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Evaluation of Rail Behavior at the Facility for Accelerated Service Testing

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Results of two experiments conducted at the Facility for Accelerated Service Testing to investigate the wear and defect behavior of various rail metallurgies under unit train operations are presented. Five types of rail were used: standard carbon, high-silicon, head-hardened, chrome molybdenum, and fully heat-treated. The load demarcation between the two experiments was at a traffic loading of 122 million gross Mg (135 million gross tons). In the first experiment, a condition of underlubrication existed up to 36 million-41 million gross Mg (40 million-45 million gross tons), after which point lubrication could be described as generous, a condition maintained throughout the second experiment. Railhead profile measurements taken in both experiments revealed that head-hardened and chrome molybdenum rail exhibited the best resistance to high-rail curve wear. In the first experiment, there was a strong lubrication-metallurgy interaction that caused the premium metallurgies to benefit less than standard rail from generous lubrication. In the under-

lubricated condition, the 1:14 tie-plate cant produced about 20 percent more gage-face and head-area loss than the other cants. The cant effect was considerably reduced by generous lubrication. Position-in-curve effects were dependent on the level of lubrication. When generous lubrication permitted the accumulation of greater loads on the rails, fatigue failure became the dominant failure mode in both railhead and weldments. Standard rail exhibited the greatest number of failures from railhead fatigue.

The rail metallurgy experiment at the Federal Railroad Administration's Facility for Accelerated Service Testing (FAST) has as its primary intent the development of information on rail wear in a controlled environment. However, useful information on rail and weld failure

behavior has also been forthcoming.

The FAST track (see Figure 1) is a specially constructed 7.7-km (4.8-mile) loop divided into 22 sections in which specified combinations of track components and structures are installed for testing. It contains 3.5 km

(2.2 miles) of tangent, 0.64 km (0.4 mile) of 3° curve, 0.48 km (0.3 mile) of 4° curve, and 1.8 km (1.1 miles) of 5° curve; the remaining 1.29 km (0.8 mile) is in transitional spirals.

The FAST consist is made up of four-axle locomotives

Figure 1. Diagram and profile of FAST track.

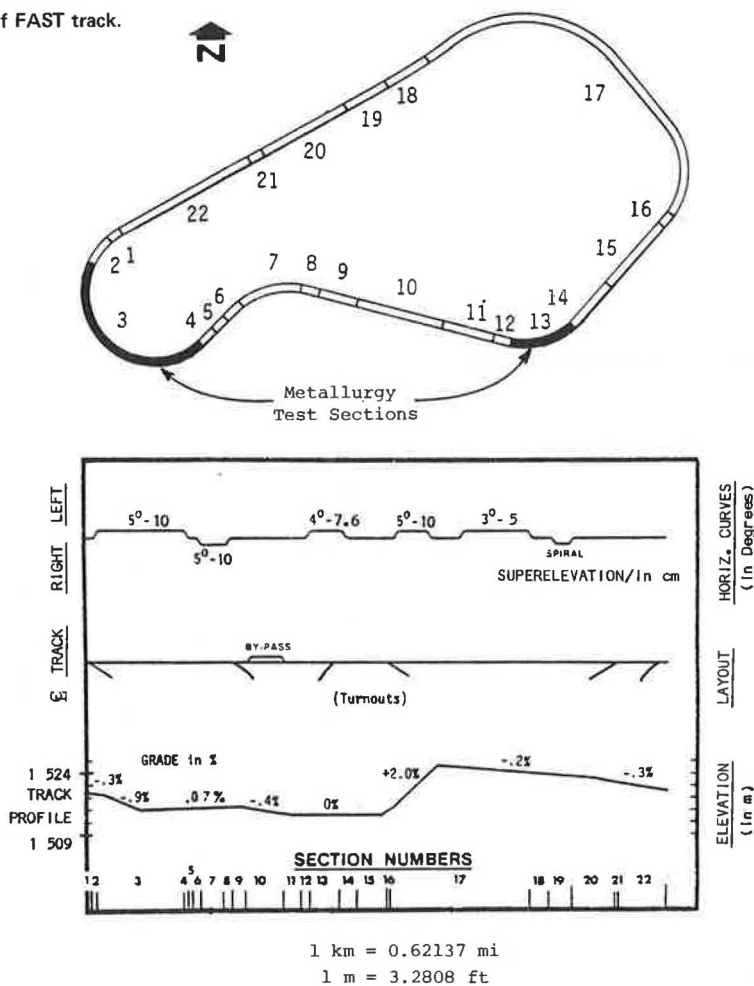


Figure 2. Layout of FAST section 3.

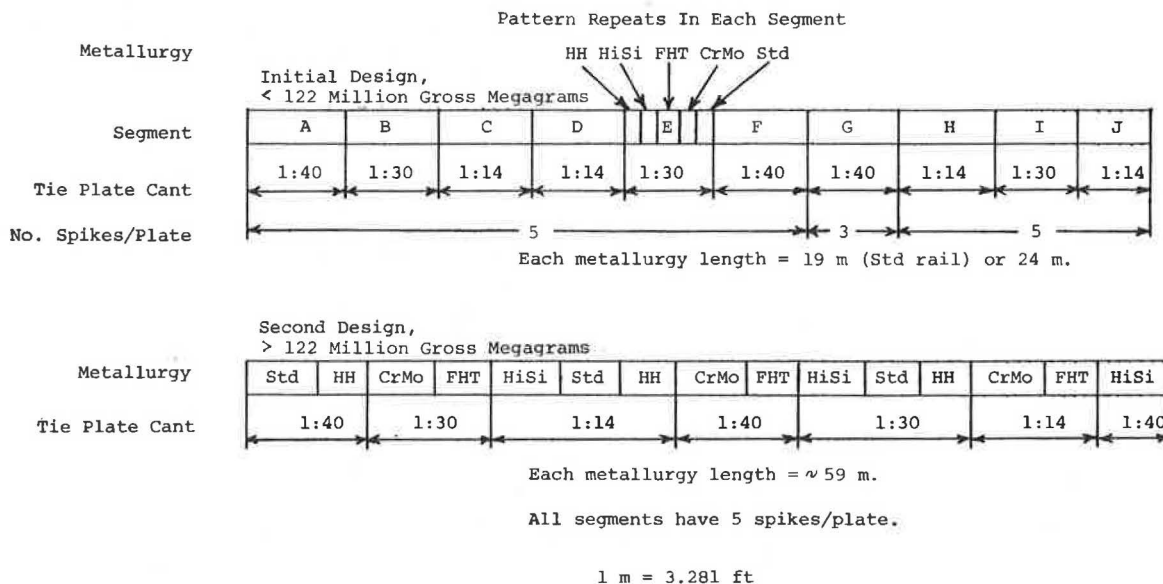
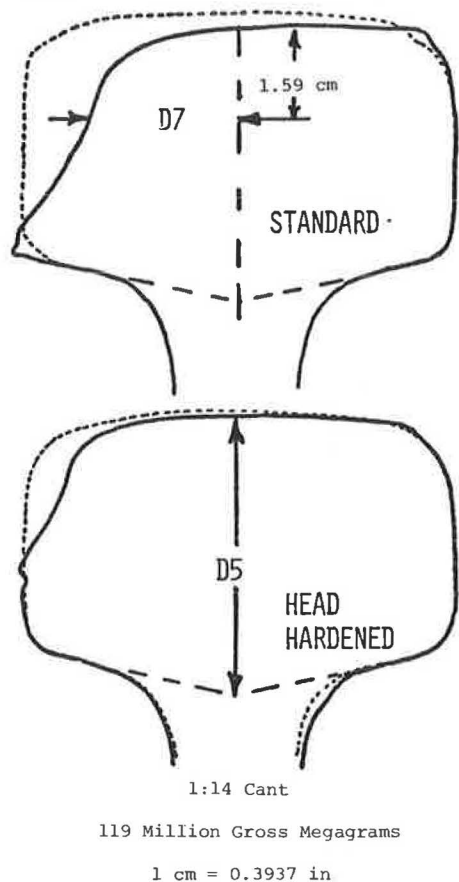


Table 1. Average chemical analyses of rail in first FAST metallurgy experiment.

Sec- tion	Metal- lurgy	w/o					
		Carbon	Man- ganese	Phos- phorus	Sulfur	Silicon	Chro- mium
3	HH	0.79	0.84	0.009	0.018	0.16	-
	HiSi	0.76	0.86	0.028	0.027	0.63	-
	FHT	0.69	0.81	0.018	0.032	0.18	-
	CrMo	0.80	0.82	0.026	0.025	0.25	0.78
	Standard	0.78	0.86	0.027	0.025	0.15	-
13	HH	0.77	0.88	0.015	0.025	0.18	-
	HiSi	0.77	0.88	0.029	0.024	0.68	-
	FHT	0.77	0.81	0.020	0.041	0.15	-
	Standard	0.73	0.86	0.024	0.020	0.17	-

Figure 3. Measurements and extremes of railhead profile.



that normally haul a 75-car, 8616-Mg (9500-ton) train. The majority of the cars are 91-Mg (100-ton) hopper or gondola cars; the remainder are 91-Mg-capacity tank cars and laden trailer on flat cars. The average train speed is 65.9 km/h (41 miles/h), and the maximum speed is 72.4 km/h (45 miles/h).

Tests are run five days a week. Each test run begins in the afternoon, continues all night, and ends the next morning. On each run, the consist makes approximately 120 laps of the track, imposing a traffic loading of about 0.907 million gross Mg (1 million gross tons) on the track and putting about 966 km (600 miles) on the cars (throughout this paper, loads are in gross megagrams and gross tonnage).

The rail metallurgy tests have been conducted on track sections 3 and 13. Section 3 is a 1097-m (3600-ft) long 5° curve. The north half is on a 0.9 percent grade, and the south half is virtually level. Section 13

is a 381-m (1250-ft) long 4° curve that is level throughout its length (Figure 1).

As of June 1979, two rail metallurgy experiments had been completed. The first extended until 122 million Mg (135 million tons) was imposed on the track, and the second extended for an additional 263 million Mg (290 million tons) until a load of 385 million Mg (425 million tons) was imposed. At the beginning of the first experiment, rail lubrication was provided from track lubricators in sections 5 and 17 only. However, between 27 and 45 million Mg (30 and 50 million tons), two additional lubricators were installed in sections 2 and 18, and the section 17 lubricator was moved to section 14. Thus, two regimes of behavior, one of underlubrication and the other of generous lubrication, existed in the first experiment, the transition occurring at 36–41 million Mg (40–45 million tons). In the second experiment, only the generous lubrication was used.

The physical layouts of the first and second experiments in section 3 are shown in Figure 2. Section 3 was laid with American Railway Engineering Association (AREA) standard carbon, high-silicon (HiSi), chrome molybdenum (CrMo), fully heat-treated (FHT), and head-hardened (HH) rail, all in rail sections of 65.5, 67.5, or 69.5 kg/m (132, 136, or 140 lb/yd). In both experiments, the same five metallurgies and three tie-plate cants were the primary test parameters. However, the change in physical layout was necessitated by an unexpectedly large number of weld failures in the first experiment and by a concern that the short lengths of each metallurgy segment in the first experiment—19–24 m (62–78 ft)—would produce nonrepresentative wear results. Possible position-in-curve effects were compensated for by providing at least three replications of the metallurgies around the curves.

In each experiment, section 13 was configured almost identically to section 3 except for a reduced number of metallurgies and the use of 1:40 tie-plate cant throughout. In the first experiment, four metallurgies were tested: standard, HiSi, FHT, and HH, each replicated four times. All rail in section 13 was 57.1 kg/m (115 lb/yd).

The average ladle chemistries of the rails tested in the first experiment are given in Table 1. With the exception of the FHT rail tested in section 3, which had a carbon content slightly less than 0.70 percent by weight (w/o), and the standard rail tested in section 13, which had a carbon content slightly less than 0.75 w/o, all metallurgies had average carbon contents in the range of 0.76–0.80 w/o. The average manganese levels ranged from 0.81 to 0.88 w/o.

Wear measurements were taken by using profilometers that produce 1:1 tracings of the railhead, beginning at the fishing surface under one side of the head and tracing around to the other. Correction procedures were applied to compensate (sometimes only partly) for instrument and operator variability. In addition, a change in the correction procedure was introduced at

72.5 million Mg (80 million tons), and this change was believed to be responsible for the transients in wear data observed at that load. Measurements were taken at intervals of approximately 18 million-23 million Mg (20 million-25 million tons), at a minimum of two measurement sites on each test rail.

Profiles were digitized and then processed to produce the dimensions shown in Figure 3 along with gross area (complete area above the lines projected from the fishing surfaces) and total head area (above projections from the fishing surfaces but within the original profile). Portions of these data have been subjected to two types of statistical analysis by independent organizations. The Association of American Railroads (AAR) made the more elaborate, and more rigorously correct, analysis of covariance by using all original data for decisions about statistical significance in which wear is described by a linear wear model. The Transportation Systems Center (TSC) of the U.S. Department of Transportation made the second, simpler, analysis. This analysis also used a linear wear model and determined the parameters of the model by regression techniques, but testing for statistical significance was applied only to the wear rates derived from the regression analysis and the original data were not used.

Results of both analyses are presented for rates of gage-face wear from the first experiment in section 3. The more elaborate method has also been used to study the head-height loss and head-area reduction indicators of wear in section 3 (first experiment). The simpler method has been applied alone to the rates of gage-face wear from section 13 (first experiment) and from section 3 (second experiment); at this time, results are available only for the high rail.

WEAR

The extremes of profile shape that occur after approximately 118 million Mg (130 million tons) in conditions of combined underlubrication and very generous lubrication are shown in Figure 3. The standard rail has a well-developed "front porch" formed by metal flowing down the gage face. This porch forms in the underlubricated regime. All of the other metallurgies are far less susceptible to this behavior than is standard rail.

The wear data on gage-face loss for all five metallurgies on the 1:40-cant tie plate in section 3 are shown in Figure 4. The scatter for standard and HiSi rails was substantially greater than that of the other metallurgies because there were about 10 different heats of standard and HiSi rail but only one or two different heats of the other metallurgies.

The wear rates for the three different measures of wear above and below the transition in lubrication and for the different tie-plate cants are summarized in Table 2. The results indicate that both tie-plate cant and metallurgy have a significant effect on all three measures. Wear rates above 41 million Mg (45 million tons) are substantially lower than those below 41 million Mg. At <41 million Mg, the 1:14 tie-plate cant yields about 20 percent higher wear rates for gage-face wear and head-area loss and the 1:40 cant produces higher rates of head-height loss. Typically, wear rates for HH and CrMo rail are lower than those for the other metallurgies. HH shows the least gage-face wear, but CrMo shows the least head-height loss. The degree of difference between the behavior of the different metallurgies is less above 41 million Mg than below that load, which does suggest the presence of a metallurgy-lubrication interaction.

To explore this last point further, figures of merit

(FMs) were calculated for all the metallurgies in each lubrication regime to provide a quantitative average ranking of each metallurgy. The FM is the number of times better a premium rail wears (on average) than does standard rail tested under the same condition. The FMs are given in Table 3. This type of presentation reveals clearly that generous lubrication tends to decrease the advantage in wear resistance achieved by using a premium metallurgy.

The decrease is most marked for gage-face wear, where only HH rail seems significantly better than standard rail in the generously lubricated regime. In addition, the ranking of the metallurgies is not the same for head-area and gage-face loss. Although FHT rail is no better than HiSi rail in its resistance to gage-face loss, it is significantly better in terms of head-area loss.

Tables 4 and 5 illustrate that the agreement between the two different types of analysis is very good even if the transition traffic load is shifted slightly to 36 million Mg (40 million tons). Based on observed standard deviations, the FMs for gage-face wear have a tolerance of +25 to -15 percent.

The simpler TSC method of analysis is more easily implemented and was used, therefore, to test for position-in-curve effects and to provide a preliminary glimpse of the data from section 13 (first experiment) as well as those from section 3 (second experiment).

The magnitude of the position-in-curve effect in section 3 is illustrated by the data given in Table 6. In the underlubricated regime, the section 4 end of section 3 produced slightly higher wear rates on average than did either the middle or the section 2 end. In the more generously lubricated regime, however, the relative differences were greater, the highest wear occurring at the center of the curve. Again, the behavior was not strongly dependent on where the lubrication transition was selected. Table 7 summarizes the results of statistical testing for significance and shows that, indeed, the position-in-curve effect tended to increase at the expense of the primary metallurgy and cant effects as lubrication improved.

Rates of gage-face wear from section 13 (first experiment) are summarized in Table 8. The same general pattern was observed as that in section 3 except that a statistically significant position-in-curve effect was not noticed. HH rail gave the highest resistance to gage-face wear, and FHT rail was noticeably better than HiSi and standard rail. In the more generously lubricated regime above 36 million Mg (40 million tons), the behavior of all metallurgies was essentially the same.

Before the results from the second experiment in section 3 are discussed, it will be informative to comment briefly on the effect of heat-to-heat variations that occurred in the standard rail of the first experiment. There were four combinations of high-wear-rate heat and tie-plate cant. If these four combinations were removed, variations of the standard rail data set would be comparable to those of the premium metallurgies. For all three measures of wear, however, the removal of these combinations would reduce average wear rates by only 10 percent, and the FM would be reduced by a corresponding 10 percent.

Preliminary results on gage-face wear from the second experiment in section 3 are summarized in Table 9. The table below compares these results with results from the first experiment (1 cm/Mg = 0.358 in/ton):

Location	Gage-Face Wear (cm/million Mg)	
	First Experiment	Second Experiment
Section 2 end	0.003-0.004	0.001 25
Middle	0.0044-0.005	0.001 37
Section 4 end	0.0014-0.0022	0.001 03

The results in terms of FM are in close agreement with those from the generously lubricated regime of the first experiment except that the CrMo rail performed somewhat better than the HH rail. The reader must exercise some caution in deciding whether the difference in FM for CrMo and HH is real because it was only in the section 2 end that both appeared to be appreciably different.

Overall, the observed wear rates in the second experiment were only one-third to one-half the magnitude of those observed in the first experiment.

Table 10 summarizes the pertinent statistical information. Tie-plate cant did not appear to be statistically significant, although the position-in-curve effect did appear to be statistically significant when tie-plate cant was included in the analysis. If tie-plate cant was removed as a variable, the statistical strength of the position-in-curve effect weakened.

It will be informative to consider how these results compare with those from other investigations. Figure 5 shows the range of wear rates (head-area loss) for the metallurgies tested in section 3 (5° curve) relative to those reported by others (1-3). The data of Hay and

Figure 4. Gage-face wear of all five metallurgies on 1:40-cant tie plates in section 3.

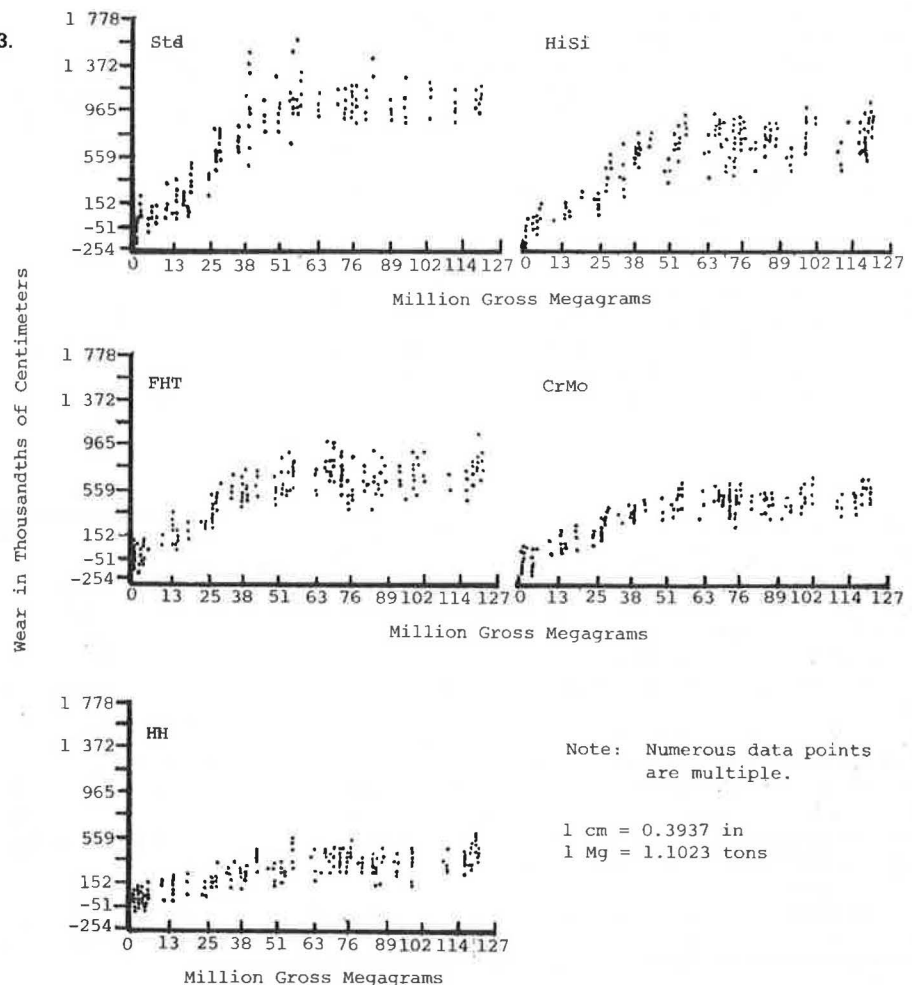


Table 2. Wear rates above and below the 41 000 000-Mg lubrication transition for various tie-plate cants.

Wear	Tie-Plate Cant	HH		HiSi		FHT		CrMo		Standard	
		Below	Above	Below	Above	Below	Above	Below	Above	Below	Above
Gage-face wear (cm/million Mg)	1:40	0.007 57	0.000 83	0.016 17	0.000 86	0.015 36	0.002 29	0.009 91	0.002 01	0.022 59	0.002 01
	1:14	0.010 72	0.002 51	0.019 75	0.004 16	0.018 38	0.003 10	0.012 40	0.003 77	0.023 32	0.003 77
	1:30	0.008 32	0.001 51	0.014 33	0.002 71	0.015 31	0.002 85	0.011 20	0.002 76	0.021 73	0.002 76
Head-area loss (cm ² /million Mg)	1:40	0.005 49	0.003 28	0.058	0.007 85	0.050 28	0.003 28	0.032 07	0.006 57	0.091 93	0.011 93
	1:14	0.003 67	0.006 57	0.064 78	0.008 5	0.047 64	0.010 64	0.030 21	0.007 64	0.088 93	0.009 07
	1:30	0.003 03	0.006 93	0.050 57	0.011	0.044 78	0.013 07	0.034 43	0.006 07	0.087 78	0.011 14
Head-height loss (cm/million Mg)	1:40	0.003 54	-*	0.004 02	-*	0.002 71	-*	0.002 04	-*	0.007 15	0.000 03
	1:14	0.003 04	-*	0.003 74	-*	0.001 56	0.000 14	0.001 48	-*	0.006 51	0.000 31
	1:30	0.002 51	-*	0.003 41	-*	0.002 20	-*	0.001 45	0.000 16	0.006 23	0.000 83

Note: 1 cm/Mg = 0.358 in/ton; 1 cm²/Mg = 0.14 in²/ton.

*No significant wear.

Table 3. Figures of merit above and below the 41 000 000-Mg lubrication transition for various tie-plate cants.

Wear	Metallurgy	1:40 Cant		1:14 Cant		1:30 Cant		Avg	
		Below	Above	Below	Above	Below	Above	Below	Above
Gage-face wear	HH	3.0	2.4	2.2	1.5	1.8	1.8	2.6	1.9
	HiSi	1.4	1.3	1.2	0.9	1.0	1.0	1.4	1.1
	FHT	1.5	0.9	1.3	1.2	1.0	1.0	1.4	1.0
	CrMo	2.3	1.2	1.9	1.2	1.0	1.0	2.0	1.2
	Std	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Head-area loss	HH	2.6	3.6	2.4	1.4	2.9	1.6	2.6	2.2
	HiSi	1.6	1.5	1.4	1.1	1.7	1.0	1.6	1.2
	FHT	1.8	3.6	1.9	0.8	2.0	0.8	1.9	1.8
	CrMo	2.9	1.8	2.9	1.2	2.5	1.8	2.9	1.6
	Std	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Head-height loss	HH	2.0	- ^a	2.1	- ^a	2.5	- ^a	2.2	- ^a
	HiSi	1.8	- ^a	1.7	- ^a	1.8	- ^a	1.8	- ^a
	FHT	2.6	- ^a	4.2	- ^a	2.8	- ^a	3.2	- ^a
	CrMo	3.5	- ^a	4.9	- ^a	4.3	- ^a	4.2	- ^a
	Std	1.0	- ^a	1.0	- ^a	1.0	- ^a	1.0	- ^a

Note: Figures of merit = standard carbon wear rate ÷ premium metallurgy wear rate on specific tie-plate cant.

^aNo significant wear.

Table 4. Average gage-face loss for section 3: comparison of results of AAR and TSC analyses.

Metallurgy	Below Lubrication Transition						Above Lubrication Transition					
	AAR (<41 000 000 Mg)			TSC			AAR (>41 000 000 Mg)			TSC		
				<41 000 000 Mg						>41 000 000 Mg		
	Gage-Face Wear (cm/million Mg)	FM		Gage-Face Wear (cm/million Mg)	FM		Gage-Face Wear (cm/million Mg)	FM		Gage-Face Wear (cm/million Mg)	FM	
HH	0.0089	2.6		0.0086	2.8	0.0089	0.0016	1.9		0.0022	1.4	0.0025
HiSi	0.0167	1.4		0.0167	1.4	0.0178	0.0025	1.1		0.0033	0.9	0.0042
FHT	0.1620	1.4		0.0159	1.5	0.0170	0.0028	1.0		0.0025	1.2	0.0036
CrMo	0.0112	2.0		0.0114	2.1	0.0117	0.0025	1.1		0.0030	1.0	0.0036
Standard	0.0226	1.0		0.0243	1.0	0.0254	0.0028	1.0		0.0030	1.0	0.0044

Note: 1 Mg = 1.1 tons; 1 cm = 0.3937 in.

Table 5. Tie-plate-cant effect for section 3.

Cant	Gage-Face Wear (cm/million Mg)					
	Below Lubrication Transition			Above Lubrication Transition		
	AAR (<41 000 000 Mg)			AAR (>41 000 000 Mg)		
		TSC			TSC	
		<41 000 000 Mg	>37 000 000 Mg		>41 000 000 Mg	>37 000 000 Mg
1:40	0.0142	0.0145	0.0156	0.0015	0.0022	0.0031
1:30	0.0142	0.0145	0.0156	0.0025	0.0031	0.0036
1:14	0.0170	0.0173	0.0178	0.0033	0.0033	0.0044

Note: 1 cm = 0.3937 in; 1 Mg = 1.1 tons.

others (1) are shown as average curves. FAST data are consistent with the trend of results reported by Curcio and others (2) for unit-train-type operations in Australia. FAST wear in the underlubricated region was substantially more severe than that reported by Hay and others for more general types of railroad service in the United States. Even wear reported by Rougas (3) for heavy unit train service on the Bessemer and Lake Erie Railroad was less severe than FAST wear.

The expression proposed by Kalousek and Bethune (4) for volumetric wear can be recast into the following form:

$$V_1/V_2 = (C_1/C_2) \cdot (H_2^{\alpha_2}/H_1^{\alpha_1}) \quad (1)$$

where

- V = volumetric wear,
- H = hardness,
- 1 and 2 = different metallurgies, and
- C and α = empirical constants.

The presumption is that lateral force, lateral and vertical creep, and the angle of the gage face to the lateral force vector are not functions of metallurgy. Thus, the

ratio V_1/V_2 is really an FM if V_1 is taken to represent standard rail. If volumetric wear is thought to be best represented by head-area loss, the FAST FM can be plotted versus the gage-face hardness ratio, as shown in Figure 6.

Two different linear plots ($\alpha_1, \alpha_2 = 1$) appear to obtain for the premium rails—one for heat-treated rails and the other for alloy rails. Furthermore, the slopes of the lines appear to be a function of lubrication and the heat-treated rails to be less influenced by lubrication than alloy rails. Whether the gage-face-wear results for the CrMo rail in the second experiment contradict this will not be known until the data on head-area loss are analyzed and hardnesses are taken on the gage face.

RAIL AND WELD FAILURE

The very low wear rates of standard rail observed under conditions of generous lubrication would project to a total rail life (on a 5° curve) between 680 million Mg (750 million tons) (first experiment results) and 1.134 billion Mg (1.25 billion tons) (second experiment results) for a 19-mm (0.75-in) gage-face-wear condemning limit. However, long before these traffic loads were reached, appreciable amounts of rail would have to be replaced

because of fatigue. Indeed, FAST has been a prodigious generator of fatigue failures, in both rail and weldments, in the well-lubricated regime. Table 11 summarizes the total number of weld- and head-type failures that have occurred to 227 million Mg (250 million tons) in the first and second metallurgy experiments.

In the first experiment, 24 percent of the plant welds in section 3 and 27 percent in section 13 failed. Although only 22 (section 3) and 10 (section 13) field welds (thermite) were placed in the original construction, the total number of field weld failures exceeded these numbers because replacement welds also failed. These weld

failures, along with rapid wear in the underlubricated regime, necessitated the rerailling of sections 3 and 13 at 122 million Mg (135 million tons). However, limited traffic load was accumulated in the first experiment, and relatively few head-type defects occurred; of those defects, three each were in FHT and standard rail, two were in HH rail, and one was in HiSi rail.

In the second experiment, less wear and greater load resulted in the generation of more head-type defects. In addition, redesign of the experiment configuration reduced the number of plant weld failures to 8 percent in both sections 3 and 13. Although the number of field weld failures was reduced, it still remained at an inconveniently high level.

Not all of the rail defects should be considered true fatigue defects. Since four of the head defects that occurred in section 3 were at or very near the ends of metallurgy segments, they can be related to mechanical joint assemblies or maintenance problems or both. If these four defects were removed from consideration, along with five head defects associated with an apparently very dirty heat of standard rail in section 13 (5), the overall defect rates would drop to 12 defects/km (20 defects/mile) for section 3 and 6 defects/km (10 defects/mile) for section 13. These rates would be relatively un-

Table 6. Position-in-curve effect for section 3.

Location	Gage-Face Wear (cm/million Mg)			
	Below Lubrication Transition		Above Lubrication Transition	
	<41 000 000 Mg	>37 000 000 Mg	>41 000 000 Mg	>37 000 000 Mg
Section 2 end	0.0145	0.0148	0.0028	0.0039
Middle	0.0148	0.0156	0.0044	0.0050
Section 4 end	0.0170	0.0187	0.0014	0.0022

Note: 1 cm = 0.3937 in; 1 Mg = 1.1 tons.

Table 7. Results of statistical tests for significance for section 3: gage-face-wear rates for various tie-plate cants and positions in curve.

Lubrication Transition (Mg)	Effect or Interaction	Observed F	99 Percent Level		95 Percent Level	
			F Required	Significant	F Required	Significant
<37 000 000	Cant	7.98	6.23	Yes	3.63	Yes
	Position in curve	16.79	6.23	Yes	3.63	Yes
	Metallurgy	90.96	4.77	Yes	3.01	Yes
	Cant position in curve	3.73	4.77	No	3.01	Yes
	Position in curve/metallurgy	1.27	3.89	No	2.59	No
	Metallurgy/cant	0.75	3.89	No	2.59	No
>37 000 000	Cant	3.86	6.23	No	3.63	Yes
	Position in curve	57.97	6.23	Yes	3.63	Yes
	Metallurgy	14.85	4.77	Yes	3.01	Yes
	Cant/position in curve	4.57	4.77	No	3.01	Yes
	Position in curve/metallurgy	0.96	3.89	No	2.59	No
	Metallurgy/cant	2.19	3.89	No	2.59	No

Note: 1 Mg = 1.1 tons.

Table 8. Gage-face-wear results for section 13.

Lubrication Transition (Mg)	Metallurgy	Gage-Face Wear by Position in Curve (cm/million Mg)					Avg FM
		A	B	C	D	Avg	
<37 000 000	HH	0.0058	0.0047	0.0070	0.0058	0.0061	3.5
	HiSi	0.0145	0.0137	0.0125	0.0120	0.0131	1.6
	FHT	0.0106	0.0106	0.0095	0.0103	0.0103	2.1
	Standard	0.0176	0.0257	0.0262	0.0167	0.0215	1.0
	Avg	0.0123	0.0137	0.0139	0.0128		
>37 000 000	HH	0.0039	0.0033	0.0008	0.0028	0.0028	1.3
	HiSi	0.0070	0.0003	0.0016	0.0039	0.0033	1.1
	FHT	0.0056	-0.0003	0.0028	0.0033	0.0028	1.3
	Standard	0.0044	0.0028	0.0028	0.0044	0.0036	1.0
	Avg	0.0053	0.0017	0.0019	0.0036		

Note: 1 cm/Mg = 0.358 in/ton; 1 Mg = 1.1 tons.

Table 9. Preliminary gage-face-wear results for second tests on section 3.

Metallurgy	Gage-Face Wear by Location (cm/million Mg)				
	Section 2 End	Middle	Section 4 End	Avg*	FM
HH	0.0011	0.0008	0.0005	0.0008	2
HiSi	0.0016	0.0019	0.0014	0.0016	1
FHT	0.0014	0.0016	0.0014	0.0014	1.2
CrMo	0.0003	0.0005	0.0005	0.0005	3
Standard	0.0016	0.0019	0.0014	0.0016	1

Note: 1 cm = 0.3937 in; 1 Mg = 1.1 tons.
*Rounded off.

Table 10. Results of statistical tests for significance of section 3 gage-face-wear rates: second experiment.

Presence of Cant Effect	Effect	Observed F	99 Percent Level		95 Percent Level	
			F Required	Significant	F Required	Significant
Present	Metallurgy	71.496	9.15	Yes	4.53	Yes
	Position in curve	11.806	10.9	Yes	5.14	Yes
	Tie-plate cant	3.791	10.9	No	5.14	No
Removed	Metallurgy	42.115	7.01	Yes	3.84	Yes
	Position in curve	6.995	8.65	No	4.46	Yes

Figure 5. Comparison of wear-rate data from various sources with those from the first FAST experiment.

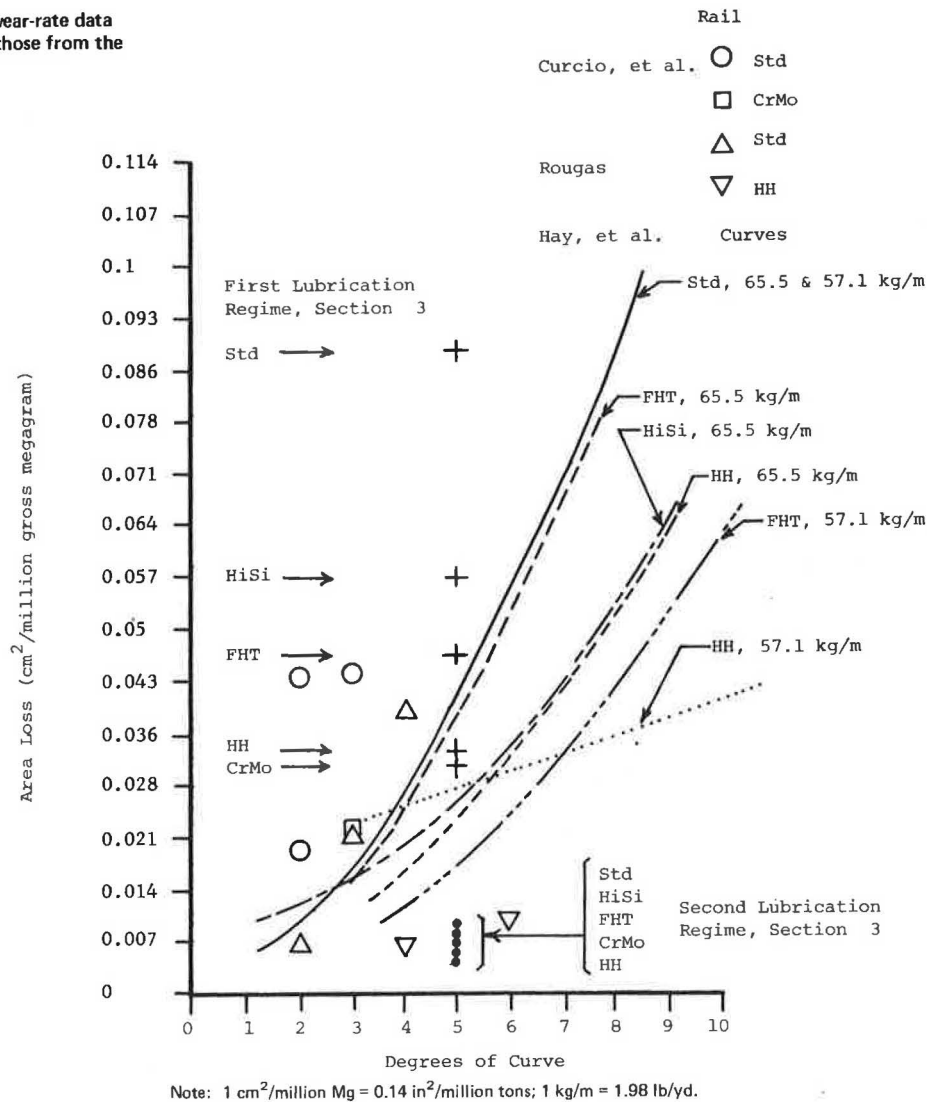
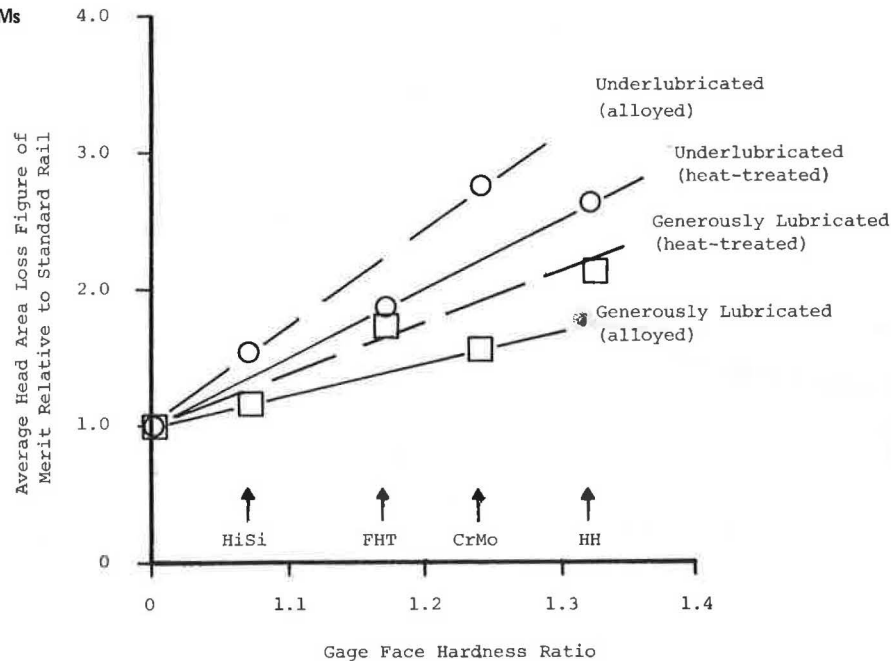


Figure 6. Gage-face hardness versus FMs for head-area loss.



biased for head defects to 227 million Mg (250 million tons).

Figure 7 shows the location by metallurgy and tie-plate cant for plant weld and head-type defects in the high rail of section 3. Without counting defects near segment ends, standard rail had five head-type fatigue

defects, for a rate of 27 defects/km (44 defects/mile) of rail. HiSi rail was next, with only two defects for a rate of 11 defects/km (18 defects/mile). HH rail had only one head defect that was not at a segment end or weldment, which yielded a defect rate of 5.5 defects/km

Table 11. Total rail failures in metallurgy test sections 3 and 13.

Experiment	Section	Plant Welds		Field Welds		Head Defects	
		Initially Installed	Failed	Initially Installed	Failed*	Total	Rate (defects/km)
1 ^b	3	180	44	22	44	2	
	13	64	17	10	17	7	
2 ^c	3	120	10	0	12	15	17 ^d
		48	4	0	8	7	6 ^e or 18.6 ^e

Note: 1 km = 0.62 mile.
*Includes replacement welds that also failed.
^bTraffic load of 123 million Mg (135 million tons).
^cTraffic load of 227 million Mg (250 million tons).
^dIndicates defect rate at 142 million Mg/km (250 million tons/mile) of track.
^eDefect rate adjusted to eliminate failures and rail length associated with "dirty" standard rail.

Figure 7. Occurrence of weld and head failures in high rail of section 3.

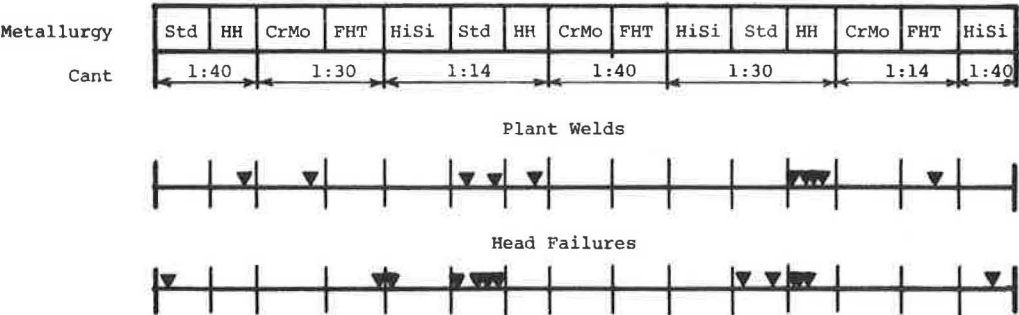
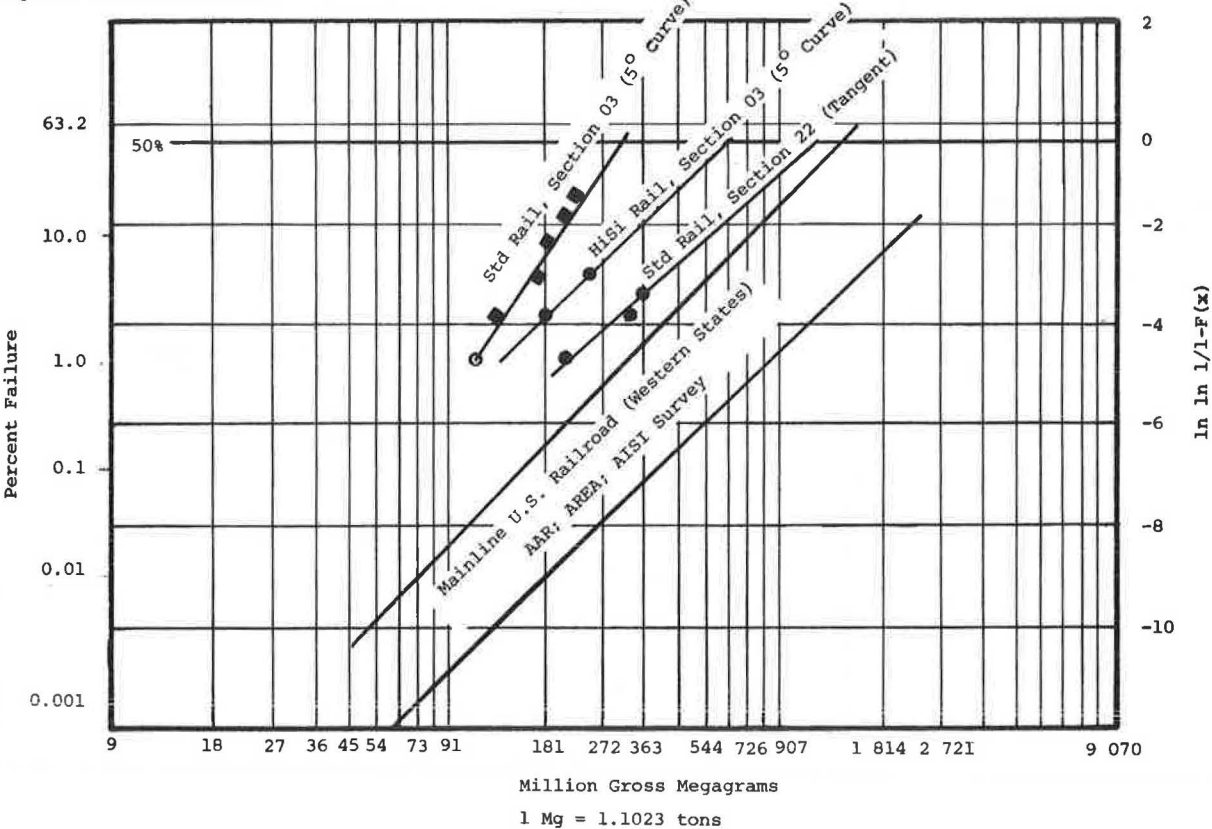


Figure 8. FAST rail failure data.



(9 defects/mile). FHT rail had only one head defect, and it was at a segment end.

HH rail had the most plant weld failures—six. Standard rail had two plant weld failures, and CrMo and FHT rail had only one each within the metallurgy test section. In section 13, standard rail had two plant weld failures, and FHT and HiSi rail had one failure each.

The 1:14 tie-plate cant was associated with 9 failures (4 plant weld and 5 head defect), the 1:30 cant with 10 failures (5 plant weld and 5 head defect), and the 1:40 cant with 3 failures (1 plant weld and 2 head defect). However, some of these did occur near segment ends and may therefore be considered suspect. In addition, the experiment design placed the 1:14 and 1:30 cants in the midregion of the curve whereas the 1:40 cant was positioned at the ends of the curve under standard, HH, and HiSi rails.

The relation between rail failure and traffic load is shown in Figure 8 for two of the rail metallurgies tested in section 3. The behavior of standard rail in FAST section 22 (continuous welded rail, tangent track) and that of rail in some western U.S. main-line service (6) are also shown for comparison. In section 3 (5° curvature), the percentage failure of standard rail at 181 million Mg (200 million tons) has been approximately 10 times that of standard rail in section 22 and more than 100 times that of the average of rail in some western U.S. main-line service. HiSi rail has a slightly lower failure rate than standard rail. There were not enough fatigue failures in FHT, HH, and CrMo rail to permit any quantitative assessment of how much better they might be than standard rail. Although the rail population of each metallurgy is small and a larger sampling might have produced less extreme behavior, the heavier wheel loads and unit train character of the FAST operation, along with the relatively high portion of curved track, have contributed to a substantial increase in the rate of rail fatigue failure.

Typically, both plant and field welds have a nearly horizontal web crack that extends to either side of the weld region. However, the plant weld failure originates from a transverse vertical crack that develops at the edge of the shear drag region under the gage side head-web fillet. A substantial period of vertical fatigue growth [~18 million Mg (~20 million tons)] frequently occurs before the crack turns horizontal in the web. On the other hand, the field weld failure sometimes appears to be initiated in the heat-affected zone, the crack then propagating through the weld itself. Detail fractures initiate at depths near 9.5 mm (0.375 in) below the gage corner just beneath the heavily cold-worked surface region. The growth of the transverse crack develops clearly demarked growth rings because of the change in train direction each day [~0.9 million Mg (1 million tons)]. The period in which the crack grows from the 10 percent size [10-mm (0.4-in) diameter] to final fracture at a radius of 40.6 mm (1.6 in) is typically between 9 million and 13 million Mg (10 million and 15 million tons).

CONCLUSIONS

The wear tests in the first and second metallurgy tests have shown that HH and CrMo rail exhibited the best re-

sistance to wear in the FAST loading environment.

There was a strong interaction between lubrication and metallurgy and, under conditions of generous lubrication, the premium metallurgies did not appear to benefit as much from lubrication as did standard rail.

In the underlubricated wear regime, the 1:14 tie-plate cant produced about 20 percent more gage-face and head-area-loss wear than did the other cants. However, the 1:40 cant produced somewhat greater head-height loss. The tie-plate-cant effect was diminished considerably under conditions of generous lubrication, and position-in-curve effects depended on the level of lubrication (they reversed in character as lubrication level varied from one extreme to another).

When conditions of generous lubrication served to extend rail life substantially, fatigue failure—both in the head of the rail and in weldments—became the dominant failure mode. At 227 million Mg (250 million tons) of traffic, the true FAST head-defect rate was near 6-12 defects/km (10-20 defects/mile). Substantially more rail and plate weld failures were associated with the 1:14 and 1:30 cants than with the 1:40 cant. The fatigue failure rates of standard rail in track with a 5° curve and in tangent track were approximately 100 and 10 times, respectively, that reported for rail in some western U.S. main-line service.

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