FAST HEAVY AXLE LOAD PROGRAM SAFETY COMPENDIUM

INTRODUCTION

Experimental work performed at FAST has been essential to understanding the safety implications of operating increased axle loads.

The Federal Railroad Administration (FRA) and the Association of American Railroads (AAR) have jointly funded research activity at the Facility for Accelerated Service Testing (FAST) to study the effects of increasing the nominal North American railroad axle load from 33-tons (263,000-lb gross vehicle weight) to 39-tons (315,000-lb gross vehicle weight). Since its inception in 1988, the FAST Heavy Axle Load (HAL) program has generated a substantial amount of test data concerning track and vehicle performance under 39-ton axle loads. Experimental work performed at FAST has been essential to understanding the safety implications of operating increased axle loads and to the development of models defining their economic viability. The intent of this document is to summarize FAST/HAL test results as they relate to railroad operational safety.

BACKGROUND

Phases I and II quantified the effects of 39-ton axle loads under standard suspension trucks.

Phases I and II of the HAL program investigated track performance under vehicles equipped with standard design freight car trucks. Phase I, in which 160 million gross tons (MGT) of traffic was accumulated, quantified the effects of 39-ton axle loads on standard track components and provided a comparison with track performance previously measured under 263,000-lb vehicles. During Phase II, the performance of an improved track structure with premium track components under standard suspension trucks was measured over a 300 MGT period.

Premium track components provide a significant performance advantage in the HAL operating environment.

In general, the results of the first two phases indicated that material characteristics were critical to the behavior and service life of track components under 39-ton axle loads. Premium track components, especially head-hardened rail, high-integrity frog castings, premium chemistry thermite welds, and hardwood ties with elastic fasteners were found to have a significant performance advantage over standard materials under 39-ton axle loads.

In 1995, the train was re-equipped with improved suspension trucks (Phase III) and over 320 MGT has been generated to date.

The current operation (Phase III) is measuring the effects of improved truck suspension designs on track degradation. In 1995, the FAST train was re-equipped with trucks having primary suspensions and increased warp stiffness. Phase III operations began in November 1995 and have generated over 320 MGT as of this writing. Phase III is scheduled to conclude at the end of 1998 with approximately 450 MGT produced by the improved suspension consist.

HAL SAFETY ISSUES

Improved Truck Suspension Designs

Much of the derailment potential inherent with HAL operations can be attributed to poorly curving trucks that generate high lateral forces.

Much of the derailment potential inherent with HAL operations can be attributed to poorly curving freight car trucks that generate high lateral wheel/rail forces. As previously mentioned, Phases I and II of the program operated with standard suspension trucks that were installed while the cars were in revenue service. About 95 percent of the cars in the original HAL consist were equipped with National Castings (now NACO) Wedgelok trucks with constant column friction damping, roller side bearings, D-5 secondary suspension and no primary suspension. In operation at FAST, these trucks exhibited many of the curving problems associated with standard three-piece truck performance, including high lead-axle forces and angle-of-attack and a tendency to warp and generate high truck-side lateral forces.

Three trucks were selected for Phase III operation based on analytical and field test results.

During Phase II, preparations were made for a third phase of operation in which the consist would be re-equipped with improved suspension trucks. Three trucks were selected for Phase III testing from an initial group of 7 designs. The selection criteria included NUCARS modeling and AAR Chapter XI New Freight Car Service Worthiness field test results.[1] A description of each truck is included in Table 1.

All three trucks were designed for improved wheel set steering and increased truck warp resistance.

All three trucks were designed for improved curving performance with enhanced wheel set steering capability and increased resistance to truck warp. Steering is provided by the longitudinal and lateral stiffness of the shear pads and by the steering arms of the AR-1 truck. Truck warp is controlled by

Steering is enhanced with primary suspension shear pads.

the frame bracing of the S-2-HD trucks and the increased friction wedge surface of the XC-R VII truck. In addition to improved curving, the primary suspension pads have the potential of attenuating high frequency vertical forces.

Secondary suspensions are not greatly different from the standard trucks.

Secondary suspension designs are not substantially different from the standard design trucks, therefore, low frequency vertical forces are not substantially reduced.

Improved suspension trucks have reduced lateral forces by 50 percent.

Dynamic rail force measurements taken during Phase III have verified the effectiveness of the improved suspension designs in reducing lateral forces at FAST. In Figure 1, lateral forces produced by standard and improved trucks in the 6-degree curve of High Tonnage Loop (HTL) Section 25 are compared. The data in Figure 1 was collected with the train operating at 40 mph, with normal rail lubrication and with FAST worn wheel profiles and conformal wheel/rail contact.[2]

Phase III results suggest that nominal improvements to standard truck suspensions can reduce derailment potential.

In general, lead-axle lateral forces produced by the improved suspension trucks during Phase III have been half those of the standard trucks. In addition, truck-side L/V ratios in excess of 0.5 typically produced by warped trucks have not been measured under the improved suspension consist. These results strongly suggest that nominal improvements to standard three-piece freight car trucks can significantly reduce the potential of flange climb and rail roll-over derailments in a heavy haul operating environment.

Table 1. Description of FAST Phase III Test Trucks

Manufacturer	General Description	Suspension Characteristics	No. of Cars Equipped
Standard Car Truck S-2-HD	Frame brace design for truck warp resistance and variable column damping.	D5 secondary suspension with double side coils. Elastomeric shear pads between the bearing adaptor and side frame for primary suspension.	37
Buckeye Steel Castings XC-R VII	Increased friction wedge surface area for truck warp resistance and constant column damping.	D5 secondary suspension with hydraulic snubbers. Elastomeric shear pads between the bearing adaptor and side frame for primary suspension.	36
American Steel Foundries AR-1	Passive radial steering design with constant column damping	D5 secondary suspension with hydraulic snubbers. Elastomeric shear pads between the bearing adaptor and side frame for primary suspension.	4

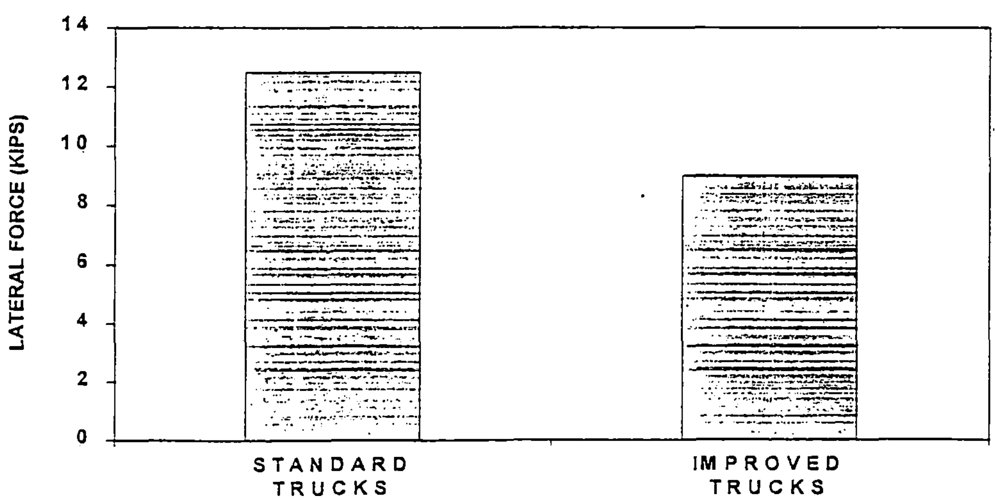

Figure 1. Comparison of Median Lead Axle Lateral Force Values Measured on 6-Degree Curve

Effects of Rail Lubrication and Profile on Curving Forces

The highest lateral forces were measured when the gage face of the high rail was well lubricated and the top of the low rail was relatively dry.

FAST data has consistently shown that truck performance and curving forces are influenced by lubrication and wheel/rail contact. In Figure 2, the effect of rail lubrication on standard suspension truck curving is shown by plotting the average lead and trail axle lateral force as a function of lubrication condition.[3] The data in Figure 2, which was measured in the 6-degree curve of Section 25, also compares the lateral force of a conformal wheel/rail profile with a 2-point contact profile. Figure 2 shows the highest lateral forces were measured when the gage face of the high rail was well lubricated (<0.2 coefficient of friction) and the top of the low rail was relatively dry (>0.3 coefficient of friction).

FAST data indicates that strong 2-point wheel/rail contact negates much of the steering benefits of improved suspension trucks.

Two point wheel/rail contact tended to increase standard truck lateral forces under all lubrication conditions by an average of 1 kip to 4 kips. However, the effect of 2-point contact on improved suspension truck curving performance was more detrimental. The median lead-axle lateral forces measured with conformal and 2-point contact for standard and improved suspension trucks are compared in Figure 3.[4] Once again, the data in Figure 3 was collected in Section 25 with the train operating at 40 mph and normal lubrication. FAST data indicates that strong 2-point contact negates much of the steering benefits of the primary suspension pads causing lead axle lateral forces to increase.

Rail Fatigue

The objective of the FAST rail profile grinding project is to find the optimum rail grinding frequency in terms of minimizing fatigue defects and maximizing rail wear life and truck curving performance.

Since 1994, rail fatigue testing at FAST has centered around the issue of 2-point contact rail profile grinding. Two-point profile grinding is a common rail maintenance technique used in Australia and North America to control gage corner fatigue on curves. The gage corner of the high rail is periodically removed by grinding to prevent development of detail fractures and other transverse defects caused by fatigue. A substantial amount of revenue service data exists confirming the benefits of 2-point grinding in terms of rail defect reduction.[5] However, as described above, 2-point wheel/rail contact diminishes truck curving behavior, especially the behavior of improved suspension trucks. The objective of the FAST rail profile grinding project is to find the optimum 2-

The test simulates 2-point grinding practices currently used in revenue service

point profile grinding frequency in terms of minimizing fatigue defects and maximizing rail wear life and truck curving performance. Test zones simulate 2-point grinding practices currently used in revenue service ranging from minimal (0.010 inch) gage corner removal at 12.5 MGT intervals to heavy removal (0.40 inch) at 75 MGT intervals. There is also a conformal profile zone in which the rail has not been ground. All test zones have 133-lb premium head hardened rail (NKK 378 Bhn).

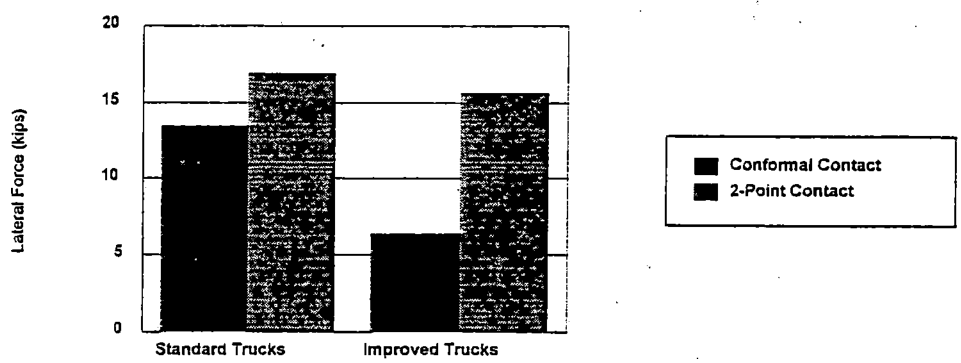

Figure 3. Effect of Rail Profile on Lead Axle Lateral Forces

After 420 MGT, test results indicate that head hardened rail may not require frequent 2-point profile grinding to prevent fatigue defect development on medium degree curves.

Over 420 MGT has accumulated thus far without development of fatigue defects in any of the test zones, 2-point or conformal profile. These test results would indicate that premium head hardened rail may not require regular 2-point profile grinding to prevent fatigue defect development on medium degree curves, at least early in the life of the rail.

A previous profile grinding test at FAST, however, did show that standard carbon 300 Bhn ingot cast rail did benefit from 2-point profile grinding in terms of fatigue behavior. The test was performed over a 180 MGT period using 300 Bhn ingot cast 136-10 RE rail section and continuously cast 136-10 RE

300 Bhn standard rail section. Test zones included control zones where no grinding was performed, a 2-point profile zone in which the gage corner was relieved by 0.025 inches at 12.5 MGT intervals, 2-point profile zones maintained at 25 MGT intervals, and conformal profile zones maintained at 25 MGT intervals. The conformal profile was produced by establishing and maintaining a naturally worn FAST outside rail profile

Continuously cast standard rails produced no defects regardless of the grinding maintenance practice selected.

Continuously cast 136-10 rails produced no defects throughout the test, regardless of the grinding maintenance practice selected. Metallurgy lab results showed this rail to be cleaner and slightly harder than the ingot cast rails. Since this rail was maintained the same as the 136 RE ingot cast rails, its resistance to fatigue was attributed to improved steel characteristics.

Ingot cast standard rails produced defects in all test zones except the 2-point contact zone maintained at 12.5 MGT intervals.

Beginning at about 100 MGT, the ingot cast rails produced defects in all zones except the 2-point contact zone maintained at 12.5 MGT intervals. This zone remained defect free throughout the test, although it did have the highest gage face wear rate. Shelling rates of the ingot cast rails were highest in the control zones and in the conformal profile zones. However, the detail fracture rates were similar in the control, conformal profile, and 2-point profile 25 MGT interval zones. Two-point contact profiles ground at 25 MGT intervals reduced the shelling rate but not the detail fracture rate as a higher percentage of shells turned into detail fractures.[6]

The effect of wheel load on fatigue defect occurrence depends on rail hardness with standard rails showing the largest increase.

Rail hardness was also found to be a key parameter in rail defect occurrence behavior when axle loads were increased in Phase I. In Figure 4, the increase in defects/rail during the first 150 MGT of 39-ton axle load operation is plotted as a function of rail hardness. This data implies that the effect of wheel load on fatigue defect occurrence depends on hardness with standard rails showing the largest increase.[7]

Back-to-back tests showed improved suspension trucks reduced fatigue defect occurrence in standard rail.

The effect of improved suspension trucks on the fatigue behavior of non-ground ingot cast standard rail was measured in Section 25. Three hundred and twenty track feet of rail was installed during Phase II and similar rail installed at the beginning of Phase III. The rail was removed after 178 MGT of standard truck operation due to 25 shells and 6 detail fractures. The same rail has produced 1 shell and 6 detail fractures after 320 MGT of improved suspension operation. One hundred sixty track feet of the rail remains in service and will be used as a mini-profile grind test in the future.

Performance testing of bainitic rails has been initiated at FAST.

Two types of bainitic steel rails (NKK and AAR J6) have recently been installed at FAST for testing. The first full scale performance testing of bainitic steel for rails and special track work in North America will be performed at FAST.

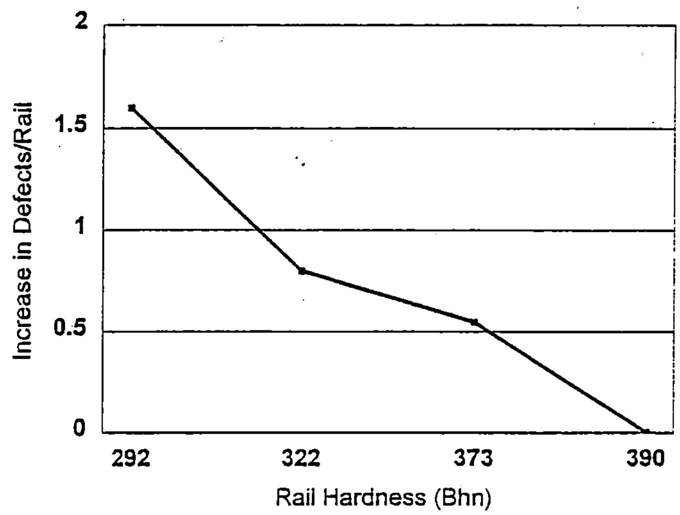

Figure 4. Effect of Increasing Axle Loads on Rail Fatigue Occurrence at FAST

Thermite Welds

During Phase I, the average life of high-rail thermite welds was approximately 62 MGT, with 144 MGT maximum life and the average life on the low rail was 114 MGT.

During Phase I, the average life of high-rail thermite welds was approximately 62 MGT, with 144 MGT maximum life and the average life on the low rail was 114 MGT. Most welds failed from shelling and horizontal web cracks.[8] As a result of the Phase I performance, the AAR and the weld manufacturers set out to improve the reliability of welds under 39-ton axle loads. AAR implemented extensive welder training and the manufacturers concentrated on changes to procedures and designs, including a new mold design aimed at reducing failures from web cracking.

In Phase II, a new weld test was implemented with combinations of standard and premium chemistries and/or standard or modified mold designs installed in a 5-degree curve test section of the HTL. Seventy-one thermite welds were installed, including 36 standard welds (16 on the low rail and 20 on the high rail) and 35 premium welds (18 on the low rail and 17 on the high rail). Using Weibull analysis, the projected life of Phase I standard welds and Phase II premium welds is plotted in Figure 5.[9]

Despite the performance improvement provided by premium welds and improved techniques, thermite welds remain one of the least reliable track components in the HAL environment.

Despite the performance improvement provided by premium welds and improved techniques, thermite welds remain one of the least reliable track components in the HAL environment. A histogram of tonnage at weld failure recorded during Phases II and III is shown in Figure 6. The average tonnage at failure was 88 MGT, although a small percentage of weld failures occurred at much higher tonnage. In general, the higher tonnage weld failures occur on the low rails of curves and on tangent track. The FAST experience indicates a continued need to further improve thermite weld service life.

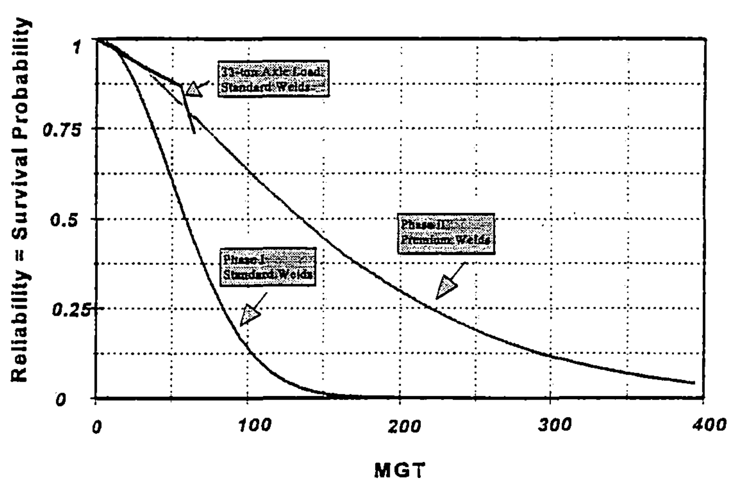

Figure 5. Projected Life of Thermite Welds

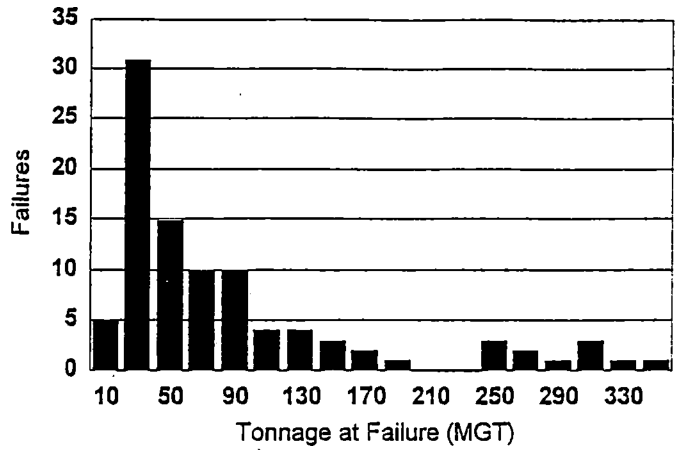

Figure 6. FAST Weld Failure Distribution Phase II and III

A new thermite weld test has been implemented to determine the effectiveness of weld conditioning and post weld treatment as means of preventing undesirable residual stresses from developing during the welding process.

A new thermite weld test has been implemented to determine the effectiveness of weld conditioning and post weld treatment as means of preventing undesirable residual stresses from developing during the welding process. Both techniques apply vibrational energy to the rail during the welding process (weld conditioning) and after the weld as the rail is cooling (weld treatment). Sixty five test welds, including non-treated control welds, have been installed in Sections 30, 31 and 32 (5-degree curve and spirals) of the HTL.

Ties and Fasteners

Oak was the only species to accumulate over 400 MGT without requiring re-gaging under standard truck operation.

Wood ties with assorted rail fasteners have been under test throughout the HAL program. During Phase II, much of the testing was concentrated in the 6-degree curve of Section 25. Curving forces and L/V ratios tend to be the highest in this curve and it represents the most severe operating environment on the HTL. The performance of ties of various wood species equipped with cut spike and elastic (Pandrol) rail fasteners was measured. Of the ties tested in Section 25 with cut spikes, which included oak, Douglas fir, hem-fir, southern yellow pine, and red maple, oak was the only species to accumulate over 400 MGT without requiring re-gaging. Maximum gage widening (ignoring rail wear) of oak ties after 460 MGT was about 0.75 inches. Gage widening of hem-fir and southern yellow pine exceeded 1 inch and required re-gaging at 200 MGT. Douglas fir ties required re-gaging between 360 MGT and 375 MGT and the red maple ties were ready for re-gaging when removed from track after 360 MGT [10]

Changing from cut spikes to an elastic fastening system will improve the gage restraint of softwood ties, but the long-term effectiveness will depend on the tie condition.

Use of the Pandrol fastening system with screw spikes significantly improved the gage retention capability of the hem-fir, southern yellow pine and Douglas fir ties. Installed when the ties were re-gaged, the rate of gage widening with the Pandrol system was about half that experienced with cut spikes when the ties were new. There was a tendency, however, for some coach screws to back out of the ties under traffic. Threaded coil inserts were installed in the coach screw holes to remedy the problem, but were not particularly effective if the tie had been split at the hole. The performance of the softwood ties in Section 25 suggests that changing from cut spikes to an elastic fastening system with screw spikes will improve the existing gage restraint, but the long-term effectiveness of the elastic fastening system will depend on the tie condition.

Gage retention of softwood ties was greatly improved with improved suspension trucks.

Tie performance, especially gage retention, also benefits from improved vehicle curving characteristics. The results of gage widening measurements performed on southern yellow pine and Douglas fir ties located in Section 25 (6-degree curve) is shown in Figure 7. The ties used in the comparison were equipped with 14-inch AREA tie plates and track spikes. The data clearly show the effects of lower lateral forces on softwood tie performance

There has been no indication of concrete tie structural problems in over 780 MGT 39-ton axle load operation.

Concrete ties have been under test in the 5-degree curve of Section 03 since the start of the HAL program in 1988. Other than some tie center cracking that occurred early in the program -- all of the cracked ties have remained in track -- there has been no indication of concrete tie problems in over 780 MGT 39-ton axle load operation.

In addition to concrete tie structural performance, the issue of rail seat abrasion has been also studied. This phenomena, in which the concrete directly under the rail is worn away, is fairly common in the North American heavy haul environment. It is also a significant safety concern since loss of material under the rail results in loss of fastener toe load and loss of lateral and longitudinal rail restraint. A number of materials and components designed to resist or prevent abrasion have been evaluated at FAST. Results showed that of the remedies tested, tie pads of dual durometer materials (hard and soft materials bonded to a single pad) and pads of sandwich materials (multiple products such as a sealant, steel plate and resilient material on one pad) offer the best resistance to abrasion.[11]

Rail seat abrasion is a safety concern due to loss of fastener toe load.

Dual durometer and sandwich tie pads offer the best resistance to abrasion.

In addition to wood and concrete, tests of nontraditional tie materials such as steel and recycled plastic have been implemented in the past 2 years. These tests will provide performance data concerning vertical and lateral track stability, rail fastener reliability and tie structural integrity before the ties are introduced into general revenue service use.

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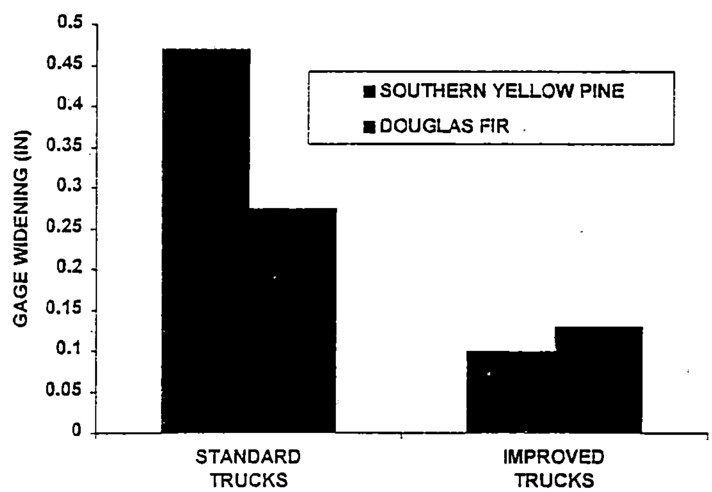

Figure 7. Comparison of Gage Widening on Softwood Ties After 250 MGT

Track Substructure

A Low Track Modulus (LTM) test zone was installed in Section 29 to simulate lower-end, but not worse case, mainline track support conditions.

Although the relationship between track vertical stiffness/modulus and track performance has not been firmly established, it is likely that much track geometry degradation is related to deficiencies in the track substructure which allow large rail deflections under load. To gain as complete a determination as possible of track performance 39-ton axle loads, a Low Track Modulus (LTM) test zone was installed in Section 29 by replacing the existing soil with a low strength clay. The purpose of the LTM zone was to simulate lower-end, but not worse case, mainline track support conditions. Track modulus of about 2,000 lb/in/in was used as the target value for the LTM design and construction. A control zone with modulus of approximately 5,000 lb/in/in was also established.[12]

Instrumentation was installed to measure vertical load path characteristics.

In addition to quantifying track geometry degradation, the LTM and control zones were equipped with instrumentation to measure vertical load path characteristics. A measurement cell was installed in both zones to collect vertical rail force, vertical rail seat force, and ballast/subgrade pressure data. Load path data was collected under a consist of equal numbers of 33-ton and 39-ton axle load vehicles.

LTM results indicate that track modulus less than 2,000 lb/in/in will not sustain operations of 39-ton axle loads and modulus between 2,000 lb/in/in and 2,500 lb/in/in should be considered marginal for HAL operations.

After 60 MGT of operation in its original configuration, LTM test results strongly indicated that track modulus less than 2,000 lb/in/in will not sustain operations of 39-ton axle loads and modulus between 2,000 lb/in/in and 2,500 lb/in/in should be considered marginal for HAL operations, with frequent maintenance cycles to be expected. The LTM zone required surfacing at 12, 28, 37, 48, and 60 MGT due to cross-level deviations in excess of 1.5 inches. Geometry degradation in the control zone was not significant during the same 60 MGT period. Vertical subgrade pressures were measured under 39-ton axle load vehicles were in the range of 10 psi to 20 psi in both the LTM and the control zones. The difference in subgrade stiffness between the two zones did not have a significant effect on subgrade pressures.

A geosythetic material known as GEOWEB® was installed in the LTM zone in 1996 to test its effectiveness as a soft subgrade remediation technique. With GEOWEB®, the zone

GEOWEB® has demonstrated the ability to improve track stability in poor subgrade conditions.

has accumulated over 100 MGT with minimal loss of geometry and no required maintenance, as compared to nominal 15 MGT tamping cycles before. GEOWEB® has demonstrated the ability to improve track stability in poor subgrade conditions by introducing a stiff layer between the ballast and subgrade which reduces traffic induced stresses in the subgrade.[13]

Dynamic vertical wheel forces from the standard suspension trucks were measured in the LTM and control zones and were found to increase linearly with track profile roughness.

As a related issue, dynamic vertical wheel forces from the standard suspension trucks were measured in the LTM and control zones and were found to increase linearly with track profile roughness. In Figure 8, the standard deviation of the vertical wheel force measured with instrumented wheel sets is plotted as a function of the track profile standard deviation as measured with the EM80 track geometry car. The rate at which the forces increase with profile degradation will serve as a baseline for the evaluation of improved suspension performance. Work is currently in progress to further define the relationship between wheel forces and track geometry.

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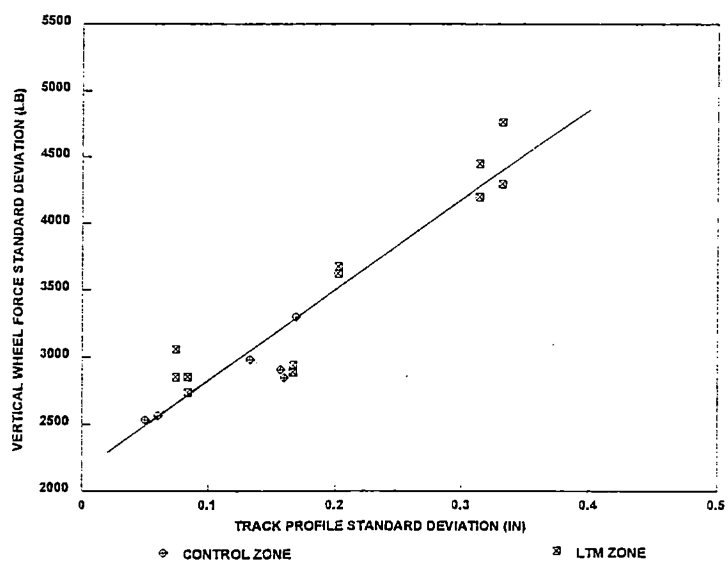

Figure 8. Vertical Force Standard Deviation vs. Profile Standard Deviation

CONCLUSIONS

Conclusions regarding the safety aspects of HAL operations based on FAST research to date are as follows:

- Modest improvements to conventional 3-piece truck designs, namely addition of primary suspension shear pads and devices to prevent truck warp, can reduce curving forces on the order of half. Reduction of lateral wheel/rail forces have positive implications concerning gage widening and rail roll over, gage corner rail fatigue, flange climb, and lateral track stability (track panel shift and track buckling). Data collected during Phase III has enabled the FAST engineering staff to determine, for the first time in recent railway research, the overall benefits to track and operating safety due to improved truck suspension systems. Prior to this experiment, benefits were estimated through models and expert opinion.

- Rail fatigue and defect occurrence is highly dependant on rail hardness and cleanliness. The fatigue life of standard (300 Bhn) ingot cast rail in a well lubricated 6-degree curve was 180 MGT under standard suspension trucks. Premium (378 Bhn) rail currently in test has over 420 MGT on the same curve as the ingot cast rail without any fatigue development, although the majority of the tonnage (320 MGT) has been generated by improved suspension trucks. Harder rail also showed the least impact in terms increased fatigue defect occurrence when axle loads increased from 33-tons to 39-tons.

- Two-point profile grinding has been proven to increase the fatigue life and reduce the number of fatigue defects in revenue service and on standard ingot cast rail at FAST. However, tests in revenue service and at FAST have shown that 2-point profile grinding accelerates rail wear and increases lateral forces.[14] The long term effect of 2-point profile grinding as a means of controlling fatigue defects in premium rail is not clear at present. The FAST rail profile grinding test will eventually provide much needed data concerning grinding practices for premium rail.

- The failure rate of thermite welds increased over 100 percent when axle loads at FAST increased from 33-tons to 39-tons. Improvements in the weld material and procedures and an emphasis on welder training and adherence to procedures reduced the failure rate. However, thermite welds still show a propensity for early failure in the operating environment at FAST. Tests are in progress to determine the effectiveness of applying vibrational energy to welds during and after being poured to reduce residual stresses.

- Oak ties have a definite performance advantage in terms of gage retention over the softwood ties tested. Oak ties with track spikes have accumulated over 780 MGT without need for re-gaging. Southern yellow pine and hem-fir ties required re-gaging at 200 MGT and Douglas Fir and red maple ties required re-gaging at about 360 MGT. Use of elastic fasteners with softwood ties reduced their gage degradation by half. The introduction of improved suspension trucks applying lower lateral forces also provided gage retention benefits for softwood ties. Concrete ties have shown no structural or fastener problems in over 780 MGT.

- Tamping was required in the LTM soft subgrade test zone with nominal track modulus of 2,000 lb/in/in, at 10 MGT to 15 MGT intervals due to plastic deformation of the clay subgrade and subsequent track geometry degradation. Installation of a geosythetic material known as GEOWEB® has effectively reduced traffic induced subgrade stresses and lengthened the maintenance cycle to over 100 MGT.

REFERENCES

1. Klauser, P., C. Urban, and R. Florom. "On-Track Test Results For the Heavy Axle Load Alternative Suspension Project,"AAR Report No. R-896, October 1996.

2. Read, D., S. Kalay. "Phase III 300 MGT," Railway Track and Structures, February 1997.

3. Read, D., S. Kalay. "Results of Phase II Heavy Axle Load Tests at FAST," American Railway Engineering Association Bulletin No. 757, October 1996.

4. Hannafious, J. "FAST Heavy Axle Load Program Rail Grinding Evaluation," *Proceedings, 2nd Annual AAR Research Review,* Pueblo, Colorado, December 1996.

5. Zarembski, A. "On the Benefits of Rail Maintenance Grinding," American Railway Engineering Association Bulletin No. 760, May 1997.

6. Read, D., S. Kalay. "Track Performance as Measured at FAST Under 39-ton Axle Loads and conventional Three-Piece Trucks," Conference Paper, Sixth International Heavy Haul Conference, Cape Town, South Africa, April 1997.

7. Steele, R. "Overview of the FAST/HAL Rail Performance Tests," *Proceedings, Workshop on Heavy Axle Loads*, Pueblo, Colorado, October 1990.

8. Brave, G. "FAST/HAL Rail Weld Performance," *Proceedings, Workshop on Heavy Axle Loads*, Pueblo, Colorado, October 1990.

9. Garcia, G., "Thermite Weld Performance Under Heavy Axle Load Operation at FAST," *A World of Change; 1st Annual AAR Research Review Proceedings, Volume 1*, Pueblo, Colorado, November 1995.

10. Trevizo, M., "Analysis of Wood Tie and Fastener Performance in a Heavy Axle Load Environment, *A World of Change, 1st Annual AAR Research Review Proceedings, Volume 1*, Pueblo, Colorado, pp. 63-70, November 1995.

11. Gage, S. and Reiff, R., "Concrete Tie Rail Seat Abrasion Test," *A World of Change, 1st Annual AAR Research Review Proceedings, Volume 1*, Pueblo, Colorado, pp. 71-75, November 1995.

12. Read, D., S. Chrismer, W. Ebersohn, and E. Selig, "Track Modulus Measurements at the Pueblo Soft Subgrade Site," Transportation Research Record No. 1470 Rail Research Issues, Transportation Research Board, Washington D.C. 1994,

13. Chrismer, S. "Test of GEOWEB® to Improve Track Stability Over Soft Subgrade," Association of American Railroads Technical Digest TD 97-045, December 1997.

14. Hannafious, J. "AAR Rail Grinding Update," American Railway Engineering Association Bulletin No. 762, December 1997.