systems, rail metallurgy, and wheel/rail profiles than by axle load increases.

During Phase I of the program, in which 160 MGT of HAL traffic was accumulated at FAST, Rail Wear Test results suggested that increasing axle loads from 33 to 39 tons reduced the rail life benefit, in terms of gage face wear, offered by premium rails over standard rails, increased the rate of high rail gage face wear and head height loss, and had little effect on low-railhead height loss. These tests also indicated the importance of utilizing premium head hardened rails under consistent lubrication and wheel/rail profile maintenance practices when operating 315,000-pound cars with standard three-piece trucks.

During later phases of the program, a direct comparison was made of the effects on rail performance under standard three-piece trucks and improved suspension trucks. Results showed that operating the heavy axle load train with improved-suspension trucks reduced gage face wear about 70 percent in standard rail and about 75 percent in premium rails and reduced railhead vertical wear such that it was just becoming measurable at 250 MGT.

Additional tests were run with the objective of determining the effects of dry rail conditions on rail performance under improved suspension trucks. Wear performance of a wide range of premium rail steels, which had hardnesses in the range of 342 to 378

Bhn, showed that partial lubrication (changing friction from about 0.5 to 0.35) produced a dramatic reduction in wear, by a factor of about 4. This confirms the great benefits to wear resistance offered even by limited lubrication. Better lubrication would be expected to result in even less wear.

Replacing rail for wear when about 35 percent of the head has worn away would give wear lives of more than 5,000 MGT for the premium rails (under lightly lubricated conditions). These values are very high for a 5-degree curve and illustrate the benefits that can be obtained from premium suspension trucks, especially when lubrication is applied.

2.3 Field Welds

Field welds on curves were a major problem during the first 160 MGT of heavy axle load operations at FAST. Welds that had performed well under the 33-ton regime failed quite early under the 39-ton regime. Eighty percent of the welds in the high rail and 19 percent in the low rail had failed by 75 MGT. Ninety-five percent of the welds installed in the high rail of curves failed while 83 percent failed in the low rail by 144 MGT.

Improvements were made to welds installed in later phases of the program. These included the use of premium welds, improved weld portions and molds, and improved installation techniques and training. The thermite weld failure frequency decreased dramatically over the next 400 MGT operations to about 20 percent in the high rail of curves. Although the frequency of weld failures has greatly decreased, the same type of defects (inclusions) that affected Phase I operations is still occurring in recently installed premium welds, and these defects lead to relatively early weld failures.

Operations with improved suspension trucks considerably reduced weld batter, and could reduce problems associated with thermite welds.

A recent development in thermite welding is the availability of wide gap welds which can be used to replace weld failures or other rail defects less than 2.75-inches long. Thus, a suitable defect can be replaced with a single weld without the use of a rail plug, which requires a rail segment as well as two thermite welds.

Proper installation is vital to extending weld life. The performance of thermite welds installed in revenue service will likely differ slightly from those observed at FAST as installation conditions are not always optimal.

2.4 Special Track Work

After Phase I, turnouts were viewed as a major constraint on HAL loads, as the life of the frogs appeared to decrease substantially with an increase in axle loads. However, over the course of the HAL testing, high-integrity frogs, low-impact heels, and gage plates were introduced for use on high-tonnage lines. Evidence from field test sites on the Union Pacific indicates that these frogs are lasting 3 to 4 times as long as standard frogs had lasted on the same line, even though HAL loads (286,000-pound cars) now account for more than 50 percent of the MGT on the line.

At the beginning of the FAST HAL experiment, a standard turnout consisting of an AREA No. 20 switch, a rail-bound manganese (RBM) frog, and standard (300 Bhn) rail was installed. This turnout was typical of those used by a major western carrier. Surface damage on both the switch points and frog were noted after 6 MGT. Corrugations and surface damage continued to develop throughout the life of the turnout. This turnout survived just over 100 MGT of 39 kip wheel loads. Improvements in turnout life came from the use of better designs and premium materials. Lower entry angle switches and frogs that eliminate flangeway gaps have proven successful in the HAL environment. The pre-HAL turnout was replaced by a turnout built with premium components, such as high integrity casting frogs, premium ties and fasteners, and premium rail. Switch points and frogs made with premium components have lasted over 400 MGT at FAST and required less maintenance.

More premium components and design features have become "standard" today. As a result, the base case standard turnout has improved greatly in the last few years. Comparisons to the mid-1980's standard turnout are meaningless for heavy haul mainline applications.

FAST results show that turnout maintenance becomes more important under HAL operations. With higher loads, it is more likely that bolts will need to be tightened and that grinding and welding will be needed to maintain the geometry of the frog and switch points. Once problems arise, deterioration is apt to be greater, so frequent inspection and excellent routine maintenance are more essential under HAL operations. Many design improvements are aimed at reducing maintenance or making it easier to perform. This has contributed to extending the service life of turnouts in HAL operations.

Crossing diamonds present a larger technological problem than turnouts under HAL. But there are only 4,000 to 5,000 crossing diamonds in the United States compared to over 100,000 turnouts, so the direct spending on turnouts is significantly higher. However, the indirect costs in train delay make total crossing diamond costs as large as turnout costs.

Several typical revenue service crossing diamonds were tested in the HTL during Phase II of 39 kip operations. While these diamonds were adequate performers in revenue service, with lives of 100 to 300 MGT, they survived only 2 to 15 MGT under HAL traffic. Most of the difference in performance can be attributed to the wheel load increase. With no crossing diamond test experience at FAST under 33 kip wheel load traffic, it is difficult to determine the relative effects of the operational differences on diamond life. Premium material diamonds had service lives of 15 to 30 MGT; this is still far short of revenue service lives under 33 kip wheel loads.

AAR sponsored work on advanced materials and advanced design crossing diamonds shows promise of greatly extending high-angle diamond life by producing a stronger material for frogs and reducing the impact loads on frogs, respectively. A bainitic rail crossing diamond was removed from track after 97 MGT, more than three times the life of conventional rail steel diamonds at FAST. The bainitic three-rail diamond is an excellent choice for locations where one track carries most of the traffic. The cost of a premium bainitic three-rail diamond over a conventional three-rail diamond is estimated to be less than 10 percent.

Initial tests of flange bearing frogs are encouraging. Development of a crossing diamond that fully utilizes the potential benefits of flange bearing to reduce impacts is at least one design iteration away.

2.5 Crossties and Fasteners

Ties were found not to be a major problem in any of the HAL tests. The test results suggest that HAL traffic causes relatively little additional damage to ties and fasteners under the conditions at FAST. The tests cannot tell, however, if these conclusions could be extended to territory where ballast and subgrade are poor, where drainage is a problem, or where ties are already in poor condition at the start of HAL traffic.

Gage widening is the predominant failure mode or cause for maintenance on wood-tie track at FAST. Due to dry climate, decay was not a significant factor in tie degradation. The dynamic loading of ties in curves at FAST is dependent upon rail profiles, lubrication, and truck types used. These factors affected the lateral loading and gage widening performance of all test ties.

Note that variation in the characteristics of truck suspensions was the largest single factor in tie performance during the HAL experiment. The use of improved-suspension trucks with better steering capabilities greatly improved the performance of all ties tested under 39-kip wheel loads. It increased the projected gage-widening life of hardwood and softwood ties by a factor of four, from about 500 to 2000 MGT on the test ties in the marginally lubricated 5-degree curve at FAST. The oak ties in this curve were recently re-gaged after 940 MGT of HAL operations.

In the 6-degree lubricated curve, under standard-truck operations, hardwood ties with cut spikes had a gage widening life of about 500 MGT compared to 200 to300 MGT for softwood ties. Under standard-truck operations, use of elastic fasteners versus cut spikes decreased the loss of gage-widening strength by a factor of five.

Some concerns had been expressed about the effects of HAL loads on concrete ties, but the concrete ties at FAST have performed well over 1,000 MGT of HAL operations, and the industry has taken steps to identify and remove high impact wheels. This was not viewed as a problem for HAL operations.

Premium fasteners are recommended to mitigate gage widening on softwood ties installed on sharp curves. Premium fasteners are recommended more generally to help maintain the integrity of the track structure under 33-ton as well as HAL loadings. Due to climatic and operating conditions, the performance of the ties and fasteners tested may differ from revenue service. In fact, revenue service monitoring of HAL performance showed that one railroad operating 286,000-pound cars has returned to cut spikes in a 5-degree curve to alleviate tie plate cutting associated with the smaller plates used with elastic fasteners.

2.6 Ballast and Subgrade

Where there is a good track structure, track geometry deteriorates slowly as a function of MGT, not of axle loads. Therefore, cost increases related to HAL loads are negligible and may decrease if there is an improvement in the net-to-tare ratio. Both surfacing and renewal cycles were predicted to remain about the same under 33- to 39-ton axle loads.

The FAST ballast tests showed that "good" ballast performance is more dependent on accumulated tonnage than on increased axle load. Four ballast materials, ranging from marginal to good, were tested under 39-ton axle loads. Results from these studies showed that all four ballast materials were able to withstand the heavy axle load environment during the first 160 MGT of traffic.

Among the four different ballast materials tested, granite and traprock maintained adequate geometry over 750 MGT of HAL and did not require out-of-face surfacing. The test section with dolomite required out-of-face tamping at 40 and 260 MGT traffic, after which the test was discontinued. The track section with limestone required an out-of-face tamping after 70 MGT. The test results suggested that discrete track surface anomalies (welds, joints, etc.,) can cause rapid, localized degradation of the ballast particles under heavy axle loads. A quick repair of the local running surface anomalies at FAST was the only solution to prevent long-term ballast problems.

The FAST track was undercut after about 940 MGT HAL traffic due to ballast fouling over several sections. More than 50 percent of the ballast in the 6- and 5-degree test curves was replaced with granite ballast.

Subgrade stresses increased under 39-ton axle loads. While the increases in stresses did not cause failure at locations with native soil, they could be sufficient to cause significant subgrade related maintenance on track with clayey, soft subgrade conditions on some North American tracks.

Where the subgrade is weak, or the ballast is heavily fouled, track geometry could be a serious problem under HAL loads. Tests over a section with low track modulus at FAST showed that surfacing cycles grew progressively shorter as the test progressed, with surfacing required approximately every 15 MGT. This level of maintenance would be unacceptable for any significant length of track and should certainly be considered one of the major constraints on axle loads. In Phases III through

V, tests showed that track geometry deterioration could be controlled through the use of remedial actions, such as geoweb and hot mix asphalt (HMA) underlayments, so that even this potentially serious problem could be controlled through the use of better components and maintenance practices.

2.7 Bridges

Bridges are a major constraint for HAL traffic, primarily because of their longevity. It is not uncommon to find many bridges that are 80 to 100 years old or older on potential HAL routes. Operation of heavier axle loads is expected to affect the fatigue life of existing bridges. Depending upon local conditions, most of these bridges may have to be strengthened or even replaced before any HAL traffic can be operated. In other cases, converting to HAL operations will dramatically shorten their remaining life.

In Phase II, an extensive analysis was conducted to estimate the effects of HAL loads on bridges. This analysis estimated the changes of fatigue life for various bridge elements for more than 30 bridges believed to be typical of those to be found on coal routes. The cost increases predicted for bridges were higher than for any other component and must therefore be considered a major constraint on HAL operations. The results of this analysis predicted that the bridge fatigue life would decrease up to 15 percent for 286,000-pound cars and to more than 50 percent for 315,000-pound car operations.

However, the reader must be cautioned that, for the six individual routes evaluated, the total bridge costs varied by nearly an order of magnitude. Therefore, a specific route analysis is essential when assessing the impact of HAL traffic on any route involving major steel structures or a significant number of timber structures. Additionally, although the bridge maintenance is a much smaller dollar item than track maintenance, it is important to recognize that this maintenance cannot be deferred indefinitely without the possibility of severe economic or operational consequences.

As part of the AAR Bridge Research Program, TTCI has developed a methodology to determine the remaining life of steel bridges (timber bridge life estimation methodology is still under development by TTCI). Route specific analyses can be conducted by individual railroads to determine the economic impact of heavy axle loads on bridges using these models. These models can be used to minimize the impact of heavy axle loads by selective member replacement strategies to extend the life of existing bridges.

3.0 OPERATING COSTS

This section summarizes the various categories of operating benefits that can be achieved through HAL operations. Additional details are available in the studies listed in Appendix J.

3.1 Train Crews

Two basic operating situations were considered in the HAL economic analysis: (1) length-limit and (2) weight-limit. In the length-limit scenarios, HAL operations allowed more tonnage to be carried in the same length of train, which provided savings in crews and improvements in capacity. In the weight-limit scenario, HAL operations resulted in shorter trains with much more modest operating benefits. In both scenarios, improvements in the net-to-tare ratios provided some savings in terms of crews and fuel.

Over the course of the HAL studies, the railroads made substantial progress in implementing labor agreements that allowed two-member crews to operate over longer crew districts. These productivity savings certainly reduced crew costs, but also reduced the benefit from HAL operations.

3.2 Fuel

Fuel consumption is roughly proportional to MGT, so the fuel benefit comes from an improvement in the net-to-tare ratio of the cars. In Phase III, there was an additional fuel benefit because of the superior curving characteristics of the improved suspension trucks. Fuel consumption at FAST was reduced by about 25 percent, and computer models predict savings of 6 to 8 percent in heavy haul service.

3.3 Congestion

In the length-limit scenarios, fewer trains will be needed to handle the same net tonnage. As a result, delays from meets and passes should decline for any given level of traffic. Also, there will be an increase in the operating capacity that will enable more traffic (on the same number of trains) to be operated through bottlenecks. While increased capacity was hardly a consideration during Phase I, by Phase III it was clear that increased capacity is a major concern for all of the Class I railroads in some locations and at certain times of the year. HAL operations can therefore be viewed as a low-cost (and often "no-cost") means of increasing capacity.

4.0 EQUIPMENT

4.1 Freight Cars

Car design and car costs are both key factors in the economic analysis. The 286,000-pound car was viewed initially as an overloaded 263,000-pound (59,700-pound empty weight) car. Since there was no additional tare weight, all of the added gross weight could be revenue freight. The car cost per net ton of capacity clearly would decline in proportion to the added load. The cost of the car is also a key factor.

Car design limitations hindered the 315,000-pound (68,000-pound empty weight) car with heavier trucks and a stronger — but heavier — design; the net-to-tare ratio for this car was worse than for the 263,000-pound car.

The length of the car is also a very significant constraint. At the outset of Phase I, the length of the coal car was assumed to remain at 53'1" so that it would fit into rotary dumpers. However, sensitivity analysis showed that this is a very critical assumption because many of the benefits of HAL cars could be obtained by using ***shorter*** cars. A shorter, 286,000-pound car could obtain the capacity and crew benefits of a 315,000-pound car without the cost consequences for track. The effects on bridges could be more or less severe than for 315,000-pound cars depending on the bridge. A preliminary analysis showed that customers shipping high volumes of coal long distances could justify the costs of modifying their dumpers in order to get the operating benefits of shorter cars.

For hopper cars, length is much less of a constraint than for rotary dump cars. For these cars, more efficient designs can provide large increases in the key ratio — net tons per foot of car length.

4.2 Locomotives

Locomotive requirements depend upon the route as well as the characteristics of the train. In rough terms, locomotive requirements are proportional to the gross tonnage of the train, so that there would only be a modest benefit from any improvements in the net-to-tare ratio. In any particular case, however, the train-consist represents a balance among locomotive costs, train length, and train weight. Depending upon the length and weight of the train and the type of locomotive that is used, a particular consist could have more power than is required. If length constraints are binding, then using HAL cars provides a way to add more tonnage to the train without adding another locomotive. In such a situation, HAL operations will appear to provide locomotive benefits.

5.0 ECONOMIC ANALYSIS

5.1 Phases I and II

Following Phases I and II, economic analyses of HAL operations were conducted under the supervision of an industry committee. In both cases, the conclusions and recommendations were similar: HAL operations are justified in some circumstances, but the potential benefits are (a) highly site specific and (b) dependent upon improved maintenance procedures. The Phase II economic analysis (Hargrove, Guins, and Martland, TTCI LA-007, October 1996) is the most relevant today because Phase II of HAL operations used what are now the recommended premium track components and the economic analysis included an assessment of bridge costs (Sharma, Kalay, and Otter, AAR Report R-895, 1996).

Phase II economic analysis concluded:

> *"The use of heavier cars — 286,000 pounds and 315,000 pounds — has strong potential for achieving significant savings for certain rail operations. In terms of specific car sizes, the 286,000-pound cars offered significant benefits when compared to both the conventional 263,000-pound cars...and the 315,000-pound cars used in the FAST Heavy Axle Load (HAL) tests.*
>
> *"For the cases analyzed, potential net reductions in cost in the range of 2-6 percent warrant serious investigation as a means to increase the productivity of specific services over specific routes. More specifically, increases in track and bridge capital and maintenance costs are more than offset by reductions in equipment capital and maintenance costs, and train crew and fuel costs. These results assume operation over well maintained track that has good quality track components and over bridges of sufficient strength.* ***Results are highly route and service specific. Thus, individual railroads should analyze their specific service alternatives."*** (Hargrove, Guins, and Martland, TTCI LA-007, October 1996, p. i)

This study found that the 315,000-pound car was technically feasible, but not as economical as the 286,000-pound car. The heavier car incurs greater costs related to bridges, rail grinding and defect costs, surfacing and subgrade, and operations on yard and industry tracks that lack the proper support to handle heavier cars.

Phase II analysis updated the unit cost and productivity assumptions to reflect typical heavy-haul operations in 1995. Between 1990 and 1995, the Railroad Cost Recovery Index rose 15 percent, but there were significant variations for specific cost items. Fuel costs actually declined over this period, as did crew costs. For crews, the widespread introduction of two-member crews and the increase of the basic day from 108 to 130 miles offset increases in average wage rates. Equipment costs and most elements of track costs were increased on the order of 20-25 percent based upon feedback from the industry. The rise in track costs tended to increase the costs of HAL operations, while the decline in fuel and crew costs tended to reduce the benefits of HAL operations. Nevertheless, as we have already seen, Phase II conclusions were similar to those in Phase I in recommending implementation of 36-ton axle loads.

Phase II economic analysis (Martland, TTCI LA-007, October 1996) also included sensitivity analyses related to the following factors:

1. Net-to-tare ratios of the cars ("...the results of the HAL analysis are robust across a reasonable range in net-to-tare ratios.")
2. Surfacing cycles and ballast life ("In terms of the HAL analysis,...the percentage of bad track could be important, but minor changes in the definitions of what constitutes good or poor ballast would not be critical.")
3. Tie life and the HAL effect on tie life ("Tie costs are largely insensitive to HAL effects.")
4. Unit costs for track components and the extent of HAL effects ("...the basic conclusions of the HAL economic analysis are quite robust with respect to changes in the unit costs of track maintenance or in the HAL deterioration rates.")

Phase II analysis showed that the magnitude of HAL effects on the track structure was lower than predicted in Phase I as a result of better track components as well as a better understanding of deterioration rates. In addition, the continued FAST/HAL testing, along with railroad experience with HAL traffic, "*...has strengthened the economic assessment of track costs relative to what was possible in Phase I.*" The analysis pointed out the importance of having good components and, especially on poorer quality track, the necessity of budgeting for increased maintenance activities on lines with significant amounts of HAL traffic.

Phase II results would not change significantly if updated to current cost levels, as inflation was very low in the late 1990s. From the 4th quarter of 1995 to the 4th quarter of 1998, the "All Inclusive Rail Cost Adjustment Factor" only rose 3.1 percent (*Railroad Facts*, 1999 edition). Furthermore, there were no significant relative changes in costs akin to those provided between Phases I and II by lower fuel prices, reduced crew consists, and changes in the basic daily mileage.

5.2 Phase III

Phase III looked at the extent to which better equipment could reduce the negative effects of HAL operations. The HAL Phase III economic analysis (TTCI *Technology Digest* 98-09, Guins, 1998) concluded that the extra costs associated with improved-suspension trucks could indeed be justified by reductions in expenditures for track, equipment maintenance, and fuel. The improved suspension trucks offer a savings of 1 to 2 percent in total direct cost; further cost savings of 7 to 8 percent are possible in going from a 263,000-pound base case car (with standard three-piece trucks) to a 286,000-pound car with improved-suspension trucks. As in Phases I and II, the 286,0000-pound car was found to be superior to the 315,000-pound car. The potential returns on investment ranged from 35 percent to 85 percent, depending upon the route and the type of service.

These economic analyses built upon the results of HAL Phase III were completed in three years. The nature of this analysis was in some aspects quite different from that of the earlier phases. In Phase III, the FAST/HAL tests were used to justify changes in assumptions that led to reductions — not increases — in track and equipment costs. In Phases I and II, the analysis had to compare the immediate operating benefits with the eventual increase in track costs. In Phase III, the analysis had to compare the immediate increase in equipment costs with the opportunity for some immediate operating benefits and eventual track and equipment benefits.

The results from 425MGT of Phase III testing supported the following findings:

1. An 8 percent reduction in fuel consumption.
2. A 25 percent increase in the life of wheel-sets.
3. A 33 percent increase in the life of improved suspension trucks (relative to the rebuild cycle for standard trucks).
4. A 50 percent reduction in the rail grinding required to control corrugation.
5. Increasing the life of rail in curves less than 2-degrees to 90 percent of the life of tangent track.
6. A 50 percent increase in the life of rail in curves greater than 2-degrees.

Additional changes were made to the track cost analysis from test results during Phase III (TTCI *Technology Digest* 96-025, Read and Kalay, November 1996):

1. Base grinding was reduced for tangent track and 2-degree curves because corrugations were not a problem with the improved suspension trucks.
2. Additional reductions in the amount of routine rail maintenance required reflecting the longer lives of field welds in Phase III operations.
3. Much better performance for poor ballast/subgrade segments to reflect the use of GEOWEB® (the damage factor used to predict the deterioration rate for track geometry and ballast renewal was reduced from 2 to 1 and the base renewal and surfacing cycles were increased by 50 percent).

The main difficulty with the economics of improved suspension trucks is that the costs and benefits are likely to be incurred by different organizations. In Phases I and II, customers benefited from the improvements in equipment utilization, while railroads benefited from reductions in operating costs that were greater than the predicted increases in track and bridge costs. In Phase III, customers (at least those that own cars) paid extra for the improved suspension trucks, but most of the benefits will go to the railroad in terms of better fuel efficiency and slower track deterioration. Customers will eventually benefit from longer life for wheel sets and for the truck itself, but those benefits may not be enough to justify the higher initial cost.

5.3 Optimal Car Design

Throughout the HAL studies, axle loads were treated as the dominant variable in car design. In fact, other variables can be adjusted so as to achieve similar operating benefits without as much harm to the track structure. Guins, Chapman, Robert, and Martland (TTCI *Technology Digest* 98-010, January 1998) examined the factors influencing optimal axle loads for HAL operations. This study examined the effects of car design and train length on HAL economics.

The study considered Eastern and Western coal networks, which were loosely modeled on typical coal operations in each part of the country. The approach and assumptions were similar to those used in the HAL Phase II analysis. Chapman used the computer model TRACS to model track costs, including segments with tonnages representative of each portion of the route from the mine to the utility. Robert used a model of unit train operations to estimate congestion effects; with fewer trains operating, there is less congestion and therefore a reduction in cycle times that allows an additional reduction in train sets.

Several key conclusions resulted from this study: (1) If the car length can vary, then axle load becomes a much less important variable; (2) Most of the operating and capacity benefits can be obtained by improving car design to make better utilization of the space occupied by the train; (3) On congested routes, a shift to trains with higher net tonnage will help to reduce congestion, thereby providing additional equipment utilization benefits.

If car length is varied, it is possible to increase the loading density of a train (i.e. increase the tons per linear foot of train), but customers may have to modify their unloading facilities. Robert and Haskell (internal TTCI Report December 1997) documented the constraints for unloading coal cars at utilities and estimated the costs of upgrading the facilities to handle cars of different sizes. In general, the costs for modifying a facility for handling shorter, higher cars would be less than the costs for handling longer cars (since there may not be space to handle longer cars). For customers receiving large volumes of coal transported long distances, the savings in transportation costs were enough to justify the modifications necessary to handle shorter, higher rotary-dump coal cars.

In his master's thesis (June 1998, "Car Design for More Productive Heavy Haul Rail Operations: Increasing the Capacity of Length-Limited Trains," Department of Civil Engineering, Massachusetts Institute of Technology) Chapman delved into issues of car design to determine the characteristics of gondolas and hopper cars that might be used to transport coal. He considered cars that were shorter and higher, cars that were wider, and cars with axle loads up to 42 tons. His analysis included the costs of modifying loaders and dumpers where necessary to handle rotary dump cars, using results from Roberts and Kiersten (internal TTCI Report December 1997). He concluded that improving car design without increasing axle loads appears to be a very cost-efficient and capacity-effective alternative for North American heavy-haul railroading. In effect, removing the length constraint will allow car designers to optimize the use of the space within the clearance limits available for operations. But the shorter cars with more weight per unit length could have a negative effect on the life of some bridges. Further research is needed before any conclusions can be drawn on the relationship between axle spacing and bridge costs.

6.0 CONCLUSIONS

For track and bridges, there are four main areas where rising costs act as a constraint to axle loads:

1. Age, type, span length, and condition of bridges.
2. Rail defects (especially sections with poor quality rail).
3. Sections with poor ballast/subgrade conditions.
4. Other areas requiring extensive routine maintenance (welds, turnouts, other special track work).

Premium track components, improved maintenance procedures, and improved suspension trucks tend to reduce the effects of HAL traffic on track maintenance costs. Hence, continued technical innovation along with continued upgrading of the infrastructure (especially the strengthening and replacement of older bridges) will make HAL operations more attractive.

Improvements in the track structure that reduce the costs of HAL operations also tend to reduce the costs of the base case (263,000-lb gross vehicle weight) operations as well. As the HAL studies progressed from Phase I to Phase III, considerable improvements in track and vehicle components reduced the costs of the base case as well as the HAL options. Table 1 lists the base case costs for the Eastern and Western coal lines for the three phases. Using better components in Phase II provided a 7 to 8 percent reduction in base case costs for track, with most of the improvements coming in maintenance rather than capital costs. In Phase III, the use of improved suspension trucks provided another 8 to 10 percent improvement in track costs, with equivalent cost savings in both maintenance and capital costs.

Table 1. Comparison of Base Case Track Costs for HAL Phases I, II, and III

	West I	West II	West III	East I	East II	East III
Maintenance	100%	92.4%	75.7%	100%	82.2%	75.1%
Capital	100%	91.4%	88.6%	100%	97.2%	86.3%
Total:	100%	91.7%	85.1%	100%	93.2%	83.3%

The savings from Phase I to Phase II amounted to more than $3,800/mile/year in the west and nearly $1,600/mile/year in the east, resulting in considerable annual savings for the heavy haul networks. In 1998, the US Class I railroads operated 56,200 track miles with at least 20 MGT. It is estimated that this network is equivalent (in terms of total ton-miles of traffic) to 10,500 miles of track represented by the 80-MGT case and 46,200 miles of track represented by the 30-MGT case. If this entire network were upgraded to the level of the Phase II base case, then the annual savings from track improvements would amount to approximately $100 million.

Results from Phase II are the best to use in estimating the costs and savings from implementing HAL operations. These results consider HAL loads in cars with standard trucks. Although the savings in Phase III appear to justify the use of cars with improved suspension trucks, they have yet to be introduced in significant quantities for coal transportation. Phase II results (Table 2) show that the use of HAL operations has a much greater effect on maintenance than on capital costs, which are much more important in terms of life-cycle cost. Total track costs were predicted to rise 5 to 10 percent under 286,000-pound cars and 15 to 18 percent under 315,000-pound cars. Bridge costs, which were included as a separate category, were predicted to rise faster than track costs. While the predicted increases for bridges were extremely high, bridge costs were only 10 to 15 percent of track costs in the base case, so they did not dominate the analysis.

Table 2. Infrastructure Costs Under HAL Operations, Phase II Results

	West 263	West 286	West 315	East 263	East 286	East 315
Track:						
Maintenance	100%	111.3%	132.7%	100%	122.6%	147.5%
Capital	100%	102.6%	108.6%	100%	106.5%	110.0%
Total:	100%	105.0%	115.1%	100%	110.3%	118.8%
Bridges	100%	112.7%	156.9%	100%	114.0%	137.7%

For operations, the key source of benefits from HAL loads is the ability to operate with more net tons per train. Constraints on train length and improvements in the ratio of net-to-gross tonnage therefore tend to increase the operating benefits.

Table 3 lists the basic HAL economics. Although the infrastructure costs rise substantially, operating costs decline. Since operating costs are so much greater than infrastructure costs, total costs decline. In these examples, the operating costs actually decline more for the 286,000-pound car case than for the 315,000-pound car case, primarily because of the net-to-tare benefits of the particular 286,000-pound car that was used. In other cases, the differences were somewhat different, but in every case, the 286,000-pound car was found to be superior to the 315,000-pound car.

Table 3. Operating Costs with HAL Equipment, Phase II Results

	West 263	West 286	West 315	East 263	East 286	East 315
Track	100%	105.0%	115.1%	100%	110.3%	118.8%
Bridges	100%	112.7%	156.9%	100%	114.0%	137.7%
Operations	100%	90.4%	93.8%	100%	91.1%	95.3%
Total:	100%	92.6%	97.5%	100%	94.0%	99.6%

The track costs shown in Table 3 are steady-state life-cycle costs. The study estimated the lives of the track components and assumed that maintenance and renewal activities were being conducted at a uniform rate each year. The study did not estimate the initial investment that would be required to upgrade the track (i.e. rail, ties, ballast, and turnouts) to handle HAL loads.

For bridges, however, there were concerns that substantial initial investments might be required before HAL loads could be accommodated. The economic analysis therefore began with an estimate of the number of bridges that would have to be replaced or strengthened (immediately or sooner than would otherwise be necessary) to handle typical HAL routes. The HAL cost was estimated as the incremental cost compared to a base case where these bridges would eventually have to be replaced or strengthened to continue to handle 263,000-pound cars. This incremental bridge cost was first expressed as a net present value, then transformed into an equivalent annual cost per 1,000 net ton-miles for the HAL traffic.

By using steady-state costs, the HAL analysis provided a clear comparison of the alternatives without getting into the complexities dependent upon the initial track structure or the age and condition of the existing bridges. Individual railroads will have to consider the timing of investments required to introduce HAL loads as well as the increases in engineering budgets that will be required to cover the costs of more frequent inspection and maintenance activities.

For equipment, the key benefit is that the costs (per ton of capacity) of owning and operating larger cars are expected to decline. Flexibility in car design, particularly the length of cars, tends to reduce HAL benefits, as increased space utilization provides similar operating benefits without increasing axle loads.

Customer characteristics can also be important. Loading and unloading constraints that restrict car length will tend to promote heavier cars; where such constraints do not exist, shorter cars may provide a better overall solution. The length of the haul is also important because the operating benefits increase with the length of the trip, thereby justifying greater investment in adapting loading and unloading facilities to a superior car design. Likewise, higher annual shipment volumes help justify investments that may be required in new facilities.

Average cycle time can also be important, as equipment costs per trip depend upon the time required for the trip. If car costs go up (as will be the case for cars with improved suspensions), then these costs can best be justified for cars that travel many miles per year.

The magnitude of benefits from HAL operations depends upon the extent to which HAL loads have been implemented and the extent to which the predicted effects have taken place. The evidence suggests that the railroads have in fact followed the recommendations of the HAL Economic studies:

1. The industry adopted the 286,000-pound car as the HAL standard, as was recommended in Phases I, II, and III. When room was available in existing equipment, railroads increased loading limits very soon after the Phase I study. Railroads then upgraded their fleets through attrition, replacing older cars with 286,000-pound cars.
2. The extensive studies of possible HAL effects on track were critical in identifying and avoiding potential problems associated with weak elements in the track structure.
3. The actual effects have generally been consistent with the assumptions of the HAL economic analysis (i.e. no significant problems in implementation have yet been identified).

The annual operating benefits are very substantial. The annual net benefit from HAL operations (286,000-pound cars) is approximately $23,000 per mile for the 80-MGT line and just under $10,000 per mile for the 30 MGT line. These benefits are in addition to the benefits from improved track components described above. For the same assumptions — 10,500 miles similar to the 80-MGT case and 46,200 miles similar to the

30-MGT case — the annual savings would be over $500 million per year if all of the traffic were moved in 286,000-pound cars.

In fact, the transition to 286,000-pound cars is still under way, with a quarter to a half of the traffic on high-density lines moving in HAL cars. Using aggregate data for coal tonnage and car-loadings, we find that the average carload of coal has increased from 96.3 tons in 1987 to 106.6 tons in 1998. This increase includes the effects of the shift to lighter aluminum cars as well as the increase in axle loads.

To isolate the axle load effects, we used data from three wayside load stations to estimate the percentage of loaded cars with HAL loads. At a typical detector on a coal line in the west, 38 percent of the cars were HAL loads; this figure is the percentage of cars for which the wheel loads indicated a gross vehicle weight of more than 278,000 pounds. Since the HAL loads carry more traffic, the percentage of tonnage was somewhat higher, namely 42 percent. At two typical detectors in the east, an average of 11 percent of the cars and 13 percent of tons were estimated to be HAL loads. However, there is some of each type of track in the east and in the west. Therefore, the average rate of implementation was 38.7 percent in the west (9,500 miles of track modeled as the 80 MGT line and 24,200 miles as the 30 MGT line) and 27.1 percent in the east (with 1,000 miles modeled as the 80 MGT line and 22,000 miles as the 30 MGT line).

For this level of implementation, the annual benefits are estimated to be in the range of $250 to 500 million. If we look at the cumulative savings over the 1990s, assuming a steady rate of implementation, then the total savings to date from HAL operations is on the order of $1 to 2 billion.

7.0 RECOMMENDATIONS FOR FURTHER RESEARCH

1. **Best practices and components**: continued use of the FAST environment to test new materials and techniques for strengthening the track structure. These include improved welds, rail, new tie materials, and soft subgrade remediation techniques.

2. **Bridges:** since bridges and structures have been identified as the cost element most sensitive to axle loads, continued research concerning the need for inspecting, repairing, strengthening, rehabilitating, and replacing bridges is essential. The combined effects of increased loads per linear foot and increased axle loads need to be investigated more fully.

3. **Crossing Diamonds**: several typical revenue service crossing diamonds were tested in the HTL during Phase II of 39-kip operations. While these diamonds were adequate performers in revenue service, with lives of 100 to 300 MGT, they survived only 2 to 15 MGT under HAL traffic. Most of the difference in performance can be attributed to the wheel load increase. With no crossing diamond test experience at FAST under 33-kip wheel load traffic, it is difficult to determine the relative effects of the operational differences on diamond life. The premium material diamonds had service lives of 15 to 30 MGT; still far short of revenue service lives under 33-kip wheel loads. Therefore, the crossing diamond maintenance is still a potential economic impediment to HAL implementation.

4. **Equipment design**: work to date has shown that it is possible to design both gondolas and hopper cars that make much more effective utilization of the cross-sectional area allowed by standard railroad clearances. These designs appear to allow capacity and operating cost benefits similar to what can be obtained through heavier axle loads, but without the attendant increase in track costs. In order to understand the effects of shorter cars with higher loading density on bridges and structures, further studies are required.

5. **Branch lines/distribution systems**: work to date has focused on coal and has specifically recommended caution in using HAL cars on low-density lines with poor track. Nevertheless, regional railroads and state governments have expressed interest in making substantial investments to bring some light density lines up to 286,000-pound standards. Research would be useful for determining a range of recommended strategies for handling 236,000-lb cars on the wide range of conditions that exist on low-density track. Economic analysis is needed to determine the tradeoffs in upgrading the track, improving equipment, and maintaining the current operation.

6. **Customer capabilities and requirements**: customers are the ones who ultimately determine which types of equipment and operations are successful. Involving the customer in the design of the next generation cars will enable consideration of the broader context of transportation and logistics and could produce innovative changes in equipment.

APPENDIX A
GRINDING AND FATIGUE

Kevin Sawley

1.0 INTRODUCTION

Five rail grinding and defect experiments have been carried out on the FAST High Tonnage Loop (HTL) within the last 20 years. In order of first to last, these have been traditionally referred to as the:

1. Defect Origination and Growth (DOG) Test
2. Pilot Test
3. Third Grinding Trial
4. Premium Rail Grinding Trial
5. Continuously Cast Standard Rail Grinding Test

The sections below give brief summaries of these tests and the results obtained.

2.0 DEFECT ORIGINATION AND GROWTH (DOG) TEST

2.1 Test Conditions

The test was conducted in Sections 3 (5° curve) and 25 (6° curve) of the FAST High Tonnage Loop with the train running counterclockwise. The test ran for 154 MGT; wheel loads were 33 kips. The high rail was fully lubricated, although lubricators were shut down at 3-5 MGT intervals, for about ½ MGT, to clean the rails for flaw inspection. There were four test segments in all, one in Section 3 and three (Segments A, B and C) in Section 25. Segments A and C of Section 25 and the segment in Section 3 were not ground, and the rail profiles became conformal with the FAST train wheels. The center Segment B of Section 25 had the high rail ground to give a two-point contact profile, which was restored periodically at about 20 MGT intervals. All four segments contained rails of at least nine different hardnesses (from 284 to 394 Bhn) and levels of metallurgical cleanness. Lubricators were located at the entrances to Sections 3 and 25.

2.2 Summary Of Results in Test Curves

The results can be summarized as:

1. Most shells (158) were found in rails less than 300 Brinell hardness in Segment B of Section 25 (two-point contact zone). Of these 158 shells, most turned to give detail fractures.

2. In comparison, Segment A, which was closest to the lubricator, yielded 44 shells, while Segment C gave only 20 shells.

3. Section 3 was much less prone to shell formation than was Section 25.
4. In all test segments the 285 Bhn rail, which was an ingot cast rail, produced the greatest number of shells.
5. In rails ground to the two-point contact profile, the shells formed were shallow and biplanar. They grew typically only 0.5" before turning to detail fractures.
6. Those that formed in the nonground test segments tended to develop much deeper within the rail and were monoplane in nature.

Shell occurrence for all rails is shown in Table A.1

The surprisingly high shell defect rate and the high gage face wear in the segment ground to give a two-point contact profile prompted a second experiment described as the Pilot test.

2.3 Tabulated Data

Table A.1: Shells from the DOG test (33 kip wheel load)

		Number of shells in 90 MGT			
Rail	**Hardness Bhn**	**Section 25 (6° curve)**			**Section 3 (5° curve)**
		Segment A (not ground)	**Segment B** (2-point ground)	**Segment C** (not ground)	**Not Ground**
A	284	1	4	0	11
B	285	43	143	9	19
C	290	0	0	0	0
D	296	0	11	11	0
E	302	0	0	0	0
F	309	0	0	0	0
G	321	10	2	0	0
H	324	0	0	0	0
I	343	0	0	0	0
J	371	-	0	-	0
K	390	0	-	-	-
L	394	-	-	-	4

Segments A and C high rails were not ground.
Segment B high rail was ground to give two-point contact.
Section 3 rail was as-manufactured

3.0 THE PILOT TEST

3.1 Test Conditions

Four different high rail profile configurations were used in four segments, each containing two 80-foot long lengths of ingot cast 133 RE rail of 300 Bhn nominal hardness. The performance of the rails was assessed under 39 kip wheel loads. The four segments contained rail in the following condition:

1. Worn dry in the 5-degree curve of FAST Section 7 for 10 MGT under 33 kip wheel loads and for 15 MGT under 39 kip wheel loads. It was intended to grind the rail subsequently to the FAST as-worn profile at 25 MGT intervals.
2. Ground conformally to the FAST as-worn wheel profile, and subsequently ground to the same profile at 25 MGT intervals.
3. Ground to a two-point contact profile to relieve the gage corner, and subsequently ground to the same profile at 25 MGT intervals.
4. As manufactured with no subsequent grinding.

Although it was intended to grind the first two segments conformally to the FAST as-worn wheel profile, this was not done initially. Instead, the profile intended for the third segment (two-point contact) was ground. After 50 MGT the situation was corrected. In all segments the low rail was ground to position the wheel footprint slightly to the field side of the center of the rail top.

3.2 Summary of Results on 5- and 6-Degree Curves

1. The two-point contact profile segment again gave the greatest number of shells.
2. The segment ground to be conformal had the second largest number of shells.
3. The rails that had been dry worn to conformality (Segment 1) and then ground gave no shells at all, while the nonground rail yielded only two shells.

It was thought there might be metallurgical cleanness differences among the rails, which could have affected the results. One half of the rail in Segments 2, 3 and 4 was from the top of hot topped ingots, which would be expected to have a higher inclusion content. In contrast, the first segment contained only rail from toward the center of the ingot, which should have been cleaner. However, metallographic examination of specimens taken from each rail suggested that the rail in the two-point contact segment, which contained the greatest number of shells, was perhaps the cleanest rail in the test. Results of the metallographic tests are shown in Table A.2.

The small size of the Pilot Test led to a larger scale and longer duration test described in Section 4.

3.3 Tabulated Data

Table A.2: Rail and defect information from the Pilot test (39 kip wheel load)

		Profile type							
		Dry worn and ground conformal		Ground conformal		Two-point contact		Unground	
Rail ingot ident.		C28	C30	C32	B32	C33	B13	C17	B14
Rail defects		0	0	3	6	0	13	0	2
ASTM E45 rating	**Sulfide**	2.5	2.5	3	3	3	2	3	3
	Oxide	1	1	1	1	4	<1	1	2

4.0 THIRD GRINDING PROFILE TEST

The objective of the experiment was to examine the effect of different rail grinding strategies on the rolling contact fatigue and wear behavior of three different standard carbon rail steels. The experiment was undertaken in Sections 3 and 25 at FAST. Testing began in December 1990 and finished in June 1993, when the rails had accumulated 178 MGT of traffic with a wheel load of 39,000 pounds.

4.1 Test Conditions

The experiments were conducted in the 6-degree curve of Section 25 and the 5-degree curve of Section 3. The focus was on the high rails, with the low rails a passive part of the experiment. The test train initially had 5 locomotives, with about 65 gondolas and 15 covered hopper cars, all with 39 kip wheel loads. It ran at 40 mph with an overbalance of about 1.7 inches. The train was reversed every two days of operation. The experiment was conducted with the outer rail in a well-lubricated condition. Grease was supplied from two wayside lubricators located at either end of Section 25. The inside rail top was lightly lubricated with oil supplied from an onboard lubricator. The track was maintained to FRA Class 4 track standards.

Rail flaw inspections were conducted at 5 MGT intervals, and lubricators were turned off for 30-train laps to "dry down" the track for inspection. Shells were discovered by visual inspection but often left in track and monitored for growth until they chipped or shelled out.

Three different manufacturers — CF&I (now known as Rocky Mountain Steel Mills) Bethlehem Steel (now known as Pennsylvania Steel Technologies) and Rodange (ROD) — produced the rail steels. Rails from CF&I and Bethlehem were rolled to a 136-pound, 10-inch crown radius rail section. Rodange rails were rolled to a 132 RE Section. CF&I rails were produced from ingots; whereas, the other two manufacturers used continuously cast billets. The CF&I rails were further differentiated by their position in the ingot. The CF&I "B" rails were closer to the top of the ingot than the "C" rails and would be expected to have higher inclusion content. Rail hardness was measured on transverse sections of rail removed from track at the end of the experiment.

Five grinding strategies were examined:

1. **CONT: Control zones:** It was intended to leave rails unground throughout the experiment.
2. **FAST-2: Conformal zone, ground 2 millimeter per 100 MGT:** The intention was to grind rails to a shape conformal to typical FAST train wheels. The aimed-for rate of metal removal by grinding was 2 millimeter per 100 MGT, at 25 MGT intervals.
3. **FAST-4: Conformal zone, ground 4 millimeter per 100 MGT:** The FAST-4 grinding was to be the same as FAST-2, but with a removal rate of 4 millimeter per 100 MGT.
4. **2-PT-12.5: Two-point contact zone, ground every 12.5 MGT:** Rails were to be ground to give gage corner relief, and hence distinct two-point contact between wheel and rail (that is, contact on the gage face and rail top). Grinding was to be every 12.5 MGT on average.
5. **2-PT-25: Two-point contact zone, ground every 25 MGT:** This grinding was to be the same as 2-PT-12.5, but with grinding every 25 MGT.

The head-hardened low rails of Section 3 were ground when the high rails were ground. Initially they were ground to give an 8-inch crown radius that created a contact path towards the gage side of the top of rail. After shelling occurred, the profile was changed to a 10-inch crown radius that placed the contact in the center of the railhead.

In the FAST-2 and FAST-4 grinding zones the grinding rates were, in general, held to the original plan. The Rodange rails (132-pound section) were ground to the FAST worn profile using grinding stones set for 136-pound rail. This concentrated wheel contact on the gage corner (noticed by visual observation and profile measurement), which most probably led to the high incidence of early gage corner shelling in these rails.

The 38-inch test train wheels began the experiment with worn profiles generated in a previous test. After a derailment at 13.3 MGT (on a track used for turning the train) 16 Union Pacific gondolas with worn revenue service profiles were added to the train. These wheels were not measured upon arrival, but profiles collected subsequently from Union Pacific showed that the wheels were very similar to FAST-worn wheels in the flange throat. Revenue service worn wheels were not the only non-FAST wheels used during the test. Wheels were trued to an AAR-1B wheel template, condemned wheels were replaced with new AAR-1B wheels, and 16 new AAR-1B wheels were installed at 3.3 MGT for a wheel wear test. The AAR-1B wheel profile took approximately 5,000 miles and 18 MGT to wear to a FAST-worn profile.

4.2 Summary of Results

The main conclusions drawn are:

1. Section 25 had many more shells and detail fractures than Section 3. It appears unlikely that this difference can be solely due to curvature. The difference may be due to the presence of lubricators at each end of Section 25, since lubricants have been shown to adversely affect crack propagation. Section 25 also had wood ties, while Section 3 had concrete.

2. The Bethlehem steel, which had much fewer oxide inclusions than the CF&I steel, gave no shells or detail fractures during the 178-MGT test. Although the Bethlehem steel was in Section 3, which gave fewer defects, the implication is that clean standard steel is able to resist the formation of shells and detail fractures — even under 39 kip axle loads. It is possible that the Bethlehem rails would have eventually formed damage at higher tonnage if the test had been continued past 178 MGT.

3. In Section 25, the CF&I: B rails gave more shells and detail fractures than the CF&I: C rails, under all grinding regimes. Rails from the B position in an ingot are expected to be less clean than those from the C position.

4. Grinding to give two-point contact significantly reduced the number of shells formed. The FAST-2 and FAST-4 grinding regimes appeared to have little effect on shell formation.

5. Although two-point contact grinding was effective in suppressing shell formation, it had less effect on detail fractures. This is seen most clearly in the data for Section 25, where all four grinding regimes (including no grinding), give a normalized detail fracture rate of about 1.10^{-4} per rail-foot. MGT (RFM).

(No detail fractures were found in the two-point contact segments of Section 3, but only two were recorded in the control no-grinding segment.)

6. In summary, the control, FAST-2 and FAST-4 segments gave most shells, but few turned into detail fractures. Two-point contact grinding gave least shells, but most (6 out of 9 in total, and 6 out of 6 in Section 25) turned into detail fractures.

7. A Weibull analysis of the detail fractures in terms of tonnage to crack detection indicated that all the data (from all test zones) could be described by a single population. That is, grinding appeared to have a negligible effect on time to detail fracture detection. An incubation period of 70 MGT was indicated.

Finally, detail fracture crack growth measurements indicated that the cracks grew at an exponential rate described by:

$$\mathrm{Log}_n\text{ (crack area, \%)} = a^*\mathrm{MGT} + b$$

There was some evidence that at large values of crack area (above 10 percent but varying from defect-to-defect), the area increased linearly with tonnage. Analysis of the fracture faces in the test curves also showed that the detail fractures in the two-point grinding zone were consistently larger (at ultrasonically detection) than the fractures in the other segments.

4.3 Tabulated Data for the Third Grinding Profile Test

Table A.3: Rail Steel Chemistries

Rail	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V
CF&I	0.77	0.88	0.009	0.013	0.24	0.25	0.07	0.22	0.014	0.003
BETH	0.78	1.00	0.022	0.013	0.17	0.21	0.07	0.20	0.014	0.004
ROD	0.78	0.81	0.014	0.024	0.19	0.03	0.03	0.03	0.003	0.003

Table A.4: Rail Steel Hardness (Average Values taken from the Field Corner and the Center of the Head)

	CF&I	BETH	ROD
Average	275	284	301
Std. Dev.	8.5	11.4	2.5

Table A.5: Shells and Detail Fractures in Test Section 3

Grinding Zones	Shells	Detail Fractures	Rail-Feet.MGT (RFM)	Shells per RFM ($x10^{-4}$)	Detail fractures per RFM ($x10^{-4}$)
CONT					
CF&I:B	2	1	13,952	1.43	0.72
CF&I:C	7	1	28,330	2.47	0.35
ROD	12	0	3,350	35.80	0
BETH	0	0	13,900	0	0
FAST-2					
CF&I:B	16	1	12,955	12.35	0.77
CF&I:C	13	3	26,759	4.86	1.12
ROD	9	0	5,646	15.94	0
BETH	0	0	13,398	0	0
2-PT-12.5					
CF&I:B	0	0	14,256	0	0
CF&I:C	0	0	28,512	0	0
ROD	0	0	13,900	0	0
BETH	0	0	13,900	0	0
2-PT-25					
CF&I:B	3	0	13,186	2.28	0
CF&I:C	0	0	28,512	0	0
ROD	0	0	13,900	0	0
BETH	0	0	13,900	0	0
Totals	**62** shells, of which **6** turned into detail fractures				

Table A.6: Shells and Detail Fractures in Test Section 25.

Grinding Zones	Shells	Detail Fractures	Rail-Feet.MGT (RFM)	Shells per RFM ($x10^{-4}$)	Detail fractures per RFM ($x10^{-4}$)
CONT					
CF&I:B	26	5	27,387	9.49	1.83
CF&I:C	7	1	27,550	2.54	0.36
ROD	10	0	5,827	17.16	0
FAST-4					
CF&I:B	16	4	25,712	6.22	1.55
CF&I:C	7	2	27,510	2.54	0.74
ROD	29	1	4,718	61.47	2.12
FAST-2					
CF&I:B	20	0	25,957	7.71	0
CF&I:C	10	5	26,455	3.78	1.89
ROD	19	0	6,261	30.35	0
2-PT-25					
CF&I:B	5	5	26,722	1.87	1.87
CF&I:C	1	1	28,512	0.35	0.35
ROD	0	0	13,048	0	0
Totals	**150** shells, of which **24** turned into detail fractures				

Table A.7: Summary of Shell and Detail Fracture Rates for CF&I Rail

	Shells per RFM ($x10^{-4}$)	Detail fractures per RFM ($x 10^{-4}$)
Section 25		
CONT	6.00	1.09
FAST-4	4.32	1.12
FAST-2	5.72	0.95
2-PT-25	1.08	1.08
Section 3		
CONT	2.12	0.47
FAST-2	7.30	1.00
2-PT-25	0.72	0
2-PT-12.5	0	0
Combined Sections		
CONT	4.30	0.82
FAST-2	6.40	0.97
2-PT-25	0.93	0.62

5.0 PREMIUM RAIL GRINDING TRIAL

5.1 Test Conditions

Rails were installed in two curved test sections in the High Tonnage Loop (HTL) at FAST. Section 3 is a 5-degree curve and contains wood and concrete ties; Section 25 is a 6-degree curve with wood ties. Premium head-hardened rail (NKK 133-lb RE section) was installed in November 1993 and currently has accumulated 625 MGT of heavy axle load traffic. In the first 100 MGT, the cars were equipped with standard three-piece trucks. For the next 425 MGT, the cars had improved suspension trucks, which have more warp restraint and primary suspension pads that allow the axles to steer better than conventional three-piece trucks. The train was then re-equipped with standard three-piece trucks. Annual tonnage has been about 125 MGT, applied mostly by the HAL train, which consists of 65 to 75 cars, (currently coal gondolas and tank cars) each with a gross vehicle weight of 315,000 pounds. Train speed is 40 mph, which results in a cant deficiency of about 1.7 inches in both curves. Traffic is split nearly equally in each direction. High-rail lubricators are at both ends of the 6-degree curve. The top of the low rail is lightly lubricated with oil at the same locations.

The 5-degree curve is split into five separate test sections; two are ground and three are non-ground. The 6-degree curve is separated into three grinding regimes. The test zones are arranged as follows:

5-degree curve

Zone	Description
Control zones	There are two control zones, one at each end of the curve. Each zone is 480 feet long. The rail in these zones is not ground.
Dry-wear zone	There is one dry-wear zone, 880 feet long. The high rail in this section was originally installed for 15 MGT in a 5-degree curve with very light lubrication on the high rail. Thus, the rail was already worn when it was installed in the lubricated high rail of the test curve. The high rail in this zone has not been ground since installation. The low rail was ground to a 5-inch crown radius when installed in the test curve and has not been ground since.
Grind zones	There are two grind zones near the center of the curve, each 880 feet long. One zone is on concrete ties with elastic fasteners, and the other is on wood ties with cut-spikes. Both zones are ground every 50 MGT, with a nominal 0.025 inch (0.63 mm) ground from the high-rail gage corner. Actual grinding is close to this amount, but may vary. The rail is generally worn to a conformal shape by the time it is ground. The low rail was initially ground to a 5-inch crown radius. Normal grinding is intended to maintain this crown radius, but this is difficult with the grinder used.

6-degree curve

Zone	Description
Aggressive grind	800 feet long. High rail is ground every 12.5 MGT to produce a nominal gage corner relief of 0.010 inch. The low rail is ground to an 8-inch crown radius.
Moderate grind	800 feet long. High rail is ground every 25 MGT to produce a nominal gage corner relief of 0.025 inch. The low rail is ground to an 8-inch crown radius.
Passive grind	800 feet long. High rail is ground every 75 MGT to produce a nominal gage corner relief of 0.040 inch. The low rail is ground to an 8-inch crown radius.

5.2 Summary of Results

1. No internal defects have been detected in any of the rails, ground or non-ground, in any of the test zones in either curve. In this respect, continuous-cast premium rail — whether ground or not — appears highly resistant to internal head defects.

2. Non-ground rails have less metal loss than ground rails. Assuming a combined gage/head wear limit of 7/8 inch, predictions for the lives of the various rails are: ground rail in 6-degree curve: 1,000 MGT; ground rail in 5-degree curve: 1,700 MGT; non-ground rail in both curves: over 5,000 MGT. These figures assume rail failure by wear only and reflect the improved steering performance of improved suspension trucks.

3. Surface conditions of the ground and non-ground rail are comparable, with the exception of high rail gage corner checking on some of the non-ground rails. The non-ground rails have performed at least as well as the ground rails.

4. The only gage corner spalls/shells that developed were on the high rails in the 6-degree passively ground zone.

5. After about 50 MGT, spalls developed towards the gage side of the low-rail top in the wood tie ground zone of the 6-degree curve. Track gage in the section was wide, ranging from 57 inches to 57.5 inches. Though the wheels on the FAST train are not typically hollow, it was found that the rims of the wheels were riding on the top of the low rail (and directly over the spalls). After re-gaging, and without corrective grinding, the spalling mostly wore away.

6. There was no significant difference in performance between the dry-worn and control rails in the 5-degree curve. That is, a period of dry wear prior to normal curve lubrication has had no effect on rail performance.

5.3 Tabulated Data

Since no internal defects were found at any of the test sites, there is no tabulated data on shell or detail fracture formation. Wear was calculated for the sites, and is given in Table A.7.

Table A.7: Total Metal Lost from the High and Low rails in All Test Zones over 515 MGT

Section-Zone	Total metal loss (thousandths of an inch)		
	High rail		Low rail
	Gage face	Head height	Head height
25-Aggressive grind	302	155	153
25-Moderate grind	312	145	132
25-Passive grind	263	105	108
03-Control 1	18	18	37
03-Wood – ground	173	74	106
03-Concrete – ground	176	86	90
03-Dry Wear – nonground	65	31	55
03-Control 2	31	23	43

6.0 CONTINUOUSLY CAST RAIL GRINDING TEST

6.1 Test Conditions

New standard chemistry (nominal) 310 Bhn rail was installed in the 6-degree curve of the HTL in 1999. The curve was divided into three test sections, one 720 feet long and two 680 feet long. One section serves as a control and will not be ground. The other two sections are being ground to profiles recommended by grinding representatives from the rail industry. The gage corner of the high rail is lightly relieved, with approximately 0.010 inch of metal removed each grinding. The top of the high rail is ground lightly. The rail quickly wears to a conformal profile. The low rail is ground to an 8-inch crown radius. The grinding interval is 17.5 MGT (preventive grind zone) and as needed based on rail condition (corrective grind zone).

6.2 Summary of Results after 135 MGT (the test is ongoing)

- Surface conditions generally good on ground and non-ground rail
    - Slightly better on ground rail
- Minor gage corner checking on high rail, non-ground zones
- Low rail in non-ground zones very flat

  - More metal loss in ground than non-ground rail

- Metal flow and minor flaking, field side low rail, non-ground zone
- Very light corrugations, non-ground low rail near field weld
- Four TDs in non-ground rail (gage corner)
  - 43% (of railhead area), removed; 10%, removed due to nearby weld failure; 7% and 8%, still in track.
- The corrective grind zone was ground at 135 MGT because of the occurrence of transverse defects

6.3 Tabulated Data

Table A.8 shows total metal loss for the zones at 117 MGT. Since the corrective zone had not been ground at that time, its measurements are included in "non-ground rail".

Table A.8: Total Area Loss at 117 MGT

Test zone	Total metal loss (square in.)	
	High Rail	Low Rail
Preventive grind zone	0.22	0.13
Non-ground rail	.020	0.14

APPENDIX B
RAIL WEAR ON CURVES

Rafael Jimenez and Kevin Sawley

1.0 BACKGROUND

Rail wear tests have been conducted on curves the High Tonnage Loop (HTL) since its construction in 1985. The first HTL experiment to investigate rail wear and fatigue was the Defect Occurrence and Growth Test (DOG). The primary objective at that time was to evaluate the wear and fatigue performance differences between various rail metallurgies under 33-ton axle load traffic.

1.1 PHASE I

The objective of the rail portion of Phase I testing was to study the effects of 39-ton axle load traffic on rail performance and to make a comparison with the performance documented during 33-ton axle load operations. Phase 1 testing accumulated 160 MGT on the test rails.

1.2 PHASE II

HAL operations during Phase II were conducted using a train equipped with standard three-piece trucks. Operations during Phase III, on the other hand, involved the use of improved suspension trucks on the HAL train. The last 100 MGT of Phase II and the first 100 MGT of Phase III were designed to provide a back to back test, using the same rail types. This provided a direct comparison of the effects of standard trucks on rail performance to that of rail performance under the improved trucks. The improved-suspension trucks provide the benefit of improved curving response with enhanced wheel-set steering and resistance to truck warp.

1.3 PHASE III

The second rail installation of Phase III included new rail metallurgies such as hypereutectoid and bainitic rails. Most of rails were subjected to about 165 MGT of HAL traffic under improved suspension trucks with the high rail lightly lubricated. The J6 bainitic rail was installed about 65 MGT after the other rail.

1.4 PHASES IV AND V

During Phase IV, the rails of the second Phase III installation remained in track. The objective of Phase IV was to leave all other variables the same except lubrication. Phase IV operations were conducted on dry rail conditions. Phase V testing, currently in progress, will study the effects of running a standard three-piece truck, heavy axle load train on the new rail metallurgies still in track. Lubrication will be as it was in Phases I to III.

Table 1 summarizes the Rail Wear Test during the five phases of the Heavy Axle Load (HAL) Program.

Table B1. Summary of the Heavy Axle Load Program Rail Wear Test

Phase	Date	Tonnage (MGT)	Objective	Operating Conditions Section 7
I	Jul 1988	160	Rail wear under 39-ton vs. 33-ton axle load	**Standard trucks** Slight lube-contaminated high rail Light indirect lube low rail
II	Dec 1990	300	Rail wear of premium vs. standard rail	**Standard trucks** Slight lube-contaminated high rail Light indirect lube low rail
III	Nov 1995	424	Rail wear under improved suspension trucks vs. standard 3-piece trucks	**Improved trucks** Slight lube-contaminated high rail Light indirect lube low rail
IV	Jan 1999	56	Rail wear during dry rail operation	**Improved trucks** Dry rail
V	Sep 1999	In progress	Premium rail wear under standard trucks	**Standard trucks** Slight lube-contaminated high rail Light indirect lube low rail

2.0 METHODOLOGY

The rail wear test zone is located in Section 7 of the HTL. Section 7 is a 1,000-foot, 5-degree, 4-inch superelevation curve that is typically slightly contaminated on the high rail with lubrication and receives light indirect lubrication on the low rail. Except during Phase I, when the rail was ground due to rail corrugations, the Rail Wear Test rails are not ground and have conformal profiles.

During the 33-ton axle load test and the 39-ton axle load test of HAL Phase I, the train operated primarily in a counterclockwise direction around the HTL. The train consist itself, however, was turned every 3 MGT. After Phase I, all train operations on the HTL became bi-directional. The HAL train typically operates with 70 to 80 315,000-pound gondola and tank cars at a constant speed of about 40 mph. The 1.6-inch cant deficiency is equivalent to 6 mph overbalance speed.

Rail wear measurements are taken at 10 to 20 MGT intervals during the first 60 MGT of testing to capture the initial break-in wear and metal flow characteristics. Subsequent measurements are taken at about 50 MGT intervals. Measurements include gage wear, head height wear, cross-sectional rail profile, top of rail hardness, and longitudinal rail profile measurements during the phases when rail corrugation occurred. Snap-gage wear measurement instruments used at Transportation Technology Center (TTC), Pueblo, Colorado, were designed and fabricated there. Transverse rail profiles were taken with a Yoshida Rail Profilometer during the early phases of testing. During the latter phases, a MiniProf™ profilometer has been used.

A typical rail-type test zone consists of 160 track feet — two 80-foot rails on the high side of the curve and two on the low side.

The snap gages work by referencing the top and field side of the railhead as the measurement is taken 5/8 inch down from the running surface. The head-height measurement instrument takes a direct measurement at the center of the railhead while referencing the base and web of the rail.

The MiniProf™ traces the actual railhead profile and stores the data on a computer disk. The profiles are then overlaid to determine head height loss, gage wear at 3/8 inch and at 5/8 inch down from the running surface, and area loss; that is, total metal loss.

Brinell hardness numbers (Bhn) are taken on the running surface of the rail with hardness testers. The testers are portable and provide a 3,000 kilogram (kg) load on a 10-millimeter ball. Bhn is used to study the relationship between surface hardening and rail wear and fatigue performance.

The Longitudinal Rail Profilometer (LRP) is used to record a 1-meter-longitudinal tracing of a rail's running surface onto a 10-inch strip chart to study corrugation wavelengths and depths and rail-end batter.

3.0 RESULTS

3.1 Phase I

The objective of the rail wear portion of this experiment was to investigate the effect of 39-ton axle loads on rail wear on curves, especially as compared to the effects of 33-ton axle loads.

This test accumulated over 160 MGT of 33-ton axle load traffic from June 1985 until March 1988. When operations started in 1985, only the outside rail of the HTL was lubricated using a wayside lubricator in Section 24. The difference in top of rail friction between the highly lubricated outside rail and the dry inside rail contributed to high lateral forces. This combined with weak track caused fastener weakening and eventual rail rollover in Section 25. To reduce the differential friction, a light oil was applied to the top of the inside rail. The standard operating procedure was changed such that lubrication is applied to the gage face of the high (outside) rail and a light oil is applied to the top of the low (inside) rail. The change in lubrication preceded the wear test.

Table B2 compares the gage face wear rate of the seven rail types that were in-test during the 33-ton and Phase I 39-ton axle load tests. Note that cars and trucks were changed at the start of HAL operations.

Table B2. Gage Face Wear Rates in Section 7

Rail Metallurgy	Brinell Hardness (Bhn)	33-Ton Axle Load in./1000 MGT	39-Ton Axle Load in./1000 MGT
Alloy HH (Off-Line)	360	1.371	2.323
CrMo	316	2.812	N/A
HH (Off-Line)	369	1.914	2.513
HH 1 (In-Line)	362	1.768	2.323
HH 2 (In-Line)	367	1.476	2.143
Standard	291	2.604	3.243
Alloy HH (In-Line)	380	1.067	2.081

Three main groups of rail types were included in the test: (1) the standard and the CrMo rails – controlled cooled rail (CC), (2) the in-line and off-line head hardened rail (HH), and (3) the in-line and off-line head hardened alloy rail (HH Alloy).

One of the secondary objectives of this experiment was to compare the wear performance of different metallurgies. This can be accomplished by examining the gage face wear figure of merits. A figure of merit (FM) is calculated by dividing the control rail wear rate by other rail wear rates. For example, during the 33-ton axle load test, the gage FM for the alloy Bhn 380 is calculated by dividing the standard 291 Bhn rate of 2.604 in./1,000 MGT by the alloy wear rate of 1.067 in./1 ,000 MGT. The resulting FM of 2.4 means that the alloy rail performed 140 percent better, or would last over twice as long as standard rail under the 33-ton axle load condition. Table B3 lists the gage face wear figure of merits for the seven rail types tested.

Table B3. Gage Face Wear Figure of Merits in Section 7, Control Rail Wear Rate / Wear Rate

Rail Metallurgy	Brinell Hardness (Bhn)	FM 33-Ton Axle Load Test	FM 39-Ton Axle Load Test
Alloy HH (Off-Line)	360	1.9	1.4
CrMo	316	0.9	N/A
HH (Off-Line)	369	1.3	1.3
HH 1 (In-Line)	362	1.5	1.4
HH 2 (In-Line)	367	1.8	1.5
Standard	291	1.0	1.0
Alloy HH (In-Line)	380	2.4	1.6

Review of the FMs is appropriate for relative rail performance, but it does not display the actual effect of increasing axle loads on individual rails. Table B4 lists the Penalty Factors (PF) encountered from increasing axle loads from 33 tons to 39 tons. PFs are calculated by dividing the 39-ton axle load wear rate by the 33-ton axle load wear rate.

Table B4. Gage Wear Penalty Factors for Increasing Axle Loads in Section 7, 39-ton Axle Load Wear Rate / 33-Ton Axle Load Wear Rate

Rail Metallurgy	Brinell Hardness (Bhn)	Penalty Factor
Alloy HH (Off-Line)	360	1.694
CrMo	316	N/A
HH (Off-Line)	369	1.295
HH 1 (In-Line)	362	1.301
HH 2 (In-Line)	367	1.452
Standard	291	1.245
Alloy HH (In-Line)	380	1.950

The gage face wear data gives an incomplete picture of the wear that took place in Section 7. A comparison of high- and low-railhead height loss PFs for increasing axle loads provides a clearer picture. Table B5 lists the head height loss rates that were used for the comparison.

Table B5. Head Height Loss Wear Rates in Section 7

Rail Metallurgy	Brinell Hardness (Bhn)	33-Ton Axle Load In/1000 MGT		39-Ton Axle Load In/1000 MGT	
		High Rail	Low Rail	High Rail	Low Rail
Alloy HH (Off-Line)	360	0.242	0.0850	0.440	0.0780
CrMo	316	0.741	0.282	N/A	N/A
HH (Off-Line)	369	0.236	0.201	0.506	0.221
HH 1 (In-Line)	362	0.293	0.165	0.516	0.167
HH 2 (In-Line)	367	0.273	0.172	0.517	0.234
Standard	291	1.039	0.472	1.462	0.436
Alloy HH (In-Line)	380	0.251	0.192	0.463	0.143

Table B6 shows a comparison of the head height loss PF ratios of 39-ton axle load wear rate to 33-ton axle load wear rate. The high railhead height loss increased in all cases.

Table B6. Head Height Loss Penalty Factors for increasing Axle loads,

39-Ton Axle Load Wear Rate / 33-Ton Axle Load Wear Rate

Rail Metallurgy	Brinell Hardness (Bhn)	Penalty Factor High Rail	Penalty Factor Low Rail
Alloy HH (Off-Line)	360	1.8	0.9
CrMo	316	N/A	N/A
HH (Off-Line)	369	1.9	1.1
HH 1 (In-Line)	362	1.8	1.0
HH 2 (In-Line)	367	1.9	1.4
Standard	291	1.4	0.9
Alloy HH (In-Line)	380	1.8	0.7

During operation of the 33-ton axle load test, corrugations were observed to have begun at a joint or a battered weld in standard rail and then carry through the remainder of the rail as tonnage was accumulated. The longer the rail was in track, the deeper the corrugations became until the rail had to be ground (the grinding effectively ended the wear test on these rail). Corrugations were also noticed in HH rails, but they were light and did not worsen with tonnage. A LRP measurement was taken on standard rail after 71 MGT of 33-ton axle load. The test site chosen had the deepest corrugations. Assuming the corrugations began to develop immediately with train operations, and a corrugation depth of .09 inch after 71 MGT, the growth rate is .0013 in./MGT.

Under 39-ton axle loads, corrugations in rail with the same hardness of the previously discussed rail and in nearly the same location were first noticed at rail joints after 5 MGT, and within the rail itself at 10 MGT. The rate of corrugation growth increased from 0.0013 in./MGT during the 0 MGT to 31 MGT period of operations to 0.0017 in./MGT during the 31 MGT to 49 MGT period, and averaged 0.0014 in./MGT. This indicates that the growth rate increases as the corrugation depth increases.

It was found that the length of corrugations can change. The 13-inch-long corrugation measured at 31 MGT grew to 14 inches by 49 MGT.

To determine the rail load environment in the corrugated sections, vertical load data was collected from corrugation peaks and valleys in Section 7. Strain gages were applied to the rail at two peaks and two valleys with depths of 0.070 inch to 0.080 inch. A special consist of cars from both the 33- and 39-ton axle load tests then passed over the gages at 40 mph.

The most striking result of the corrugation load data is the difference between the peak and the valley loads. Peak and valley loads for the 33 kip wheel ranged from 11 kips to 35 kips and from 32 kips to 80 kips, respectively. Wheel loads for the peak and valley under 39 kip wheels ranged from 19 kips to 43 kips and from 65 kips to 93 kips, respectively. The increase of 6 kips in static wheel load resulted in an increased maximum load at 40 mph the peaks of 8 kips and at the valleys of 13 kips.

3.1.1 Phase I Conclusions

The evaluation of the Section 7 Rail Wear Test results suggest that increasing axle loads from 33 tons to 39 tons on curves:

- reduced the rail life benefit, in terms of gage face wear, offered by premium rails over standard rails,
- increased the rate of high railhead height loss and had little effect on low railhead height loss, and
- increased (relatively) the rate of high railhead height loss nearly the same as the rate of gage face wear.

It should be noted again that the railcars and trucks were changed at the same time the axle loads were increased. This may have affected wear rates as much or more than the increase in axle load. The 6 kip increase in static wheel load caused vertical loads at the bottom of 0.070- to 0.080-inch corrugations to increase from maximums of 80 kips under 33 kip wheel loads to 93 kips under 39 kip wheels.

3.2 PHASES II-III

The objective of Phases II–III rail wear testing was to study the effects that operating a train equipped with improved suspension trucks has on the performance of standard and premium rail, and further to compare rail performance under improved suspension trucks to rail performance under the standard three-piece trucks.

The last 100 MGT of Phase II rail wear testing consisted of a new installation of several premium-rail types and one standard-rail control zone. Phase II testing was conducted under the standard-truck equipped HAL train. To conduct a back to back test comparing the effects of improved-suspension trucks, a new installation of same-type rails was made. The new rails were then subjected 257 MGT of HAL traffic after the train was re-fitted with improved-suspension trucks. The improved-suspension trucks provide the benefit of improved curving response with enhanced wheel-set steering and resistance to truck warp.

The use of improved-suspension trucks reduced the lateral load environment and the wheel-set angle of attack by approximately 50 percent. Figure B1 shows that the typical median lateral load in Section 7 during Phase II standard-truck operations was about 5.8 kips. Under the improved-suspension truck operations of Phase III, the median lateral load was reduced to about 2.5 kips. Lateral load was measured with instrumented wheel-sets.

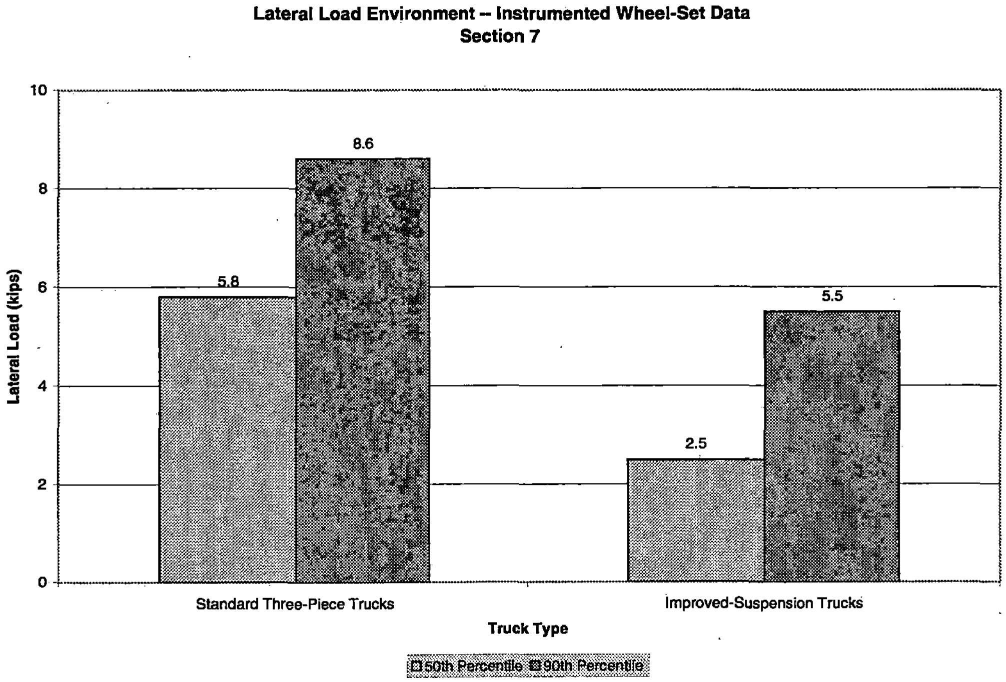

Figure B1. Lateral Load Environment in Section 7 Measured using Instrumented Wheel Sets. Standard vs. Improved Suspension Truck Operations

Gage wear rates in Section 7 were reduced significantly under improved-suspension truck operations. Vertical wear, which was a minor concern during standard-truck operations, was nearly eliminated with the introduction of the improved trucks. Due to the substantial reduction in wear, Figure B2 compares total wear of the standard-rail control zone under standard-truck operations during the 100 MGT period of testing to the 257 MGT period of testing under improved-trucks. Standard-rail gage wear was reduced about 70 percent under the improved trucks.

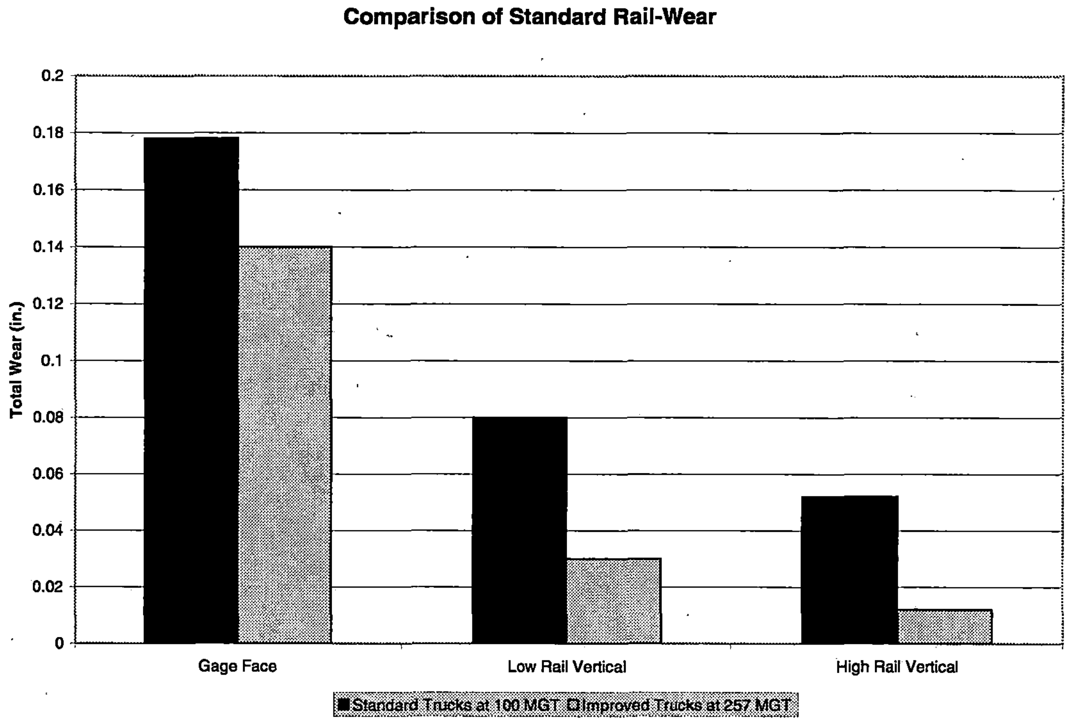

Figure B2. Comparison of Standard-Rail Wear, 100 MGT Under Standard Truck Operations to 257 MGT Under Improved Truck Operations.

Figure B3 compares the average total wear of all the premium rails under standard-truck operations during the 100 MGT period of testing to the 257 MGT period of testing under improved trucks. The premium-rail gage wear was reduced about 74 percent under the improved trucks.

Corrugations developed on the high rail of the Standard 300 Bhn rail under standard truck operations and grew to a depth of 0.1 inch in the first 70 MGT. Corrugations did not develop during the 257 MGT of improved truck operations.

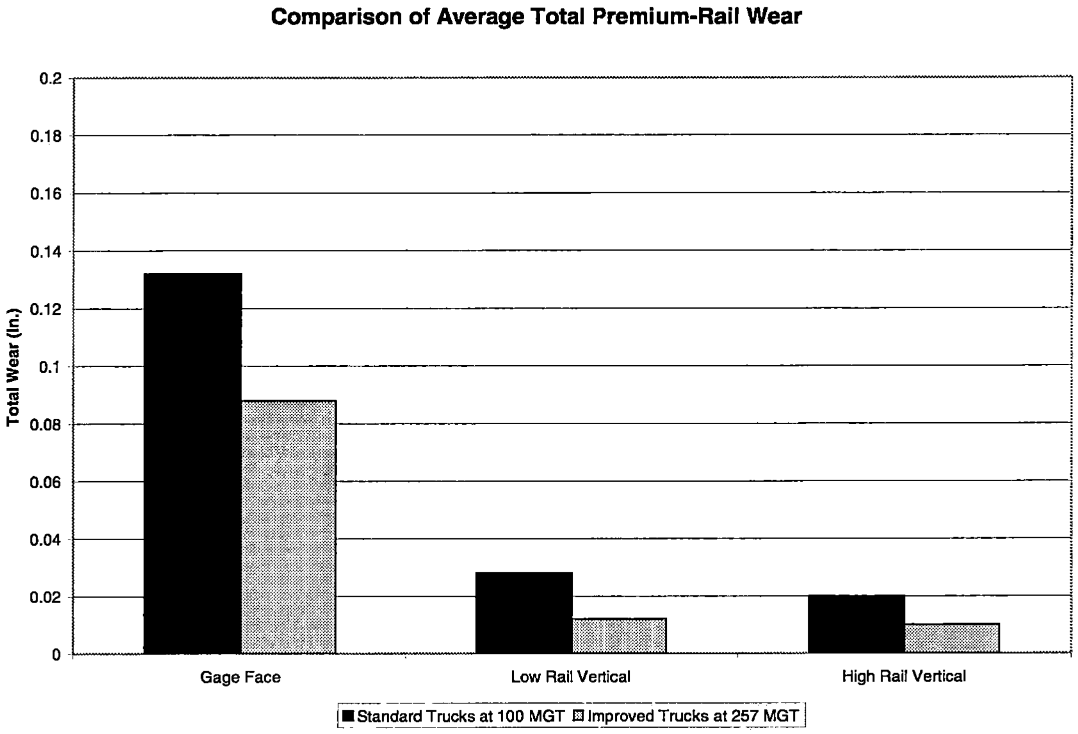

Figure B3. Comparison of Average Premium-Rail Wear, 100 MGT Under Standard Truck Operations to 257 MGT Under Improved-Truck Operations.

3.2.1 Conclusions from Phase II–III

Evaluation of the back to back test indicates that operating the heavy axle load train with improved-suspension trucks:

- Eliminated the development of corrugations, for at least 257 MGT, in standard and premium rails.
- Provided a reduction in rail gage wear of about 70 percent in standard rail and about 75 percent in premium rails.
- Reduced railhead vertical wear such that it was just becoming measurable at 257 MGT.

3.3 PHASES III-IV

The objective of Phase III testing was to compare the wear performance of new rail metallurgies under improved suspension trucks. The objective of Phase IV was to study the effects of running the HAL train with improved suspension on totally dry rail and to compare the results to the light lubrication conditions of Phase III.

Phases III–IV of rail wear testing were conducted on the same rails. During Phase III, the typical FAST lubrication policy was in place. During that period of testing, the coefficient of friction on the gage face of the high rail in Section 7 was 0.35 to 0.40. This is light lubrication. Values of 0.25-0.3 would be typical of normally lubricated rail. During the Phase IV dry rail test period, μ was 0.5 to 0.55.

Figure B4 illustrates the area loss in square inches of the seven rail types. Area loss is derived by overlaying MiniProf™ profilometer railhead profiles. All the rail types except the J6 bainitic rail were installed at the same time. The J6 rail was installed after the initial installation and is, therefore, the shortest curve on the graph. A vertical line marks the beginning of Phase IV dry rail operations. The graph, therefore, illustrates the increase in wear that occurred as a result of operating under dry rail conditions.

The average of three railhead internal Bhn measurements, taken at 3/8 inch inward from the top of the rail and read with a typical scope, was used to define the rail hardness of the seven rail types tested. Table B7 lists the rail types, the Bhn of measurements taken at the TTCI Metallurgy Lab, and the average taken at two independent labs. All three labs measured the Brinell hardness indentation manually. Results from a fourth lab, using an automated method, were slightly higher. Included in Table 7 is Comparative Wear, "Lightly" Lubed and Dry, where each rail is compared to the rail with the least wear, and the Dry to Lubed ratio.

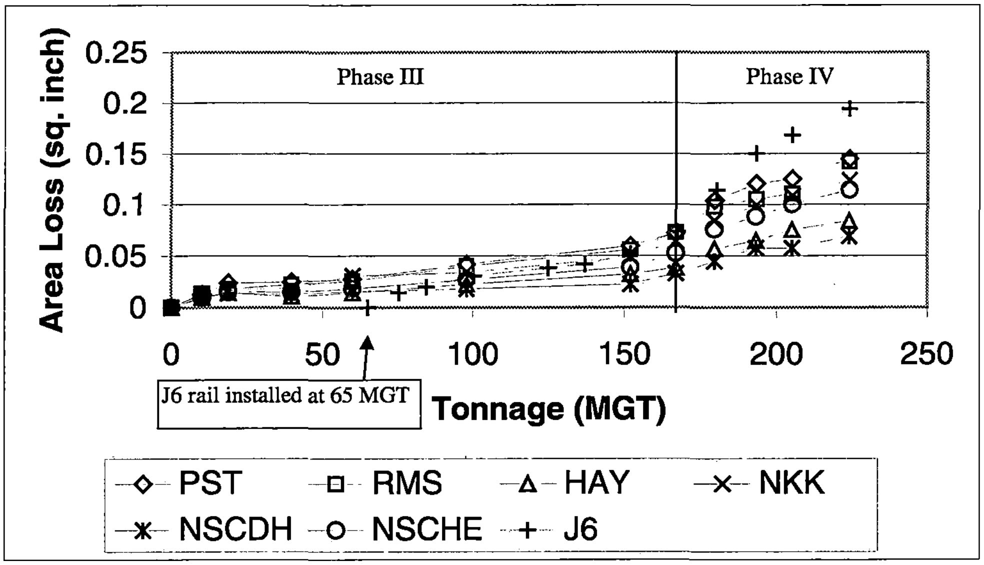

Figure B4. Area Loss (square inches) of the Seven Rail Types Tested during Light Lubrication and Dry Rail HAL Operations

Table B7. Rail Wear Ratios

Rail	TTCI Hardness	Avg. Lab Hardness	Comparative wear Best = 1		Ratio
			Lubed	Dry	Dry/lubed
Hayange	363	361	1.88	1.05	6.58
NSCDH	356	359	1.00	1.00	11.86
PST	341	345	3.74	1.92	6.09
NKKTH	363	372	3.17	1.40	5.26
NSCHE	363	369	2.41	1.42	6.99
RMSM	380	378	3.65	1.31	4.24
J6	415	413	5.69	3.12	6.49

3.3.1 Conclusions from Phases III–IV

Results of Phase III–IV testing indicate that profile differences affect the type of early wear.

- Steady-state rail wear ratios occurs after about 40 MGT.
- Differences in wear behavior is not simply related to hardness.
- Light lubrication of about 0.35 to 0.40μ decreases wear by about a factor of 6 compared to dry rail conditions.

3.4 EARLY PHASE V RESULTS

After 100 MGT of Phase V traffic, current design standard three-piece trucks, rail wear rates have stabilized. Several trends are evident. Rail wear has increased, confirming a previously noted benefit of improved suspension trucks. Average wear in Phase V is approximately seven times as high as in Phase III. This is shown in Figure B5.

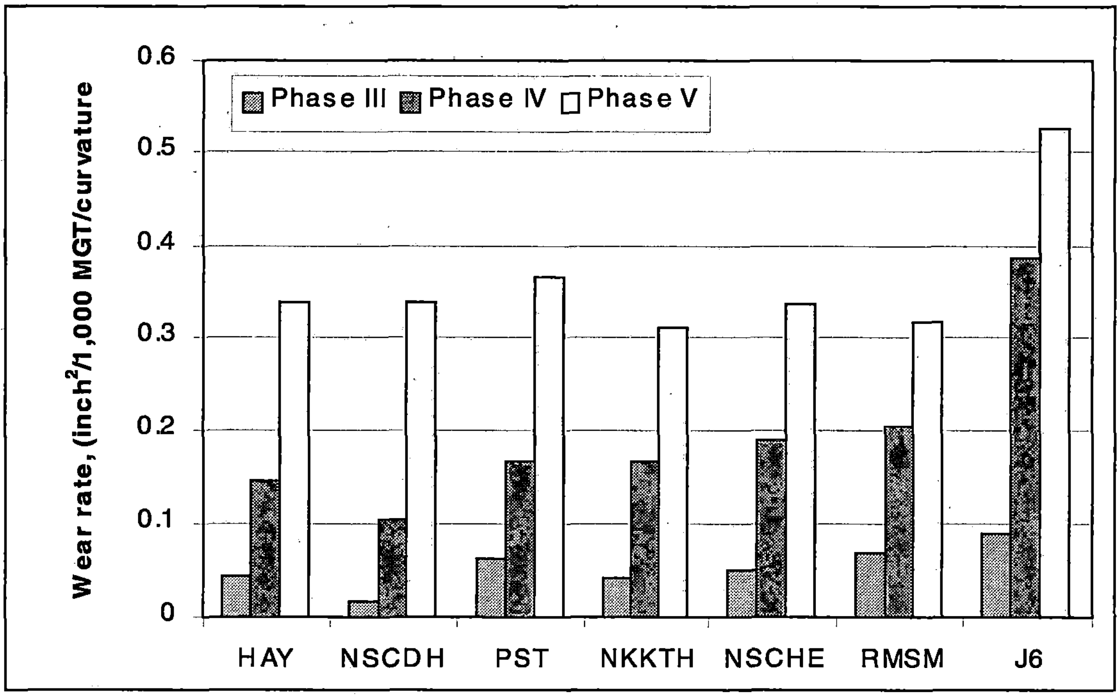

Figure B5. Early Phase V Wear Rate Results

Another change that became evident in Phase V is the effect of rail hardness on rail wear. During Phases III and IV, when wear rates were relatively low, there was no measurable effect of hardness on premium rail wear. In fact, one of the hardest premium rails had the highest wear rate, while one of the softest had a lower wear rate.

This is not the case in Phase V. The harder rails have the least wear during this phase, as shown in Figure B6. Possible reasons for this include:

- Wear was so slight during the earlier phases that most of the wear was probably in the decarburized layer of the rail. This layer is softer than the parent metal, and the thickness of the layer varies slightly from manufacturer to manufacturer. Wear in this layer would not be representative of wear in the parent metal.
- Wear rates were so low because of the improved suspension trucks that factors other than rail characteristics may have dominated. This could include minor, discrete difference in track conditions in the test zone.

Figure B6 shows the effect of rail hardness on wear during Phase V.

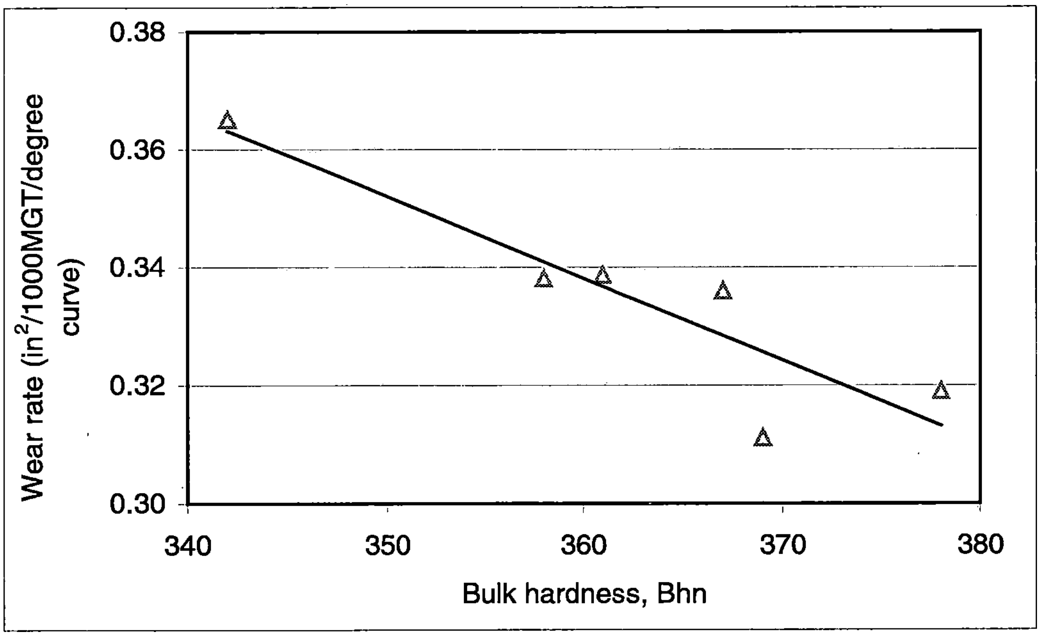

Figure B6. Effect of Rail Hardness on Wear during Phase V

APPENDIX C
WELD PERFORMANCE

Joseph Kristan

1.0 OBJECTIVE

The objective of monitoring the performance of thermite welds installed in the High Tonnage Loop (HTL) at the Facility for Accelerated Service Testing (FAST) is to characterize the performance of these welds subjected to heavy axle loads and varying conditions as imposed by each operational phase.

2.0 BACKGROUND

The monitoring of weld performance at FAST has been performed since Phase I operations and continues today to characterize weld performance and correlate phase operations with performance. Both electric flash-butt and thermite welds are widely used in revenue service for both rail installations and maintenance. The electric flash-butt weld is known to possess properties approaching that of the parent rail. Thus, the performance of this weld type has not been monitored during recent phases of HAL operations. Conversely, the reliability of the thermite weld currently does not meet that of the electric flash-butt, but, because of its utility, it is used in great numbers by the railroads. Thermite welds can be installed in remote areas by a small welding crew and limited equipment. Recent thermite weld developments such as wide gap (2.75-inch) and single use weld crucibles have increased their utility.

3.0 METHODOLOGY

The majority of FAST weld data is from track installation and maintenance welds installed during each of the operational phases. Each of these welds is logged in a database immediately following installation. Subsequent to weld removal, the reason for removal and date are entered in the database. This provides tonnage and statistical information. The welds are classified in each respective phase by their installation date though the weld may have sustained tonnage in subsequent FAST operational phase(s).

4.0 WELD PERFORMANCE

The performance of thermite welds installed in curves in the HTL is summarized in Figures C1 through C6 and Tables C1 and C2. The high rail in curves is the most severe environment to which the thermite joint is subjected. Table C1 shows that the performance of the standard thermite welds installed during Phase I of FAST operations performed extremely poorly. Eighty percent of the welds in the high rail and 19 percent in the low rail had failed by 75 MGT. Ninety-five percent of the welds installed in the high rail of curves failed while 83 percent failed in the low rail by 144 MGT. Improvements were made to welds installed in later phases which include the use of premium welds, improved weld portions and molds, and improved installation techniques and training. The thermite weld failure frequency decreased dramatically during Phase II and III operations to 17 percent and 20 percent in the high rail of curves, respectively. This data is subsequent to 301 MGT in Phase II and 424 MGT in Phase III of FAST operations.

With the exception of the failures at low MGT in Phase II, the accumulated MGT to failure has not changed dramatically over the different operational phases as Figure C1 show. This is because the same type of defects (inclusions) that affected Phase I operations are still occurring in recently installed welds, and these defects lead to relatively early weld failures. The major difference is that the frequency of weld failures has greatly decreased. Though weld performance has greatly improved since Phase I operations, the current welds and installation practices can be further improved to increase the reliability, ease of installation, and utility of the thermite weld.

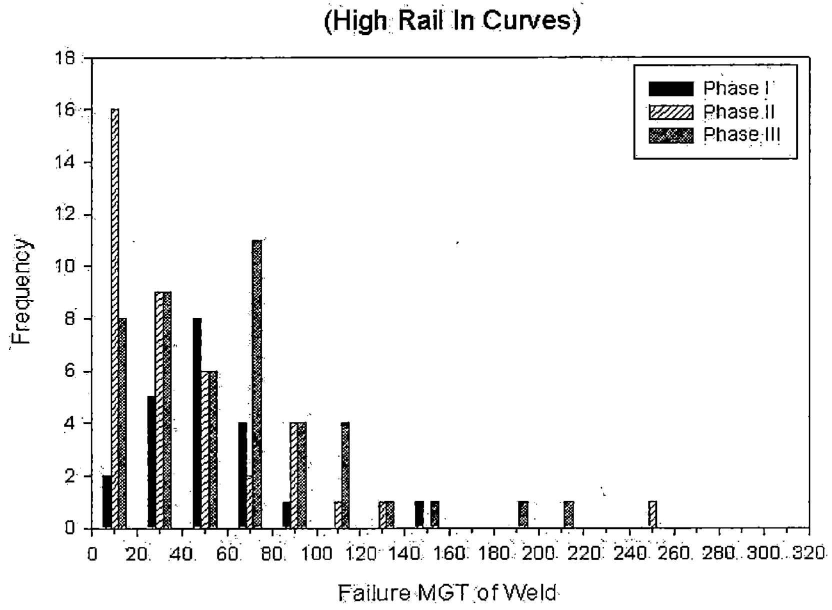

Figure C1. Thermite Weld Performance from the High Rail in Curves during all Phases of FAST Operations

Operations with improved suspension trucks (Phase III) did provide other benefits that affect thermite welds. There was a 75-percent reduction in average wear and batter after 60 MGT with the improved suspension trucks. This could reduce surface and other problems associated with battered welds.

Additional thermite weld information has been gained by research performed at FAST. Thermite welds treated with vibrational treatments both during and subsequent to weld installation have shown that welds installed with attention to proper installation techniques provide a reliable rail joint even under heavy axle loads. In approximately 150 MGT of FAST train operations through Phases III, IV and currently V the control welds in the test zone have performed identically to the treated welds. Thus, the treatment did not improve the performance of the treated welds, which were installed in a 5-degree curve and adjacent spirals. However, there have been only six failures during the first 150 MGT of operation, a failure percentage of 9 percent. This performance can be attributed to the care taken during weld installation as well as continually improving weld consumable and installation techniques.

Table CI. Thermite Weld Failures From Curves in the High Tonnage Loop (HTL)

	Phase I (144MGT)		**Phase II** (301 MGT)		**Phase III** (424 MGT)	
	High Rail	Low Rail	High Rail	Low Rail	High Rail	Low Rail
Weld Numbers	21	15	40	12	46	4
Failure Percentage	95%	83%	17%	11%	20%	9%
Average MGT to Failure	53.1	100.3	43.3	79.0	63.5	126.5
Standard Deviation (MGT)	28.7	41.5	45.2	84.7	45.1	115.3
Median	55.5	94.9	30.2	37.9	61.2	95.5

Table C2. Thermite Welds Removed for Maintenance in the High Tonnage Loop (HTL)

	Phase I		Phase II		Phase III	
	High Rail	Low Rail	High Rail	Low Rail	High Rail	Low Rail
Weld Numbers	1	3	197	101	189	43
Average MGT to Failure	143.9	143.9	120.0	151.1	144.3	236.9
Standard Deviation (MGT)	N/A	N/A	154.6	181.6	108.2	95.7
Median	143.9	143.9	66.0	76.4	117.4	220.8

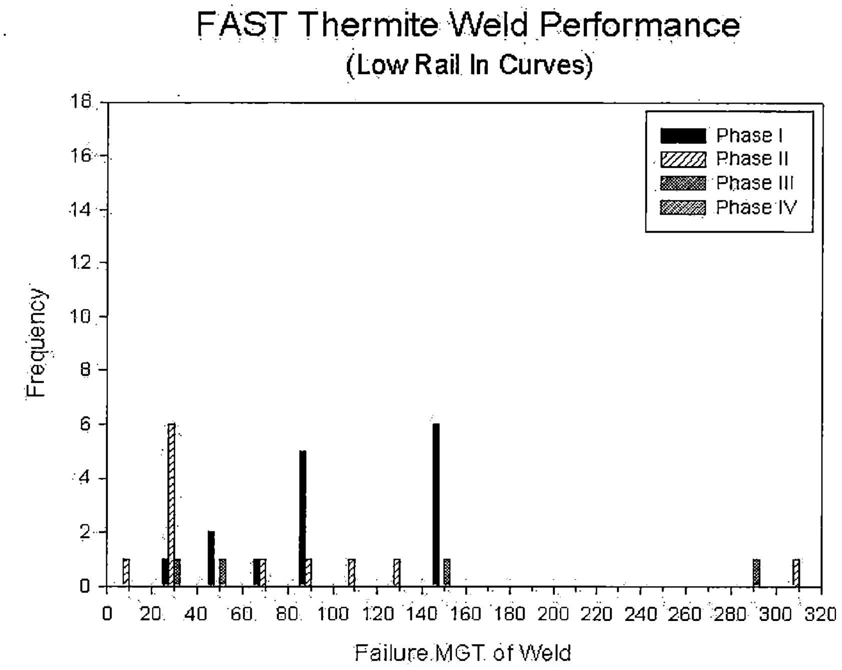

Figure C2. Thermite weld performance from the low rail in curves during all phases of FAST operations

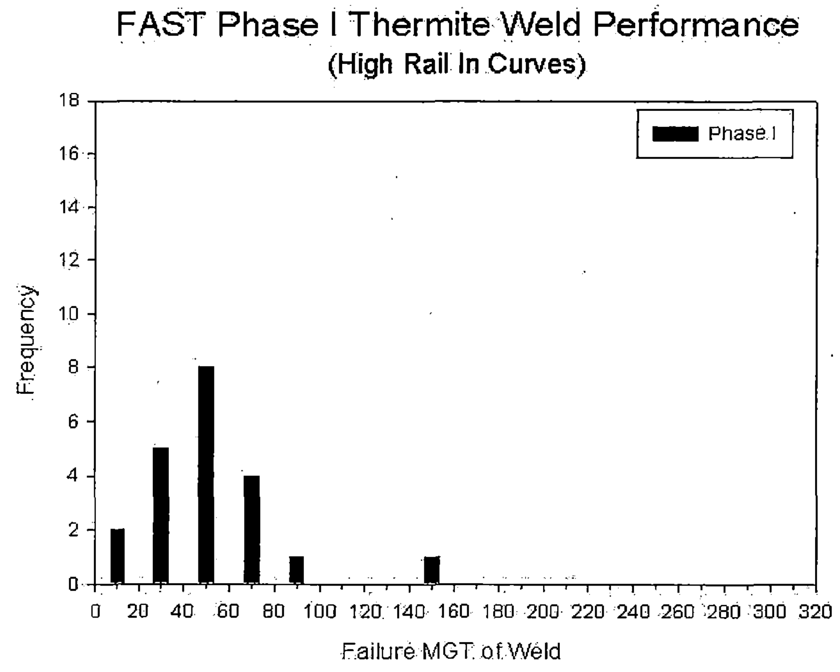

Figure C3. Thermite weld performance during Phase I FAST operations

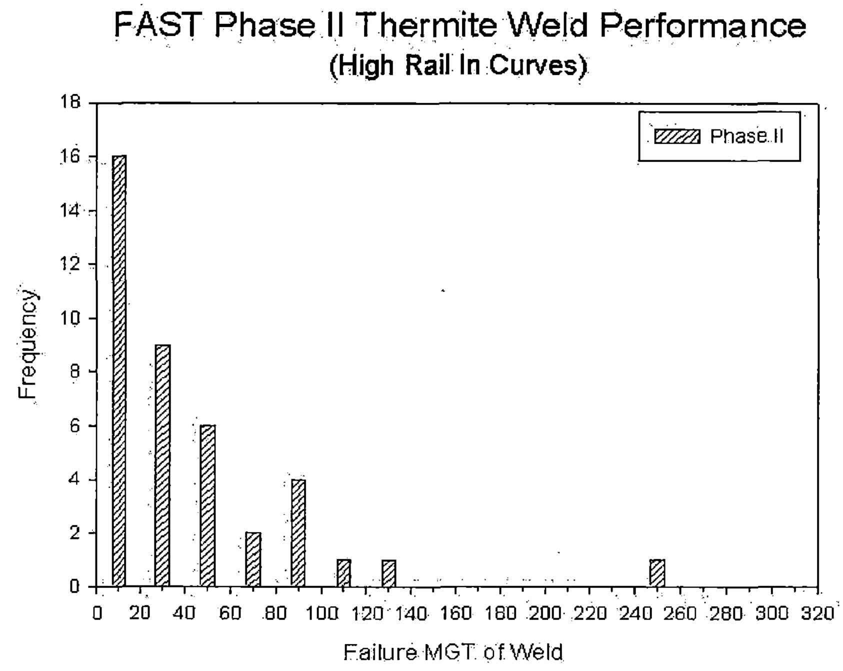

Figure C4. Thermite weld performance during Phase II FAST operations

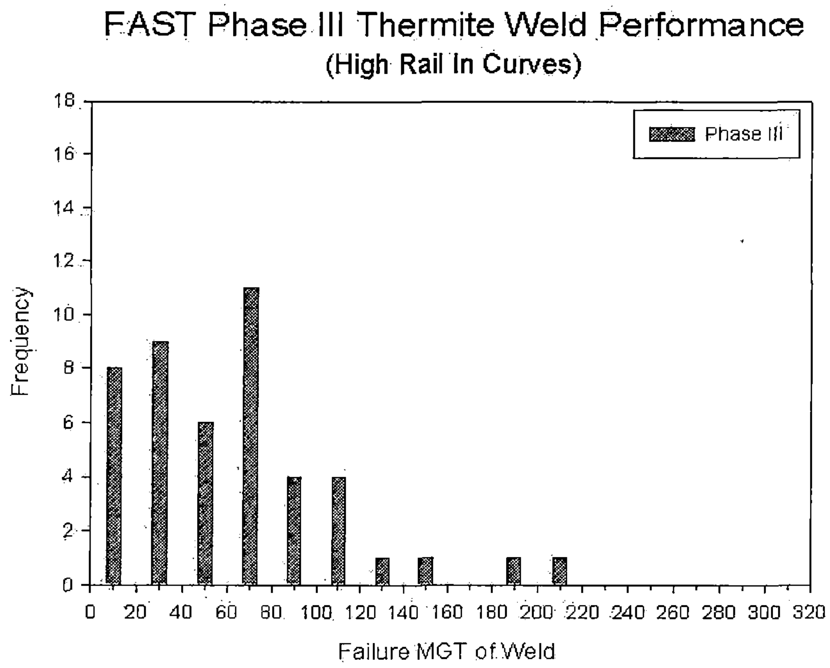

Figure C5. Thermite weld performance during Phase III FAST operations

5.0 CONCLUSIONS

- Though weld performance has greatly improved since Phase I operations, the current welds and installation practices can be further improved to increase the reliability, ease of installation and utility of this joint type.
- Operations with improved suspension trucks reduced weld batter.
- The vibrational weld treatments evaluated have not had a significant effect on weld performance.
- Proper installation is vital to extending weld life.

APPENDIX D

FAST SPECIAL TRACK WORK

David D. Davis and Don Guillen

1.0 INTRODUCTION

The Association of American Railroads (AAR) has sponsored the evaluation of turnout designs for heavy haul operation. Along with a co-sponsor, the Federal Railroad Administration (FRA), the AAR has tested several turnout designs in the Facility for Accelerated Service Testing (FAST). The results of these evaluations and similar evaluations conducted by TTCI in revenue service have shown continuing improvement in turnout performance in the face of increasing demands. The average life of turnouts continues to rise as wheel loads and tonnage rates increase. Analysis and testing under heavy axle loads (HAL) conditions have shown that intermediate design turnouts for mainlines are cost effective over a wide range of tonnage rates. Intermediate turnouts are defined as designs which fall between those in the AREMA portfolio and high performance designs incorporating features such as moveable point frogs, tangential geometry, and asymmetric section switch points.

2.0 BACKGROUND

Turnout testing at FAST is comprised of several phases that are related to, but do not necessarily coincide with the Phases of FAST/HAL testing. The performance of a turnout with standard design and materials was evaluated first. The next turnout tested was of standard design, but included improved materials. A tangential geometry turnout, improved design and materials, was installed slightly later, but tested in the same time frame. Current testing is focused on designs that incorporated improved designs and/or materials, but without the cost premium of many advanced turnouts

These turnouts are tested under a train made up of 315,000-pound cars being operated at 40 mph. A high percentage, (40% – 50%) of the traffic is over the diverging route. Traffic is split nearly evenly between facing- and trailing-point. Thus, the operating environment is severe. However, the FAST train was equipped with improved suspension trucks from 1994-1999. And, operating conditions at FAST prevent the formation of severely hollowed wheels. Both of these factors should reduce damage to special track work.

Table D1 lists the chronology of FAST turnout testing under the HAL experiment. This table shows the evolution of turnout design as suppliers attempted to mitigate the effects of heavier axle loads on turnouts. The use of improved materials allowed existing designs to live longer under the increased loading. Better designs and better materials reduce the loading on — and extend the life of — special track work. Components being tested now are intended to retain the performance benefits of advanced design, but at a lower cost premium.

Table D1. Chronology of FAST HAL turnout testing

	Improved Materials		Improved Designs	Lower First Cost
Turnouts Tested at FAST:	"SP"	"Bethlehem"	"ATS/BWG	"Intermediate"
Description	33-kip load standard design	39-kip load premium component standard design	Advanced designs Premium components	Lower cost advanced designs
	1985	1990	1995	2000

3.0 TEST PHASES AND RESULTS FOR TURNOUTS

3.1 Standard Design and Materials

At the beginning of the FAST/HAL experiment, a standard turnout consisting of an AREA No. 20 switch, a rail bound manganese (RBM) frog, and standard (300 Bhn) rail was installed. This turnout was typical of those used by a major western carrier. Surface damage on both the switch points and frog were noted after 6 MGT. Corrugations and surface damage continued to develop throughout the life of the turnout. This turnout survived just over 100 MGT of 39 kip wheel loads. A switch point had failed, and maintenance demands were excessive.

3.2 Improved Materials

Recent turnouts, with AREMA geometry, high integrity RBM frogs, and 370 Bhn rail have survived 500 to 1,000 MGT in revenue service. The lives of frogs and switch points made of improved materials have reached 300 to 400 MGT under 39 kip wheel loads at 40 mph. Similar results have been documented in revenue service, where frog life has gone from 170 to 500 MGT under unit coal traffic.

Some of the changes that have contributed to the increase in life include: improved plate work (especially gage plates) and fasteners, improved guard rails, improved frog heel designs, thicker walled castings, high integrity castings, higher strength steels and metallurgically cleaner steels. Weld repairs are more likely to be viable with the larger section, high-integrity castings available today.

The premium component – standard geometry turnout tested at FAST, manufactured by the Bethlehem Steel and installed in 1989, had significantly improved performance. This turnout used a standard layout (e.g. AREA switch geometry and an RBM frog) with premium materials and components. It included fully heat-treated rail, elastic fasteners, and a high-integrity frog casting. This turnout lasted longer and required less maintenance than the standard turnout.

3.3 Improved Design and Materials

Further improvements in turnout life came from the use of better designs and premium materials. Lower entry angle switches and frogs that eliminate flangeway gaps have proven successful in the HAL environment. The ATS turnout, installed in 1992, had a tangential geometry switch and a moveable point frog. The turnout, as originally installed, required frequent maintenance. The running surface components were selectively hardened in critical areas, such as the frog and switch points. The rest of the running surface was standard rail (300 Bhn). This material quickly deteriorated under 39-kip wheel loads, eventually affecting the frog and points. The entire running surface (including frog and points) was replaced after 132 MGT. The premium material/premium design turnout performed well, with a service life of 394 MGT. Additionally, the ATS turnout had lower peak forces than the comparison AREA design turnouts.

3.4 Intermediate Design

The current round of tests is aimed at retaining the performance benefits of the advanced designs while lowering the cost premium over standard designs. The AAR intermediate turnout, installed in 1998 embodies this approach by using a shortened, lower entry angle switch and a spring frog. The low entry angle "Willow" switch provides most of the performance benefits of a tangential switch with a shorter lead length for a given allowable speed. The shorter switch points eliminate some of the negatives associated with tangential turnouts. The long, thin part of the switch point is reduced, and the intermediate turnout fits in the same basic footprint of an AREMA turnout. FAST experience with the intermediate geometry switch points has been mixed. The low entry angle switches have been effective at reducing lateral forces. Instrumented wheelsets operated at FAST consistently measure lateral forces in the switch point area of this turnout that are about 1/3 lower than in a comparable AREMA geometry turnout. But, the Willow curved switch points are failing sooner than the AREMA switch points due to chipping in the first 5 feet of the points. Though the switch points are not as long or as thin as those in a tangential turnout, they are not as heavy as those in an AREMA turnout. This may contribute to their shorter life. The spring frog eliminates the flangeway gap for the mainline route of turnout, but does not require signaling or a switch machine. Table D2 lists the performance of major components from various No. 20 turnouts tested at FAST during the HAL experiment.

Table D2. Performance of Selected #20 Turnouts at FAST/ HTL

Turnout	Frog	Life (MGT)	Curved point	Life (MGT)	Straight point	Life (MGT)
Standard (SP)	RBM	106	AREA, Undercut	106	AREA, Undercut	106
Bethlehem	RBM	290	AREA, Thick Web	250	AREA, Thick Web	250
			AREA, Undercut	250	AREA, Undercut	580
American Track Sys.	Moveable point	132* 120 274*	Tang. Asymmetric	132** 394 (190)*	Asymmetric	132** 394 (204)*
AAR Intermediate	Spring (moveable wing)	In service at 207	Willow Geometry, Undercut	140 (50), In service at 77 (41)	Willow Geometry, Undercut	In service at 207 (115)
AREMA (BNSF Std)	RBM heavy point	In service at 77	AREMA, Undercut	In service at 77 (41)	AREMA, Undercut	In service at 77 (36)

* Removed prior to failure, ** Still serviceable, but non-premium components required excessive maintenance, ( ) denote tonnage over component.

3.5 Economic Analysis

AAR conducted an initial economic analysis of three turnout types in 1995. This analysis compared the life cycle costs of turnouts representative of the eras described above: a pre-HAL standard turnout, a premium material, intermediate geometry turnout, and an advanced design turnout. The analysis was based on limited field data and the expected performance of those designs. At that time, the intermediate turnout was economical over a wide range of heavy haul freight applications. Using a cost premium of 20 percent over the standard turnout, this type of turnout is the low cost turnout for main lines with tonnage rates of about 25 to 100 MGT/yr. The standard turnout was most economical for lines with 25 MGT/yr or less. The advanced design turnout, with moveable point frog and tangential switch, was the low cost turnout for lines with traffic rates above 100 MGT/yr. While they perform very well in service, the high initial cost of the moveable point frog and attendant control apparatus limit their use. Table D3 summarizes the economic study findings.

Table D3. 1995 Turnout Economics Study Findings for Heavy Haul Freight Applications

Turnout	Switch	Frog	Relative Initial Cost (vs. Std)	Recommended Use (MGT/yr)
Standard	AREA	RBM	1.0	<25
Intermediate	Modified Tangential	High integrity RBM or Spring	1.2 – 1.4	25 – 100
Advanced Design	Tangential	Moveable Point	2.0 – 3.0	>100

Since the economics study, more performance data has been collected on all three types of turnouts. The performance of moveable point frogs in heavy haul situations has been as good as expected where proper maintenance has been given. Low entry angle switches have also performed well at FAST and in the field. Major concern for tangential switches are the cost of re-configuring interlockings (due to the longer switch length) and chipping of thin switch point tips. There is not much data on the performance of larger spring frogs in heavy haul service. The No. 20 in FAST has accumulated 170 MGT with two weld repairs to date. The short 5 MGT average life of the spring frog retarders is driving maintenance costs.

In addition, more premium components and design features have become "standard" today. As a result, the base case standard turnout has improved greatly in the last few years. Comparisons to the mid-1980's standard turnout are meaningless for heavy haul mainline applications. This has the effect of driving the high performance, higher cost products into a smaller niche.

High performance products do have potential applications in many other operating situations. A key factor is train delay costs. On lines with higher train delay costs, such as passenger service or freight lines that are near capacity, the performance benefits of advanced designs are more easily affordable. Additional benefits can be obtained from advanced design switches on lines that are not limited by FRA cant deficiency criterion for turnout speeds.

4.0 CROSSING DIAMONDS

Crossing diamonds have also been evaluated under the same joint AAR/ FRA funded program. And the AAR has spent considerable additional effort in fostering the development of new technologies for high performance crossing diamonds. While crossing diamonds present a larger technological problem than turnouts, they present what is considered to be a smaller economic issue. This is due to the number of turnouts (estimated at over 100,000 in the U.S.) versus the number of crossing diamonds (estimated at 4,000 – 5,000). The direct spending on turnouts is significantly higher.

However, the indirect costs in train delay make total crossing diamond costs as large as turnout costs.

The history of crossing diamond performance in HAL service has been rather dismal. Several typical revenue service crossing diamonds were tested in the HTL during Phase II of 39 kip operations. While these diamonds were adequate performers in revenue service, with lives of 100 to 300 MGT, they survived only 2 to 15 MGT under HAL traffic. Table D4 shows the performance of FAST diamonds. Most of the difference in performance can be attributed to the wheel load increase. However, the FAST HTL is truly an accelerated test for crossing diamonds. Unlike some revenue service locations, HTL diamonds do not have speed restrictions. Every train is operated at 40 mph. Also, unlike revenue service, the HTL has no operational need for a crossing diamond. Thus, there is no penalty for removing the diamond from service. In revenue service, the cross track must be kept in service, even if at low speed. Additionally, in the HTL the same train crew rides over the diamond 100 or more laps per MGT (as opposed to 100 different trains per MGT in revenue service). Train crew tolerance for single discontinuities is greater than it is for repetitive discontinuities. The end result is that in revenue service, diamonds will have a longer average life than in the HTL. With no crossing diamond test experience at FAST under 33 kip wheel load traffic, it is difficult to determine the relative effects of the operational differences on diamond life.

As with turnouts, the application of premium materials to standard crossing diamond designs followed during Phases II and Phase III. The premium material diamonds had service lives of 15 to 30 MGT; they still far short of revenue service lives under 33 kip wheel loads. One difference noted with crossing diamonds, as opposed to turnouts, is a subtle change in failure modes under HAL loading. A threshold limit may be near with the impact loading on high-angle diamonds. The deformation and flow in AMS castings seen under 39-kip wheel loads is significantly higher than under 33-kip loads. The deformation occurs deeper in the castings and continues well beyond the traditional work hardening periods seen in revenue service. A stronger, yet still durable material may be needed for unsupported flangeway gap, high-angle diamond frogs.

Table D4. FAST Crossing Diamond Test Results

Design	Materials	Angle (Deg)	Design Type	Running Surface (Bhn)	Life (Mgt)	Failure Mode	Comments
Std	Std	89	Rev. Ins	360	1.9	Deformation	
Std	Prm	89	Rev. Ins	380	15.2	Broken Wing Rail	
Std	Std	76	Solid	380	15.9	Crack	
Std	Prm	76	Solid	450	4.5	Crack	AMS Casting
Std	Std	62	3-Rail	340	4.6	Crack & Battered	
Std	Prm	62	3-Rail	370	29.4	Crack	Head-Web Separation
Std	Prm	62	3-Rail	430	56.7	In Service	Bainitic Rail
Prm	Std	90	FBF Solid	380	36.8	Cracked Casting	AMS Casting
Prm	Std	75	FBF Solid	380	4.1	Pumping & Metal Flow	AMS Casting

AAR sponsored work on advanced materials and advanced-design crossing diamonds shows promise of greatly extending high-angle diamond life by producing a stronger material for frogs and reducing the impact loads on frogs, respectively.

To date, the bainitic steels research has developed a medium carbon bainitic rail that has performed well in crossing diamond tests. The bainitic rail crossing diamond was still in service after 97 MGT, almost three times the life of conventional rail steel diamonds at FAST. The bainitic three-rail diamond is an excellent choice for locations where one track carries most of the traffic. The cost premium of a bainitic three-rail diamond over a conventional three-rail diamond is less than 10 percent.

Use of a flange bearing frog diamond design is seen as the cutting edge solution to increasing wheel loads and in eliminating slow orders on crossing diamonds. Initial tests of the concept are very encouraging. Development of a design that fully utilizes the potential benefits of flange bearing to reduce impacts is at least one design iteration away.

APPENDIX E

CROSSTIES AND FASTENERS

David D. Davis and Rafael Jimenez

1.0 BACKGROUND

Results from 11 years of testing wood ties and fasteners in heavy axle load (HAL) environment have been compiled recently by Transportation Technology Center, Inc. (TTCI). This compilation provides the railway industry with information concerning the performance of the tested track components under heavy-haul operating conditions.

The Wood Tie and Fastener Test, sponsored by the Federal Railroad Administration (FRA) and the Association of American Railroads (AAR), has been an integral part of the HAL Research Program since 1988.

2.0 OBJECTIVE

The main objective of the test program has been to quantify the performance of different tie types and fastening systems under 39-ton axle load traffic. Another objective has been to compare the results gathered during the 460 million gross tons (MGT) logged in Phases I and II of HAL operations under standard three-piece trucks to the results of 450 MGT of testing in Phase III using vehicles equipped with improved-suspension trucks.

3.0 METHODOLOGY

The effects of heavy axle loads on ties and fasteners were examined by operating the HAL train at the Facility for Accelerated Service Testing (FAST) on the High Tonnage Loop's (HTL) three 5-degree curves with 4 inches of superelevation, one 6-degree curve with 5 inches of superelevation, and tangent sections. The train normally consists of 70 to 80 315,000-pound gondola and tank cars and operates 4 days per week, generating between 3 and 5 MGT per week.

Test zones on the 2.7-mile HTL consist of various hardwood and softwood tie species with different fastening systems. In addition to the traditional solid-sawn timber crossties, other ties in-test include dowel-laminated, glue-laminated, parallel-strand lumber, reconstituted and plastic composite ties.

The two primary quantifiable performance characteristics that were measured and documented during the Wood Tie and Fastener test period were fastener stiffness and gage-widening as functions of traffic.

3.1 Static / Dynamic Measurements of Fastener Stiffness Using the Track Loading Vehicle

Track Loading Vehicle (TLV) measurements were used to compare the gage-spreading response of various tie/fastener types to the application of simulated heavy axle loads. The TLV is equipped with hydraulic actuators, a laser unloaded-gage measurement mechanism, and a split-axle wheelset loaded-gage measurement mechanism.

The gage-spreading loads used in the stationary tests varied from 2 to 26 kips under the 39 kip wheel load, a 0.05 to 0.7 lateral to vertical load (L/V) ratio. The in-motion tests, run at 20 mph, were made with gage-spreading loads ranging from 10 to 24 kips under a 39-ton axle load, 0.3 to 0.6 L/V ratio.

3.2 Static Measurements of Fastener Stiffness Using the Rail Force Calibration (605) Car

Measurements from the 605 Car were used to look at the long-term degradation of gage-spreading strength with respect to MGT of traffic over the different tie/fastener combinations.

The 605 Car uses hydraulic actuators capable of applying a 40,000-pound vertical force to each rail and a 20,000-pound lateral gage-spreading force. Lateral rail stiffness is used to quantify rail fastener performance. It is determined by measuring the lateral response of the railheads to the applied lateral and vertical forces. The static gage-spreading 605 Car data was acquired by maintaining a constant 40 kip vertical wheel load while applying a 20 kip lateral wheel load in 5 kip increments. The railhead deflection of both rails was measured and summed.

3.3 Gage Widening Measurements Using the EM-80 Track Geometry Car

The gage-widening rate for the various test sub zones was calculated using EM80 data. The Plasser EM80 track geometry car measures the following parameters:

- Profile from mid-chord offset from a 31-foot chord with 62-foot chord data calculated.
- Alignment from mid-chord offset from a 31-foot chord with 62-foot chord data calculated.
- Gage
- Cross level/Superelevation
- Twist over 31-feet and 11-feet

4.0 HTL LOAD ENVIRONMENT

The FAST load environment and operations allow for the rapid accumulation of HAL tonnage. With 39-kip wheel load cars, 40-mph operation and 100 to 150 MGT/year traffic, the vertical load environment is more severe than most revenue-service lines. Loads are applied in large concentrated doses of 100 to 130 trains all operating in the same direction on 4-minute headways.

The lateral loading could be less severe than that found in revenue service due to curvature and truck type. FAST has 5- and 6-degree curves versus a range of curves up to 14 degrees in revenue service. Also, for 425 MGT, improved suspension steering trucks were used in the train. These trucks reduced the average and maximum lateral forces in the train by about 50 percent. Grade, lubrication, and rail profile also affect the lateral load environment. Each curve at FAST is unique due to its combination of these factors. Table E1 summarizes operating conditions and typical lateral load environment in the 5-degree curve of Section 7 and the 6-degree curve of Section 25.

Typical lateral load environment is in Sections 7 and 25 where: L_{50} = median lateral loads and L_{90} = lateral loads at the 90th percentile.

Table E1. Operating Conditions and Load Environment at FAST

Wheel Load (kip)	Truck Type	Lubrication	Degree of Curvature	Operating Speed (mph)	Rail Profile	L_{50} (kip)	L_{90} (kip)
39	Standard	High rail slightly contaminated. Low rail light indirect.	5	40	Conformal	5.8	8.6
		High rail gage face direct. Top of low rail light.	6	40	2-point	8.1	13.3
39	Improved	High rail slightly contaminated. Low rail light indirect.	5	40	Conformal	2.5	5.5
		High rail gage face direct. Top of low rail light.	6	40	2-point	4.5	8.1

There is a smaller range of values on most operating and track-maintenance variables with FAST than in revenue service. This is by design in order to isolate the effects of specific test variables such as wheel load. However, another result is to reduce the occurrence of infrequent high dynamic loads.

5.0 MAJOR FINDINGS

5.1 Effect of Truck Suspension

Truck suspension has been the largest single factor in tie performance during the HAL experiment. The use of premium-suspension trucks with better steering capabilities greatly improved the performance of all ties tested under 39-kip wheel loads as follows:

- Improved-suspension trucks provided a reduction of about 50 percent in the average lateral loads as compared with standard three-piece trucks.
- The gage-widening rate of ties in the 5-degree curve was affected more by the reduced lateral load environment under the improved-suspension trucks during Phase III than by tie specie/type or fastening system.
- In the 6-degree curve, during standard-truck operations in Phase II, two Western Hemlock Fir and two southern yellow pine subzones reached 1 inch over standard gage after 200 MGT. Two Douglas fir subzones reached the same limit after 360 MGT. These subzones were fastened with cut spikes.
- The gage-spreading strength of softwood ties with e-clip and SAFELOK® fasteners under standard trucks was comparable to that of softwood ties with cut spikes under improved-suspension trucks in Section 7 at 0.5 L/V static loads.

5.2 Effect of Materials/Design

Under the more severe load environment of standard trucks, oak hardwood tie performance, in gage-widening, was superior to the performance of softwood ties. Under the more benign load environment of improved suspension trucks, the performance of both hardwoods and softwoods was good. Both were markedly improved in gage-widening performance (compared to standard trucks). Other details are as follows:

- Parallel-strand (ties manufactured by laminating parallel strands of soft wood lumber with a weather-resistant adhesive) are the lumber ties currently in test in the 5-degree, 4-inch superelevation curve of Section 7 and in the 6-degree, 5-inch superelevation curve of Section 25 have accumulated over 220 MGT of 39-ton axle load steering truck traffic without signs of gage-widening problems.

- Ties in the Section 7 curve that were regaged after 920 MGT of service include:

  — Douglas fir ties with cut-spike fasteners

  — Douglas fir ties with e-clip fasteners

  — Oak ties with e-clip fasteners

- Oak ties in the Section 7 curve, fastened with cut spikes and double elastic fasteners, have been in service for over 940 MGT without regaging.

- Glue-laminated ties in the Section 7 curve were regaged after 781 MGT

- Plastic composite ties installed in Section 7 have accumulated over 240 MGT of steering truck traffic without signs of gage-widening problems.

- Single Tie Push Test results show that newly installed (unconsolidated ballast) rough-sided plastic composite ties provide more than twice the lateral resistance of newly installed wood ties.

- In the 6-degree curve, during standard-truck operations in Phase II, two Western Hemlock Fir and two southern yellow pine subzones reached 1 inch over standard gage after 200 MGT. Two Douglas fir subzones reached the same limit after 360 MGT. These subzones were fastened with cut spikes.

- Although higher than in solid hardwood tie track, the gage-widening rate of the mixed-specie subzone, where three southern yellow pine ties were installed for every oak tie, was a low 0.07 inch per 100 MGT under improved-suspension trucks.

- There has been no significant gage degradation in the Azobe cut-spike (520 MGT) and elastic-fastener subzones in the 5-degree curve of Section 31.

- During Phase III improved-truck operations, the parallel-strand lumber ties with e-clips and screw spikes, the dowel-laminated oak ties with cut spikes, and both the vertical and horizontal glue-laminated ties with cut spikes, performed comparably well in the 6-degree curve with an average gage-widening rate of about 0.02 inch per 100 MGT.

- Cedrite ties, spaced at 19.5 inches and secured with four screw spikes, were removed after 178 MGT during Phase II standard-truck operations due to rail-seat cracks in 90 percent of the 6-degree curve installation. The installation in the tangent test zone, spaced at 24 inches and held down with four screw spikes, remains in service after more than 400 MGT.

- Spruce ties, predrilled at ¾ inch for screw-spike hold-downs, were removed from service after 3 MGT due to screw spikes working out.

- In the 5-degree curve, the gage spreading degradation rate of both oak and Douglas fir ties fastened with cut spikes was nearly five times greater than similar track fastened with e-clips during standard truck operations.

- Two hundred steel-ties were installed in the 6-degree curve, with 64 ties extending into the spiral. The test zone was removed after 170 MGT. Track surface maintenance throughout the test zone was required about every 7 MGT. Curvature re-alignment was performed 7 times during the 170 MGT. There was significant ballast degradation and migration to the low rail due to track pumping. No surfacing or re-alignment was required in a wood-tie comparison zone during the period of performance. None of the steel ties or their components failed during the test.

5.3 Effect of Fasteners

Under standard-truck operations, use of elastic fasteners generally improved the gage-widening performance of most ties tested. The effect is larger for low-density species and ties. Under the premium-suspension truck operations, many more ties provide acceptable gage-widening performance. Other fastener findings include:

- The type of fastening system and the lateral load environment plays a greater role in determining the long-term degradation of gage-spreading strength than tie type or specie. The gage-spreading degradation rate of both oak and Douglas fir ties fastened with cut spikes was nearly five times greater than that of track fastened with e-clips during standard-truck operations in Section 7.

- The gage-spreading strength performance of softwood ties with e-clip and SAFELOK® fasteners under standard trucks was comparable to that of softwood ties with cut spikes under improved-suspension trucks in Section 7 at 0.5 L/V static loads.

- Under improved-suspension truck operations, the number of hold-down cut spikes in three southern yellow pine subzones, where all the ties were 7" x 9" x 8'5" and all had three rail spikes, did not affect the rate of gage-widening.

- During standard-truck operations of Phases I and II, problems with the fastening systems included loss of toe load, fractures of elastic fasteners, and hold-down screw spikes working out and fracturing below the tie surface.

- During improved-truck operations, screw spikes in softwood ties continued to work out and some fractured below the tie surface. One elastic fastener type fractured regularly at two rail-joint locations.

- With the cut-spike fastening system, increasing gage-spreading loads resulted in further weakening of gage-spreading strength. On the other hand, the elastic fastening systems tested provided increasing gage-spreading strength as gage-spreading loads were increased.

- Refitting the softwood ties in Section 25 with e-clips (originally installed with cut spikes) improved gage-retention after regaging. Maintenance of the badly split ties increased, however, due to screw spikes working up. The splits were caused by repeated track work due to the numerous rail defects that were removed and replaced in that test zone.

- Although the condition did not affect track geometry or stability, tie-skewing occurred in 19.5-inch tie-spaced track and in 24-inch tie-spaced track where double elastic fasteners were used.

5.4 FAST Test Section Effects

The limited space available in curves for testing rail materials, rail-maintenance policies, and crossties leads to an undesirable overlapping of component tests. The small size of the test sections in FAST and the lack of stiffness transition zones leave the tests vulnerable to the effects of uncontrolled variables such as rail breaks, bad joints, or other test section end effects, as described here:

- In the 5-degree test zone of Section 7 and the 6-degree test zone of Section 25, as much as 70 percent of the gage-widening measured was attributed to rail wear.

- Numerous rail changes, due to rail defects in the 6-degree curve was the cause of spike-killed ties during Phase II standard-truck operation.

- Out-of-face surfacing and alignment of the Wood Tie and Fastener test zones at FAST is generally required at 100 MGT+ intervals.

5.5 Failure Modes

Gage-widening is the largest cause of wood-tie maintenance at FAST. Lateral loading resulting in gage-widening, tie-splitting, and spike-killing are all seen. Vertical loading problems have been minimal, except at abrupt test-section stiffness changes. The dry climate of southeastern Colorado prevents wood decay from being a significant factor. Other failure-mode findings include:

- Tie-plate cutting has not been significant at FAST under improved trucks.
- Cracks in ties occur mostly on the field side of high rails, although cracks in ties have not been a major problem.
- Cracks originating at the high-side gage hold-down spikes on the majority of the oak dowel-laminated ties have not affected track strength while in service for 470 MGT.

6.0 SUMMARY

Gage widening was the predominant failure mode or cause for maintenance on wood-tie track at FAST. Due to the dry climate, decay was not a significant factor in tie degradation. The dynamic loading of ties in curves at FAST is dependent upon the rail profiles, lubrication, and truck types used. These factors affected the lateral loading and gage-widening performance of all test ties.

Variation in the characteristics of truck suspensions was the largest single factor in tie performance during the HAL experiment. The use of premium-suspension trucks with better steering capabilities greatly improved the performance of all ties tested under 39-kip wheel loads.

Under standard-truck operations, the use of elastic fasteners decreased the gage-spreading degradation rate by a factor of five compared top ties with cut spikes in a 5-degree curve.

Due to the climatic, geologic, and operating conditions under which tests are conducted at FAST, including the use of improved-suspension trucks which significantly reduce the lateral load environment, the performance of the ties and fasteners tested may differ from revenue service.

7.0 FUTURE WORK

Future crosstie testing at FAST will emphasize new and unproven materials or materials/fastener systems. The performance of existing materials and fastener systems has been shown for a variety of heavy-haul operating conditions during the first three phases of HAL testing at FAST. The testing of wood tie/fastener systems under standard trucks will continue. The lengths of tie test sections will be at least 100 ties to provide stiffness transition zones and to isolate the effects of uncontrolled variables; i.e., rail breaks, joints, etc.

APPENDIX F
BALLAST AND SUBGRADE STUDIES

Dingqing Li

1.0 INTRODUCTION

During the earlier phases of the FAST/HAL program, the ballast and subgrade studies were focused more on ballast performance and subgrade stresses under heavy axle loads. Four ballast materials were tested to quantify their performance based on the test results of track geometry, ballast density, track settlement, and ballast particle degradation. Tests were also conducted to quantify the amount of fine materials in the ballast generated by ballast tamping.

Recently, the effort has been focused on determining the effects of heavy axle loads on a low track modulus track built on a soft clay subgrade. Various remedies aimed at limiting soft subgrade deformation and failure have been tested, and their effectiveness have been evaluated.

2.0 BALLAST STUDIES

Four ballast materials: dolomite, limestone, granite and traprock were tested to determine their capability of supporting traffic in a 39-ton axle load environment. Test results showed that all the four ballast materials were able to withstand 39-ton axle loads. No substantial ballast degradations were measured for the four ballast materials at the end of 160 MGT. Granite and traprock ballast performed better in geometry retention than dolomite and limestone. The track segment with the dolomite ballast required an out-of-face tamping at 40 MGT and more frequent spot tamping (especially at surface problems on the rail). The track segment with limestone required an out-of-face tamping at 70 MGT. On average, the total accumulated track settlement was close to 2 inches during 160 MGT of traffic.

Testing showed there was no significant difference in track modulus caused by ballast types (granite, traprock, limestone, and dolomite). Track modulus, however, did vary with time and tonnage. Reasons for the variation include surfacing operations and frozen ballast. The measured average track modulus varied between 3,000 and 4,000 lbs/in/in for track built on the silty sand subgrade (with wood ties).

The ballast tests continued until 750 MGTs were accumulated. Through a direct comparison between 33- and 39-ton axle load, traffic cannot be made due to differences in ballast type and tonnage, it appeared that degradation was more dependent on accumulated tonnage than on increase in axle load. The granite and traprock ballast maintained adequate track geometry condition throughout the 750 MGT.

The dolomite required a second out-of-face surfacing after the first 260 MGT because of the increasing need for track maintenance and the addition of a concrete-tie rail-seat abrasion test section. It was then removed from the track.

Although the four ballast materials experienced different breakdown rates, the amount of breakdown under HAL traffic was relatively small after more than 750 MGT. Note that semi-arid climate conditions at TTC might be a factor in these results. Wetter climatic conditions might produce more particle breakdown under HAL.

Tamping operation caused significant ballast degradation. The dolomite ballast appeared to be more susceptible to tamper damage than the granite. Note that a related AAR study (AAR research report R-863, Chrismer, July 1994) showed that tamping every 15 MGT may decrease ballast life by about 43 percent, assuming a ballast life of 900 MGT.

3.0 SUBGRADE STUDIES

3.1 Native Silty Sand Subgrade

The measured increase in subgrade stresses varied 10 to 30 percent as a result of axle load increase from 33-ton to 39-ton. The largest subgrade vertical stresses were measured directly under the rail seats. However, the increase in subgrade stresses due to HAL did not affect the performance of the native subgrade soil (a firm subgrade support consisting of silty sand).

3.2 Soft Subgrade (Low Track Modulus Tests)

To characterize and to test potential remedies to large soft subgrade deformation and failure under heavy axle loads, a soft subgrade test section was built in 1991 in the High Tonnage Loop. The soft subgrade section was built by excavating a 700-foot-long, 12-foot-wide and 5-foot-deep trench into the native subgrade soil (silty sand). The trench was then backfilled with a Vicksburg (Buckshot) clay with high moisture content. To prevent the loss of clay moisture over time, the sides and bottom of the clay subgrade were lined with a plastic membrane. Since its installation, this subgrade has remained at an average moisture content of 33 percent.

The resulting track modulus with an 18-inch granular layer thickness ranged from 2,000 lb/in/in to 2,500 lb/in/in. For that reason, this test track is often referred to as the low track modulus (LTM) test track.

The LTM test showed that track built on a soft subgrade with a track modulus of 2,000-2,500 lb/in/in experiences rapid track geometry deterioration under 39-ton axle loads, due to excessive subgrade deformation. With an industry-standard granular layer thickness (12 to 24 inches) and a conventional ballasted track structure, HAL induced stresses at the surface subgrade were 10 to 20 psi in vertical stress. Stresses above about 12 psi can result in uneconomical maintenance requirements.

The measured vertical stresses in the subgrade under HAL were slightly lower for the LTM subgrade than for the strong silty sand subgrade (both with similar track structures). However, low soil strength of the LTM subgrade caused poorer LTM track performance than with the silty sand subgrade.

As a general comparison, the increase in settlement for a clean ballast or a strong subgrade (such as silty sand) due to the increase in axle load will be less than proportional, (the power for the clean ballast settlement increase is less than 0.5). However, the increase in settlement for the soft subgrade due to the increase in axle load will be more than proportional (in a power of greater than 2). This is illustrated in Figure F1.

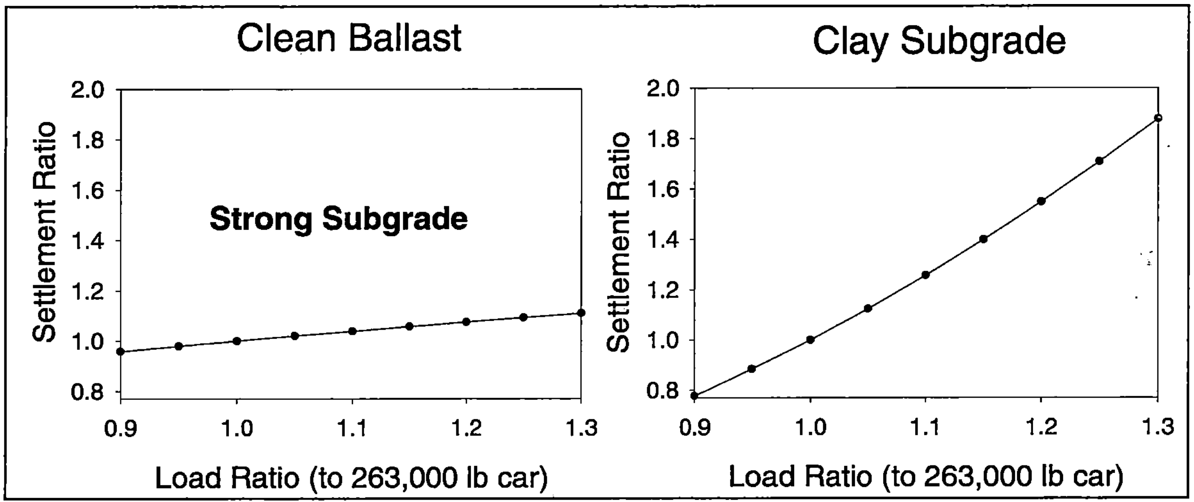

Figure F1. Change in Settlement with Increase in Axle Load

If poor track geometry is due to excessive soft-subgrade deformation, ballast tamping will not fix the geometry problem for the long term. Load-induced subgrade stresses will actually increase as a result of ballast tamping (30 to 50 percent in the LTM test). Tamping increases subgrade stresses for two reasons:

- The ballast is disturbed, which temporarily reduces its stiffness and ability to distribute loads

- The tamping tines tend to concentrate ballast under the railseats, which concentrates vertical forces transmitted to the subgrade.

For the LTM track, the increased subgrade stresses required up to 5 MGT to return to pre-tamping levels.

From 1991 to 1996, approximately 130 MGT was accumulated over the LTM. Under 39-ton axle loads, the LTM track with the early conventional construction (ballast and subballast) required frequent surfacing and several track rebuilds in order to maintain acceptable track geometry for normal FAST train operations.

With an 18-inch granular layer construction, the surfacing cycles required to maintain an acceptable track geometry averaged only 15 MGT. However, on several occasions (near the end before the next rebuilding, or with excessive free water on the subgrade), track geometry deterioration became rather rapid. Ballast tamping and surfacing was then required at a cycle as short as one or two MGT. Eventually, traffic had to be stopped for complete track rebuilding.

Subsequent investigations indicated significant subgrade squeezing (i.e., subgrade progressive shear failure) in the test zone. Subgrade surface soil from under the rail to the tie end was pushed outward and upward to the ballast shoulder. Free water was often observed in the depression formed at the subgrade surface.

Together with the field test, laboratory tests were also performed to quantify the failure mechanisms of the soft subgrade soil under repeated load applications for the benefit of selecting the most effective remedies. By using undisturbed soil samples from the LTM subgrade, it was found that the actual variation of soil saturation (or moisture content) had a tremendous effect on soil sample performance under repeated load applications. Higher confining stress applied to a soil sample led to higher strength in resisting soil deformation and failure. A comparison between laboratory soil strength test results and field stress measurements indicated that subgrade stresses generated under the HAL train frequently exceeded soil dynamic strengths, especially at the nearly saturated locations. Therefore, the most effective remedies to the soft subgrade deformation and failures, without replacing and improving subgrade soils, should provide subgrade stress reduction, minimize free water, and increase confinement to the subballast and subgrade.

To reduce stresses in the LTM subgrade, the granular layer thickness was increased to 27 inches by increasing the subballast layer from 6 to 15 inches, based on design analysis. Therefore, the most effective remedies to the soft subgrade deformation and failures, without replacing and improving subgrade soils, should provide subgrade stress reduction (increased granular layer depth or stiffness), minimize free water (improve drainage), and increase confinement to the subballast and subgrade (cellular confinement or hot mix asphalt). The track geometry car recorded little geometry degradation until 9.3 MGT, when a heavy rainfall completely flooded the thick subballast layer, limiting the ability of the subballast layer to distribute load-induced stresses to the subgrade. Due to increased stresses in the subgrade, the subgrade deformed rapidly and track geometry was out of specification within the next several MGT.

In early 1997, the track was rebuilt with the application of a geosynthetic reinforcement called GEOWEB®. Because the sides of GEOWEB cells provide lateral confinement to the subballast, the compacted GEOWEB/subballast composite layer became much reinforced, resulting in increased stiffness, and therefore, more load-bearing capacity than the subballast layer alone. As a result of the GEOWEB application (24 inches of total thickness for ballast plus GEOWEB/subballast), track modulus was increased and stresses in the subgrade were reduced by about 25 percent. The LTM track did not require major track maintenance for close to 200 MGT (or close to three-year duration). Therefore, use of the granular layer with GEOWEB reinforcement greatly improved LTM track performance under heavy axle loads. A comparison with standard track is shown in Figure F2. The profile deviations shown wouldn't have required tamping to maintain FRA Flass 4 standards. But, the cross-level deviations that correspond to the profile deviations did.

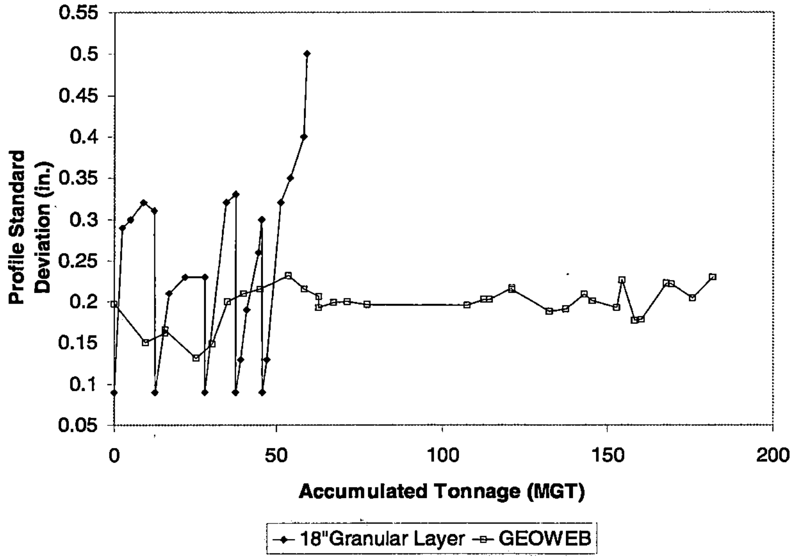

Figure F2. Comparison of Track Degradation with Standard Track and GEOWEB

In the summer of 1999 following the conclusion of the LTM GEOWEB test, a different potential remedy to the soft subgrade under HAL was constructed over the soft subgrade. This remedy involves the application of asphalt track beds (underlayments) over the soft subgrade for the HAL environment. The entire LTM was divided into two subsections: one for testing a 4-inch hot mix asphalt (HMA) layer, the other for testing an 8-inch HMA layer. The combined thickness (ballast, HMA and subballast) was 20 inches for both subsections. At this time, about 40 MGT has been accumulated over this test track, and it has been performing well.

3.3 Cost Comparison of Remedial Methods to the Soft Subgrade

A cost analysis was conducted in 1999 to compare several techniques of repeated tamping, increasing granular layer thickness and placing a GEOWEB or HMA layer, aimed at stabilizing the track over a soft subgrade similar to the LTM test track. Using typical industry cost figures, the economic analysis showed that the most cost-effective selection is very dependent on traffic volume. For the HAL condition studied at FAST, the analysis indicated that continued tamping of the ballast could be the best choice when the annual tonnage is less than 40 MGT. While tamping does not fix a subgrade problem, it may provide economically maintainable track geometry for lower tonnage track. For track with moderate to high tonnage levels, it may be cost effective to more permanently fix the problem, even if this involves removing the track from service for a short time. For annual tonnage greater than 50 MGT, fixing the problem with a remedial technique is less costly. Of the two remedial techniques compared, increasing the granular layer thickness appears to be the lower cost option, mainly because of the lower material cost compared to GEOWEB or asphalt. Extremely heavy rainfall can cause the thick granular layer to fail, as was experienced at FAST. However, this is less likely in ballast than in a finer subballast.

APPENDIX G

FAST BRIDGE

Richard Joy and Duane Otter

1.0 INTRODUCTION

In November of 1997 construction of a 121-foot bridge in Section 5 of the High Tonnage Loop (HTL) at FAST was completed. This test bridge is being used to evaluate practices for track maintenance and design on bridge decks and approaches, and to improve safety and performance under heavy axle load (HAL) traffic.

2.0 OBJECTIVE

One objective of the program is to evaluate variations in bridge deck design. The original bridge deck was built according to Conrail specifications. Other deck designs will be evaluated as the original deck deteriorates. A second objective is to evaluate bridge approach design and maintenance practices. Because several cracks have initiated in the steel bridge girders, a study of fatigue characteristics of welded steel bridges has been initiated.

3.0 BACKGROUND

The test bridge consists of two steel plate girder spans donated from a Conrail bridge in Jersey City, New Jersey. Although the spans were built in 1957 and 1968, they had experienced very little tonnage since installation. It is likely that the 56-foot span carried less than 5 MGT total and the 65-foot span less than 10 MGT total. The traffic most likely consisted of 70-ton cars (220,000 pounds gross rail load) or lighter. The spans were originally designed for a Cooper E-72 loading with diesel impact. The bridge accumulated about 300 MGT. Figure G1 shows the bridge shortly after installation.

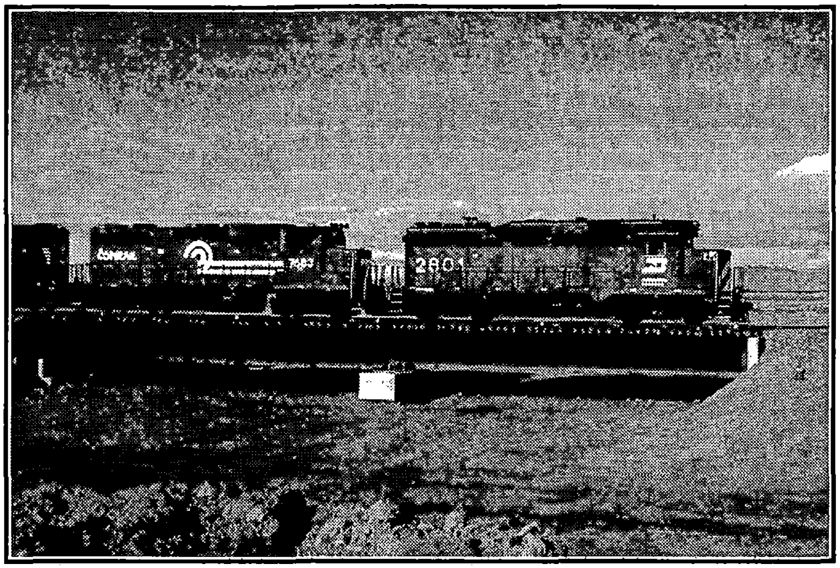

Figure G1. FAST Bridge

4.0 METHODOLOGY

Tests to date have been carried out to monitor degradation of the deck and approaches and to characterize the load environment. Specific tests have included:

- Monitoring of track geometry on the bridge and approaches using regular track geometry car measurements as well as standard survey measurements
- Initial vertical track modulus (VTM) measurements on bridge approaches using TTCI's Static Track Loading Vehicle (605 car)
- Initial wayside measurements of dynamic forces and displacements under standard Phase III operation
- Regular instrumented wheelset measurements
- Measurement of longitudinal loads experienced by the bridge under operation of high adhesion, alternating current locomotives
- Measurement of thermal loads
- Monthly inspection of the bridge during train operation
- Monitoring and recording of all bridge maintenance
- A crack growth study as described below

Both spans have developed cracks originating in the beam web between the bottom of the intermediate stiffener and the flange. The first crack was discovered in the

65-foot span only 14.4 MGT after bridge installation. Cracks continue to be discovered and grow. All cracks appear to have initiated at fabrication details with intersecting welds at the bottom of intermediate stiffeners. By 82 MGT, one of the cracks propagated into the tension flange of a girder, and it was decided to install a helper crib beneath that span.

In order to observe crack growth, TTCI engineering staff, along with the AAR Engineering Research Committee decided to allow the 65-foot span to deflect freely under load. This crack growth study coincided with the start of Phase IV with 144 MGT of traffic over the bridge since installation. At that time, a no-load clearance of about 1-1/2 inches was provided between the helper crib and the span.

Several measures were put in place to assure safety in the event of a sudden failure. A second helper crib was installed opposite of the vertical crack to provide additional support and stability in case of sudden failure, and an alarm was installed to alert train operators of abnormally high deflections.

At the beginning of the crack- growth study, ultrasonic inspections of the vertical crack were scheduled daily. With little or no crack growth apparent, the inspection interval was increased to every other day of operation, then to once a week, corresponding with ultrasonic rail inspections.

5.0 PHASE III RESULTS

Wayside measurements of forces under normal FAST operation were taken in several places on the bridge about 90 MGT after bridge installation. Maximum vertical load was about 50 kips, and maximum lateral load was about 5 kips.

Instrumented wheelset (IWS) measurements were taken at 110 and 130 bridge MGT. During this period, maximum vertical loads ranged from about 50 kips to about 55 kips. Lateral loads increased from 4 to 8 kips over the same period. The increase in lateral force corresponds with an increase of cross level as measured by the track geometry car over the same period.

Bridge approach settlement had resulted in rail profile deviation from a 62-foot chord of about 1.3 inches by 120 MGT since bridge installation. Both approaches were raised and tamped at that time.

The bridge deck showed little deterioration during this period. Maximum movement of the ties along the girder was about ½ inch. One tie hook-bolt was found broken and was replaced. About 16 hook-bolts had loosened enough to be ineffective, but no corrective action was taken.

A total of 14 cracks were discovered in the 65-foot span during Phase III. All cracks initiated in the area of intersecting welds between the bottom of an intermediate stiffener and the bottom flange of the girder. Two of the cracks have had stress-relief holes drilled at the ends to arrest growth.

The largest crack (see Figure G2) was detected after 37 MGT (230,000 cycles) of HAL traffic. This crack is at intermediate stiffener No. 6. Intermediate stiffener No. 7 is at mid-span. The crack runs nearly 7 inches vertically into the beam web. Shortly after it was detected, a 7/8-inch hole was drilled at the top of the crack to stop crack growth in the upward direction. During inspection after 82 MGT (520,000 cycles), it was noted that the crack ran downward into the tension flange. At that point, the crack in the tension flange was about 4 1/2 inches long and up to 3/16 inch deep.

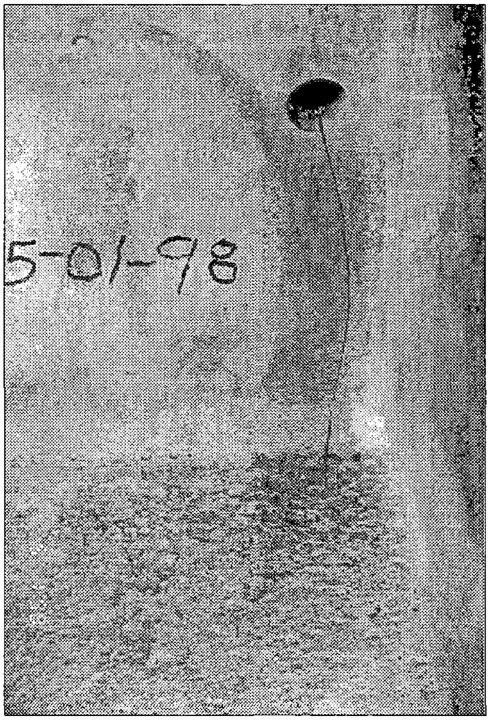

Figure G2. Crack Propagating into Tension Flange of Welded Girder

Figure G3 shows a crack near intermediate stiffener No. 7 in the same girder. This crack is typical. Similar cracks have been found in both girders of this span. This particular crack has been drilled at both ends with 7/8-inch diameter holes. So far no growth has been noticed beyond the stop-holes. Some of the smaller cracks that are not big enough to drill properly have continued to grow.

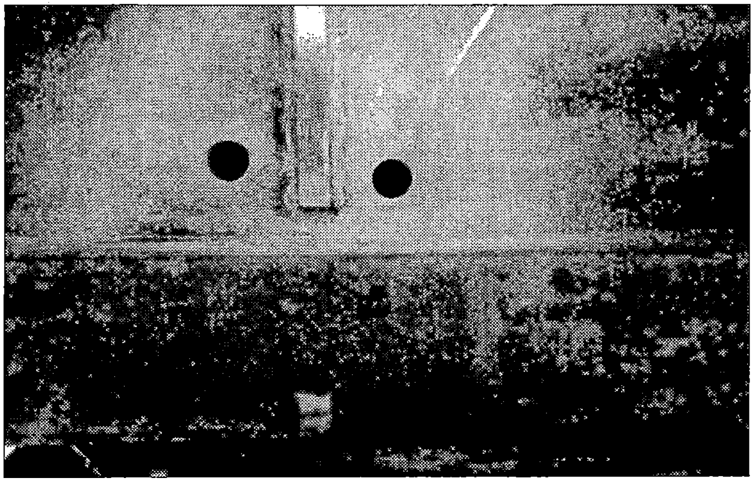

Figure G3. Typical Crack in 65-Foot Welded Steel Bridge Girder with Poor Weld Detail

6.0 PHASE IV RESULTS

The change in operating conditions that occurred between Phases III and IV did not affect bridge performance.

Thermal rail forces measurements were taken over a one-week period during July of 1999, when daily ambient temperature differences as high as 40° F were recorded. During this period, peak-to-peak force rail force swings as high as 350 kips for both rails were measured. Maximum compressve or tensile forces cannot be given since the rail neutral temperature was not determined.

Deterioration of the approaches was minimal (less than a ½-inch change in profile) during Phase IV, but the east approach was resurfaced in conjunction with other maintenance at about 201 bridge MGT. The bridge deck was also quite stable, but several more turned hook-bolts were discovered.

Instrumented wheelset measurements taken at 190 MGT showed no change in maximum vertical loads. The maximum lateral load increased to about 10 kips, again corresponding to an increase in cross level.

By 144 bridge MGT, the vertical crack in the 65-foot span had propagated to a depth of almost 1 1/8 inches into the tension flange. No further growth has been detected. Smaller cracks continue to grow and are noted.

Additionally, two significant cracks were discovered in the 56-foot span. These cracks are on the beam web at the first intermediate stiffener from the end of the span. The first crack was noted as a minor defect at 180 MGT after bridge installation. By 193 MGT the crack was clearly evident, running about a 4 ½ inches along the web-to-flange weld on the outside of the web. A second crack was also noted at that time on the inside of the web, at the bottom of the same intermediate stiffener. This crack was about 2 1/2 inches long at the time of discovery. Figure G4 and G5 show the cracks on the inside and outside of the 56-foot girder.

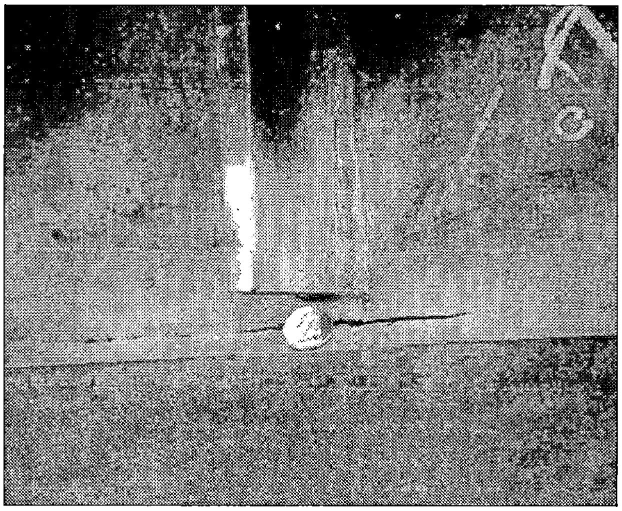

Figure G4. Crack in Outside of 56-Foot Girder

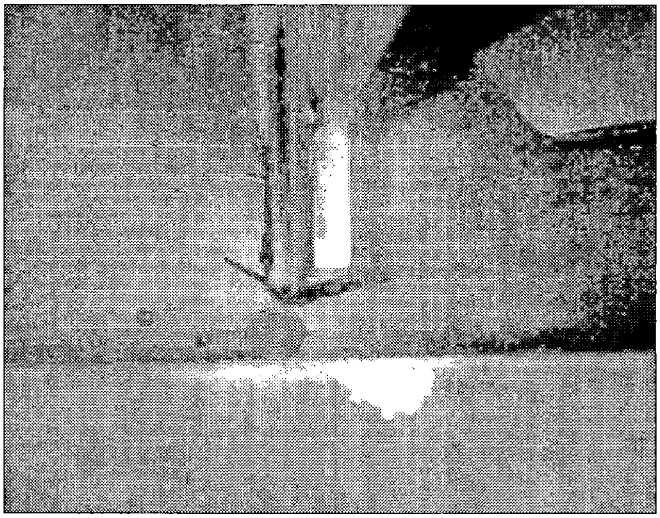

Figure G5. Crack in Inside of 56-Foot Girder

7.0 SUMMARY/CONCLUSIONS

Bridge deck and approach deterioration has been minimal during the first 300 MGT since installation of the FAST Bridge. The approaches have required tamping approximately every 100 MGT. Fatigue cracking in the steel spans has been a larger concern.

Numerous cracks have developed in the first 300 MGT (1.3 million cycles) of heavy-axle-load train operation. The following results have been noted since installation of the bridge in November 1997:

- Several cracks developed in both bridge spans.
- Some cracks were visible after only a few weeks of HAL-train operations.
- End-stress relief by hole drilling has halted the growth of some cracks.
- New cracks continue to be noted and are growing.

All girders in both spans are of welded fabrication. This type of fabrication is very stiff compared to bolted or riveted construction. The span that cracked earliest, and has more cracks, is one of the earliest welded-steel railway bridge spans.

The intermediate stiffeners of the 65-foot span were designed to allow 3/4-inch clearance from the bottom of the stiffener to the top of the tension flange, with welds wrapped around the bottom of the stiffener. Figure G4 shows this detail. On the 56-foot span, the intermediate stiffeners were designed to allow 1-inch clearance from the bottom of the stiffener to the top of the tension flange. The welds do not wrap around the bottom of the stiffener. Current American Railway Engineering and Maintenance of Way Association (AREMA) recommended practice calls for a distance of four to six times the web thickness between welds, which would be 2 1/2 to 3 3/4 inches for the 65-foot span.

Although the detail for the 56-foot span still does not meet current AREMA-recommended practice, fewer cracks have been noted in this span. The fact that there is some separation rather than overlap between welds might be one reason that fewer cracks have been noted so far.

Research is currently being conducted under AAR's Strategic Research Initiative (SRI) program to determine the number of bridges in service with these poor details. As HAL traffic increases, these bridges are more likely to develop cracks. They should be evaluated for inspection on an accelerated basis so that appropriate action may be taken in case cracking occurs.

APPENDIX H

HAL-RELATED BRIDGE RESEARCH

Shakoor Uppal and Duane Otter

1.0 INTRODUCTION AND OVERVIEW

In 1989 the Association of American Railroads (AAR) began a bridge research program which relates directly to the issue of heavy axle loads (HAL). The emphasis early in the program was on steel bridges. Steel bridges account for about 55 percent of all railroad bridges by length on Class 1 lines in the U.S.A. and Canada. A majority of the steel railway bridges are more than 60 years old, and they took into account what are now called "fatigue effects", based on experience and intuition rather than the formal design calculations used in modern design and ratings. With increases in carloadings, fatigue has become a significant issue for steel bridges.

The bridge research program began by measuring several bridges to develop load spectrums for various types of train traffic, including unit trains, intermodal, and mixed freight.

Wheel and axle load distributions were determined, and the effects of impact were quantified. Bridges tested included deck plate girders with both open and ballast decks, through plate girders with both open and ballast decks, and three through truss bridges.

These tests also were used to develop stress spectrums for specific members in these various types of bridges. Additionally they tests were used to develop an understanding of the stress distributions and load paths in various members of these bridges. In conjunction with the tests, models were developed to accurately reflect the actual behavior of bridges, as opposed to the simplified behavior typically assumed for design.

Using the knowledge obtained from these tests, the AAR developed a steel bridge fatigue evaluation computer program and fatigue life charts for steel bridges. These tools can be used to estimate fatigue life of various components in different types of steel railway bridges. They consider different types of traffic, and assume a more realistic behavior than is typically used for design.

Since development of these tools, they have been used by the AAR to evaluate specific bridges carrying HAL traffic, to evaluate effects of HAL traffic on the bridges along a typical coal route, and to contribute to economic analyses of the costs and benefits of HAL traffic to the industry. These tools have also been used to recommend member replacement strategies for prolonging the life of specific bridges on lines being considered for HAL traffic.

Similar work is now proceeding for timber bridges. As with steel bridges, the timber bridge inventory has provided several decades of service. Timber bridges make up about 28 percent, by length, of the bridges on Class 1 railroads in the U.S.A. and Canada.

As with the steel bridge program, the timber bridge research began with testing of load path and load distribution in timber trestles. This was followed by testing of various strengthening techniques used to upgrade timber bridges for HAL traffic.

Testing is currently under way to develop S-N curves for timber stringers, so that timber bridge life estimates can be made. In addition, timber bridge maintenance cost information is being gathered from member railroads. The end goal is to complete development of an economic model for timber bridges, similar to what has been done for steel bridges.

2.0 SELECTED TEST RESULTS

2.1 Static and Dynamic Testing of a Through-Truss Bridge

This bridge was instrumented to measure truss deflection, and vertical and lateral wheels loads on the track at various locations. Many static and rolling tests were conducted using a work train. In addition to the controlled static and moving test, unattended tests were conducted utilizing remote site monitoring to record the passage of revenue freight trains.

For the truss members, the measured stresses were larger than the theoretically calculated stresses by 10 to 30 percent. For the floor structure, the calculated values were 10 to 30 percent larger than the measured values.

2.2 Loading Spectrum and Response for a Railway Bridge on a Mixed Freight and High Speed Intermodal Line

Some of the primary conclusions reached from the analysis of the experimental and theoretical results are:

- Bending strains in the flanges of the plate girders and bracing members can be measured accurately and easily in the field.
- Adequate agreement is obtained between measured and calculated girder strains and displacements when measured wheel loads are used for the analysis.
- Measured vertical loads on this line are smaller than those expected for

100-ton cars. Only 11 percent of the wheel loads on the mixed freight cars and 13 percent of the wheel loads on the intermodal cars exceeded 30,000 pounds.

- Impacts measured on this bridge are about 1/3 of those presently used for design and evaluation.
- The low level of strains measured on the primary members indicates that there is little fatigue damage occurring in the bridge under the current traffic environment.

2.3 Investigation of a Ballasted Deck Steel Plate Girder Railway Bridge

Vertical and lateral wheel loads were measured for 80 train passages. Bending strains were measured in the flanges of both girders for each train passage. Axial force and moment were also estimated for six of the bracing members.

The maximum bending stress experienced by either flange was about 4.5 ksi. This corresponds to about a Cooper E46 locomotive without impact. Each train passage caused an average of 56-stress cycles in the girders that ranged from 1 ksi to 4.5 ksi. The equivalent constant amplitude stress cycle was only 1.4 ksi. Therefore, very little, if any, fatigue damage is occurring under current operating conditions. This result, however, may not be generalized to other bridges.

Calculated bending stresses are typically larger than measured values by 10 to 20 percent. Calculated displacements are at most 10 percent larger than measured ones. Moments and axial forces in the bracing members are typically quite small.

This span responded dynamically to the passage of a work train crossing at high speeds. More significant cycles of stress occurred, and the peak stresses were higher than for slow passes.

2.4 Investigation of an Open Deck Through-Truss Railway Bridge: Work Train Tests

Both static and controlled dynamic tests were performed using a work train. The objectives of this investigation were as follows:

1. Determine the magnitudes of secondary bending moments in main truss members under static and dynamic loadings.
2. Determine how the floor system participates with the trusses in carrying vertical loads.
3. Evaluate the ability of various analytical models to predict the measured bridge behavior.

4. Determine the effective fixity of floor beam-to-truss connections and of stringer-to-floor-beam connections.

The results indicate that the secondary moments produce significant stresses in truss members.

In-plane vibration of hangers during a train passage caused a significant increase in the stresses in the hangers and a smaller increase in stresses in the adjacent chord members. This vibration may have a significant impact on fatigue damage of hangers.

The measured stresses were compared to analytical results from five different models of the bridge. The calculated results indicate that the floor system and bracing members have a significant effect on the axial forces carried by the lower chord members. The stringers carry tensile axial forces.

The results of this investigation lead to the following conclusions:

- Secondary bending moments in truss members are important since they produce combined stresses that range from about 20 percent to over 60 percent of the axial stress in members. Bending moments are assumed to be zero for design.
- For some members (most notably hangers) the secondary moments are larger under dynamic loads than under static loads. Therefore it is important to measure static and dynamic bridge response for evaluation purposes. Vibration of members makes a significant contribution to this effect.
- The hangers are the most highly stressed members with combined stresses exceeding those predicted by the models used.
- A simple pinned truss model will overestimate the axial stresses in all of the members in a truss bridge except the hangers. This is especially true for the lower chord members. The reason for this is that the stringers participate with the lower chord members in carrying axial tensile forces.

2.5 Investigation of an Open-Deck Through-Truss Railway Bridge: Revenue Traffic Tests

There were three objectives of the revenue traffic tests. The first was to develop a spectrum of wheel loads at the site. The second was to measure the dynamic stresses that this truss bridge develops in selected members under this loading environment. The third objective was to demonstrate the use of field measurements in predicting the remaining life of railway bridges.

Fourteen percent of the freight car dynamic axle loads exceeded 70 kips, but only 0.2 percent exceeded 80 kips. These are primarily from unit coal trains. For locomotives, 24 percent of the dynamic axle loads are between 70 and 80 kips.

The hangers vibrated considerably with each train crossing. This led to relatively large stresses and large numbers of cycles.

An evaluation of the estimated fatigue life at seven member locations was made using the measured spectrum of stress cycles.

The measured data and analytical studies lead to the following conclusions:

- Localized vibration of members during a train crossing leads to a large number of cycles of member response at low stress levels. These cycles were found to be significant for the level of loads that the bridge is currently carrying.

- The combination of strain measurements and analytical models provide a convenient method for evaluating the remaining fatigue life of existing bridges.

2.6 Response for an Open-Deck Through Plate Girder Railway Bridge

The primary objective of this study was to determine the participation of the knee braces in the response of the bridge. Another objective was to determine the load path through the floor system of the bridge and investigate the continuity of the stringer-to-floor beam connection. The final objective was to determine the influence of the track structure in distributing the rail forces into the floor system. The experimental results indicated that the knee braces do not participate in the transfer of load from a floor beam to a plate girder. However, the knee braces may still be essential in providing lateral stability to the compression flange of the plate girder.

The continuity of the floor system in this bridge reduced the mid-span bending moments in the stringers from what would be expected if simple connections were assumed at the ends. The shear and bending moment in the floor beams and plate girders were hardly influenced by the continuity of the floor system. Similar results were reported for the influence of the track structure.

2.7 Investigation of Effects of 110-Ton Cars on a Pin-Connected Truss

Results of revenue service testing on a 165-foot, pin-connected, open-deck, through-truss bridge conducted by the AAR showed that HAL trains (286-kip cars) caused more fatigue life than conventional (263-kip cars) trains in all members of the bridge. The use rate of remaining fatigue life due to the HAL train was about 1 to 7 times higher than the axle-load increase for some members and their components.

Fatigue life usage rates increased 9 to 12 percent in the stringers, 16 percent in the floor beams, and up to 37 percent in hangers. Lower chord and diagonal members experienced less fatigue life useage, but the increase in fatigue life usage rate under HAL trains ranged from 9 percent to as high as 63 percent.

2.8 Economic/Fatigue Implications for Heavy Axle Loads on Steel Railway Bridges on An 1100-Mile Coal Route

The AAR used its Steel Bridge Fatigue Model, which evaluates the remaining economical life of steel railway bridges, to evaluate the maintenance costs of steel bridges on an existing coal route with heavy axle load traffic.

In terms of bridge maintenance expenses on a net ton basis, running 286-kip cars is 12 percent more expensive than running 263-kip cars. Running 315-kip cars is 67 percent more expensive. Note, however, that these conclusions are highly route specific.

3.0 CONCLUSIONS

The AAR bridge research program has accomplished the following for steel railway bridges:

- Developed load spectrums for various train traffic
- Developed stress spectrums in various types of bridges and members
- Increased understanding of load paths in various members and types of bridges
- Developed models to accurately reflect actual behavior of bridges
- Developed steel bridge fatigue evaluation model
- Developed fatigue life charts
- Evaluated specific bridges carrying HAL traffic
- Recommend member replacement strategies
- Evaluated HAL traffic effects on bridges on a typical HAL coal route
- Conducted economic analyses of the bridge costs due to HAL traffic.

Similar work is proceeding for timber bridges:

- Testing of load path and load distribution in timber trestles has been completed
- Testing of various strengthening techniques for HAL traffic has been completed
- Development of S-N curves for timber stringers is ongoing
- Gathering of timber bridge maintenance cost information from railroads is ongoing
- Development of an economic model for timber bridges is planned.

APPENDIX I

HAL REVENUE SERVICE STUDIES

David D. Davis and Ryan McWilliams

1.0 BACKGROUND

The Association of American Railroads (AAR) and the Federal Railroad Administration (FRA) have jointly funded a research program to evaluate the safety and performance of operating heavy axle load trains for freight service. This program has evaluated the effect of 315-kip cars on track, track components, and track maintenance at the FAST facility since 1989.

The AAR has funded companion efforts to evaluate the economics of heavy axle load (HAL) service and to monitor the effects of, and the rate of introduction of, 286-kip cars in revenue service.

The HAL Revenue Service Monitoring Experiment is a supplement to the HAL Experiment at the Facility for Accelerated Service Testing (FAST). As such, the HAL Revenue Service Experiment has served as the "bridge" between the theoretical work done by Transportation Technology Center, Inc. in modeling and testing under controlled conditions and the typical heavy haul mainline railroad conditions.

HAL revenue service tests have concentrated on areas of concern that are not or cannot be adequately represented in FAST. These include bridges, special track work and wood ties in a moist environment. Space limitations at FAST prevent the testing of a statistically valid sample of bridges and turnouts in a reasonable amount of time.

The results from the introduction of 286-kip cars in revenue service have been similar to what was expected from theoretical and experimental work. There has been an increase in measured loads and strains for most components. However, the rate of introduction of 286-kip cars has been gradual enough that the effect on most component replacement rates and maintenance spending has been economically acceptible. Some exceptions have been noted in the area of bridge maintenance. As stated in previous HAL economics reports, the effects of HAL on bridge costs are likely to be very site specific.

Table I1 lists these revenue service test sites.

Table I1. HAL Revenue Service Test Sites

Location	Railroad	Test Component	Recent Annual Tonnage Rate	Percent HAL Traffic
North Platte Sub	Union Pacific	Turnout Frogs	170	38
North Platte Sub	Union Pacific	Bridge Maintenance	170	38
Oakvale, WV	Norfolk Southern	Wood Ties and Fasteners	50	Estimated 20
St. Albans	CSX	Load station	40	20
Various	BNSF, NS, CSX	Thermite Welds	Various	Various

2.0 LOADS

Two load stations have monitored the rate of introduction of 286-kip cars in track on the Union Pacific and CSX railroads. The rate of introduction of 286-kip car traffic has been similar at both sites, with a rapid introduction starting in the early 1990's. The percentage of 286-kip cars has leveled off since 1996 at about 38 percent. Figure I1 shows the volume of 263- and 286-kip car traffic for each year since 1992.

Another fact gleaned from the Union Pacific load station data is that the typical 286-kip car is carrying 111 tons of coal and has a gross vehicle weight of about 286 kips. However, the average "100-ton" car is carrying 105 tons and has a gross vehicle weight of about 270 kips.

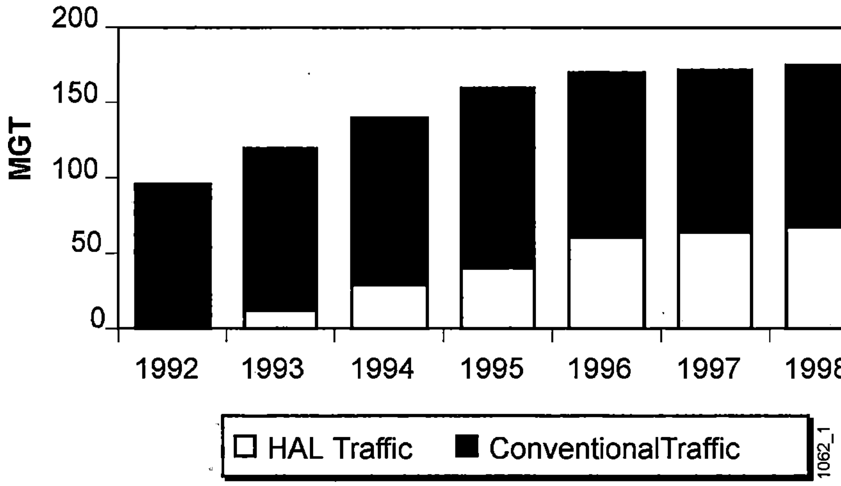

Figure I1. Percentage of HAL Traffic vs. Time

3.0 TURNOUT FROGS

The effect of HAL traffic on No. 20 turnout frogs at one test site on a busy coal line has been less than the improvements in technology over the period of 1990 to 1998. Turnout frog life has increased from 346 to 595 MGT over the period when HAL traffic has increased from 0 to 38 percent of the total. The implementation of design and maintenance improvements in turnout frogs during this time includes the use of elastic fasteners, gage plates, independent guard rails, low impact heel joints and high-integrity castings. These factors have strengthened the frog while also reducing the impact loading.

The use of high-integrity castings has had the largest positive effect on frog life. The high-integrity casting makes weld repairs more likely to be successful. Thus, while the increased impacts have kept the running surface life of the casting (or time to first weld repair) about constant at 100 MGT over the period of the study, the average life of weld repairs has increased from 22 MGT to 39 MGT. The average life of each type of frog and its weld repairs are shown in Figure I2. The blocked segment at the left indicates tonnage until the first weld repair. The vertical lines indicate subsequent welds. About the same number of repairs were made on the standard and high integrity frog castings.

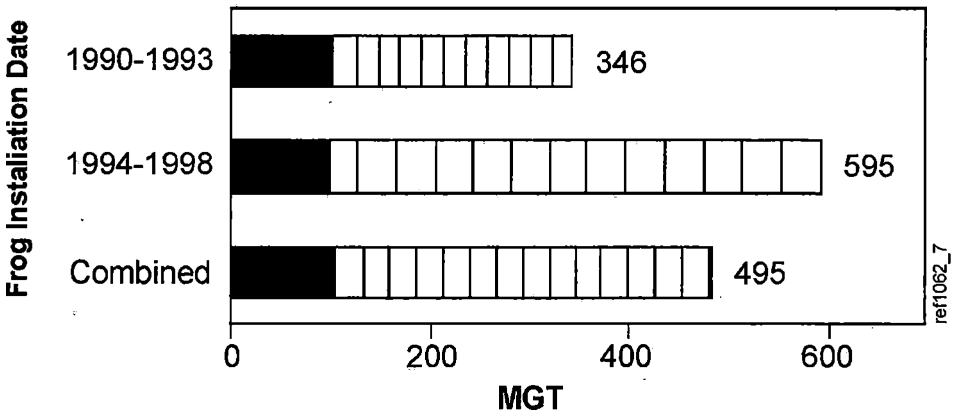

Figure I2. Frog Life by Installation Date

4.0 BRIDGE MAINTENANCE

The effect of HAL traffic on bridge maintenance for one heavy haul line segment has been quite illuminating. Because of the wide range of bridge designs, ages and conditions in service, the results from this study are not universally applicable.

However, they do suggest what can happen on a major mainline that has a rapid introduction of HAL traffic.

The HAL traffic caused pumping of the steel pile trestles on this particular line, resulting in the loss of track surface. Thus, the effect of HAL traffic on a particular bridge foundation was to exceed a capacity threshold. The effect of the pile pumping on bridge maintenance spending was actually small. The problem was confined to a few locations; where a large portion of the bridge maintenance budget was spent. The short-term effect was to shift resources from other bridge maintenance activities; rather than to increase the overall spending.

The line and its bridges had undergone a significant amount of upgrading work in preparation for the introduction of HAL traffic. Previous studies of the effects of HAL traffic on a variety of bridge types suggested that the effect of 286-kip cars would be to increase fatigue life utilization by 3 to 15 percent per unit of traffic as compared to 263-kip cars. It is still too early to see the effects of HAL traffic on bridge component fatigue.

A study of a through-plate-girder bridge on this Union Pacific line showed that selective member replacement was a sound economic strategy for HAL upgrading. Often, it is the floor system of the bridge that is most prone to fatigue damage from heavier loads. In this case, it was the floor beams that were most affected by HAL traffic.

5.0 CONCRETE TIES

Introduction of HAL traffic has caused an increase in the strains measured in concrete ties in service on an eastern coal line. The increased strains are generally still below the tie design cracking strains. Thus, the effect on tie life and tie replacements has been nil to date.

6.0 WOOD TIE/ FASTENER GAGE WIDENING STRENGTH

The effect of HAL on gage widening in wood tie track on NS was relatively low with a rate of 0.128 inch per 100 MGT with elastic fasteners. The rate was higher than it had been under cut spike fasteners and large (18 inch) tie plates. The smaller elastic fastener plates suffered from a higher rate of plate cutting. The elastic fastener ties had a higher gage widening strength than the ties with cut spikes, however. Other tests have shown reduced gage widening with elastic fasteners.

APPENDIX J

HAL Economic Analysis: Annotated Bibliography

Carl D. Martland

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Massachusetts Institute of Technology

May 7, 1999

This bibliography identifies the reports, papers, studies, memos, and other materials that were used by or produced as part of the Economic Analyses conducted for Phases I, II, and III of the AAR's Heavy Axle Load Research Program. Brief notes summarize the contents of each item and its use in the HAL economic analysis.

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HAL Economic Analysis: Annotated Bibliography

This bibliography is divided into the following sections:

Brief descriptions of the relevant portions of each report or study are given immediately following the reference. In many cases, there is also a comment on the use of the reference in the HAL economic analysis; these notes are enclosed in brackets to indicate that they are commentary about the use of the reference rather than a continuation of the summary. Note that these reports contain information that was current at publication.

PRIOR STUDIES AND PAPERS

M.D. Roney, "Meeting the 100-ton Challenge: Report on Heavy Axle Load Lines in Australia," AREA Bulletin No. 683, June-July 1981, pp. 412-428

Roney reported his findings from participation in the First Heavy Haul conference, spending a year with the BHP Melbourne research labs, and visiting with the officials responsible for innovative heavy haul operations on railways operated by Mt. Newman Mining and Hamersly Iron. Among the practices used in Australia that were not then common in the US were profile grinding on curves, use of premium rail in medium curves (greater than 1 degree), and the use of wear standards allowing much more loss of the rail head. [Note: the Australian experience was relevant to the North American HAL studies, because these railroads moved to 36-ton axle load operations before HAL Phase I was completed. Their ability to operate with these loads, their use of premium components, and their attention to maintenance and inspection were well understood by the HAL Phase I Economic Analysis Task Force.]

Report of Subcommittee No. 3, Committee 16- Economics of Plant, Equipment and Operations, AREA Bulletin #694, January 1984, pp. 87-97

This AREA sub-committee report summarizes the expected effects of 263,000- and 315,000-pound cars on lives of the major track components. The sub-committee included well-respected members of the railway engineering community and certainly represented the best estimates of the effects of heavier loads on the track structure in place at the time. Three of the members of this committee (Allan Zarembski, Tom Hutcheson, and Lou Cerny) later participated in or reviewed the HAL Economic Analysis. The major concern in the early 1980s was the impact of the 100-ton car on costs. They estimated costs would nearly double for rail and rise 20% for other track components. The predictions were even more pessimistic regarding the 315,000 pound car: rail costs were expected to rise 50% on tangent track and 33% on curves compared to the costs for the 263,000 pound car. Tie costs were expected to rise 40-100%, while ballast & subgrade costs were expected to rise 10 to 100%. The committee concluded that the track structure could handle 263,000 pound and heavier cars and that the optimum GVW is an economic matter. [Note: the dire cost predictions were a primary motivation both for the HAL tests and for thorough economic analysis for HAL Phase I. By using research to identify problems and to develop better materials and maintenance techniques, the industry was able to ameliorate the impacts of HAL loads when they were implemented in the 1990s.]

L.T. Cerny, "Recent Developments in Heavy Axle Loads Matters," AREA Bulletin #711, May 1987, pp. 203-211

As the Executive Director of the AREA and the Engineering Division of the AAR, Cerny's comments represent the conservative views of the railroad engineering community toward heavy axle loads in the mid-1980s. Cerny emphasized that heavier cars will require more track maintenance and increase bridge costs. He indicated that the key objective is to design profitable equipment, not just heavy equipment; he preferred to consider the ratio of payload to gross vehicle weight rather than simply GVW. Since the 315,000 pound car would require additional structural strengthening, it will not necessarily provide as much of a benefit as might be expected for coal (although there would be a major benefit for double stack container trains). He therefore recommended calling the 315,000 pound car the "120 ton car" for comparison to the standard 263,000 pound "100 ton car." He advocated consideration of larger wheels (43-inch) in order to maintain the stresses at the wheel/rail interface

[Note: the "120 ton" nomenclature did not catch on, and the 315,000 pound car was generally referred to as the "125 ton car." The concern for sharply increased track costs did translate into the structure of the HAL Economic Analysis. The importance of the ratio of payload to GVW was borne out in subsequent studies, particularly when the length of the car was allowed to vary.]

S. Marich, U. Maass, "Higher Axle Loads are Feasible - Economics and Technology Agree," Pre-Conference Proceedings, Third International Heavy Haul Railway Conference, Vancouver, BC, October 1986, pp. IA-1-1 to IA-1-14.

Marich and Maass challenged the North American railroads with his conclusion that axle loads in excess of 38 tons (and perhaps as high as 45 tons) were feasible both economically and technically. They reported the experience of the Mount Newman Mining operations and research in a detailed paper that was influential to the economic analysis because it showed that HAL operations were indeed feasible in an environment that, although much more uniform and controllable than any major North American operation, was much more variable and realistic than the test facilities in Pueblo. The paper also described various problems with equipment and materials that had to be resolved when the HAL loads were introduced. Estimating that total costs would decline by 1.5 to 4% relative to the base of 35-ton axle loads, they recommended increasing axle loads in increments of 2-3 tons in order to learn from experience and to adopt new technologies as they became available.

[Note: this paper was quite important, as it showed that HAL operations were feasible in an operating environment. The Australian experience to some extent represented a best case for HAL operations, because of dry climate and the small number of curves and ascending grades on the HAL routes. Nevertheless, their experience did establish that HAL operations were, at least in some situations, quite feasible.]

R.R. Newman, A.M. Zarembski, R.R. Resor, "Burlington Northern's Assessment of the Economics of High Capacity /Heavy Axle Load Cars," AREA Bulletin #726, Vol. 91, May 1990

This BN-independent study concluded that HAL loads were economically feasible, with the exact recommendations depending upon the route. Their study considered both coal and intermodal traffic.

[Note: Ron Newman and Allan Zarembski both participated in the meetings of the HAL I Economic Committee. Their experience from this internal BN study allowed them to provide critical insights into the structure and the interpretation of the AAR study.]

HAL PHASE I
HAL ECONOMIC ANALYSIS, PHASE I

Joseph G. Saleeby, "Infrastructure and Technological Change: Assessing the Economic Consequences of Heavier Axle Loads in the Railroad Industry (Summary), AAR Affiliated Lab, MIT, June 1990

Saleeby did his master's thesis on HAL economics. Using a spreadsheet model, he conducted a sensitivity analysis related to axle loads based upon prior AAR and railroad research on track deterioration and HAL operations.. He concluded that HAL operations would not be justified on poor track, but that they could be justified given favorable assumptions concerning the route, track components, maintenance policies, car characteristics, operating policies, and traffic mix and volume. He found that train consist could have as much as a 7% impact on costs even without changes in axle loads. He identified rail and turnout costs as important costs elements that are highly sensitive to assumptions and bridges as an area where it will be difficult to estimate cost effects.

[These were the first economic results presented to the Phase I HAL Economic Review Committee. These conclusions were supported and enhanced throughout the HAL research program.]

HAL I Economic Analysis Committee (Jerry C. Danzig, editor), "Draft FAST/HAL Report," July 9, 1991 (67 pages plus Appendices:

A. Bridge Maintenance and Repair Cost Analysis - A General Approach (3 pp.)
B. Track Inputs & Assumptions - Generic Cases (7 charts)
C. Line Haul Cost Comparisons - Generic Cases (10 charts)
D. Track Maintenance Cost Comparisons - Generic Cases (5 charts)

This was the initial summary of the HAL Phase I Economic Analysis. Jerry Danzig drafted the report based upon pieces developed by various members of the committee, AAR staff, and MIT researchers. The charts in Appendices C and D are bar charts showing the components of track and of line haul costs; these were the primary results presented in Phase I and served as models for presentation of subsequent results. Appendix B summarizes the component lives and costs used in Phase I; these were used in the subsequent studies unless there were specific reasons to change them.

AAR, "The economies of heavy axle loads," Vehicle Track Systems Newsletter, Vol. 3, No. 4, (published in Railway Age, September 1991, pp. 96-99)

This is the short version of the Phase I economic analysis.

C.D. Martland, "Physical Effects of 125-Ton Cars on Track Structure and Mechanical Components," Chapter 3 of Detailed Phase I Report, AAR Affiliated Lab, MIT, July 25, 1991 and C.D. Martland, "Economic Interpretation of FAST/HAL Test Results," Chapter 4 of Detailed Phase I Report, AAR Affiliated Lab, MIT, July 25, 1991

The Detailed Phase I Report was never published, and only Chapters 3 and 4 were completed. These chapters give the most complete documentation of the track analysis used in Phase I.. Chapter 3 summarizes the engineering basis for the Phase I economic analysis. This included three types of material: prior track research, FAST/HAL results, and experience on other railroads. Chapter 4 summarizes how the research results were translated into changes in track costs. Since the FAST/HAL experiments had certain important gaps (very little tangent track, no bridges, and very little on rail fatigue or ballast effects), other research and expert judgment was required. [Note: these two chapters have been edited and included as separate appendices to this report.]

Carl D. Martland, "Notes on the Use of HALTRACK in the HAL Economic Analysis," AAR Affiliated Lab at MIT, technical note, July 29, 1991

This technical note documents the many detailed assumptions that were made during the analysis of the Phase I case studies, which included the eastern and western coal line, a mountainous and a flat route, and case studies of a CSX and a BN coal route. [Note: this technical note included company specific data and was therefore limited in distribution to MIT and AAR researchers; the results of the case studies were reported as part of the Phase I economic analysis.]

M.B. Hargrove and A.R. Auzmendi, "BN Case Study," Memo to Ron Newman, Bill McCarthy, Carl Martland, Allan Zarembski, and Randy Resor dated May 6, 1991, 5 pp. and M.B. Hargrove and A.R. Auzmendi, "BN Case Study - Format for Publication of Results," Memo to Ron Newman and Bill McCarthy dated May 8, 1991, 4 pp. and C.D. Martland, BN Case Study, Results from HALTRACK spreadsheet HALBNG2.WK3 dated 4-30-91

These memos summarize the results from the BN case from the HAL Phase I economic analysis. The AAR examined the BN case from two perspectives. First, the AAR used the generic AAR assumptions for track, equipment and operations along with the route and traffic characteristics of BN's test corridors (i.e. curvature, rail type, and MGT). After comparing these results, BN provided additional information concerning cost, train consist, and car design assumptions and the AAR revised its analysis. The final AAR Base Case was within 4.3% of the BN actual track costs; both the AAR and BN analyses recommended the 286,000 pound car as offering a 5% improvement in total costs over the base case car. The conclusion was "Overall, we can say that there seems to be a good agreement between the AAR and BN analyses." The spreadsheet HALBNG2.WK3 includes the track assumptions and outputs for the BN case; Alvaro Auzmendi incorporated the track results in the overall analysis of BN costs.

[Note 1: In a separate note dated June 6, 1991, Carl Martland identified the major differences between the BN and AAR approaches to the HAL analysis. First, the AAR assumed that rail fatigue can be controlled through choice of rail hardness, grinding and attention to rail profiles. Second, the AAR approach separated routine from programmed maintenance. Third, the AAR approach separated turnouts from rail. Fourth, the AAR paid more attention to risks, with specific mention of Australian problems with both track and equipment.]

[Note 2: BN, AAR and MIT staff met on June 12 for a final discussion of the case study. BN cited a potential problem with one major bridge that would need replacement and also added that there would be a capacity benefit, as the number of coal train-sets required would drop from 293 to 251. They also cited a possible benefit from lower rolling resistance for the heavier trains: a BN test showed that they will go up grades 1-2 mph faster. The experience with the BN indicated that each railroad should calibrate a base case that reflects its own conditions.]

Carl D. Martland, editor, "The Economics of Heavy Axle Loads: Why the US Railroads Elected to Increase Axle Loads," MIT Affiliated Lab, March 1995 (unpublished)

In October 1991, the Transportation Research Forum held a panel session on the HAL Phase I study. This note summarizes presentations by Michael Hargrove (AAR), James McClellan (NS), Larry Shughart (CSX), and Carl Martland (MIT). The AAR and MIT presentations reviewed the AAR Phase I study, while the CSX and NS presentations provided some insights into why the railroads adopted the 286,000 pound GVW limit for coal. CSX also reported that their bridge engineers anticipated a 50% increase in bridge costs, which was equivalent to a 0.5% increase in operating costs for the study corridor. The note provides some historical context, beginning with Mr. McClellan's discussion of the famous Southern Railway Big John Hopper case.

SUMMARY OF RELEVANT TEST RESULTS, PHASE I

R.K. Steele, "Analysis of Gage Face Wear under Conditions of Variable Lubrication (1990) and R.K. Steele, "Rail Wear Studies," AAR working paper (1990)

These two papers consolidate the wear rates from various studies, including FAST.

R.K. Steele, "An Analysis of Recent Rail Wear Data from FAST HTL Tests," AAR working paper (unpublished)

This shows that the HAL Phase I rail wear tests were contradictory, with results in different test showing that gage face wear was reduced by at least 50%, did not change, or increased by at least 40%!

[With these inconclusive results, the HAL Phase I economic analysis assumed that wear rates would not be changed, which is about what was predicted by TRACS. Actually, TRACS predicted a slight reduction in wear rates on the gage face, but the economic committee preferred to be conservative and to assume no change.]

Brave, Glenn, Jon Hannafious, and Roger Steele, "FAST/HAL Rail Performance Experiment and Overview," AAR Report R-796, FRA report FRA/ORD-91/24, 136 pp.

This report summarizes the results of the Phase I tests on rail wear, fatigue, grinding, and welds. The major conclusions:

- Welds: "A significant increase in thermite weld failures occurred in the high rails of curves during testing."
- Wear: "in relatively sharp curves, under the influence of light lubrication or totally dry conditions, wear rates increase with increased axle loads."
- Fatigue: "intermediate strength rails that developed fatigue defects under 33-ton axle loads performed noticeably worse under HALs in one case and about the same in another case.

[NOTE: the Phase I economic analysis incorporated the increase in weld defects and in rail defects. The wear results were actually contradictory for normally lubricated curves, so the wear rate was left unchanged, as predicted by wear model use in TRACS. Since corrugations developed more quickly, additional grinding was assumed in the Phase I economic analysis.]

Read, David M. and Jon Hannafious, "FAST/HAL Turnout and Frog Performance," AAR Report No. R-798, FRA Report No. FRA/ORD-91/25, November 1991, 79 pp.

This presents the Phase I results for turnouts. Maintenance records for turnouts under the HAL traffic were compared to maintenance under 33-ton axle loads. A standard

No. 20 turnout had to be removed after 100 MGT because its general deterioration; a No. 20 turnout with premium components fared much better.

The Phase I tests also included a "frog farm," where five frogs of different composition and design were tested. The basic conclusion of the tests were that premium components are needed under HAL loads for turnouts.

Trevizo, Carmen M., "FAST/HAL Ballast and Subgrade Experiments," AAR Report No. R-788 and FRA Report No. FRA/ORD-01-10, August 1991, 109 pp.

This report concluded that good ballast could withstand HAL traffic, although softer ballast might need more frequent surfacing. Another set of tests confirmed the theoretical distribution of forces into the ballast and subgrade.

Related Research
Rail Fatigue Life

T.R. Wells and T.A. Gudiness, "Rail Performance Model: Technical Background and Preliminary Results," AAR Report No. R-474, May 1981

This report describes the Weibull approach to predicting rail defects and also includes the structure for estimating the costs of defects. This remains the most complete assessment of the detailed costs associated with rail defects. [Note: The notion that the costs include three situations (found by detector car, in service failure, and derailment) was incorporated in the costing of defects in the HAL analysis.]

R.K. Steele and M.W. Joerms, "A Fatigue Analysis of the Effects of Wheel Load on Rail Life," AAR Report R-689, September 1988, 58 pp.

This describes the Phoenix Model that underlies the rail defect analysis of the HAL economic analysis.

R.K. Steele, "Recent North American Experience with Shelling in Railroad Rails," AAR Report R-699, September 1988

This describes experience in shelling and TDs as related to the theory, i.e. to Phoenix predictions.

R.K. Steele, "The Effect of Metal Removal, Steel Cleanliness, and Wheel Load on the Fatigue Life of Rail," AAR Report R-764, December 1990

Steele used PHOENIX, the AAR's rail fatigue model, to examine the shell/transverse defect (TD), which he categorized as the "primary fatigue defect of concern on heavy duty track." PHOENIX predicts that fatigue life will be inversely proportional to the axle load, that fatigue life will "increase notably" when the rail/wheel contact is made more conformal, and that grinding may prolong fatigue life, especially for harder steel (e.g. premium 340 BHN rail) and heavier wheel loads. He cited Glavin's paper [see below] as one example where field evidence supported the notion that grinding could control defects.

Steele also suggested that defects might follow a bimodal pattern of behavior, reflecting two types of defect populations - "one very limited in size but very pronounced in defect generation, the other extensive in size but very limited in defect generation. The effect of the combined population might be to cause a rapid initial increase in defect occurrence followed by a diminution in the rate with further service exposure as the high rate defect population is consumed. ... Such drop-offs in defect rate had been observed previously before grinding had become as wide spread as it is today." [p. 10]

[Note: the HAL Economic analysis used this work by Steele and the PHOENIX model to predict grinding requirements and defect rates under HAL loads. Shyr {see below} calibrated equations to PHOENIX output, and these equations were incorporated in TRACS and HALTRACK, the models used in the HAL Economic analysis. The need for better confirmation of the relationship among rail hardness, axle loads, grinding, and lubrication has been a recommendation throughout the HAL analysis.]

W.M. Glavin, "Rail Grinding - The BN Experience," AREA Bulletin No. 722, Vol. 90, October 1989, pp. 237-255

Between 1981 and 1989, BN more than doubled their expectations for the life of rail. On tangent track, they expected standard carbon rail to last 800-1400 MGT; on 1 degree curves, they expected standard carbon rail to last 800-1100 MGT, and on 3 degree curves, they expected fully heat treated rail to last 300-500 MGT. Glavin reported that the increase in life reflected various factors, including better rail steel, lubrication, road bed improvements, but that "it has been the practice of rail grinding that has allowed the full potential of these improvements and advancements to produce the rail longevity characteristics we now enjoy." (p. 239)

The paper describes the history of rail grinding, including the transition from what was primarily corrective grinding to eliminate corrugations to profile grinding to maintain the desired wheel/rail contact and to reduce surface fatigue.

[Note: the long rail lives on BN were consistent with the predictions of TRACS. The availability of field evidence allowed the HAL Economic analysis to proceed using rail lives that were 50 -100% longer than most of the other railroad anticipated. The fact that BN achieved the longer life despite an increase in unit trains of 100-ton cars also validated the TRACS predictions that axle load would have essentially no effect on rail life, except that additional grinding might be required.]

Feng-Yeu Shyr and Carl D. Martland, "Rail Fatigue Analysis: Estimating Rail Defect Rates Using Equations Calibrated to PHOENIX Output," AAR Affiliated Lab Working Paper, MIT, October 30, 1990

Shyr calibrated a sets of three equations to represent the fatigue life predictions produced by PHOENIX. The input data represented 1080 combinations of track and traffic characteristics. Analysis of the data showed a clear bimodal pattern, so that cumulative defects tended to rise at first, then level off for a period that could be hundreds of MGT, then rise very rapidly. This is the behavior referred to by Steele. These equations provided a means of incorporating sophisticated defect predictions into TRACS and into HALTRACK, so that the interrelated effects of grinding, rail hardness, and axle load could be considered in the HAL analysis.

HAL PHASE II
HAL ECONOMIC ANALYSIS, PHASE II

M.B. Hargrove, T.S. Guins, D.E. Otter, S. Clark and C.D. Martland, "The Economics of Increased Axle Loads: The FAST/Hal Phase II Results," July 1996

This is a paper with the final results of the Phase II economic analysis that was distributed to the HAL Phase II Economic Evaluation TAG.

M.B. Hargrove, T.S. Guins, and C.D. Martland, "Economics of Increased Axle Loads FAST/HAL Results," AAR Report No. LA-007, October 1996

This report summarizes the economic analysis of HAL Phase II and compares these results to the Phase I results. The extensive analysis of bridge costs is described, and tables show the lives assumed for rail, ties, and turnout components. Even after the consideration of bridge costs, the net HAL benefits were projected to be 2-6% for routes with good track components and maintenance practices. As in Phase I, the actual costs and the actual potential for savings were expected to be highly route-specific.

M.B. Hargrove, T.S. Guins, D.E. Otter, S. Clark, and C.D. Martland, Economics of Increased Axle Loads: FAST/HAL Results, Proceedings, A World of Change, Volume 1: FAST/HAL Test Summaries, Association of American Railroads, Transportation Technology Center, Pueblo, Colorado, Nov. 1995

The major results of HAL Phase II economic analysis were summarized and presented at the TTC Open House in November 1995.

C.D. Martland, "FAST/HAL Evaluation - Phase II: Modeling the Implications of Phase II Results for the Generic Case Studies," AAR Affiliated Lab at MIT, Working Paper 95-3, December 1995, 53 pp.

This working paper describes the track portion of the Phase II economic study. It begins with a 1-page overview of the goals of Phase II and a 2-page summary of the major results from the FAST/HAL tests. It then shows how these research results were translated into specific changes in the generic eastern and western coal lines that were investigated in Phase I. The Phase II analysis was much simpler than the Phase I analysis (which involved calibrating a base case, reviewing all parameters and assumptions with an industry committee, and providing a lengthy process for reviewing, revising, and interpreting results and conclusions). In Phase II, we related the specific conclusions of the FAST/HAL tests to specific changes in the parameters used in the generic eastern and western coal cases. We also updated the unit costs and assume somewhat better track components for the base case. This working paper documents all of the assumptions and includes a 17-page printout of the case descriptions as coded in HALTRACK plus printouts of the HALTRACK results for five cases:

1. Final Phase I
2. Final Phase I, with minor corrections in HALTRACK's treatment of grinding, allocation of turnout costs, and estimation of hours required for routine maintenance.
3. Initial Phase II analysis (Phase I cases evaluated with improved models and updated calibrations based on Phase II FAST/HAL results)
4. Phase II analysis, also assuming upgraded components (superior field welds, high integrity frogs, longer-lived ballast, premium fasteners on curves greater than 4 degrees, and greater use of 300 BHN rather than 270 BHN rail)
5. Final Phase II analysis, also assuming updated costs

In addition to updating the generic case studies, this report provided sensitivity analysis related to the following factors:

1. Net-to-tare ratios of the cars ("the results of the HAL analysis are robust across a reasonable range in net-to-tare ratios")
2. Surfacing cycles and ballast life ("In terms of the HAL analysis, ... the percentage of bad track could be important, but minor changes in the definitions of what constitutes good or poor ballast would not be critical.")
3. Tie life and the HAL effect on tie life ("Tie costs are largely insensitive to HAL effects.")
4. Unit costs for track components and the extent of HAL effects ("the basic conclusions of the HAL economic analysis are quite robust with respect to changes in the unit costs of track maintenance or in the HAL deterioration rates.")

The paper concluded that the magnitude of HAL effects was lower than predicted in Phase I as a result of better track components as well as a better understanding of deterioration rates. In addition, the continued FAST/HAL testing along with railroad experience with HAL traffic "has strengthened the economic assessment of track costs relative to what was possible in Phase I.") The analysis pointed out the importance of having good components and, especially on poorer quality track, the necessity of budgeting for increased maintenance activities on lines with significant amounts of HAL traffic.

SUMMARY OF RELEVANT TEST RESULTS, PHASE II

Singh, Satya P., Anne B. Hazell, and Semih F. Kalay, "Heavy Axle Load Track Gage Widening Tests by Using the Track Loading Vehicle," AAR Report No. R-873, October 1994, 265 pp.

This experiment used the Track Loading Vehicle to test gage widening under 39-ton loads for comparison with similar tests under 33-ton axle loads. The results show that gage widening will be expected to increase under HAL loads, especially on soft wood tie. However, the effects of gage widening can be offset by the use of premium fasteners instead of cut spikes (Pandrol and Safelock fasteners were tested).

[NOTE: the HAL II economic analysis required the use of premium fasteners on curves of 4 degrees and greater under HAL loads. This caused an increase in the installed cost of ties and was assumed to provide the same resistance to gage widening under HAL loads as were provided by cut spikes under 33-ton axle loads.]

RT&S, "HAL: Putting premium track materials to the test," Railway Track & Structures, November 1992, pp. 23-29

This provides some preliminary interpretation of Phase II results. The major goal of Phase II was to determine the extent to which premium materials would reduce track degradation.

Li, D. and E.T. Selig, Evaluation and Remediation of Potential Railway Subgrade Problems Under Repeated Heavy Axle Loads, AAR Report R-884, AAR, Chicago, July 1995

The problems of poor ballast and subgrade were highlighted in the Phase II testing. This report provides the technical details.

Sharma, Vinaya, Semih F. Kalay, and Duane E. Otter, "Economic/Fatigue Implications of Heavy Axle Loads on Steel Railway Bridges on an 1100-Mile Coal Route, AAR Report No. R-895 September 1996, 33 pp. plus appendices of approx. 75 pp.

This report presents the results of a detailed assessment of the effects of HAL traffic on bridge costs. A hypothetical 1100-mile coal route was developed by combining routes and bridges that are similar to those in place on coal routes for the Class I railroads. Detailed fatigue analysis was carried out on 28 steel bridges, which were used to represent the types and numbers of bridges on the actual routes. Bridge costs per net-ton-mile were predicted to increase by 12% for the 286,000 pound car and by 69% for the 315,000 pound car.

NOTE: this bridge analysis was the most intensive part of the Phase II economic analysis. Since bridge were not included in Phase I, it was felt that this area required an in-depth analysis to justify the wide-spread introduction of HAL traffic. The structure of the study was developed by the HAL Economics Task Force in cooperation with the AAR Bridge Committee.]

RELATED RESEARCH

D.D. Davis, "Rail Defects and Their Effects on Rail Maintenance Planning," AAR Report No. WP-154, April 1992

This is a detailed survey of the nature of rail defects and inspection reliability. The percentage of defects that are not detected and result in service failures is a factor in the economics of defects. This study showed that about 15% of defects are not detected.

Davis, D. D., R. K. Steel, and E. K. Wesel, "The Impact of Rail Grinding on the Life of Rail: A Theoretical Study," AAR Report No. R-847, September 1993, 45 pp.

This report examines the relationships among head height loss, grinding, rail hardness, and wheel/rail profiles on the fatigue life of rail. The study uses the Phoenix model to estimate defect life. It goes beyond prior studies by looking at curves as well as at tangent track. Its conclusion is that grinding will generally prolong rail fatigue life beyond what would otherwise be expected for tangent track and lubricated curves.

[Note: this is similar to the analysis conducted by MIT to support the rail lives and grinding assumptions that were used in the HAL Phase I economic analysis for tangent track and mild curves. With HAL traffic, added grinding is needed to avoid premature replacement of the rail due to high fatigue defect rates.

Feng-Yeu Shyr, Roger K. Steele, Moshe Ben-Akiva, and Carl D. Martland, "Modeling Rail Fatigue: A Comparison of Phoenix Output and Field Data," AAR Affiliated Lab Working Paper, MIT, November 1993, 87 pages

This working paper, which was abstracted from Shyr's dissertation, describes statistical techniques for integrating field observations with model results concerning defect rates. The working paper examined data from a major class I railroad from 22 sites where several different grinding practices had been used, but concluded that "the field data did not show any consistent relationship between either wear rate or grinding frequency and fatigue." Rail hardness was found to be the most important factor, as harder rail had fewer defects. The field data also showed more sensitivity to rail weight, which is not a significant factor in Phoenix.

Phoenix does not distinguish between curves and tangent track. For this data set, "defect rates on curve segments were about the same as on tangent segments."

Shyr's analysis of the 22 divisions provided some evidence that a plateau in cumulative defects is reached after an initial period of a higher defect rate. Overall, he concluded that "cumulative MGT did not show a strong positive correlation with the defect rate."

[Note: although this work represented a methodological advance beyond Shyr's earlier work, it was not incorporated within TRACS for two reasons. First, the statistical approach required too high a level of mathematical sophistication for routine application, and, second, the new analysis was keyed to the situation studied (i.e. a set of segments that all used BHN 250 or 270 rail, which was known to be inadequate for HAL operations). Hence, Shyr's earlier equations continued to be used in the HAL economic analysis. The lack of any marked difference between curves and tangent track enable us to continue to use the Phoenix equations for both tangent and curved track.]

David D. Davis and Peter D. Rogers, "Comparison of Weld Repairs for Standard and High-Integrity Rail Bound Manganese Frogs in Heavy Haul Service," AAR TD-96-12, May 1996

This TD documents the performance of weld repairs to frogs in turnouts on the UP's (formerly the C&NW's) line into the Powder River Basin. The life on high integrity frogs is longer, but the weld repair life remains comparatively short and needs improvement if frog life is to be further extended.

David Davis, Jian Sun, Vin Terrill, and Bill Hansen, "Industry Survey of Frog Weld Repair Best Practices," AAR TD 97-015, May 1997

This TD provides information concerning the need for welding and grinding of frogs.

[NOTE: information similar to this was used to calibrate the frequency of maintenance activities in the Turnout Cost model used in the HAL economic analysis.]

Duane E. Otter, Pete Rogers, and David D. Davis, "Performance of Frogs Under Heavy Axle Loads," TD 97-018, July 1997

and Ryan McWilliams and David Davis, "Effects of Heavy-Haul Traffic on Turnout Components in Revenue Service," AAR TD 98-019, August 1998

These TDs update the performance of turnouts on the UP's Powder River Basin line.

No. 20 RBM frogs are lasting three times longer than standard #20 frogs lasted on this line," even though HAL traffic has increased from 0.5 to 39% of the total in 1997. The expected life for high integrity frogs installed between 1994 and 1997 is expected to be 580 MGT in the most recent TD. This TD also reports that the time between weld repairs has increased for welds installed between 1994 and 1997. [The life of frogs in the HAL economic study have been increased to match the predictions of this sample; this TD suggests an even longer life can be used in future economic studies.]

Smith, E.W. and C.D. Martland, A Preliminary Investigation into the Economics of Advanced Design Turnouts, MIT Affiliated Lab Working Paper, October 1993 and Martland, C.D. and E.W. Smith, An Updated Assessment of the Economics of Advanced Turnouts, MIT Affiliated Lab Working Paper 94-10, February 1995

These two studies examined the life cycle costs associated with premium and advanced #20 turnouts to determine the conditions in which they would be preferable to the standard #20 turnout. The premium turnout was similar in overall design to the standard turnout, but had premium components, the most important of which was a high integrity frog. The advanced turnout had a movable point frog and tangential switch points and was therefore much more expensive to acquire and install. The analysis showed that the advanced turnouts could only be justified on the heaviest tonnage lines, e.g. 100 MGT and above. However, the premium turnouts were justifiable for line densities from about 20 MGT to 100 MGT. Because of this finding, premium turnouts were used in the base case and in the HAL cases in the HAL Phase II and subsequent economic analyses.

BRIDGES

Sharma, Vinaya, John Choros and Semih Kalay, "Examining fatigue life and loadings for railway bridges," Railway Track & Structures, August 1994, pp. 25-38

This article provides an overview of the bridge problem and the AAR's bridge research program, which began in 1988.

Otter, Duane E., Joseph LoPresti, Douglas A. Foutch, and Daniel H. Tobias, "Longitudinal Forces in an Open-Deck Plate Girder Bridge," AAR TD 96-024

This was the first test in a series of AAR studies aimed at reducing the longitudinal forces in bridges. This TD shows that the longitudinal forces on a 50-foot open-deck steel deck plate-girder bridge to be nearly 100 kips, more than 20 times greater than the current design value (although similar to design guidelines used before 1968).

Singh, Satya P. and Duane E. Otter, "Estimated Effeccts of 286,000-Pound Cars on a Ballasted-Deck, Through-Plate-Girder Bridge," AAR TD-019

Tests on a 65-foot bridge were designed to yield information about the stresses in bridges that would help develop techniques for extending the life of these bridges. Compared to 263,000 pound cars, the HAL cars increased fatigue-damage rates by 8-30% in stringers and 14% in floor beams. Fatigue life of the bridge structure can be extended by replacing these fatigue-prone elements of the floor system.

Otter, Duane E., Judy Stadler, and M. Carmen Trevizo, "Bridge Maintenance Costs on a HAL Coal Route: A Case Study, AAR TD 97-017

This study documented traffic-related bridge maintenance costs on a 164-mile portion of UP's major coal routes. Annual costs ranged between $10 and $16 per foot of bridge between 1992 and 1996, a period in which heavy axle loads were increasing. Annual costs were clearly not rising, despite increasing traffic volume and an increasing percentage of traffic in 286,000 pound cars. In fact, costs per MGT were declining over this period. The authors concluded that "Preparatory work performed by the railroad in anticipation of the added HAL traffic is likely responsible for keeping bridge maintenance costs from rising." The TD also breaks out maintenance costs into major categories for steel and for timber bridges and documents that maintenance costs are roughly three times higher for the older bridges (constructed about 1910) and the newer bridges (constructed during the mid-1980s).

John Romps, The Effects of Track Maintenance on the Reliability of a Single Track Railroad Line, AAR Affiliated Laboratory Working Paper MIT 94-6, October 1994

HAL traffic has two contradictory effects on train reliability. Since the required track work increases, the amount of work windows must increase, tending to disrupt line operations. On the other hand, if train length remains constant, then the number of trains will decrease, which will tend to reduce congestion. Romps examined the relative importance of these two factors by simulating the HAL 30- and 80-MGT coal lines. He inserted work windows based upon the steady state requirements for maintenance and renewal under 33-, 36, and 39-ton axle loads based upon the HAL Phase I analysis. He found that the net effects of the HAL traffic were to improve, rather than to degrade train reliability. Romps also found that rail defects were a major problem, especially during a "cold snap" when multiple broken rails could severely disrupt service for several days.

Robert, William and Carl D. Martland, Effects of Track Maintenance on the Reliability of a Single Track Railroad Line as a Function of Axle Load, AAR Affiliated Laboratory Working Paper MIT 95-6, January 1996 and Thomas S. Guins, William E. Robert, and Carl D. Martland, "Effects of Heavy Axle Loads on Reliability of Train Operations," Association of American Railroads Technology Digest TD 97-030, August 1997

This working paper, which is summarized in TD-97-030, updated Romps analysis using the track requirements from the HAL Phase II analysis. The results were similar for the 80-MGT line, with a "reduction in trip times of 2 to 3% and a reduction in standard deviation of trip time of 5-9%." However, for the 30-MGT line, where congestion is less of a problem, the increased maintenance requirements were predicted to cause an increase of 0-1% in average trip time and approximated 18% in the standard deviation of trip times. "In both routes, the analysis indicates more favorable results for 36 than for 39 ton axle loads in terms of train delay, trip time, and reliability."

Martland, Carl D. and Eric W. Smith, HALTRACK96: A Tool for Investigating the Effects of Heavy Axle Loads on Track Maintenance Costs, AAR Affiliated Laboratory Working Paper MIT 95-8, January 1996

This report describes how to use the HALTRACK model to investigate axle load effects. HALTRACK96 differs from the earlier version of the model in that it includes sections for estimating tie costs and a greater variety of turnout costs. The model incorporates component lives from TRACS and the Turnout Cost model, then estimates route costs based upon the assumed track components and the number of turnouts.

HAL Phase III

HAL Economic Analysis, Phase III

Tom Guins and C.D. Martland, "The Economics of Increased Axle Loads: FAST/HAL Phase III," Association of American Railroads Report #LA-011, October 1997

This is the "members-only" version of the Phase III economic analysis.

Thomas S. Guins, "Economics of Improved-Suspension Trucks," AAR TD 98-009, April 1998

This summarizes the HAL Phase III economic analysis: "... higher equipment costs associated with improved-suspension trucks are more than offset by reductions in expenditures for track capital and maintenance, equipment maintenance, and fuel." The improved suspension trucks offer a savings of 1-2% in total direct cost; further cost savings of 7-8% are possible in going from a 263,000 base case (with standard 3-piece trucks) to a 286,000 car with improved-suspension trucks. The potential returns on investment range from 35 to 85%, depending upon the route and the type of service.

Improvements in asset life and productivity are the main benefits:

1. 8% reduction in fuel consumption
2. 25% increase in the life of wheel-sets
3. 33% increase in the truck-rebuild cycle
4. 50% reduction in grinding required to control corrugation
5. increase in life of curves less than 2-degrees to 90% of the life of tangent track
6. 50% increase in the life of curves greater than 2-degrees

Carl Martland, "HAL III Economic Issues," unpublished memo to Tom Guins, July 11, 1996

This memo gives the results for the initial look at the benefits of advanced suspension trucks (what we called Phase IIIa). With better suspension systems for the HAL cars, the test results showed lower wear rates on curves and much less corrugation and surface fatigue. For the track analysis, only two changes were made to the Phase II analysis: wear life in curves was doubled (or increased to the life of tangent track for the 2-degree curves) and grinding on curves was reduced by 50%.

The memo also discusses how the Phase III economic analysis differs from the prior analyses because of the importance of such things as wheel wear, car maintenance and car costs.

Carl Martland, "HAL Phase III - Preliminary Track Costs," unpublished memo to Tom Guins, November 7, 1997

This 1-page memo lists 5 changes that were made to the Phase III track cost analysis as a result of continued Phase III testing. In addition to the changes in wear life and grinding made for HAL IIIa, the following changes were made:

1. Base grinding was reduced by 25% for tangent track and 2-degree curves
2. Additional improvements in routine rail maintenance to reflect longer lives of field welds
3. Longer lives for frogs, based upon updated field tests on UP
4. Much better performance for poor ballast/subgrade segments to reflect the use of GEOWEB (damage factor reduced for surfacing and renewal from 2 to 1; base renewal and surfacing cycles increased by 50%)

Attached to this memo are printouts from HALTRACK that document the inputs and outputs for the track analysis. [NOTE: we referred to this as the HAL Phase IIIb analysis.]

SUMMARY OF RELEVANT TEST RESULTS, PHASE III

David M. Read and Semih Kalay, "Initial Results of FAST/HAL Phase III Testing," AAR TD 96-025, November 1996

This summarized the initial results from the first 145 MGT of Phase III testing, which "suggest that improved suspension trucks will substantially improve the economics of operating 315,000-pound freight cars. Benefits include reduced fuel consumption, less wheel/rail wear and other reductions in track damage." Other benefits for the track structure were less chance of gage widening, lower rate of corrugation development, and less batter at joints and welds. [These were the results underlying the HAL IIIa economic analysis.]

Curtis L. Urban, FAST HAL Alternative Suspension Systems Project, 1995

This provides background on the alternative suspension tests, with some results from the first and second mini-tests in 1993 and 1994.

Klauser, Peter E., Curtis L. Urban, and Robert L. Florom, "On-Track Test Results for the Heavy Axle Load Alternative Suspension Project," AAR Report No. R-896, October 1996, 103 pp.

This report presents the results of a 3-year research program that modeled and conducted some preliminary testing of various types of advanced trucks. Three advanced trucks were selected for further testing in HAL Phase III.

BALLAST AND SUBGRADE

Li, Dingqing and Ernest T. Selig, "Evaluation and Remediation of Potential Railway Subgrade Problems Under Repeated Heavy Axle Loads," AAR Report No. R-884, July 1995, 112 pp.

As described in the abstract, "this report discusses the types of subgrade failure, methods for identifying and assessing them, and remedial measures for their correction." The report gives "a comprehensive picture of the subgrade as the track foundation." (p. 55)

Dingqing Li, David Read, and Steve Chrismer, "Effects of Heavy Axle Loads on Soft Subgrade Performance," AAR TD 97-020, July 1997

This presents the results of test on the LTM (low track modulus) section at FAST/HAL This section, which has a track modulus less than 2000-2500 lb./in./in., required tamping at increasingly frequent intervals, as short as every 1-2 MGT at the end of the tests. "It was concluded that heavy axle load-induced stresses are too high for soft subgrades with an industry-standard granular layer thickness of 12-24 inches beneath conventional ballasted track structure. [Note: these results confirmed the use of short surfacing cycles and high damage factors for HAL traffic in the HAL economic analysis.]

Chrismer, Steven, "Test of GEOWEB to Improve Track Stability Over Soft Subgrade," AAR TD 97-045, December 1997

In prior tests at the LTM section in FAST, the average tamping cycle was about 15 MGT. After installing GEOWEB, the track accumulated 85 MGT with only minimal loss of geometry. [NOTE: this result was used to reduce the predicted effects of HAL traffic on poor ballast/subgrade.]

M. Carmen Trevizo, John D. Mazza, and Duane E. Otter, "Distribution of Vertical Loads in the Track Structure," AAR TD 97-050, December 1997

This test found that the use of improved-suspension trucks made little difference in the distribution of vertical loads through the track structure to the sub-grade. Hence, improved-suspension trucks do not alleviate sub-grade problems associated with HAL traffic.

M. Carmen Trevizo, "Fast Heavy Axle Load Ballast Test Results," Report No. R-914, December 1997

This report summarizes the results of ballast performance under the first 750 MGT of HAL operations at FAST. "Even though a direct comparison between 33- and 39-ton axle load traffic cannot be made due to differences in ballast types and accumulated tonnage, it appears that degradation of the material in test is more dependent on accumulated tonnage than on increased axle load." [Note: this provides additional support for the assumption used in the Phase II and III economic analyses that ballast life will be proportional to MGT for axle loads of 33- to 39-tons.]

TIES

M. Carmen Trevizo, "Preliminary Analysis of Wood Tie Performance in a Heavy Axle Load Environment Under Improved Suspension Trucks," AAR TD 97-013, April 1997

HAL Phase III results show that "the use of improved suspension trucks will lower track maintenance requirements and could improve some aspects of track safety." Based upon 100 MGT of testing, gage widening was reduced 50% or more in Phase III relative to Phase II, when standard trucks were used on the equipment. [Note: in the HAL Phase II economic analysis, premium fastenings were assumed for high degree curves in order to control gage widening. Under improved suspension trucks, premium fastenings might no longer be necessary.]

CROSSING DIAMONDS

Joseph LoPresti, Duane E. Otter, and David D. Davis, "Testing an 89-Degree Crossing Rebuilt with Premium Components Under Heavy Axle Loads," AAR TD 96-015

"Crossing diamond tests conducted at FAST to date seem to indicate that current designs and materials will not survive long under 39-ton axle loads." Standard crossing diamonds have failed after less than 5 MGT of traffic; premium crossing diamonds have only lasted 15-30 MGT.

Tests with instrumented wheel sets showed that the 315,000 pound car produced impacts at a crossing equivalent to those of a 263,000 pound car traveling 5-10 mph faster.

[NOTE: the HAL economic analysis has not yet considered crossing diamonds, as they constitute a small part of the track structure. These tests suggest that HAL traffic will either require frequent maintenance and shorter replacement cycles or slower train speeds. TD 97 -029 suggests that slowing down trains could be more expensive than frequent replacements and recommends development of better designs for crossing diamonds.]

David D. Davis and William F. Drish, Jr, "The Effects of Train Delay on Crossing-Diamond Economics," AAR TD 97-029

Crossing diamonds are a weak link in the rail system and could be an impediment to the introduction of HAL traffic. This study "indicates that development of improved-performance designs which eliminate speed restrictions and reduce train delays over these track components is desirable."

OTHER HAL ECONOMIC ANALYSIS

Chapman, Jeffrey D. and Carl D. Martland, Technology and Railroad Track Costs: A Historical perspective, AAR Affiliated Laboratory Working Paper MIT 96-1, November 1996 and Jeffrey D. Chapman and Carl D. Martland, "Railroad Track Productivity: A Historical Perspective," Transportation Quarterly, Eno Transportation Foundation, Inc., Vol. 51, No. 3, Summer 1997

This paper quantifies the very substantial savings in track costs that have come about because of line consolidation, improvements in net-to-tare ratios for major car types, and improvements in track components. Taken together, these changes have reduced annual track costs by up to $7 billion. Another way to consider this result is that track costs, in current dollars, have remained relatively constant since the early 1980s despite rising traffic volumes and heavier axle loads. [Note: this paper was motivated by a perception that senior railroad executives were not aware of the magnitude of savings that have resulted from the development of superior track components and maintenance practices.]

AREA, "Use of Wider Freight Cars on Railways," AREA Bulletin No. 748, December 1994, p. 431

This anonymous 1-page "speculative essay" concludes that "it would thus appear possible to go to an additional 1 ½ foot width (up to 12'2") without major infrastructure costs," which would provide a 14% increase in cubic capacity . Even wider cars (up to 13'2") might be considered, although these would require infrastructure modification. [NOTE: this was published some years prior to the work by Chapman, who investigated wider cars as one means of increasing the loading density of trains. Historically, over the life of the rail system, cars have indeed become wider, although the process is one that takes decades, not years.]

Chapman, Jeffrey D., William E. Robert, and Carl D. Martland, Factors Influencing Optimal Axle Loads for Heavy Haul Operations, AAR Affiliated Laboratory Working Paper MIT 97-1, January 1998 and Thomas S. Guins, Jeffrey D. Chapman, William E. Robert, and Carl D. Martland, "The Potential for Reconfiguring Freight Cars to Optimize Efficiency in Heavy-Haul Operations," AAR TD 98-010

This study examined the effects of car design and train length on HAL economics. The study considered eastern and western coal networks, which were loosely modeled on typical coal operations in each part of the country. The approach and assumptions were similar to those used in the HAL Phase II analysis. Chapman used TRACS to model track costs, including segments with tonnages representative of each portion of the route from the mine to the utility. Robert used a model of unit train operations to estimate congestion effects - with fewer trains operating, there is less congestion and therefore a reduction in cycle times that allows an additional reduction in train sets.

Several key conclusions resulted from this study: if the car length can vary, then axle load becomes a much less important variable; most of the operating and capacity benefits can be obtained by improving car design to make better utilization of the space occupied by the train. On congested routes, a shift to trains with higher net tonnage will help to reduce congestion, thereby providing additional equipment utilization benefits.

William Robert and Kiersten Haskell, "Coal Rail Car Size Constraints at U.S. Electric Utilities," report prepared for the AAR, Cambridge Systematics, Inc., December 1997

This report documented the constraints for unloading coal cars at utilities and estimated the costs of upgrading the facilities to handle cars of different sizes. In general, the costs for modifying a facility for handling shorter, higher cars would be less than the costs for handling longer cars (since there may not be space to handle longer cars).

Jeffrey D. Chapman, "Car Design for More Productive Heavy-Haul Rail Operations: Increasing the Capacity of Length-Limited Trains," MST Thesis, MIT, June 1998, 271 pages

This thesis is a more thorough examination of the issues raised by the Chapman, Robert, and Martland in Working Paper 97-1. Chapman delved into the issues of car design to determine the characteristics of gondolas and hopper cars that might be used to transport coal. He considered cars that were shorter and higher, cars that were wider, and cars with axle loads up to 42 tons. His analysis included the costs of modifying loaders and dumpers where necessary to handle rotary dump cars, using results from Roberts and Kiersten. He concluded that "improving car design without increasing axle loads appears to be a very cost-efficient and capacity-effective alternative for North American heavy-haul railroading. In effect, removing the length constraint will allow car designers to optimize the use of the space within the clearance limits available for operations.

Other Research

Trevizo, M. Carmen, Duane E. Otter, Peter Rogers, David D. Davis, and Ryan McWilliams, "Interim Report on the Effects of the Introduction of Heavy Axle Loads in Revenue Service," AAR Report No. R-916, December 1997, 36 pp.

In 1992, the AAR initiated the HAL revenue service program in order to monitor the rate at which HAL traffic was introduced and the effects of HAL traffic on the track structure. Test sites were established on several lines (on the UP and CSXT coal lines) and measurements were taken to determine the axle load distribution and the changes in deterioration rates of key track components. By 1997, HAL traffic accounted for 64 percent of the annual MGT on the UP line. Among the findings emphasized in this report were the following:

- Frogs (UP turnout test sites): "at this point, frog repair records indicate that there is no direct correlation between increases in HAL traffic and frog life, weld life, or numbers of repairs"
- Bridge maintenance on a 271-mile UP coal route: "no increasing trend in traffic related bridge-maintenance cost has been found, in spite of additional traffic and increased wheel loads. Preparatory work performed in anticipation of increased HAL traffic may be partially responsible for keeping bridge-maintenance costs from rising.
- Concrete ties: "the measured center bending strains for the CXT and KSA sites were well below the calculated design strain, while the center-bending strains measured on the BN are near the calculated-design cracking strain." (CXT,KSA, and BN refer to three designs for concrete ties.)

[NOTE: results such as this were used in the HAL II and III economic analyses to indicate that the predicted increases in track costs were reasonable and possibly greater than what actually happened. No significant problems related to HAL traffic were documented in this report.]

GRINDING

Jon Hannafious, "Interim Results of Norfolk Southern Rail Grinding Tests," AAR TD 97-007, February 1997

This describes tests on NS to examine the effects of grinding practices (none, one pass grind, or two pass grind). After 215 MGT of traffic, there have been no internal rail defects (shells or detail fractures).

Kevin Sawley and Jon Hannafious, "Grinding Trial on Canadian National Railroad - Interim Results," AAR TD 97-040, October 1997

"Initial results of rail-grinding trials ... indicate that heavy grinding reduces the severity of damage to the rail surface." This study is based upon six test sites on CN, each of which has fully head hardened rail that was installed in 1995. No defects were observed in any of the rails in the first 99.7 MGT.

Kevin Sawley, "Grinding-Trial Results on Canadian National and Norfolk Southern Railroads, TD 98-033

The AAR examined wear and fatigue characteristics of 4 matched sets of curves on NS and CN. Each set included curves with similar track and traffic characteristics, but with different grinding strategies. Results showed that "grinding has been clearly beneficial in preventing surface damage and maintaining desired profiles." All of the sites used premium rail, and none of the sites had had any transverse defects after 165 MGT on CN and 330 MGT on NS.

Kevin Sawley, "North American Rail Grinding on Curves in Track," AAR TD 99-004, January 1999

Sawley reports results from a survey of grinding practices as well as results from test sites on NS and CN. "Based on these results, it cannot be said which method of grinding - preventive or corrective - is best overall. Preventive grinding may be easiest to apply, and give the best control of the rail, but it may not be the most cost-effective way of maintaining the rail surface."

Economics of Heavy Axle Loads: Predicted and
Actual Benefits of HAL Operations, AAR Research
Report: Report No. R-943, 2000, AAR, S. Kalay,
J. LoPresti - 01-Track & Structures

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