Rail Research: Meeting the Challenge of Modern Traffic Loading

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The current trend in the railroad industry toward heavier cars and increased wheel loads and the subsequent effect of this trend on rail are discussed. Because of the increased loadings, the replacement criterion for rail in main-line tangent track has changed from rail wear to initiation of rail fatigue defects. An analysis of field data shows that this initiation of fatigue defects is a function of both wheel load and rail size. Rail research in North America and its thrust toward improving and extending rail service life are also discussed.

In light of the current trend in railroading toward heavier cars and trains, the railroad track structure is being called on to perform under an increasingly severe loading environment. As a result, the very nature of rail failure has changed. This change in the modes of rail failure has resulted in changes in criteria for rail replacement and consequently in changes in inspection and maintenance practices.

Track rail once lasted until it literally wore out. Under today's severe loads, however, fatigue-initiated cracks in the railhead can result in premature fracture of the rail. Furthermore, it is often not possible to see the fatigue crack, even at its critical point. Ultrasonic or magnetic inspection techniques must be used to detect these hidden defects so that they can be removed.

Rail-end batter, the traditional replacement criterion for tangent track, has been significantly reduced by the increasing use of continuously welded rail. In its place, however, fatigue-induced defects, either in the rail or at a weld, have emerged as the dominant rail-replacement criterion for tangent track. On curves, severe gage face wear, plastic flow of the railhead, and even crushed rail are all major problems that combine with initiation of fatigue defects to shorten the service life of rail.

To better understand the problem, one must only consider that a stationary 91-Mg (100-ton) car with a static wheel load of 146 kN [33 000 lbf (33 kips)] transmits a contact stress of 1200 MPa (175 000 lbf/in^2) to the head of the rail. The yield strength of the rail steel is only 520 MPa (75 000 lbf/in^2). The result can be seen in Figure 1: rail wear, fatigue defects, or both.

Thus, in recent years, rail research has been directed toward the problem of defining, quantifying, and ultimately extending rail service life. It is the purpose of this paper to briefly define and quantify some of these modes of rail failure and to discuss the current and future directions of rail research in North America.

FATIGUE DEFECTS

The modes of rail failure, particularly the types of rail defects that can occur and that result in rail failure, are amply described in the literature (1-3). In recent years, examination of track test sites—such as the six sites maintained by the American Iron and Steel Institute (AISI), the Association of American Railroads (AAR), and the American Railway Engineering Association (AREA) as part of the Joint Cooperative Rail Research Program on the Union Pacific and the Atchison, Topeka, and Santa Fe Railroads—has shown the growing predominance of the detail fracture-shell type of defect under mixed freight loading (4). This trend is clearly indicated in Figure 2, which shows that where there is a predominance of mixed freight traffic with some unit trains, defects of the detail fracture type tend to dominate the failure-inducing defects that result in rail replacement and rail maintenance.

Further examination of the occurrence of detail fracture defects with gross loading on the track indicates that there is a point at which the rate of defect occurrence increases dramatically (see Figure 3). This means that, after an initial period in service, there is a significant increase in the rate at which defects in rail occur. Recent probability analyses of defect data indicate that this increase occurs in the range of 182 million-636 million gross Mg (200 million-700 million gross tons) (5).

Evaluation of transverse defect data from the Facility for Accelerated Service Testing (FAST) at Pueblo, Colorado, where a unit-train type of operation is simulated, also shows this behavior (Figure 4). It should be noted, however, that the point of transition for the FAST data occurs at a significantly lower load level than for the mixed traffic cases shown in Figures 2 and 3 for the same size rail. This observation—that increased loadings, such as those produced by heavy 91-Mg (100-ton) cars in unit train service, results in reduction of rail service life—is supported by recent analyses of the fatigue life of rail (6, 7). These analyses, which use loads and stress values for different types of traffic together with data on the fatigue properties of rail material, indicate that as the severity of loading increases—i.e., as the size of the freight car and the corresponding axle loads increase—the fatigue life of rail in service decreases (see Figure 5). This effect agrees with general observations made in the field by track engineers (8) and clearly illustrates that the use of heavier cars results in a direct increase in maintenance costs. Thus, whatever benefits accrue from the use of freight cars with larger loading capacities, they must be balanced against these increased maintenance costs in order for a true cost/benefit comparison to be made (9, 10).

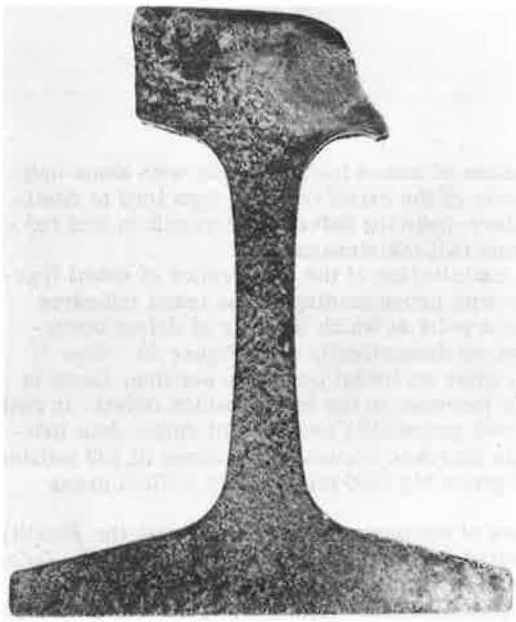
The analyses shown in Figure 5 also indicate that a definite benefit can be gained in rail service life by increasing the weight, and correspondingly the size, of the rail section in the track. This behavior is supported by field data such as those illustrated in Figure 3, which shows the number of defects versus car weight for two sections of track on the Atchison, Topeka, and Santa Fe Railway under similar traffic conditions but with different rail-section sizes. As Figure 5 further shows, this benefit of increased rail size occurs under differing traffic mixes and loading conditions as well.

These investigations, together with other ongoing work in the areas of fatigue failure, fatigue crack propagation, fracture mechanics, and rail stresses (11), represent the current state of the art in the study of fatigue defect behavior in rail steels.

RAIL WEAR

Rail wear remains the dominant criterion for rail replacement on curved track in North America. It also remains one of the most important causes of rail replacement. Thus, the ability to predict rail-wear life and to decrease the rate of rail wear has been of great

Figure 1. Rail exhibiting detail fracture combined with extreme curve wear.



concern to the track engineer.

In 1969, AREA developed an equation for the calculation of rail life based on railhead wear (12). This equation, which was empirically derived from field measurements, provided the following relation (since the equation was formulated in U.S. customary units of measurement, no SI equivalents are given):

$$T = KWD^{0.565} \quad (1)$$

where

T = life of rail in main-line track (million gross tons),
K = constant reflecting level of track maintenance and type and condition of track structure (average = 0.545),
W = weight of rail (lb/yd), and
D = annual tonnage density (million gross tons).

More recently, the Canadian Institute of Guided Ground Transport (CIGGT) has developed a rail-wear model that uses a combined empirical and analytic approach (13). This model has a capability for predicting rail wear that enables the user to define track and traffic conditions and obtain an analytic prediction of wear life. Such a prediction is shown in Figure 6, which also shows the effects of axle loads, rail heat treatment, and lubrication on rail wear.

Investigation into the mechanism of rail wear represents another approach taken in the understanding of wear and in the development of techniques to improve wear life. The recent work of several authors (14-16) represents the state of the art in the study of rail-wear behavior.

Additional research in the area of improving rail metallurgy, particularly that oriented toward improving characteristics of rail wear, is being pursued extensively both in North America and abroad (11). The results of this research, in particular the results on the different types of metallurgy and heat treatment, are being evaluated under service conditions and at FAST (17). Preliminary results from the accelerated service testing at FAST are shown in Figure 7. In the figure, each point on the curve represents the mean value of railhead area loss for a random mix of rail-cant and shoulder-width test sections. These preliminary results show that improved rail-wear characteristics can be obtained from improvements in rail steel.

WEAR VERSUS FATIGUE

As noted earlier, because of the current tendency toward heavier rail cars and increased wheel loads, the nature of rail failure in general, and the maintenance criterion for rail replacement in particular, are undergoing significant changes.

The emergence of the problem of the initiation and growth of fatigue defects in rail has resulted in major changes in rail inspection techniques and rail replacement practices. Because of the serious safety consequences of rail defects, rail must often be removed from track long before it has worn out, and this represents a serious economic consequence (9, 10).

A recent comparison of the wear life of 136 RE standard carbon rail with the fatigue life of the same rail for different wheel loads is shown in Figure 8 for tangent track. The nominal wheel load represents the largest static wheel load imposed on a section of track that experiences a defined mix of traffic. Actual dynamic loads that corresponded to these static values were then used to determine the respective lives. The fatigue line on this curve was obtained by using the slope of the S-N curve for rail steel and the calculated fatigue life of 136 RE rail under the defined loading conditions (7). The wear line was obtained by using the AREA wear formula (Equation 1).

Figure 8 shows that, as the static wheel load (i.e., the weight of a four-axle freight car) increases, the failure mode of the rail shifts from wear to fatigue. For traffic with nominal static wheel loads greater than 124 kN (28 000 lbf)—i.e., greater than 63-Mg (70-ton) traffic—fatigue failure emerges as the criterion for rail replacement. This appears to be in agreement with field experience (7).

Further examination of Figure 8 shows that the curve for fatigue life versus wheel load has a very steep slope. This suggests that there are significant rail-life penalties associated with additional increases in wheel loads. Figure 5 confirms this observation. Thus, any further increase in wheel loads should only be made after there is adequate understanding of both the safety and economic consequences (8, 9).

CURRENT RAIL RESEARCH

Rail research is currently directed toward understanding the mechanisms of rail failure and developing techniques to extend and improve rail service life. Recently, several conferences and presentations have examined the various aspects of rail research, both in North America and abroad (11, 18, 19). Therefore, only a brief overview of current, ongoing rail research in North America is presented here.

Current investigations into the failure mechanisms of fatigue and fracture in rail steel include empirical evaluations of test site data, such as those from the joint AISI-AAR-AREA test sites on the Union Pacific and the Atchison, Topeka, and Santa Fe Railroads (4, 11, 20, 21); FAST (17); and others (22). Also included are ongoing laboratory investigations into (a) cyclic fatigue behavior (Northwestern University), (b) fatigue and fracture of rail steel [Carnegie-Mellon University (11) and U.S. Steel (23)], and (c) residual stresses in steel and analyses of service-developed defects [U.S. Steel (21)]. Finally, analytic investigations, such as AAR analyses

of fatigue-defect initiation (6, 7), and analyses of stresses around verse fissure flaws [Battelle-Columbus Laboratories (11)] are also ongoing.

In current research in rail wear and rail corrugation, ongoing studies of rail wear include basic evaluation of rail-wear mechanisms (a) on tangent track [Illinois Institute of Technology (16)], (b) on curved track [Colorado School of Mines (15)], and (c) in general service (14). Rail-wear modeling work is currently being pursued at the Canadian Institute of Guided Ground Transport (13).

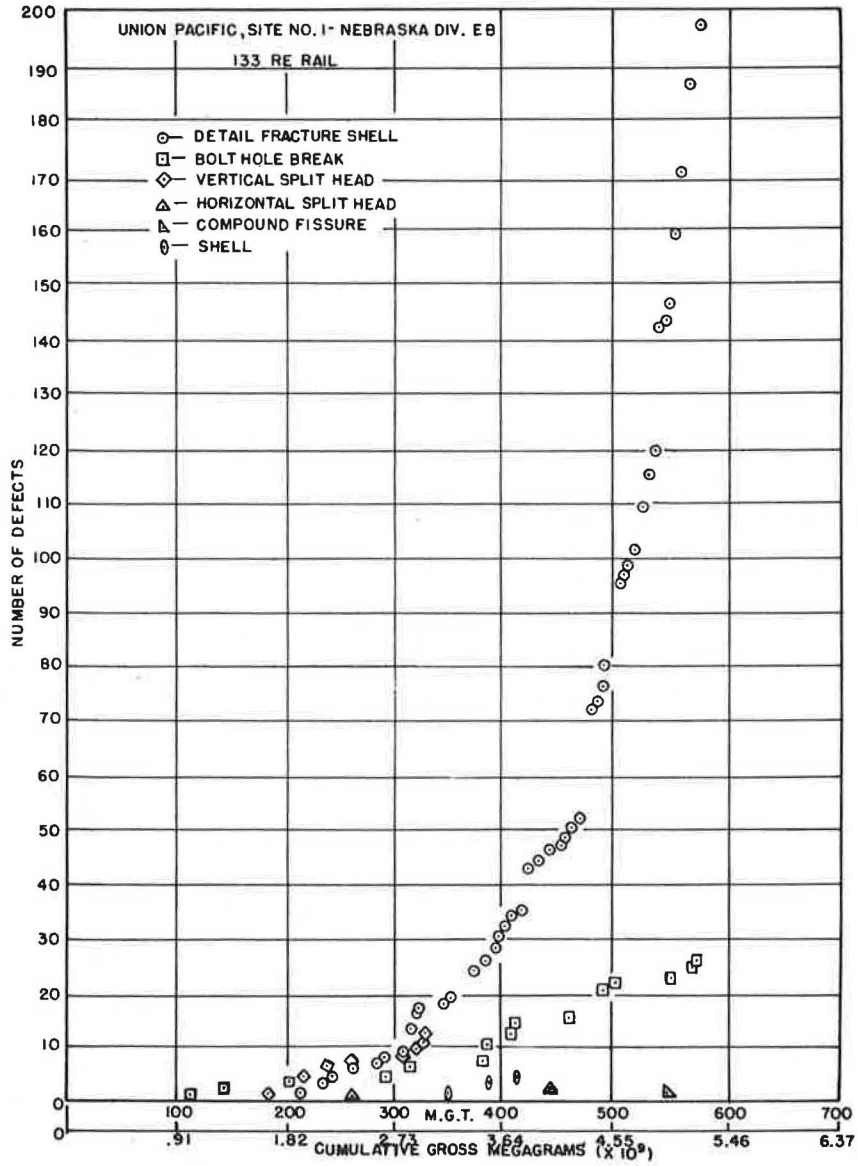


Figure 2. Distribution of rail defects at Union Pacific test site.

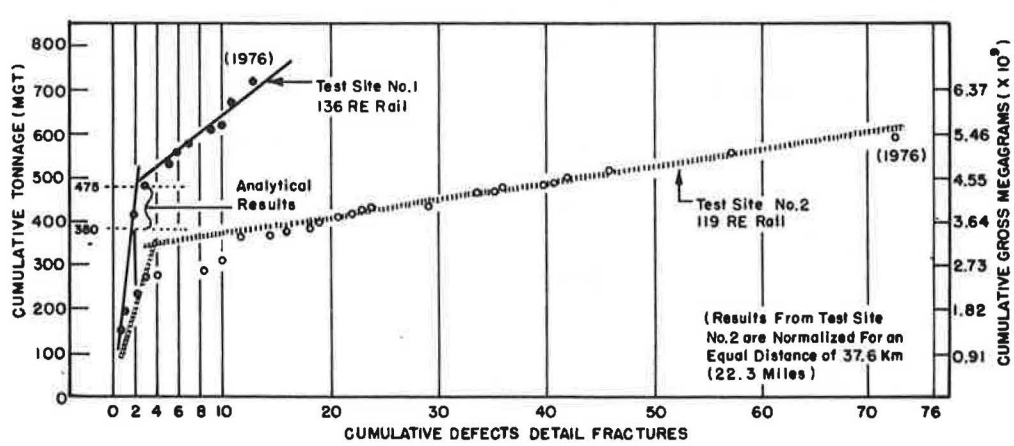


Figure 3. Cumulative rail defects versus cumulative traffic loading at Atchison, Topeka, and Santa Fe Railway test sites.

Figure 4. Cumulative rail defects at FAST.

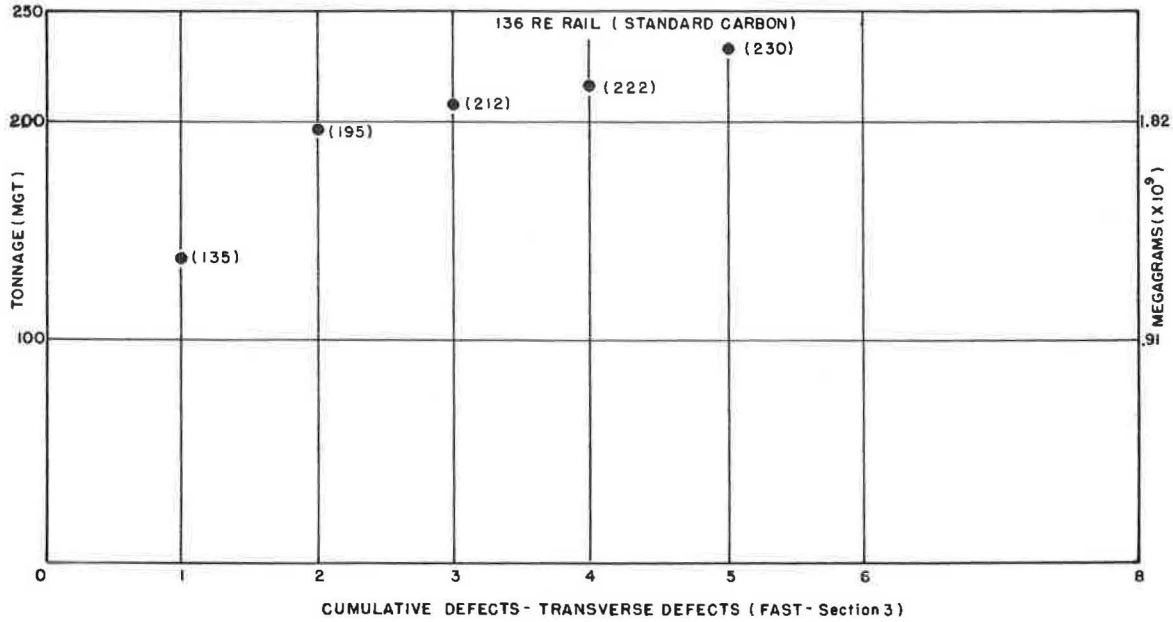


Figure 5. Effect of increasing traffic loading.

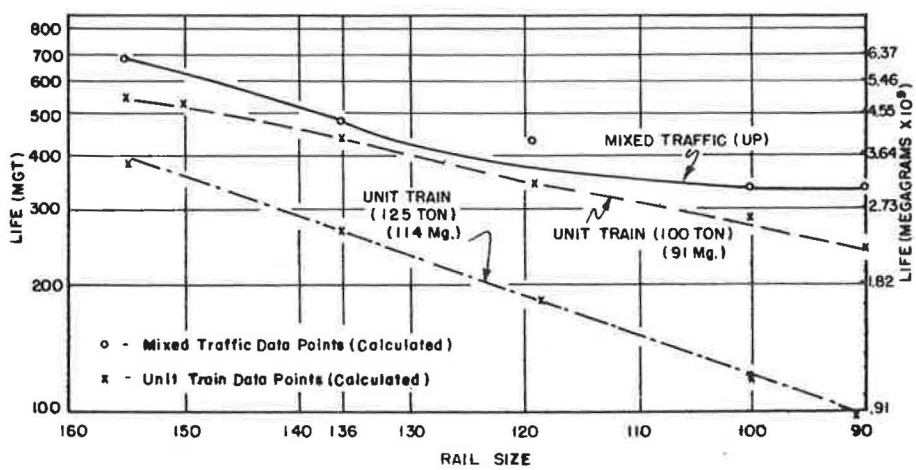
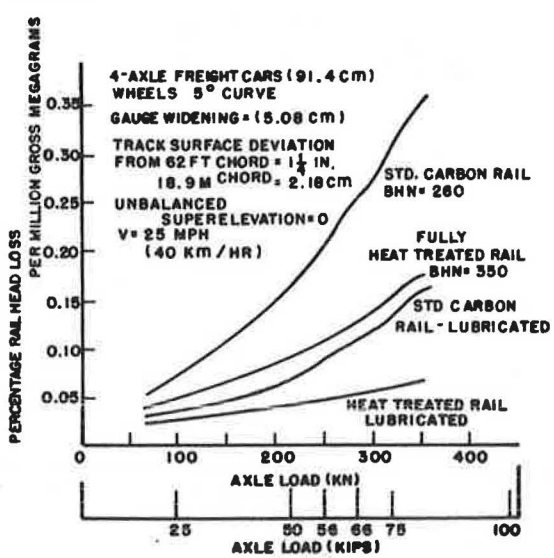


Figure 6. Prediction of rail wear by RAILWEAR 2 program of CIGGT.



Work on rail corrugation has been done by Kalousek (24) as part of the Track-Train Dynamics program. Finally, an empirical investigation of wear is ongoing at FAST, where the wear characteristics of different rail metallurgies are being studied (17). Also ongoing at FAST are investigations into the occurrence of rail corrugations.

Other rail research programs include investigation into and development of improved rail metallurgies (11, 19) and development of improved techniques of rail-flaw inspection (25, 26). In the latter area, both AAR and the Federal Railroad Administration are particularly emphasizing the extension of existing ultrasonic and magnetic inspection techniques to increase depth of penetration and speed of inspection. Work in the area of inspection of field and plant welds is also being pursued. This effort, together with studies to improve the Thermit welding process (at Arizona State University) and to develop homopolar welding techniques (at the University of Texas), is aimed at expanding and improving the state of the art in rail welding technology.

Figure 7. FAST comparison of rail wear for different rail metallurgies.

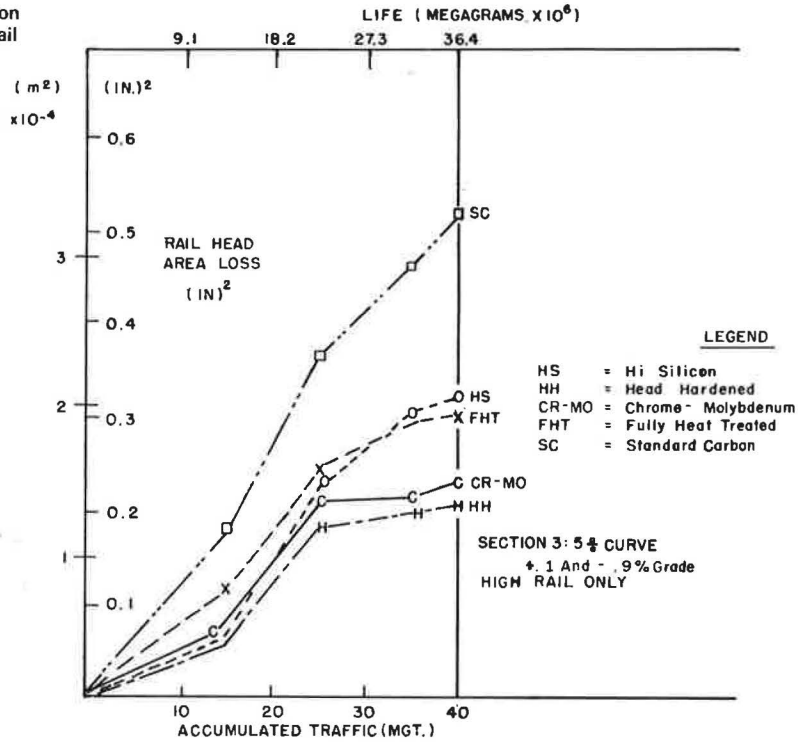
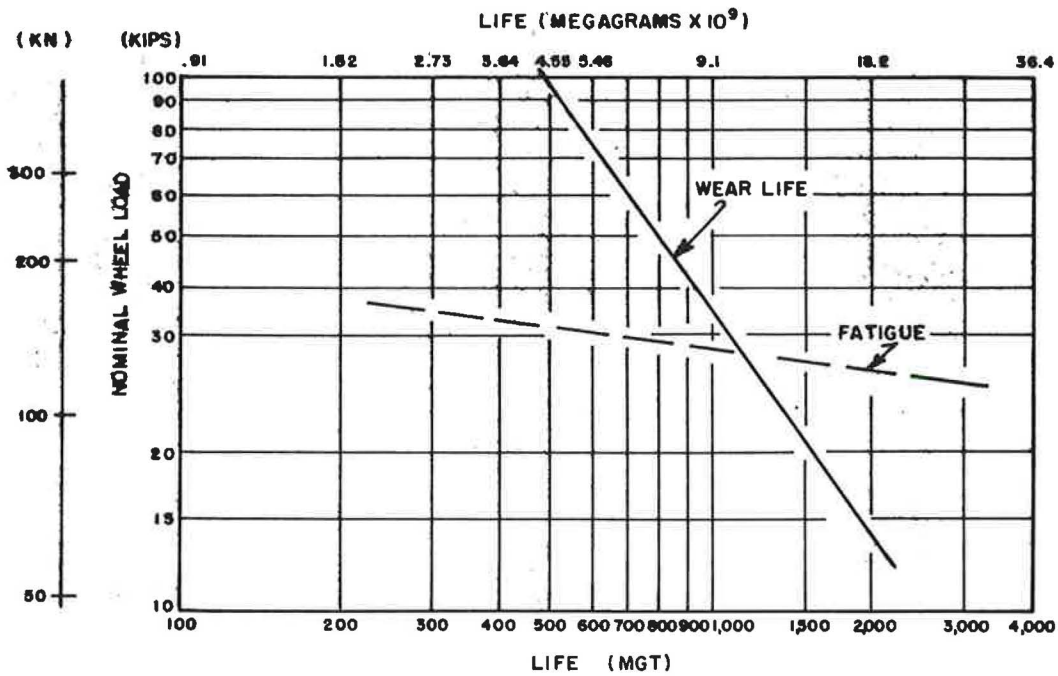


Figure 8. Rail-life fatigue versus wear for 136 RE standard carbon rail.



SUMMARY

The railroad track structure, and particularly the rail itself, are being called on to perform under increasingly severe loading conditions. Consequently, new modes of rail failure are demanding that the railroads improve, and in many cases change, their basic maintenance practices. As these new failure modes become more prevalent, railroads are finding that a more complete understanding of rail behavior under load is necessary to improve rail performance. This is the objective of current rail research. This paper is intended to serve as a brief introduction to the problem of decreasing rail service life under increasing traffic loading and to the efforts of rail research in searching for solutions to that problem.

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Publication of this paper sponsored by Committee on Track Structure System Design.

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 underlubricated 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