

Rail Lubrication: The Relationship of Wear and Fatigue

ROGER K. STEELE

ABSTRACT

Truly effective lubrication of the wheel-rail interfaces has been shown to reduce both wear and metal flow to a much greater extent than previously had been considered possible. In addition, unforeseen benefits in reduction of corrugation development are achievable. However, in many cases a metallurgy-lubrication interaction is observed such that premium rail metallurgies benefit far less than does standard carbon rail. One explanation for this behavior may be found in the manner in which the octahedral fracture strain of rail materials varies with the ratio of contact pressure to in-surface shear stress. The enormous benefits of truly effective lubrication in reducing wear, flow, and corrugation occurrence are offset significantly by the tendency of railhead fatigue failure to become the dominant mode of rail replacement. A three-dimensional fatigue model has been employed to show that the use of rail grinding and of stronger and metallurgically cleaner rail steels can be expected to delay the damage done by fatigue processes.

Reports describing the benefits of lubrication in reducing wheel-rail abrasion, noise generation, and train resistance have been available for as many as 40 years. Indeed, 50 percent reductions in curving resistance were reported to the American Railway Engineering Association in 1940 (1). Sixty-six percent reductions in electric current consumption in special laboratory test-loop operations were reported by Fujinawa in 1967 (2). Substantial reductions of about 100:1 in side wear (gauge-face wear) of rails and wheel-flange wear also were reported in the Fujinawa paper. In 1973, Czuba (3) reported that trackside lubrication reduced gauge-face wear in revenue service by factors of 5 to 7.

Generally, however, as trackside lubrication has become more widespread, appreciation for the true value of lubrication appears to have been lost. It has been replaced, in many instances, with a sense of frustration in achieving effective wheel-rail lubrication. At present, there is a resurgence of interest in the subject of wheel-rail lubrication reminiscent of the efforts during the late 1930s.

There are, however, some new, previously undiscovered effects of lubrication. There is also better understanding today of the processes occurring at the wheel-rail interfaces. This aids in the interpretation of experimental observations and also in defining the applicability of beneficial discoveries. In this paper, the authors attempt to draw a picture of how wear and structural failure by fatigue can be interrelated and how lubrication can influence both. Because of the high reliability of curve test data from the Facility for Accelerated Service Testing (FAST), emphasis will be placed on its use illustratively and on its interpretation.

WEAR AND RELATED PHENOMENA

In a narrow sense, rail wear is the loss of material by mechanical action from the running surface and gauge face of the rail in the area shown in Figure 1. However, wear may be thought to encompass all those processes occurring in the immediate vicinity

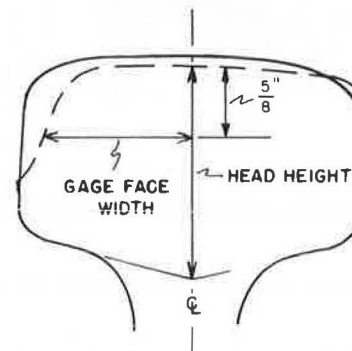
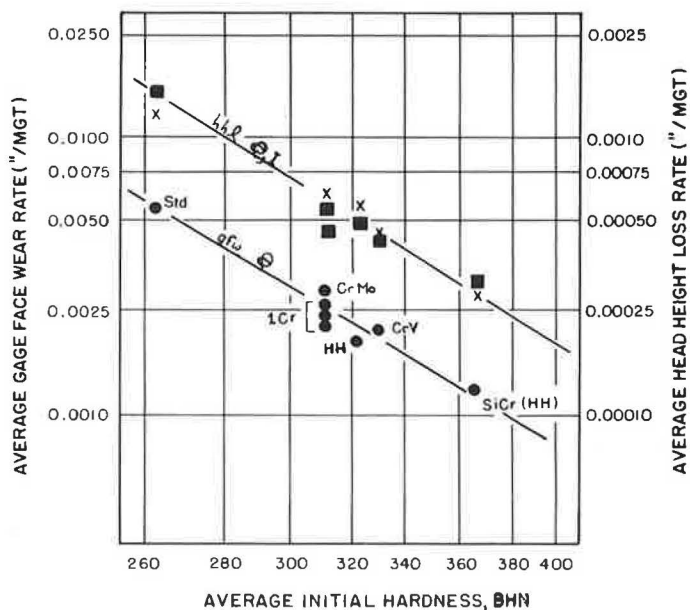


FIGURE 1 Locations of gauge-face and head-height loss measurements.

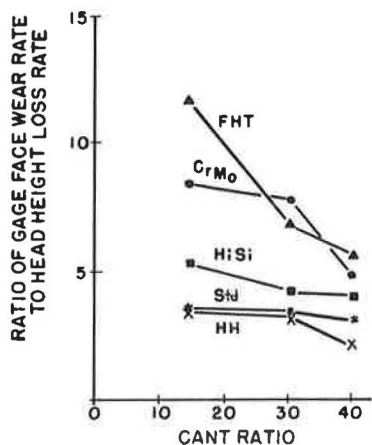
of the wheel-rail interfaces that result from the action of the passing wheel. This broader view will include the plastic deformation of the gauge face (outside curve rail) and the running surfaces (both the inside and outside rails). Corrugation development is considered here as a subset of these processes. Behavior of outside and inside rails is linked together through the action of the wheels elastically coupled together on the axle.

Results from rail metallurgy experiments conducted at FAST (4) show that in the dry condition, the gauge-face and head-height loss rates of the outside curve rail are reduced strongly by increased hardness of the rail. Figure 2 shows that although each process has a different rate of occurrence, the dependence of each on hardness is similar. The low railhead-height loss rate behaves similarly to that of the high rail. On the high rail, the ratio of the rate of gauge-face wear to head-height loss depends not only on the metallurgy but also on the tie-plate cant ratio; this is shown in Figure 3. The ratio of wear rates increases with reduced cant angle because lower cant angles shift the position of the vertical



Note: ■ = head height loss—outside rail (hhl, ϕ); X = head height loss—inside rail (hhl, I); ● = gauge-face wear (gfw, ϕ); Std = standard carbon rail; CrMo = chromium molybdenum rail; CrV = chromium vanadium rail; HH = standard carbon head hardened rail; and SiCr (HH) = silicon chromium head hardened rail.

FIGURE 2 Average wear rates as a function of average initial hardness.



Note: FHT = fully heat treated.

FIGURE 3 Ratio of gauge-face wear rate to head-height loss rate.

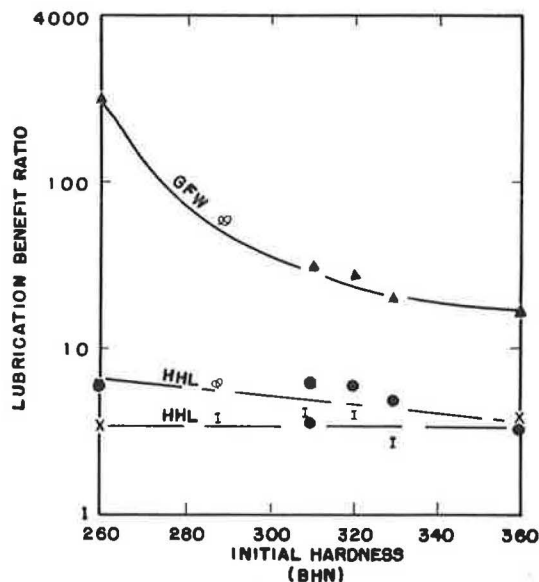


FIGURE 4 Variation of lubrication benefit ratios with hardness.

load more to the center of the railhead, tending to increase the head-height loss rate. At the same time, the lateral flange load is positioned closer to the gauge corner, leading to an increase in the gauge-face wear rate.

When lubrication is applied to only the gauge face of the outside curve rail, avoiding lubrication of the running surface of the rail, the gauge-face wear rate of all metallurgies can diminish precipitously. However, the degree of reduction is highly dependent on the type of metallurgy; this is shown in Figure 4 by the diminishing benefit factor for lubrication as the hardness of rail increases. The benefit factor is defined as the wear rate (dry) divided by the wear rate (lubricated) for different rail metallurgies. Figure 4 also shows that lubrication

of the gauge face of the outside rail can reduce the head-height loss rates on both the inside and outside rails. However, for the low rail, the variation in the benefit factor with hardness is not readily detected.

This behavior is termed a metallurgy-lubrication interaction. Its existence, apparently not recognized before the FAST rail metallurgy experiments, has been confirmed by Mutton et al. (5) for unit train ore-hauling-type service and by Kalousek (6) in laboratory tests. This phenomenon provides a key to understanding the physical processes that occur

at the wheel-rail interfaces. A wear process that has been shown (7) to be consistent with the metallurgy-lubrication interaction is one in which wear debris is generated by a cyclic mode of material failure. The failure criterion, measured as an octahedral shear strain, is a variable governed by the ratio of local normal forces to traction forces at the wheel-rail interface. A consequence of such a view is that steel metallurgical cleanliness can influence gauge-face wear; some results of FAST (7) suggest that this may be true. Metallurgical cleanliness is taken as the degree to which nonmetallic inclusions such as manganese sulfides, silicates, and aluminate are present from the steel; typical levels are near 0.2 areal percent.

Although the metallurgy-lubrication interaction has not been discerned for low-rail head-height loss, high-rail gauge-face lubrication has been shown to reduce the extent of corrugation development on the low rail (8). Furthermore, as shown in Figure 5, the corrugation extent growth rate exhibits a metallurgy-lubrication interaction; this is demonstrated by the standard carbon rail deriving greater benefit from lubrication than premium metallurgies do.

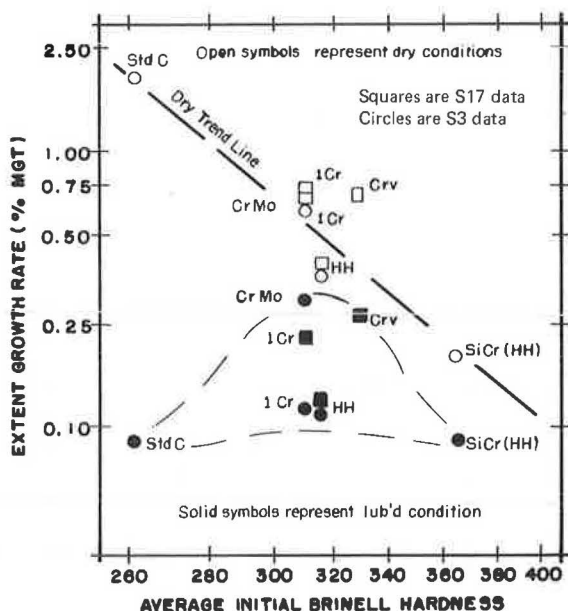


FIGURE 5 Effect of hardness on corrugation extent growth rate.

Thus, effective lubrication of the gauge face of the outside curve rail can cause significant reductions in the rates of wear and metal flow occurring on both the inside and outside rails. However, these benefits are purchased at a significant price, that is, fatigue instead of wear and flow as the reason for rail removal.

FATIGUE PHENOMENA

Verbal descriptions of rail-fatigue problems that have developed in revenue service after track lubricators had been installed are common. However, no body of data appears to have existed to confirm the relationship of rail fatigue and lubrication until the second FAST rail metallurgy experiment was completed. This second experiment was run under essen-

tially fully lubricated conditions such that the gauge-face wear rate of standard carbon rail in a 5-degree curve was reduced by a factor of approximately 10 (9). The life attributable to side wear would have increased from between approximately 80 and 100 million gross tons (MGT) for dry operation to approximately 1,000 MGT in the lubricated condition. Yet, by 250 MGT, at least one-third of the standard carbon rail on the high side of the curve had developed detail fracture service failures. A detail fracture is a transverse crack most commonly developing internally within the railhead under the gauge corner from a horizontal delamination known as a shell. A Weibull representation of the rail-failure distribution of both the 5-degree curve and the tangent track is shown in Figure 6. For comparison, the rail-defect distribution range that is typical of western United States, essentially tangent track, revenue-type operation also is shown.

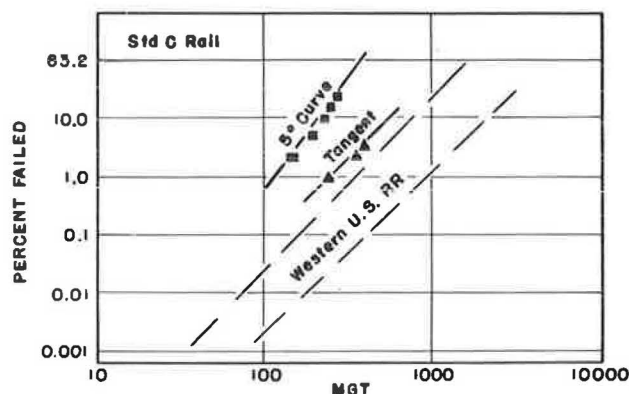


FIGURE 6 Distribution of fast rail failure.

The Weibull parameters of the FAST 5-degree curve have been used in the Association of American Railroads (AAR) Rail Performance Model (10) to estimate the value of rail characterized by such a rail-failure history. As Figure 7 shows, in the range of annual tonnage from 10 MGT/yr to 100 MGT/yr, the value of rail would have dropped to scrap value in 200 to 150 MGT. This is true despite the fact that the estimated wear life would have been approxi-

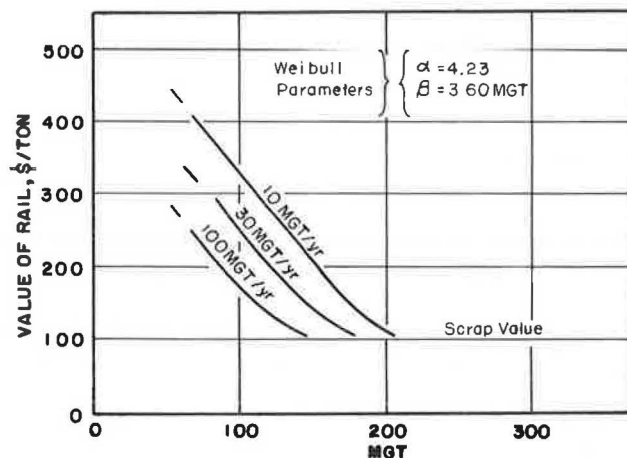


FIGURE 7 Calculated rail value for rail-failure distribution of 5-degree curve.

mately 1,000 MGT. Thus, most of the wear-life benefit derived from lubrication has been wasted. To compensate for this loss, a number of strategies are possible including (a) the use of stronger, more fatigue-resistant and/or metallurgically cleaner rail steels, (b) the allowance of some wear to occur; and/or (c) the application of rail grinding at regular intervals.

Before considering these strategies in detail, review of the specific nature of railhead fatigue will be helpful. The defect of major concern is the shell crack and detail fracture. Work by Battelle Columbus Laboratories (11) has shown that the shell crack from which the detail fracture emanates develops well beneath the region of maximum work hardening caused by the contact stresses (Figure 8). The region of maximum octahedral shear stress for Hertzian contact occurs about 0.10 to 0.15 in. beneath the surface for wheel loads in the 19 to 33 kip range (12). However, the shells form at a level two to three times that depth.

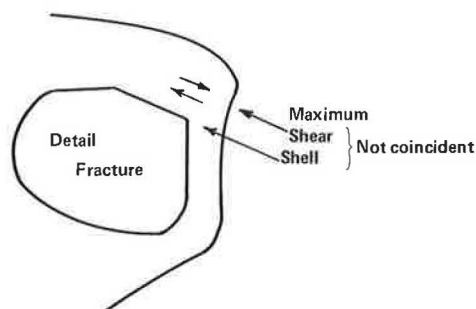


FIGURE 8 Location of shell crack and detail fracture.

The cause of shell initiation at this greater depth within the railhead is the conjoint action of the two predominant stress systems, both of which are three dimensional in nature: the contact stress system and the residual stress system. The latter system is induced into the rail by plastic deformation of the running surface under the passing wheels. The surface deformation acts in the same fashion as shot peening to create a compressive stress state in the immediate vicinity of the surface. This is balanced by a tensile residual stress state at a greater depth. A typical residual stress state in a service-worn outside curve rail is shown in Figure 9.

The residual stress level in the rail appears to vary with service exposure and to be dependent on wheel load (11). In Figure 10, the variation of five major residual stresses is shown for both general traffic and heavy (wheel load) traffic at low (83 and 100 MGT) and high (200 and 300 MGT) service exposures. The heavy-traffic condition significantly increased the maximum level of residual stress measured for, in particular, peripheral surface compression, axial compression, and transverse in-plane tension stresses. In general, increased service exposure tended to increase the maximum transverse in-plane stress levels. Simultaneously, the maximum peripheral surface stress and the maximum axial stress levels diminished or were virtually unaltered.

The deformation that occurs in the running surface is strongly dependent on whether substantial surface tractions occur in the wheel-rail contact patch (12). This is the same deformation that contributes to head-height loss and to corrugation development. The stress state that drives it is

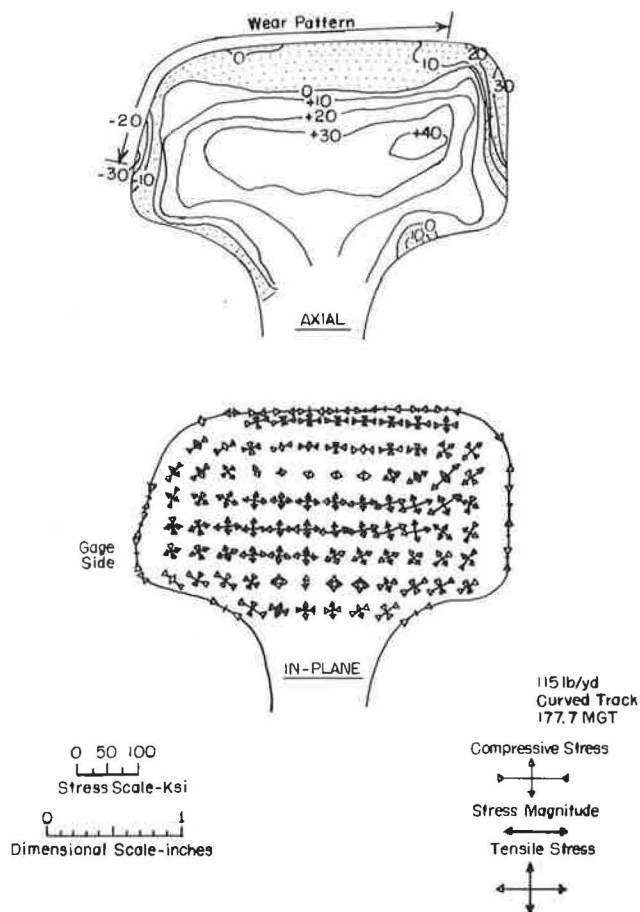


FIGURE 9 Axial and in-plane residual stresses in a service-worn rail.

shown in Figure 11. Under pure rolling conditions with the contact patch in the center of the railhead, the effective coefficient of friction at the surface approaches zero. In this case, the maximum octahedral shear stresses occur in a fully constrained region beneath the surface and are of relatively low magnitude. Ideally, this condition could be achieved with lubricant on the running surface of the rail.

As curving, braking, and/or acceleration cause surface tractions to develop, the region of maximum octahedral shear stress broadens to reach the surface. This condition is represented by an effective coefficient of friction near 0.3. There is little change in the magnitude of the maximum octahedral shear stress. Finally, the effective coefficient of friction will reach 0.5 or greater with the strong surface tractions developed under severe curving conditions. In this case, the region of maximum octahedral shear stress occurs in the surface and the maximum stress magnitude increases by 40 percent.

In addition, there is a corresponding development of large in-surface compression and tension stresses (12) as the surface tractions increase. These are shown in Figure 12 for the same wheel-load and surface-traction conditions that applied in Figure 11. As the coefficient of friction reaches 0.5, a region of in-surface compression develops under one edge of the contact patch. A region of very high in-surface tension develops slightly outside the opposite edge of the contact patch. The strong in-surface tension stresses can act to overcome residual compressive

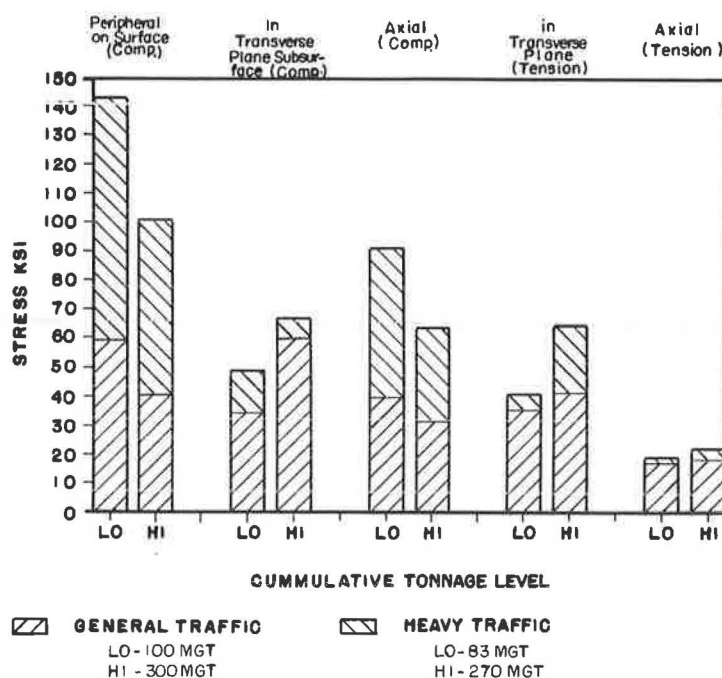


FIGURE 10 Maximum residual stresses measured.

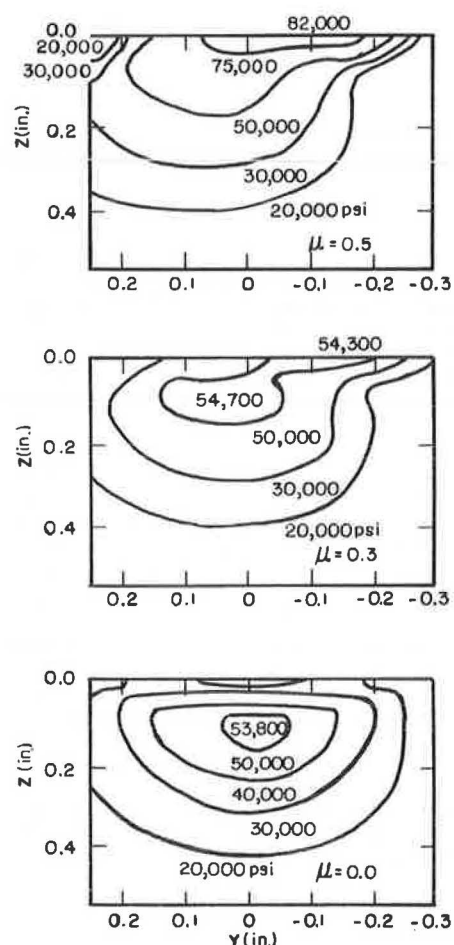


FIGURE 11 Octahedral shear stress contours (combined vertical and lateral loading).

stresses that have developed in the running surface and lead to the occurrence of head checking. Head checks are a pattern of closely spaced shallow cracks inclined to the surface and sometimes to the length of the rail when they occur near the gauge corner.

If the fully constrained condition (very low surface tractions, $\mu \approx 0$) could always be maintained under lubricated conditions, a minimum of surface deformation would be expected to occur and the residual stress levels would be minimized. Under these conditions, the prolongation of wear life by lubrication might not expose the rail to an adverse fatigue environment. The intermediate condition (≈ 0.3) is probably more commonly achieved in U.S. railroad practice; under heavy wheel loads a service-induced residual stress state will begin to develop in the railhead.

A three-dimensional fatigue model based on the Sines criterion for failure (13) has been utilized to assess the contributions of residual stress level, wheel load, steel metallurgical cleanliness, and rail fatigue strength on fatigue life and its distribution. A limitation of the model is that, at this time, it will treat only tangent track conditions. Nevertheless, it can provide quantitative assessments of the relative changes that are possible by altering basic loading and material parameters.

Figures 13 and 14 show the effect of changing the magnitude of the residual stress state and wheel-load spectra from the base values utilized to simulate the FAST tangent-track defect distribution. The degree to which residual stress level influences the predicted rail life depends on the type of wheel contact that is assumed to occur. The crown radius of new rail typically is 10 to 14 in. However, as wear and metal flow proceed, the effective crown radius will increase and the contact patch will approach a rectangular shape indicative of line contact (14). Based on the FAST experience, a 30-in. rail crown radius has been taken for Hertzian con-

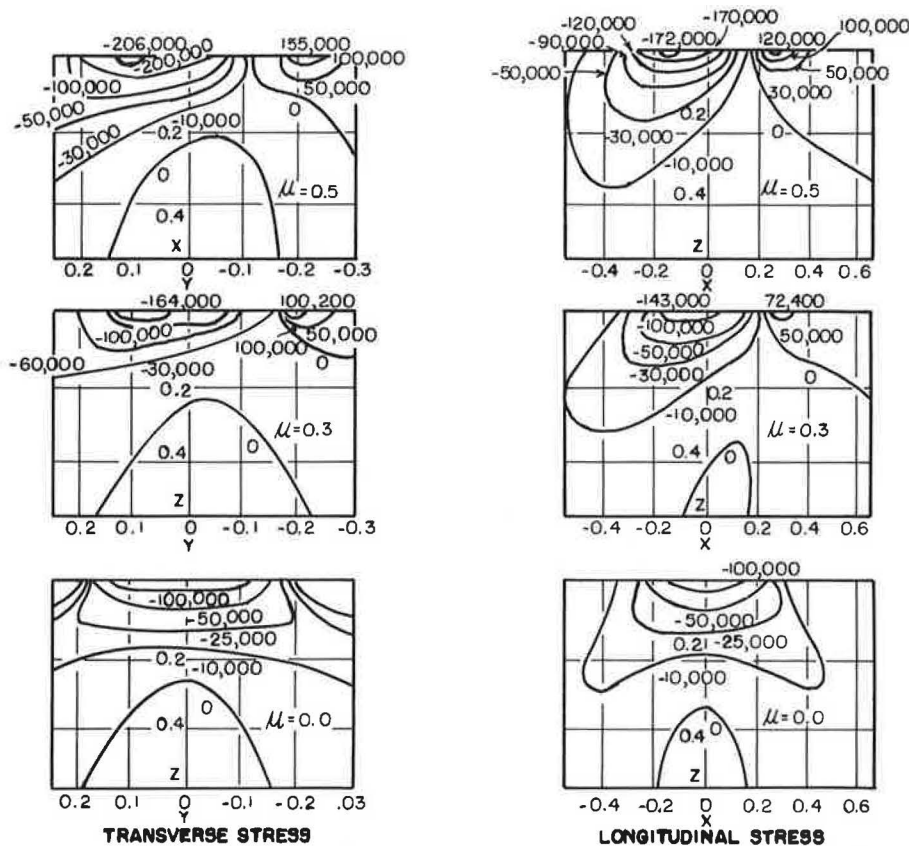


FIGURE 12 Longitudinal and transverse stresses induced by surface contact.

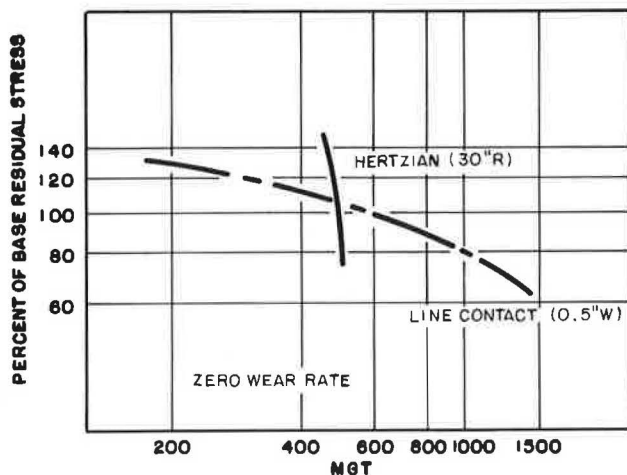


FIGURE 13 Effect of variation in residual stress magnitude on tenth percentile life.

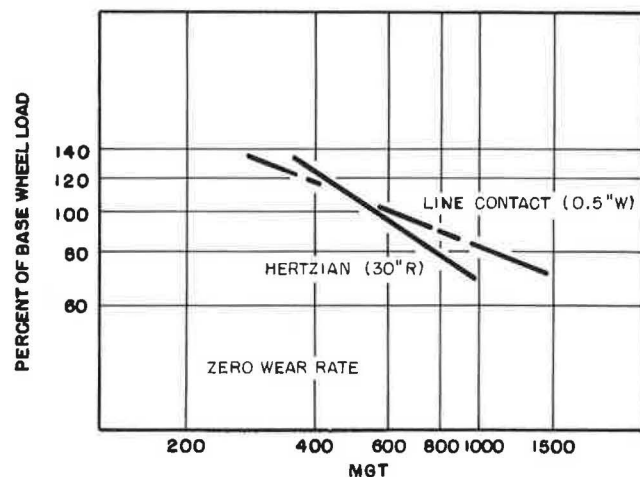


FIGURE 14 Effect of variation in wheel load spectra on tenth percentile life.

tact; a 1/2-in. width has been used for line contact. Although the type of the contact is predicted to have only a modest effect on the sensitivity of rail life to wheel load, the type of contact has a large effect on the sensitivity of rail life to variations in residual stress level. For Hertzian contact, there is virtually no effect of variation in residual stress, whereas the effect is quite strong for line contact.

The difference in octahedral shear stress depth variation between Hertzian contact and line contact

is the cause of the difference in residual stress effect (Figure 15). At fixed contact area, the line contact yields somewhat higher surface stress than does the Hertzian contact. However, the peak stress beneath the surface is significantly less. At greater depth, the line contact stress is also greater than that for Hertzian contact.

Use of 300 initial-hardness standard carbon rail and rail having the nonmetallic inclusion content about one-third to one-half that typically encountered in standard carbon rail can be expected to

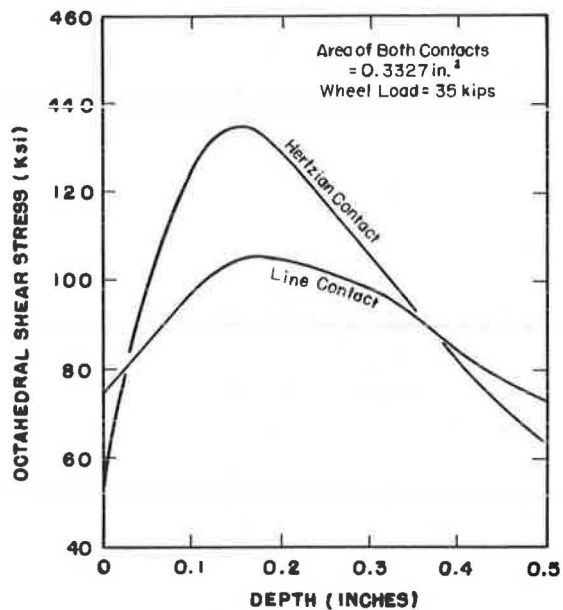


FIGURE 15 Variation of contact stress with depth.

increase railhead fatigue life. Improvements by factors of two to three are shown in Figure 16. Use of even better premium rail with higher hardnesses (and better fatigue resistance) will achieve further improvement in fatigue life.

Modest wear (head-height loss) itself appears to be beneficial (Figure 17). However, the extent to which wear appears to be beneficial depends on the character of the contact and on life percentile. The more flattened the railhead, the greater the benefit of wear at a fixed life percentile. On the other hand, at a fixed crown radius, the greater the life percentile (i.e., the longer the rail has been in service), the greater will be the benefit of wear. The practical method of synthesizing wear is programmed rail profile grinding.

Profile grinding has the additional advantage of permitting repositioning of the vertical load path away from the gauge side of the rail, effectively decoupling the effects of the tread and flange forces on curves. Potentially, under lubricated conditions, if the tread load can be forced to remain in a band toward the center of the railhead, plastic flow can be minimized and with it the railhead fatigue damage can be minimized.

The preceding discussion of the effect of lubrication in causing fatigue as the mode of rail

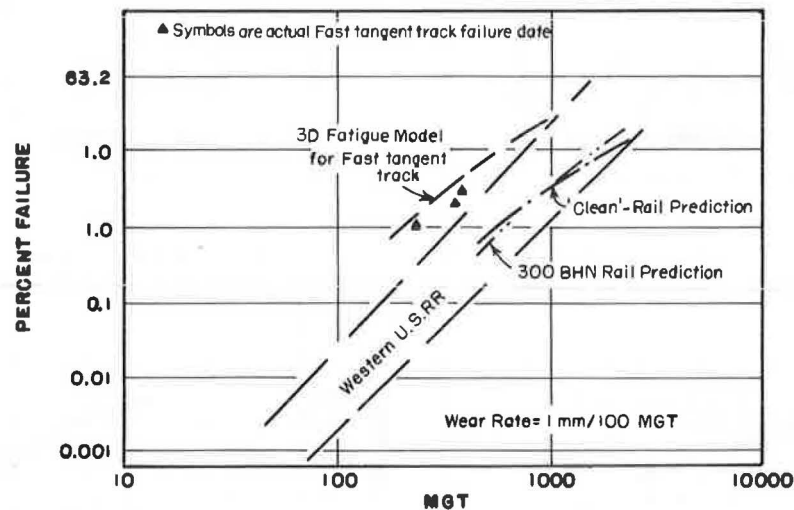


FIGURE 16 Predicted fatigue life distribution for metallurgically clean rails and for 300 bhn rails.

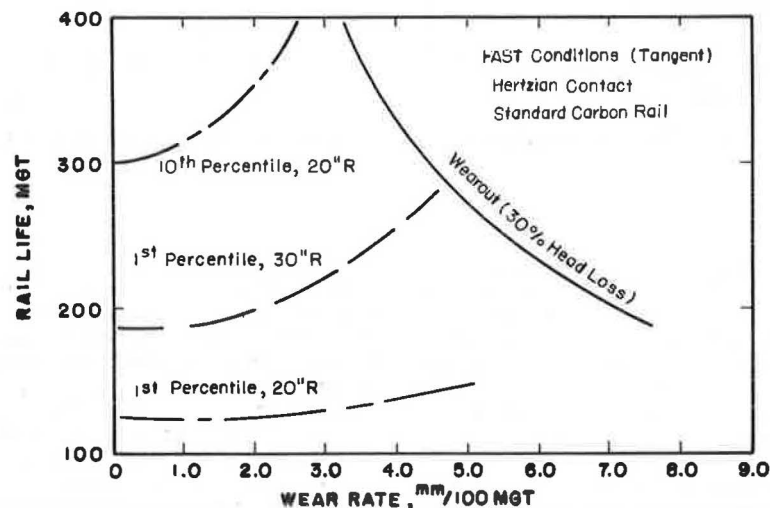


FIGURE 17 Effect of wear on fatigue life.

replacement on curves has presumed that the lubrication is maintained exclusively on the gauge face of the rail. It also has focused on the fatigue damage that is the primary result of the conjoint action of the contact stresses and the residual internal stresses. Lubrication restricted to the gauge face has only been shown (15) not to have a large effect on the vertical and lateral wheel loads acting on the high rail. However, recent studies at the Transportation Test Center in Pueblo, Colorado, have shown (16) that if the lubricant works its way over onto the running surface of the high rail without being present on the running surface of the low rail as well, the lateral forces applied to the high rail increase significantly over those observed in the dry regime (Table 1). This condition can lead to significant increases in the flexural stresses experienced by the rail.

TABLE 1 Lateral Forces on Lead Axle, High Rail

Track Condition	Speed (mph)	Force (kips)
Dry	16.5	10.2
	16.9	9.7
	22.5	10.0
	22.5	9.5
Lubricated	16.6	18.0
	16.6	13.9
	22.5	14.5
	22.6	13.7

Avg = 9.85

Avg = 15.0

These flexural stresses in the rail have been calculated by using a closed form method (17) capable of accepting lateral force as well as vertical force inputs. The results show that the maximum tension stresses occurring at the field-side bottom corner of the high railhead can be increased by approximately 35 percent and that those at the field-side tip of the high rail base can be increased by approximately 27 percent. These increases apply for track having a vertical track modulus of 2,000 psi and a lateral-to-vertical stiffness ratio (L/V) of 0.85. This shift is shown in Figure 18 for

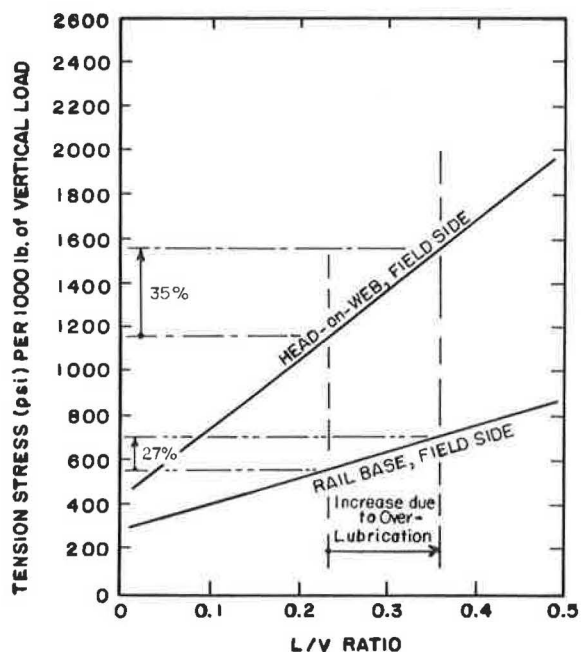


FIGURE 18 Variation of tension stress at two locations on the rail with increasing lateral-to-vertical ratio.

136-lb/yd rail. Such increases can be expected to have little effect on sound rail metal. However, they will increase the tendency of thermite and electric flash butt welds to fail and of longitudinally disposed defects within the head of the rail to turn into the transverse plane.

CONCLUDING REMARKS

Lubrication of only the gauge face of the outside rail of a curve can yield benefits in rail performance on both the inside and outside rails. On the outside rail, gauge-face wear and head-height loss rates are reduced. On the inside rail, head-height loss rates and corrugation growth are reduced. Gauge-face wear and corrugation growth exhibit a metallurgy-lubrication interaction such that premium rails benefit far less from lubrication than does standard carbon rail. At least for gauge-face wear, this behavior is consistent with a material failure criterion for wear particle generation, which increases nonlinearly with the ratio of surface normal to shear stresses.

However, much of the potential benefit of lubrication is wasted because of the intercession of railhead fatigue as the primary cause for rail replacement. Thus, efforts to improve the overall level in wheel-rail lubrication in the United States as a means of achieving energy savings may lead to unexpected rail-fatigue problems. The use of metallurgically cleaner and mechanically stronger rail steels can compensate to some extent for this shift in behavior. Rail profile grinding on a programmed basis offers great potential benefits both by simulating the wear process under more readily controlled conditions and by decoupling the tread and flange force effects. Inappropriate application of lubricant can increase rail flexural stresses under combined vertical and lateral loading to the expected detriment of rail-weld and railhead defect behavior.

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