Rail Testing: Strategies for Safe and Economical Rail Quality Assurance

OSCAR ORRINGER

Current trends toward increased mainline traffic density, greater average axle load, and extension of wear life are expected to increase the rate at which metal fatigue defects form in rails. A decade of research on rail integrity has led to better understanding of how rail defects form and propagate. The research is discussed and examples are presented to show how the results can be used to provide guidelines for improving in-service inspection methods and schedules.

A decade of federal government and railroad industry research on rail integrity has led to better understanding of how rails respond to the damaging effects of the train loads they must carry. Major elements of the research now approaching completion will soon provide guidelines for better rail quality specifications and better rail-testing strategies. These guidelines will help to meet two objectives: improved rail resistance to failures originating from defects and improved targeting of in-service inspections.

Rail quality has heretofore meant tight dimensional tolerances, high static strength, and good resistance to wear. Track and mechanical departments strive to reduce their respective wear replacement costs for rail and wheels; a generation of this competition has led to increases of 35 to 50 Brinell points in wheel tread and rail head hardness and, on the rail side, development of premium steels with strengths up to 30 percent higher than the strength of standard composition rail steel.

In the same generation the transition from 50-ton to 70-ton freight cars, quickly followed by a further transition to 100-ton cars, has placed increasing demands on rails and track structure. Rail defects statistics compiled by the Sperry Rail Service (*1*) illustrate the effects of increased axle loads and subsequent track renewal (Figure 1). The rising defect rate from 1960 to 1970 (mainly rail-end defects in bolted-joint track) reflects both increasing distress and better flaw detection by improved rail test equipment and procedures combining ultrasonic scanning with the older magnetic induction method. During the same period several railroads also established their own fleets of highway-rail-capable vehicles carrying ultrasonic test equipment (*2*). The ability of these vehicles to save time en route between test zones also increased the ratio of test hours to operating hours.

By 1970 track rehabilitations had started to turn the defect rate around, and the new trend was accelerated by improvements in rail testing. The major thrust has been to replace bolted-joint rail (BJR) with continuous welded rail (CWR), an effort that continues today at the rate of about 2,000 to 5,000 track-mi a year. Although CWR usually retains some joints to provide electrical insulation at the ends of signal blocks, these tend to be high-quality bonded joints fabricated in plants, and they number only a few per mile in contrast to the hundreds of unbonded joints per mile of BJR. Hence, it is not surprising to see that the rail defect rate has declined almost as precipitously since 1970 as it increased beforehand.

The research program that started in the mid-1970s first tended to look back to the existing problem. As the effects of track rehabilitation and improved rail testing became apparent, however, the research direction gradually shifted from the past to the future. Three current trends in railroad operations suggest the future risk potential.

First, the merger wave that began in 1980 and continued in 1987 tends to concentrate more gross tons per year on fewer miles of track, as Figure 2 shows (*3*). The major mainlines naturally receive proportionately more maintenance attention, and rail stock turnover is accelerated where high traffic densities have caused excessive shelling or curve wear. New track technologies (premium-alloy rail, CWR, concrete ties, etc.) are now being introduced at rates faster than the historical ones.

Second, the focus on energy conservation stimulated by the 1973 oil shock has caused the railroads to think beyond the original idea of lubricating a curve rail for wear reduction and to seriously consider lubrication as a strategy for fuel savings. It is likely that the railroads will react to the next rise in oil prices by adopting widespread lubrication to reduce the energy lost from wheel-rail friction drag. Reduced rail wear rate will be a beneficial side effect of such a policy (*4*), but the increase in average rail service life also brings with it the potential for an increase in the density of rail defects.

Third, loads might increase again if cars with 110- or 125-ton capacity can be designed with payload-to-tare ratios greater than those in the current freight car fleet. A transition from 100- to 125-ton cars would likely increase the maximum static axle load from 33 to 41 tons. The Transportation Test Center (TTC) will be investigating the effects of 39-ton axle loads in its next phase of testing on the high-tonnage loop of the Facility for Accelerated Service Testing (FAST). Earlier captive revenue service experience suggests that such car loads have the potential to induce rail defect formation faster than the percentage increase of wheel load would indicate (*2, 5, 6*).

The accelerated pace at which rail and the demands placed on it are changing leaves little time for reaction. Therefore, the research program must be relied on for basic results that track

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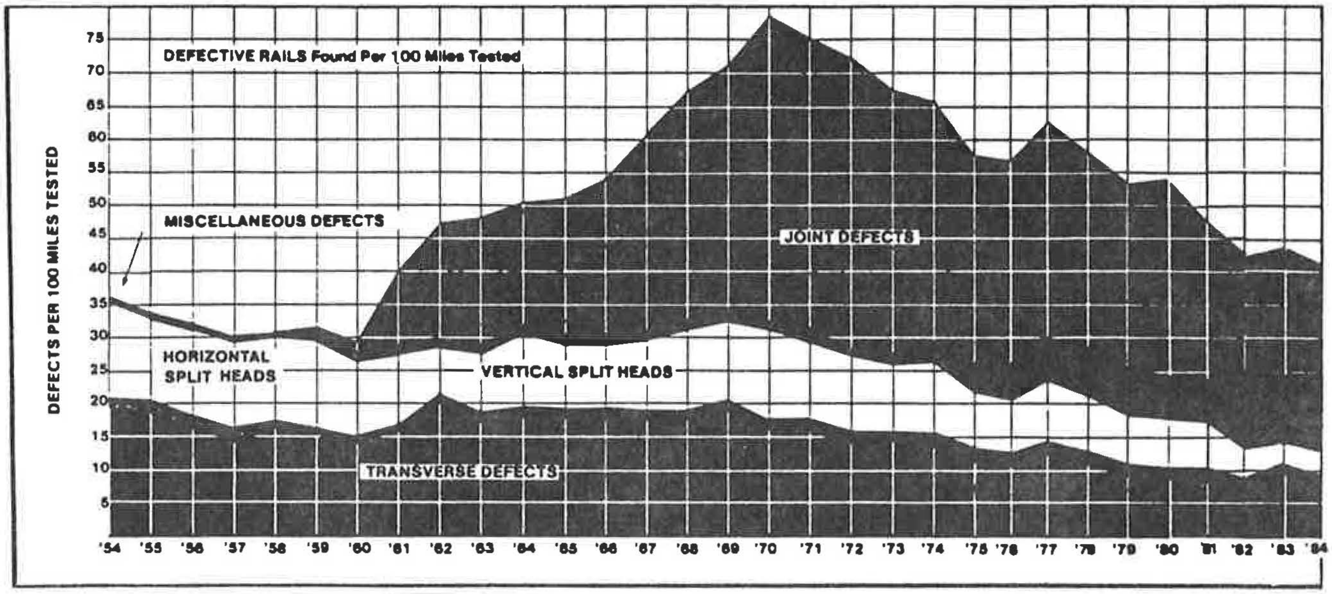

FIGURE 1 Annual density of detected rail defects (courtesy of Sperry Rail Service).

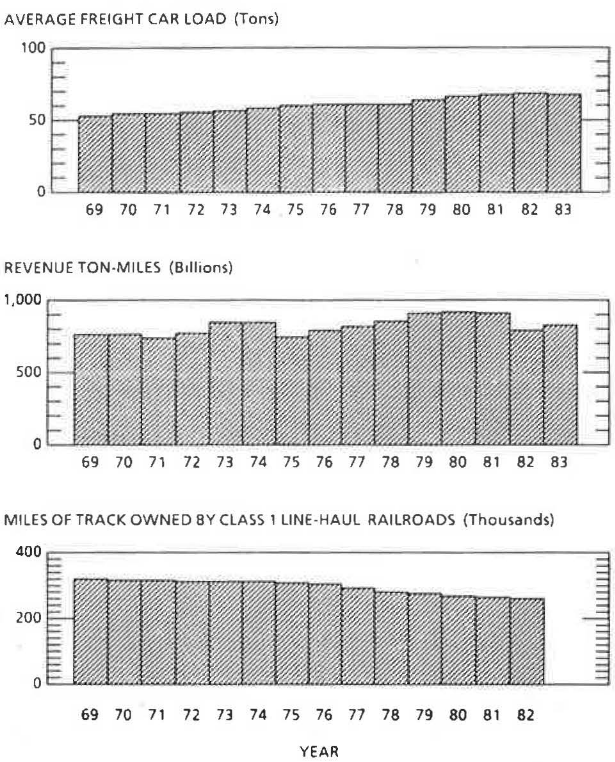

FIGURE 2 Annual statistics of railroad operations in the United States (*3*).

departments can translate into anticipatory engineering practices. The basic results and engineering practices have both economic and safety dimensions. This paper deals primarily with the safety question of where and how often to test rail for defects. The research program answers this question by applying knowledge of fatigue, fracture mechanics, and nondestructive inspection (NDI) technology to develop trade-offs between track quality and rail test frequency.

The most numerous rail defects are found to be those types that originate from metal fatigue. Knowledge of fatigue behavior can be used to define average rates of defect occurrence and to indicate when the rates might be expected to increase. It is impractical to apply NDI in service at frequencies that would guarantee opportunities to detect every conceivable defect, but occurrence-rate trends can provide a basis for adjusting the frequency to keep the rate at which trains are exposed to undetected defects within reasonable bounds.

Knowledge of fracture mechanics, that is, the propagation behavior of rail defects that have become growing cracks, can be used to translate familiar railroad engineering factors (train makeup, rail section, track curvature, etc.) into estimates of time available to detect defects. In practice such estimates are of most interest for the common defect types, those that should pace rail-testing schedules. Fracture mechanics can also quantify the potential benefit of improved NDI equipment, since a crack propagation model relates time available for detection of a defect to the defect size that the equipment is able to find.

DEFECT OCCURRENCE

The Federal Railroad Administration (FRA) annually publishes national summaries of accident statistics compiled from railroad reports and categorized by cause. The statistics of accidents caused by rail defects provide a guide to the relative importance of different defect types but must be supplemented by other data for proper interpretation. A study of railroad records of rail defect occurrences was undertaken for this purpose (*7*). The study encompassed about 25,000 detected defects and service breaks on some 8,200 track-mi owned by four railroads (Table 1).

Each railroad has its own system of record keeping for the purpose of identifying rail defects and monitoring repair and removal actions. Most of these systems closely correspond to the definitions established by the FRA for accident reporting. Those FRA cause codes that are of interest in the present case

TABLE 1 COVERAGE OF RAIL DEFECT OCCURRENCE STUDY

Territory	Years Covered	No. of Lines [a]	Total Track Miles	Density of Traffic [b]	Total Defects
Southwest BJR and CWR	1974 to 1979	6	1,005 [c] to 1,104 [d]	Average to High	2,478
Northeast Line upgraded from BJR to CWR during period covered	1976 to 1980	1	247	Average	2,000
Midwest with severe mid-continent winter climate BJR and CWR	1976 to 1981	16	6,438	Low to High	18,944
Midwest Single rail section on 80% of line	1976 to 1980	1	508	High	1,395

[a] As defined by traffic division points.

[b] Average means 10 to 20 million gross tons (MGT) per year; low density means 1 to 10 MGT/year; high density means 20 to 120 MGT/year.

[c] For the years 1974 to 1976.

[d] For the years 1977 to 1979.

(together with common industry symbols) are summarized in Table 2, which also classifies the defects by the source of the damage causing them.

Practical knowledge of two particular behavior factors is essential to the understanding of rail defect databases. First, true broken-base defects result from damage by foreign objects, for example, a nick from a misapplied spike maul, and propagate in a manner such that a half-moon-shaped piece about 4 to 8 in. long is separated from one side of the rail base. The consequent increase of base tension under train loads may later reinitiate a propagating crack and cause the rail to fail, but the distinctive half-moon separation can still be seen, and the original defect is easy to correctly classify. True broken-base defects are rare because damage by foreign objects rarely occurs. However, other types of defects are often misreported as broken bases. These mistakes are not made by track inspectors, but errors inevitably occur when others attempt to fit the inspectors' informally written descriptions into the formal definitions of the record-keeping system.

Second, true fissure defects [transverse fissures (TFs) and compound fissues (CFs)] result from the accretion of excess hydrogen into flakes that locally embrittle the rail steel and thus promote early crack nucleation. A high fissure occurrence rate early in this century led to the general adoption of the controlled cooling process around 1936, and rails manufactured thereafter generally contain too little hydrogen to form damaging flakes. Fissures can still be found occasionally in rails that have not been properly cooled, but today fissure reports more often result from misclassification of detail fractures. Rail test personnel are generally well versed in the difference between detail fractures and fissures and rely on interpretation of ultrasonic signals to classify these internal defects. Ultrasonically determined location in the rail head provides a good guideline for most such defects, which are usually small to medium-sized when found, but large defects are much less easily classified (Figure 3). Track maintenance personnel can visually examine the crack propagation surfaces of a service break, but they are not skilled fracture specialists and can easily

TABLE 2 CODES FOR REPORTING RAIL DEFECTS THAT HAVE CAUSED ACCIDENTS

Code	Symbol	Defect Type	Damage Source
130	BHC BHB	Bolt hole crack Bolt hole break	Fretting fatigue
131	BB	Broken base	F.O.D.[a]
132	DFW	Defective field weld	Fabrication
133	DPW	Defective plant weld	Fabrication
134	DF	Detail fracture	Fatigue
135	EBF	Engine burn fracture	Operations
136	HWS (O)	Head-web separation outside the joint bar area	Fatigue
137	HWS (I)	Head-web separation within the joint bar area	Fatigue
138	HSH	Horizontal split head	Fatigue
139	PIPE	Piped rail	Fabrication
141	TF CF	Transverse fissure Compound fissure	Fabrication
142	VSH	Vertical split head	Fatigue
149	---	Cause code not reported	---[b]

[a] Foreign object damage. [b] Damage sources unknown.

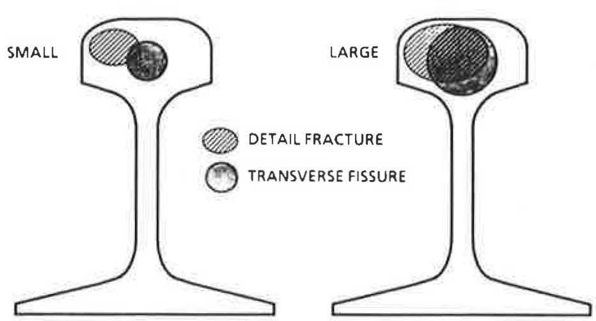

FIGURE 3 Locations of detail fracture and transverse fissure in rail section.

misclassify a detail fracture as a transverse fissure. Under these circumstances one should expect a low percentage of misclassification for detected defects, a moderate percentage for the service defects found and classified by track inspectors, and a high percentage in the summary reports that form the national accident database.

The national accident reporting system came into being in the early 1970s, and the raw statistics of accidents caused by rail defects have been consistent from year to year. The 1975 statistics are compared with aggregates of 1978–1985 and 1983–1985 in Figure 4. The accidents in each cause code are normalized as a percentage of the total accidents for the period covered to provide a common basis for comparison. The percentage of accidents caused by bolt-hole cracks has declined, as has the density of detected rail-end defects (Figure 1). The data in Figure 4 also suggest that the percentage of accidents caused by detail fractures has increased, but no other clear relative trends appear. The absolute trend of accidents caused by rail defects has been generally downward since 1970. The total number of accidents attributed to all types of rail defects has declined from a peak of about 500 a year to a steady rate of about 250 a year at present.

A superficial assessment of Figure 4 would lead one to conclude that fissures and broken bases are the most worrisome types of rail defects, but this appearance results from the reporting artifacts mentioned earlier. Track inspectors might naturally tend to use the word "fissure" or its synonyms to refer to the fractured appearance of a rail failure at a defective weld, detail fracture, or engine burn fracture. Words such as "broken through to the base" might as easily be used to describe rail failures from bolt-hole cracks, defective welds, detail fractures, or engine burn fractures. If the raw accident data are adjusted by reassigning equal proportions of the broken-base and fissure defects to the indicated categories, the relative proportions appear as shown in Figure 5, in which the defective welds have also been grouped to simplify the picture. Defective welds, detail fractures, and engine burn fractures now appear as significant accident causes in contrast to their apparently minor roles in the raw data. The recategorization probably overemphasizes engine burn fractures relative to bolt-hole cracks, defective welds, and detail fractures.

How realistic is the recategorization? One can get some idea by constructing similar plots of detected defects and service breaks. The data in Figure 6 illustrate a typical sample taken from an aggregate of the records of two railroads (Engineering Economics Division, Association of American Railroads, unpublished data, 1985). The following four adjustments have been made to account for differences between the FRA reporting definitions and the classification system used on the railroad data. First, defective field and plant welds were reported as a single category, which is shown under the field weld cause code. Second, head-web separations within the joint bar area were lumped together with bolt-hole cracks and are included under the latter cause code. Third, piped rails were included and are shown under cause code 136 (head-web separations extending outside the joint bar area). Fourth, crushed heads, broken rails, and other transverse defects are shown under the "not reported" category (149) because there are no specific cause codes for these defect types. However, those defects that the railroad classified as broken base or fissure have not been recategorized. The percentage of rail-end defects is much higher than the corresponding accident percentage, a result that probably reflects the inclusion of sidings in the sample as well as mainline track. Otherwise the sample highlights defective welds, detail fractures, head-web separations outside the joint bar area, and vertical split heads; fissures appear only as a small percentage and broken base defects have almost disappeared from the population. The

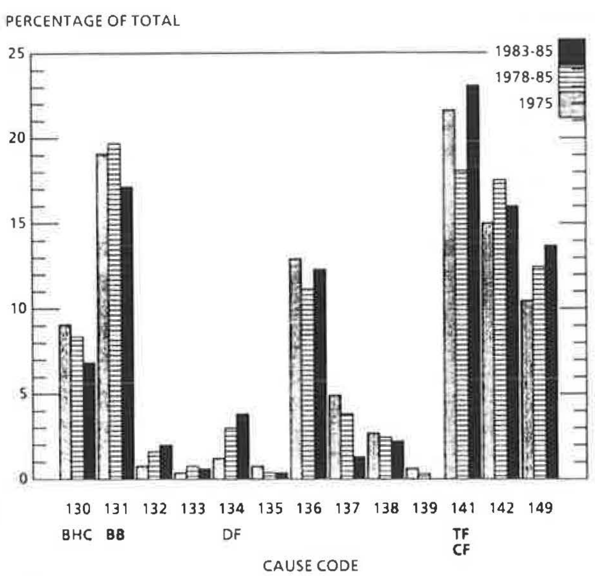

FIGURE 4 Accident causes broken down by rail defect type.

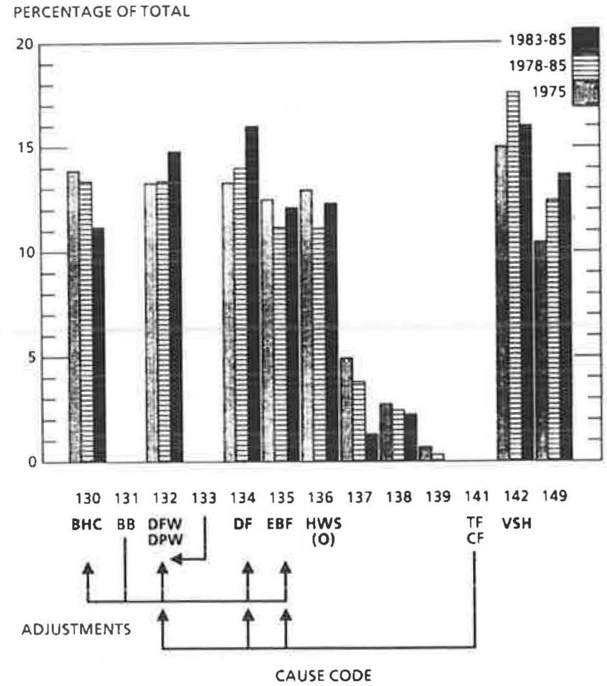

FIGURE 5 Accident statistics after adjustment for reporting artifacts.

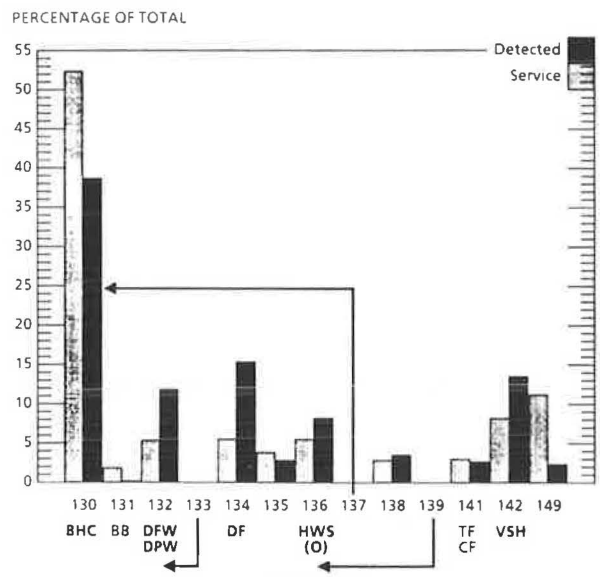

FIGURE 6 Sample of detected and service defects (1980–1983).

ratios of detail fractures to fissures reflect the previously mentioned difference in classification skill, and comparison of Figure 6 with Figure 4 reveals the existence of the reporting artifacts mentioned earlier. The relative proportions of accident causes are thus likely to lie somewhere between the proportions shown in Figures 5 and 6.

By what means are rail defects most often found? The Figure 6 data are replotted in Figure 7 to answer this question. For each defect type, the proportion found by rail test is shown as a percentage of the total found by testing and track inspectors. Bolt-hole cracks, defective welds, detail fractures, head-web separations outside the joint bar area, and vertical split heads thus emerge as the most common defect types, and rail testing emerges as the principal means by which most defects are found.

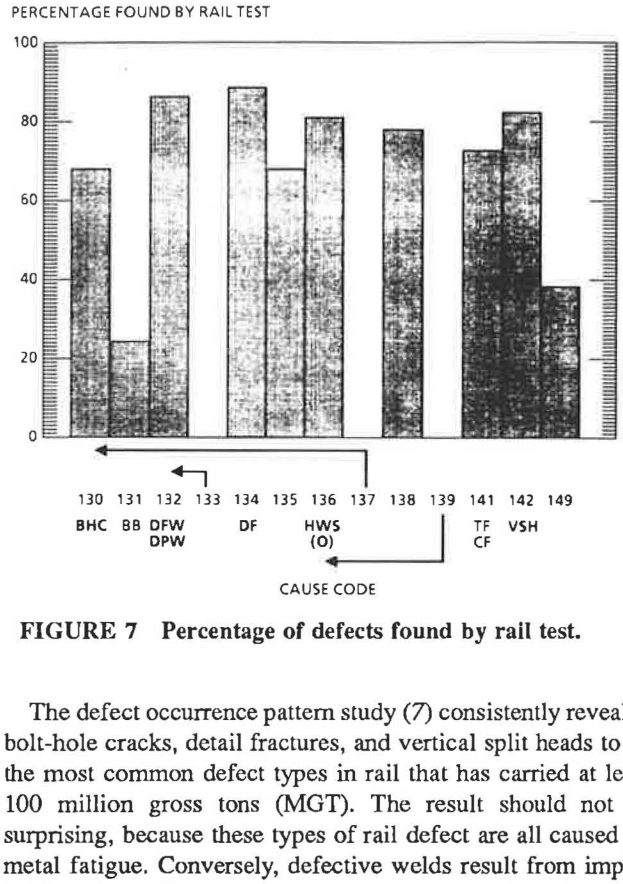

FIGURE 7 Percentage of defects found by rail test.

The defect occurrence pattern study (*7*) consistently revealed bolt-hole cracks, detail fractures, and vertical split heads to be the most common defect types in rail that has carried at least 100 million gross tons (MGT). The result should not be surprising, because these types of rail defect are all caused by metal fatigue. Conversely, defective welds result from imperfections in welding processes and reflect transient situations associated with CWR installation. The economic limit on rail life, as determined by scheduled replacement of worn rail, lies between 500 and 700 MGT and might be extended to 1,000 MGT by means of widespread lubrication. Thus, the major proportion of rail service life is and will continue to be spent in the fatigue crack nucleation regime, and the crack propagation behavior of the principal fatigue defect types should be taken into account when rail test schedules are established.

Compilations of defect rate histories on the TTC FAST track and a number of revenue lines have shown how exposure of trains to rail defects is related to tonnage (*6*). The cumulative percentage P of defective rails in a rail population is generally found to follow a Weibull probability distribution with respect to the cumulative tonnage T that the rail has carried:

$$P(T) = 1 - \exp[-(T/\beta)^{\alpha}] \quad (1)$$

where the exponent α is about 3 and the characteristic life β is about 2,000 MGT. Exposure (the rate of defect occurrence per million gross tons) is obtained by differentiating Equation 1:

$$dP/dT = (\alpha T^{\alpha-1}/\beta^{\alpha}) \exp[-(T/\beta)^{\alpha}] \quad (2)$$

The characteristic life is the cumulative tonnage at which 63 percent of the rail population would have developed defects, but rail is generally removed from service well before that point. In the service regime ($T \leq 1{,}000$ MGT), the exposure increases as tonnage accumulates. Fatigue defect occurrences generally become noticeable at about 250 MGT, when P is about 0.2 percent. Table 3 shows the increase in cumulative density and defect occurrence rate as the rail accumulates tonnage. The occurrence rates in the table are the number of new defects that would be generated in the next 20-MGT interval following the accumulated tonnage. On many revenue lines that have high traffic densities, rail tests are performed at about 20-MGT intervals.

The foregoing idealized model accurately describes exposure only when applied to short segments of track with homogeneous structural and operational characteristics. Conversely, most revenue lines contain a wide variety of rail, ballast, grade and curvature, special trackwork, and so on; are subject to varying load characteristics from the effects of train handling; and often receive rail renewals piecemeal. Exposure on a revenue line thus tends to fluctuate as particular track segments enter the fatigue regime, become problem areas, are controlled by rail test, are renewed, and relinquish the problem role to other segments.

The defect occurrence study (*7*) brought this behavior to light when analyses of defect density at 1-mi resolution revealed patterns of occurrence in clusters. The lengths and locations of defect cluster zones tended to remain stable over the study's several-year span. As a general rule, the results suggested that 90 percent of the rail defects in a revenue line would be located in 30 percent of the track miles, although there was wide variation from one line to another. For a few lines, 90 percent of the rail defects were concentrated in as little as 10 percent of the track miles, whereas for other lines, there was little or no concentration. The most concentrated zones were those associated with obvious construction features such as bridges, where sudden changes in track modulus could be expected to excite dynamic oscillations in passing trains. Zones reflecting fatigue of aging rail were similarly concentrated and were well defined by rail relay boundaries. On the other hand, well-maintained BJR of uniform age generally showed little or no concentration of rail defects.

The complexity of the actual behavior makes it difficult to define a simple measure of exposure to guide the adjustment of rail test schedules. Some of the measures that have been used by some railroads or proposed from the research activities are traffic density, a rising trend of defect density, a rising trend of service breaks, the ratio of service breaks to detected defects, cumulative tonnage, and exceedance of a specified number of defects per mile per test. There is no agreement on how to deal with exposure, and none is likely in view of the strong opinions of track engineers based on their own experiences.

TABLE 3 DEFECT DENSITY AND RATE VERSUS ACCUMULATED TONNAGE

Accumulated Tonnage (MGT)	250	500	750	1,000
Cumulative rail defects (percent)	0.2	1.5	5.1	11.7
Cumulative density (defects per track mile) [a]	0.5	4.1	13.6	31.9
Defect rate (defects per track mile per 20 MGT) [a]	0.1	0.5	1.1	1.8

[a] Based on 273 rails per track mile.

Although control of exposure is difficult to translate into a standard, the results of the research program have suggested some general guidelines that individual railroads can follow. For example, an occasional plot of defect reports by milepost is a good way to spot cluster zones, and such zones can be given supplemental inspections or special maintenance. One railroad has applied this technique to 2,500 mi of mainline track that had previously been tested three times a year. The plot revealed some 200 mi of cluster zones, a few of which were dealt with by means of track modifications. Because the line had had a low accident rate and was already being tested three times as often as required by the current safety regulations, the railroad cut back to two complete tests a year and concentrated the third test on the critical 200 mi. The service break rate has remained stable during 2 years of the revised test schedule, a result that suggests that the new strategy saves resources without sacrificing safety.

Another example of a general guideline involves the scheduling of a fixed number of rail tests so as to increase the test frequency toward the end of the rail's useful service life instead of keeping the frequency constant. This strategy has been studied by means of a simulation that combines a defect occurrence, growth, and detection model (*2*) with economic analysis of the expected costs of defective rail removal and accidents caused by undetected defects (*8*). The economic analysis employs cost factors compiled by the Association of American Railroads (AAR) and uses a national average accident rate of the order of one accident per 200 service defects. When a preliminary version of the model was applied to a hypothetical line with a traffic density of 60 MGT per year, the lowest-cost strategy was found to be 25-MGT intervals between tests of new rail, decreasing to 10-MGT intervals toward the end of the useful service life. These results suggest that cumulative tonnage can be used to control exposure, but a wide variety of cases must be analyzed to provide a good basis for guidelines on test frequency adjustment.

CRACK PROPAGATION BEHAVIOR

Once a defect has formed in a rail, it generally becomes a propagating crack; that is, its size gradually increases under the influence of the cyclical stresses that trains impose on the rail. Sooner or later the defect will grow to a size that has some chance of being detected, but if not, it will eventually grow large enough to fracture the rail under a train. The number of stress cycles or equivalent gross tonnage required to make the defect grow from the minimum size for detection to the incipient fracture size is referred to as the safe crack growth life. If the minimum detection and incipient fracture sizes were known with certainty, safe crack growth life would be synonymous with the safe interval for rail testing to find the given type of defect under the given conditions. In practice, however, these defect sizes are not well defined, and complete coverage of the possible conditions cannot be guaranteed; therefore, two or more rail tests must be performed within the safe crack growth life to properly control the risk of rail failure.

Table 4 gives 10 factors that affect safe crack growth life for detail fractures. Other kinds of rail defects have many of these factors in common, but each defect type generally has one or more unique factors. Because there are so many factors to consider, one must have a model of each defect type as a propagating crack in order to make life estimates for the many possible combinations of factors. Such models can be constructed from the principles of engineering fracture mechanics (*9*) but are necessarily idealizations of the actual rail defects. Therefore, both laboratory and field testing are also essential to establish confidence in the engineering model. Laboratory specimen testing in accordance with established standards (ASTM E-399-72) is performed for two purposes: characterization of basic material properties and assessment of memory

TABLE 4 FACTORS AFFECTING DETAIL FRACTURE PROPAGATION

Quantity	Minimum Value	Maximum Value
Track foundation modulus[a] (ksi)	1	10
Track curvature[b] (degrees)	0	8[c]
Rail section[c]	100 RE	155 PS 32.6[d]
Average axle load (tons)	10	38.5[e]
Normal dynamic load factor (*g*, rms)	0.1	0.8
Dynamic load factor for wheel anomalies (*g*, peak)	1	3
Anomalous wheel density (%)	0	0.5
Rail neutral temperature[f] (°F)	60	90
Rail service temperature[f] (°F)	−40	150
Axial residual stress in rail head (ksi)	10	30

[a]Values shown are for vertical modulus.
[b]Radius of curvature (ft) = 5,730 ÷ degree of curvature; e.g., R = 5,730 ft for a 1-degree curve; R = 573 ft for a 10-degree curve.
[c]Excludes low-density branchline track.
[d]Under current interchange rules.
[e]Loaded 125-ton cars in unit train.
[f]Affects CWR only.

effects. Field testing is required to confirm the validity of the idealized defect model.

The material property most important to safe life is the propagation rate (crack size increment per cycle) as a function of the current crack size and the cyclical stress amplitude. Several such investigations of rail steel have been made (*10–12*). The most conveniently applied life estimation models simply sum the crack-size increments corresponding to the spectrum of service stress amplitudes, without regard to the effect one stress cycle might have on the rate of crack propagation in succeeding cycles (*13*).

Memory phenomena can appear when materials are subjected to varying stresses; variable-amplitude ("spectrum") stress tests are required to assess the effect for each material and service environment. For example, cracks in aluminum alloys tend to grow more slowly than one would predict under high-low sequence aircraft stress spectra (*14*). Recent experiments on rail steel subjected to a real sequence rail head stress spectrum simulating heavy-haul train loads have shown that crack propagation is moderately accelerated (*15, 16*).

Rails containing detail fractures have also been field tested in tangent sections of revenue track and the TTC FAST track (*17*). The unique FAST traffic pattern (running direction reversed approximately once per million gross tons) during the test formed prominent ridges on the crack propagation surfaces, providing the means for accurate definition of the flaw location and area as functions of the gross tonnage applied in the test. The rail residual stresses near one of the FAST test defects were also measured by strain gauges in a destructive sectioning technique specially developed for rail residual stress determination (*18*). This detail fracture thus has the least uncertainty in the description of its service environment.

The crack-size histories for the laboratory spectrum test and the FAST test defect just mentioned are plotted in Figure 8. Also shown are predictions of the crack size histories obtained from a preliminary version of the detail fracture crack propagation model. The laboratory results have been converted to equivalent defect area and tonnage and have been shifted to correctly superimpose the starting point on the FAST test data.

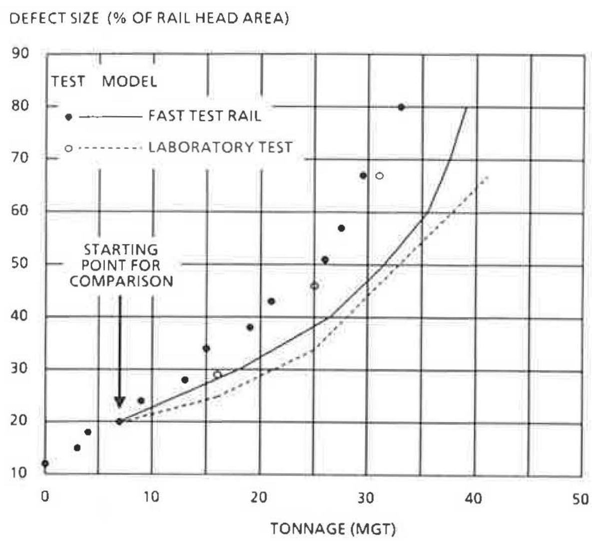

FIGURE 8 Laboratory simulation and field test results for detail fracture growth.

Comparison of the two results shows that the laboratory test was a reasonable simulation of the FAST test. Comparing the model prediction of the laboratory test with the data illustrates the moderate acceleration effect mentioned earlier. The model-to-test relation for the FAST experiment is similar to that for the laboratory experiment; that is, the actual safe crack growth life should be taken as about 80 percent of the calculated life.

Additional confidence was gained when the model was applied to the analysis of another detail fracture that had been involved in a derailment on a curve at FAST about 2 years before the tangent-track field test. Table 5 shows how the model inputs for this defect differ from those for the test defect. In Figure 9 the model prediction is compared with an estimate of the actual defect growth history. The curve of defect size versus number of wheel passages was obtained by means of post-test measurements on the crack propagation surface (*4*), but there is some uncertainty about what value of average axle load best represents the FAST train at the time this defect grew. Because of the unusually severe thermal and residual stresses in this rail, the defect grew rapidly to 11 percent of the rail head area, whereas the test defect grew slowly from 12 to 80 percent of the rail head area. Nevertheless, actual crack growth life is 75 to 80 percent of the calculated life in the present case, suggesting that the detail fracture model has a consistent bias.

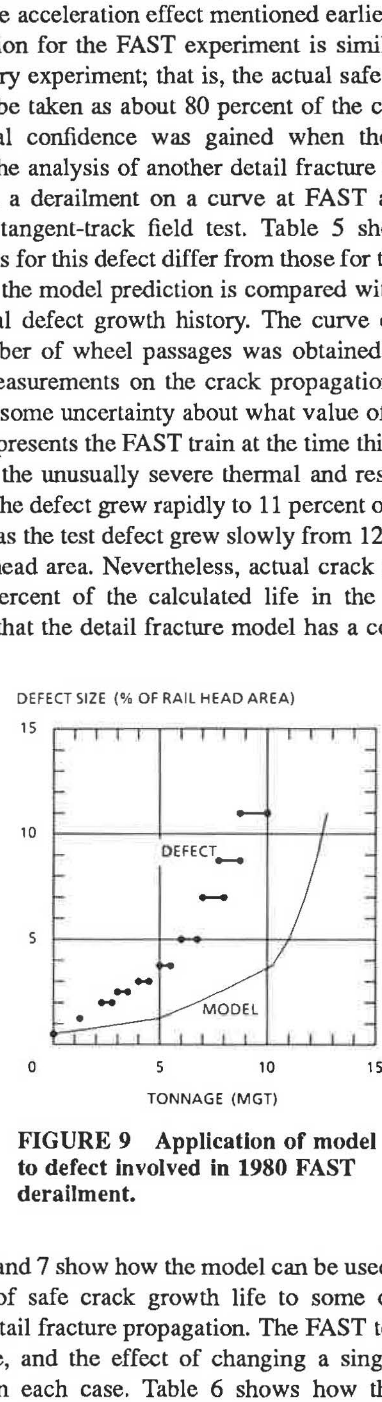

FIGURE 9 Application of model to defect involved in 1980 FAST derailment.

Tables 6 and 7 show how the model can be used to assess the sensitivity of safe crack growth life to some of the factors affecting detail fracture propagation. The FAST test is taken as the baseline, and the effect of changing a single variable is examined in each case. Table 6 shows how the safe crack growth life of the fast test detail fracture is projected to decrease as the average axle load increases, and vice versa.

The effects of three track construction features are demonstrated in Table 7. First, heavier rail sections increase safe life, but little is gained in going from 136 RE to 140 RE rail, and there is only a modest gain in going to 155 PS, the heaviest section manufactured for U.S. freight service. Second, a stiffer track foundation increases safe life. A vertical track modulus of 1 ksi represents poorly maintained wood-tie track, 2.5 ksi reflects average wood-tie track conditions, 5 ksi represents the best foundation achievable with wood-tie track or average

TABLE 5 INPUT FACTORS FOR DETAIL FRACTURES AT FAST

Quantity	Test Rail	1980 Derailment
Vertical track foundation modulus (ksi)	2.5	2.5
Track curvature (degree) [a]	0	4
Rail section	136 RE	115 RE
Average axle load (tons)	30.8	27.0 [b] 31.0 [c]
Normal dynamic load factor ("g"-rms)	0.26	0.26
Dynamic load factor for wheel anomalies ("g"-rms)	--- [d]	--- [d]
Anomalous wheel density (%)	0	0
Rail neutral temperature (°F)	95 [e] 60 [f]	60 [g]
Rail service temperature (°F)	62 [e] 26 [f]	20 [g]
Axial residual stress in the rail head (ksi)	10	30

[a] Radius of curvature (ft.) = 5,730 ÷ degree of curvature.

[b,c] Minimum and maximum estimates.

[d] Not used; no large wheel anomalies in the FAST train.

[e,f] Approximate initial and final values for the test period; monthly average mean values for service temperature.

[g] Estimated for January-February period during which crack growth occurred.

properties for concrete-tie track, and 10 ksi represents the best foundation achievable with concrete-tie track. Third, track curvature decreases safe life. The curvature effect shown here is that for the high rail, which is subject to severe lateral loads from the lead wheel of each truck (*19*). The model predicts that safe crack growth life of the FAST test defect on a 5-degree curve would have been about half that on the tangent track.

The foregoing results are realistic because they refer to a detail fracture that grows from 12 to 80 percent of the rail head area. These sizes are consistent with current detection capability and knowledge of incipient fracture size under normal conditions. The safe crack growth life estimates should not be applied to revenue track, however, because the FAST test defect was subjected to a unique history of thermal stress, which might have caused the day-to-day crack growth rate (and hence the safe life) to differ from the rates and safe lives associated with typical revenue-track thermal stress histories. Also, the preliminary detail fracture model still requires some refinement, and a modified version is now being developed (*20*). Nevertheless, the examples show that expected variations of construction and operational factors can have important effects on safe crack growth life and that track engineers might usefully consider the safe rail test interval when they assess track quality design trade-offs.

The detail fracture is currently the best understood rail defect from the viewpoint of crack propagation. Similar efforts to develop models of the bolt-hole crack and vertical split head are under way. Some factors that affect these defects but have

TABLE 6 EFFECT OF TRAIN MAKEUP ON SAFE CRACK GROWTH LIFE

Train Makeup	Average Axle Load (Tons)	Safe Crack Growth Life (MGT) [a]
Empty unit coal train: 4 locomotives; 111 cars; 3,847 trailing tons	9.9	98
Mixed revenue freight: 2 locomotives; 41 cars; 2,583 trailing tons	16.5	40
FAST test consist: 4 locomotives; 81 cars; 9,957 trailing tons	30.8	34
Loaded unit coal train: 6 locomotives; 111 cars; 15,665 trailing tons	32.6	30
Loaded 125-ton unit coal train: 6 locomotives; 101 cars; 16,950 trailing tons	38.5	25

[a] Factor of 80 % for acceleration has been applied.

TABLE 7 EFFECT OF TRACK CONSTRUCTION CHARACTERISTICS ON SAFE CRACK GROWTH LIFE

Characteristic	Safe Crack Growth Life[a] (MGT)
Rail bending stiffness	
100 RE	21
115 RE	24
132 RE	36
136 RE	34[b]
140 RE	36
155 PS	40
Track stiffness (vertical track foundation modulus, ksi)	
1.0	21
2.5	34[b]
5.0	39
10.0	47
Track curvature (degrees)	
0	34[b]
5	18

[a]Factor of 80 percent for acceleration has been applied.
[b]Baseline case.

little or no influence on detail fracture growth are rail end tolerance, train speed, and in-plane residual stress.

Rail end gap and height mismatch can have a strong influence on bolt-hole crack propagation because such conditions induce large dynamic wheel loads on the receiving rail. The dynamic load factor increases with train speed and can be comparable with the anomalous wheel factors in Table 4 when the train speed exceeds 20 mph. In this case, however, every passing wheel imposes a large load on the rail. The effects of these variables were investigated in a recent test at the TTC, where crack growth data are now being gathered as bolt-hole cracks are detected in the FAST track. A laboratory test of a short length of rail under simulated joint loading conditions provided the basis for a bolt-hole crack propagation model (*21*).

In-plane (lateral and vertical) residual stresses in the rail head promote the formation and growth of vertical split head defects, just as axial residual stress promotes detail fracture growth. The residual stress measurement program has shown that the in-plane residual stresses are three to four times as large as the axial stress (*18*). Development of a crack propagation model for vertical split heads is just starting, and field test requirements for these defects remain to be defined.

NDI TECHNOLOGY AND SAFE INSPECTION INTERVAL

The typical interval of 20 MGT for rail tests on lines with high traffic density is based on experience with current (i.e., 1960s to 1970s) technology for rail test equipment. Railroad records of detected defects and service breaks suggest that the current NDI systems are finding about 80 to 90 percent of the rail defects (see Figure 7).

NDI research projects in the mid-1970s investigated real-time signal processing, improved display, and automatic control of sensor alignment on the rail (2). The research goals were improved flaw detection reliability and the ability to test rail at higher speed with no sacrifice of reliability.

The current detector-car fleet is generally able to perform reliable rail testing at 15 mph. Each time a defect is detected, the crew must also stop to hand-test, verify, and classify the defect, an operation that generally takes about 1 min. Trains stacked up behind detector cars cause reduced revenue throughput, whereas detector cars sitting on sidings cause available equipment hours to be lost from the rail test schedule.

The data in Table 8 show the effect of the conflict between rail testing and revenue traffic from the viewpoint of the operating department. The example is for 150 mi of single-track line on which revenue traffic is assumed to travel at 45 mph without interference. The current situation is represented by a 15-mph rail test operation that is assumed to find one defect per mile per inspection, that is, corresponding to rail with just under 750 cumulative MGT (see Table 3). Under these assumptions, the time required to get the detector car over the line is 10 hr of travel at 15 mph plus 2.5 hr of 1-min stops to verify 150 defects, for a total of 12.5 hr of track occupation at an effective speed of 12 mph. Trains traveling behind the detector car close at the rate of 33 mph (45 mph − 12 mph). The product of track occupation time and closure speed (12.5 hr × 33 mph = 412.5 mi) is a measure of the stackup effect, because the number of trains delayed is simply the stackup length divided by the average headway. The second case in Table 8 shows that the stackup length can be reduced to less than 200 mi if an improved system capable of testing at 30 mph is postulated. In the third case a net benefit is shown even if the improved system is assumed to find more defects per mile.

Figure 10 shows schematically the difference between current and improved equipment in terms of the chance $P(X)$ for one rail test to detect a defect of a size represented by X. The lower limit of detection capability is represented by the size X_0 for the current technology and by a smaller size X_0' for the improved technology. In each case the chance of detection increases until the defect size reaches X_1, for which detection is virtually certain. The shaded area between the curves represents "extra" detections by the improved equipment under the idealized assumption that there exists an infinite number of defects of all sizes. Because the actual defect population is finite, however, a detection improvement will cause only a transient rise in the detection rate as the population of smaller flaws is initially accessed. The detection rate will return to the historical level determined by the defect occurrence rate after one or two tests, a fact that has been illustrated by the inspection simulations mentioned earlier (2, 8).

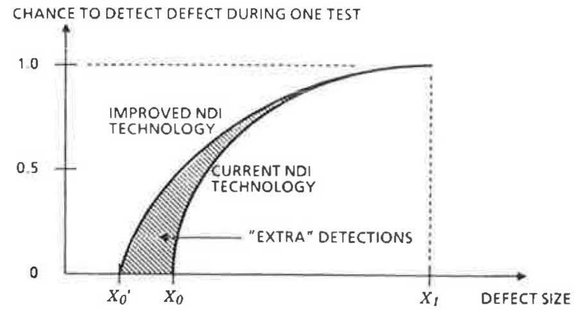

FIGURE 10 Chance of detection versus defect size.

Confusion of finite and infinite population effects led to the misconception that better equipment would always find more defects, and the reduced attractiveness of the benefit temporarily decreased the interest in research on rail test equipment. The interest has revived in the past 3 years, however, and an active program is again under way. The current program has also taken into account the current operational trends and some of the knowledge gained about defect behavior. The main thrust of the research at present is the investigation of electromagnetic

TABLE 8 EXAMPLE OF INTERFERENCE WITH REVENUE THROUGHPUT

Assumptions About Rail Test Operation		Hours Required to Test 150 Miles	Effective Speed (mph)	Stackup Distance (miles)[a]
Speed (mph)	Defect Density (defects/mile)			
15	1	12.5	12	412.5
30	1	7.5	20	187.5
30	2	10.0	15	300.0

[a] Stackup distance = (hours required) × (45 − effective speed).

acoustic transmission (EMAT) for getting ultrasonic signals and returns into and out of rails.

Conventional ultrasonic sensors require a continuous supply of couplant fluid to form a thin film for signal transmission between the probe and the rail surface. Heavy rail lubrication can degrade the couplant properties and signal quality. The couplant also restricts signal polarization and refracts the signal at the couplant–rail interface. Refraction limits the angle at which ultrasound can be injected into the rail without being trapped near the surface.

EMAT transducers subject the rail to a DC magnetic field together with a pulsed RF signal. These two electromagnetic components combine to generate ultrasound and receive return signals directly in the rail head; thus the refraction problem is avoided. Electromagnetic transduction between the rail and the probe also suggests that EMAT systems will tolerate heavy lubrication interference better than conventional systems. A prototype EMAT system is now beginning field evaluation tests at the TTC. The next phase of the research will likely focus on the performance of signal polarizations not available in conventional ultrasonic testing equipment, in particular axially traveling shear waves. The axial shear wave is a 90-degree beam that fills the rail head and inspects 8 to 12 in. ahead of the transducer. This type of polarization is expected to be highly effective in detecting detail fractures, engine burn fractures, and other transverse defects in the rail head.

Aside from the benefit of increased detector-car speed, better NDI also has the potential to reduce costs by increasing the safe inspection interval. A simple model of detection performance serves to demonstrate this benefit. The chance of detecting a defect of size X can be represented by the function

$$P(X) = 1 - \exp[-\lambda (X - X_0)/(X_1 - X_0)] \tag{3}$$

where X_0 and X_1 are defined in Figure 10 and λ is a scale factor. If X is interpreted as the size of a detail fracture in percentage of head area (HA) and X_0 and X_1 are taken as 5 and 75 percent HA, respectively, then $\lambda = 5$ gives about the right chance of detecting a 10 percent HA detail fracture and about the right fraction of defects detected based on experience with detail fracture populations ($P_{AV} = 0.9$; see Figure 7). Taking the average of $P(X)$ over the interval $\{X_0, X_1\}$,

$$P_{AV} = (X_1 - X_0)^{-1} \int_{X_0}^{X_1} P(X)dX$$

$$= 1 - \lambda^{-1} [1 - \exp(-\lambda)] \tag{4}$$

gives a reasonable approximation of the detection performance P_{AV} for two tests per safe crack growth interval (O. Orringer, unpublished data, 1987).

An improvement in detection technology might be manifested by either a larger scale factor λ or a smaller detectability limit X_0. Chances are that any improvement would involve a combination of these effects. It is therefore of interest to inquire what effect a smaller detectability limit would have on rail test strategy and cost. Because Equation 4 shows that the overall detection performance on a finite population P_{AV} is independent of X_0, it follows that safe crack growth life and safe inspection interval can increase proportionately when X_0 decreases without increasing the risk of higher service break incidence. Early removal of defective rails would partly offset the direct savings resulting from fewer rail tests, but a first-order economic analysis suggests a potential for net savings.

An improved analysis based on current knowledge of detail fracture detectability and behavior is shown in Table 9. The basic assumptions of the analysis are full service life of 1,000 MGT, scheduled rail tests starting at 100 MGT, and NDI improvement that allows the inspection interval to be doubled from 20 to 40 MGT at the cost of removing every defective rail 20 MGT sooner than would happen under the current testing schedule. Application of the crack propagation model suggests that such a doubling could be made practical by equipment that would have the same chance to find a 5 percent HA detail fracture as the current systems have to find a 10 percent HA detail fracture (Figure 11). The analysis has been applied to 50,000 track-mi, roughly the total U.S. inventory of medium- to high-tonnage lines. Although the example is idealized, it does illustrate the way in which fracture mechanics can be used to assess the real trade-offs when the behavior and detectability of all the major defect types are better understood.

The Canadian Pacific Railroad has recently adopted a performance specification for rail testing based on average detection probabilities for finite flaw-size ranges. The CPRR specification that applies to detail fracture and other types of transverse defects in the rail head (transverse fissure, compound fissure, engine burn fracture, or defective weld) is as follows:

	Defect Size Range (%HA)			
	10–20	*20–40*	*40–80*	*80–100*
Required minimum detection probability	0.65	0.80	0.95	0.99

Application of the previously developed simulation methods (*2, 8*) and current knowledge of detail fracture propagation suggest that this part of the CPRR specification accurately reflects current rail test equipment performance (O. Orringer, unpublished data, 1987).

FABRICATION AND MAINTENANCE QUALITY CONTROL

Although periodic NDI is necessary in a world of imperfect structures, it is not a substitute for good fabrication and maintenance quality. The railroads and railroad suppliers have a long record of product improvement, and the rail integrity research program has dealt with fabrication or maintenance improvement from time to time. Examples from both sources will be cited briefly.

The adoption of controlled cooling to prevent hydrogen flake defects was mentioned earlier. Other industry improvements in rail manufacturing include vacuum treatment, hot topping, and clean steel practice. Vacuum treatment removes hydrogen and other gases from molten steel, allowing more productive rail rolling through elimination of the requirement for controlled

TABLE 9 EXAMPLE OF POTENTIAL SAVINGS FROM IMPROVED NDI TECHNOLOGY

Item	Current Technology[a]	Hypothetical Improved Technology[b]
Rail tests covering 100 to 1,000 MGT	46	23
Rail test cost: 50,000 miles @ $70; $M	161.0	80.5
Additional loss of serviceable rail life[c], $M 50,000 miles @ 32 defects per mile 20 MGT lost per defective rail @ $1 per MGT	0.0	32.0
Life cycle cost, $M	161.0	112.5

[a] Testing at 20 MGT intervals.

[b] Testing at 40 MGT intervals.

[c] New technology assumed to penalize every defective rail by 20 MGT. Every defective rail assumed to require complete replacement. Number of defects based on 1,000 MGT cumulative density from Table 3.

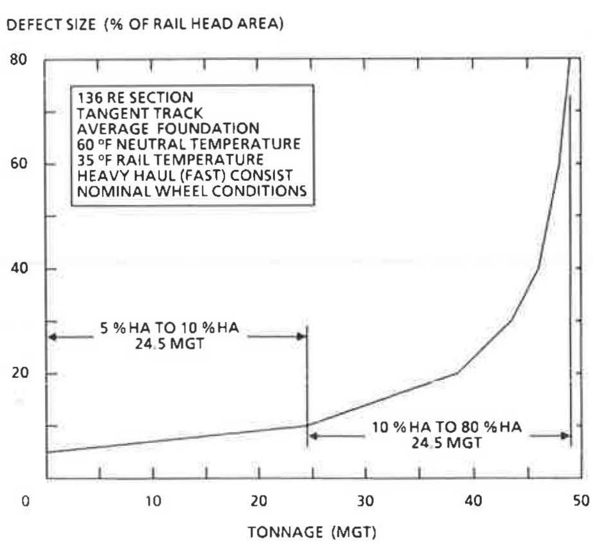

FIGURE 11 Estimated safe crack growth life for small and large defects.

cooling. Hot topping reduces ingot discard wastage and also lowers the incidence of piped rails by avoiding the formation of excessively weak dendritic seams during ingot solidification. Clean steel practice, a recent development, reduces tramp-element inclusion content and thus has the potential to improve resistance to the formation of vertical split heads.

One of the early efforts in the rail integrity research program was directed toward reduction of the high bolt-hole crack incidence that appeared in the late 1960s. Bolt-hole cracks tend to form as a result of fretting action between the bolt shanks and the rail, a common phenomenon in mechanically fastened structures. An idea borrowed from aircraft industry practice led to the development of equipment and procedures for applying cold expansion to the bolt holes in older BJR (*22*). British Rail has recently improved the procedure by reaming worn bolt holes to uniform diameter before expanding and is now beginning to apply the cold expansion practice to its older BJR tracks.

Both government and industry research projects have investigated improved rail welding methods. Flash butt welds made in CWR plants generally have low defect rates because the welding process does not use foreign materials and can be accurately controlled. However, some premium alloy rails are extremely sensitive in this regard because they achieve their properties in part by delay of the austenite-pearlite transformation to produce a fine grain structure. Research on flash butt rail welds has shown that martensite formation can be avoided by delaying and extending postweld heat application, a practice that adds about 1 min per weld to the production time (*4*).

Attention has also been paid to field welds, most of which are made today by means of expendable kits consisting of a thermite charge and a preformed mold that fits around the rail ends. Because these kits were originally developed for joining standard composition rail, a metallurgical investigation was made into the effects of using both standard and premium kits to join premium-alloy rails or to make welds between a premium-alloy rail and a standard rail (*23*). The major findings from this project were that the natural air cooling of a field thermite weld is slow enough to avoid martensite formation in all cases. However, simulated service tests at the TTC showed that these welds tended to batter because the weld metal and heat-affected zone generally had lower hardness and lower yield strength than the parent metal (*4*). The TTC has recently started simulated service tests of air-quenched thermite welds, which have the potential for sufficient strength to resist batter while still avoiding martensite formation. Whether the air quenching process can be controlled in the revenue track environment with sufficient accuracy to avoid martensite embrittlement is an open question.

The seamless butt weld, a derivative of the thermite field weld, has recently begun to be applied to the repair of transverse defects in the rail head. If such defects are to be locally repaired, it is generally necessary to remove 2 to 3 in. of rail length to be certain that the entire defect has been removed. Regular thermite weld kits cannot be used to rejoin the rail in such cases because they are limited to weld thicknesses of $^1/_2$ to $^3/_4$ in. The repair practices in common use have been whole rail removal in BJR and removal of a 10- to 20-ft plug from CWR. The seamless butt weld kit is a rail-end kit that has been modified to produce the weld thickness required for defect repair. Seamless butt welds are now undergoing simulated service tests on the TTC FAST track.

Despite all the effort that has gone into improvement of field thermite weld products, the process is still susceptible to the formation of internal sand pockets or lack-of-fusion defects when maintenance gangs are pressed for time or when welds must be made during severe cold weather. One good practice to compensate for these risks is to install safety straps on all field welds. Safety straps are used today mainly on lines where the perceived risk of derailment is high, for example, in the Northeast Corridor to protect high-speed passenger trains. Safety straps are essentially flexible joint bars that bulge around the weld upset and can be relied on to maintain rail alignment for one or two trains should a weld break. One useful product improvement that has not yet appeared would be insulated safety straps to provide positive assurance that a field weld failure would disrupt the track signal circuit and stop the next train.

A better long-term solution to the field weld defect problem might be found in alternative welding methods that can be more easily controlled. Several alternatives have been investigated by the former Japanese National Railways, but all require elaborate equipment on the track and have therefore had little appeal to the U.S. railroads. One promising improvement that has been the subject of some research in the United States is a consumable-guide electroslag weld developed under railroad sponsorship. The consumable guide is a prefabricated kit in the shape of the rail cross section, and the only equipment required on track is a portable generator to supply the welding current. Some of these welds have been made in the laboratory, and two have been placed in the FAST track.

The final example illustrates the unexpected side effects that can sometimes result from product improvements. The uniform reduction of rail camber by roller straightening makes widespread CWR fabrication practical, but the price paid for the improvement is residual stress left in the rail (*24, 25*). The residual stress magnitude generally increases as the material yield strength increases; that is, the same roller-straightening process leaves higher stresses in high-strength premium-alloy rail than in standard composition rail. In some cases, the price paid for increased hardness and strength can be decreased resistance to fracture.

Investigation of a 1983 passenger train accident led to the conclusion that such a combination of high residual stress and low fracture resistance was a major factor contributing to the sudden rail web failure that caused the derailment (*26*). Similar fractures were later produced in the laboratory (R. K. Steele, AAR Research and Technical Center, unpublished data, 1984), the potential of roller-straightening stress to drive cracks was measured (*27*), the variation of rail steel alloy fracture resistance was characterized (*28*), and the web fracture instability phenomenon was recently confirmed by dynamic crack propagation analysis (*29*) and energy release rate calculations (F. A. McClintock and S. J. Wineman, Department of Mechanical Engineering, Massachusetts Institute of Technology, unpublished data, 1987).

The 1983 derailment was an isolated case in which abusive maintenance shortly before the passage of the train triggered the conditions for initiation of the web fracture (*30*). A modest product improvement in the form of a minimum specification for rail steel fracture toughness can help to reduce the risk of sudden rail failure from maintenance abuses that would normally be tolerated by rail without roller-straightening stress. The research results suggest that most rail steel alloys in use since roller straightening started would meet such a specification.

Straightening stress can also increase fatigue crack propagation rates and thereby decrease safe crack growth life. A recent case involving rapid propagation of small surface defects through the rail web thickness is believed to have been caused by straightening stress and is now the subject of a research project. Rail makers are also investigating alternative straightening processes that have the potential to produce rails with low stress as well as low camber, for example, stretch straightening (*31*) and combinations of roller straightening with stress-relieving heat treatment.

CONCLUDING REMARKS

The framework for rational determination of safe rail test intervals is expected to be completely in place within a few years. Future rail integrity research will likely concentrate on product improvement or effects of rail transportation system modernization.

On the product improvement side, the handling of roller-straightened rail will likely receive continued attention in the near future, and new work must be started on the subject of surface head checking. Widespread surface head checking (i.e., microcrack formation) has recently started on some heavy-haul lines and is of concern because surface microcracks can mask other safety-critical defects from detection by conventional ultrasonic testing.

On the system modernization side, the anticipated transition to 125-ton cars raises a major question about fatigue behavior. The first post-transition experience with rail that has been conditioned under 100-ton service might not provide a good guide to the behavior of new rail under 125-ton loads. Laboratory fatigue experiments suggest that a historical trend from low to high loads tends to delay fatigue crack nucleation, not unlike the retarding effect of occasional overloads on crack propagation. Whether the useful service life of new rail under 125-ton loads will be lower than the life of preconditioned rail remains to be seen and will be one of the subjects of the next phase of experimentation on the TTC FAST track.

Although rail fabrication defects are best dealt with by means of ad hoc product improvements that increase production quality, most kinds of rail defects result from the repeated application of service loads and will always occur at rising rates as rail accumulates tonnage. In the long run, detail fractures and other defects that are the inevitable result of rolling contact will come to dominate the rail defect population as product improvements and BJR replacement continue.

Periodic testing of revenue track will always be required to control derailment risks arising from exposure of trains to rail failures. A damage tolerance philosophy based on fatigue behavior and fracture mechanics provides the unifying framework for understanding how inspection equipment improvements can be traded against test frequency requirements and how maintenance resources can be efficiently targeted on critical track sections without sacrificing operational safety. Examples of both kinds of applications have been presented and in most cases suggest that safe practices are also economical practices.

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