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# Second Railroad Maintenance Workshop

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# PREFACE

The quest for ways in which to make the investment in track maintenance more effective constantly occupies the attention of maintenance-of-way officers. One proven method for sharpening awareness of improved approaches to track maintenance is through the exchange of experiences among knowledgeable track engineers. This give-and-take process is at the heart of the workshop idea--the provision of an isolated environment where people sharing the same concerns can come together and participate in a carefully structured program intended to reveal alternative solutions to common problems.

This was the purpose of the Second Railroad Maintenance Workshop, held in Amherst, Massachusetts, in June 1985. It served to bring together knowledgeable speakers with a cross-section of the maintenance-of-way community to exchange information and experiences. The keynote address that was given by George H. Way, Jr., has been condensed and is included as the Introduction to this Record.

The Workshop was divided into three sessions. Session 1, Identification of Maintenance Needs, included the paper by Liddell and Roney published in this Record. Session 2, Planning for Maintenance-of-Way, included the papers by Trask and Peterson. Session 3, Innovation Maintenance, included the papers by McMichael and Steel. Presentations were also given at the Workshop by H.G. Webb, R.W. Drucker, and William J. Semioli; however, these presentations were not submitted as papers for publication.

The Second Railroad Maintenance Workshop was sponsored by the Committee on Railway Maintenance. Special recognition is given to William B. O'Sullivan, who organized the Workshop.

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# INTRODUCTION

### GEORGE H. WAY, JR.

There have been many changes to railway track and its maintenance since I have been associated with the industry. I have seen it go from very good to very bad and back again. However, that is really an oversimplification when one considers all of the changes that have taken place in traffic patterns, axle loadings, maintenance practices, and commercial pressures.

In comparison with the conditions prevalent on many main lines in the late 1960s and through part of the 1970s, today's trackage is, by and large, a thing of beauty. Somewhere along the way, railroad top management learned that to stay in the railroad business you need decent track. Of course, providing decent track is not always easy, especially when it has been allowed to deteriorate as badly as some lines had.

As I mentioned, there was some very good track in the early 1950s, but today's track must be considered superior in several respects: first, it is more uniformly maintained; in the 1950s, even on the same route there were some wide variations in quality. Second, today's main-line track must withstand more traffic with higher axle loads and higher speeds; subjected to the same loadings, I doubt that the good track of the 1950s could have stood up. Apparently, we have learned a good deal in the intervening 30 years about the importance of ballast, ties, drainage, and subgrade, as well as the more obvious matters of rail metallurgy and continuous welded rail.

Those of you who were able to be with us at the first Track Maintenance Workshop four years ago at Pennsylvania State University will recall the high standards set by speakers at that meeting. However, we should also recall the challenges that they issued to the maintenance community. At that workshop, we heard of activities such as research directed at optimizing gang size for various track occupancy rates, the effects of heavy axle loads on track maintenance requirements, the use of innovative inspection devices such as the Track Train Dynamics Decorator, and the pursuit of computer-based track data bases. Some 4 years later, we find that many of the concepts discussed at the first workshop have become reality. However, for those of you who are concerned with providing quality track structure at the lowest possible cost, challenges still remain.

A month ago I had the opportunity to participate in a TRB conference, similar to this one, focusing on railroad productivity issues. At that conference it became clear that to remain competitive with heavy trucks, the railroad industry must strive to become more productive in all aspects of its activities. Although productivity is usually thought of as increasing output per man-hour of labor, and there is certainly room for continued improvement in that account in maintenance-of-way, productivity must also be thought of as putting physical resources to the best possible use. These physical resources include the rails, ties, and ballast that railway management is purchasing and the maintenance machines we have at our disposal.

The recession of 1982 severely limited the purchase of rail and new ties the railways could place in track. At that time, the Class I railroads had achieved perhaps the best track conditions that had been seen in a generation. It is doubtful that the volume of maintenance activities conducted in the late 1970s will be reached again in the near future. The large quantities of rails and ties placed in track at the end of the last decade were primarily the result of catching up from the deferred maintenance that grew out of the financial problems that many railroads were burdened with in the late 1960s and early 1970s. However, today, under deregulation, financial problems of that magnitude are not expected to occur again. On the other hand, deregulation puts considerable pressure on us to keep costs under control. The challenge currently facing the maintenance-of-way community arises from the need to maintain the current level of quality of North American track, while at the same time providing adequate return for our investors and maintaining an adequate market share for the railroad industry.

It is now accepted that quality track is a requisite for any viable railroad. Although many of us have believed this all along, work currently under way at the Association of American Railroads (AAR) and other research institutions is beginning to quantify the benefits that the railroad industry can derive from quality track structure. Many have understood that poor track degrades more quickly; in other words, track geometry degrades and component lives are shortened as track deteriorates. Studies currently under way at the AAR have shown a tendency for clusters of failed ties to develop. One explanation for this clustering phenomenon is the overloading of sound ties adjacent to failed ties. Such overloading would be expected to shorten the life of sound ties and bring about their premature failure.

Other studies currently under way indicate the relationship of track structure condition to the cost of other components of the railroad transportation system. In connection with our freight car structural fatigue program we have noted that infrequent track irregularities can impose large loads on freight car structures. In some cases, these loads have been noted to be as much as twice the static design criteria for our freight equipment. Analysis has shown that these infrequent, but high, loads shorten the fatigue life of the vehicle significantly. Studies are currently under way to identify the particular track characteristics that are responsible for developing these significant loading patterns. These studies will compare the cost of maintaining track geometry to eliminate these dynamic loads with the true costs of building cars to accommodate them, including the costs of hauling the extra dead weight around.

An additional preliminary study has shown significant differences in fuel consumption for various track conditions. At the AAR track dynamics laboratory in Chicago, it has been noted that stiffer track reduced the rolling resistance of a 263,000-lb car. Studies are currently under way to quantify the relationship between vertical stiffness and possible reduction in rolling resistance and therefore in fuel consumption. Analytical studies under way at Massachusetts Institute of Technology are an investigation of the relationship between track surface and alignment errors and train resistance. The energy dissipated in the suspension and at the wheel-rail interface resulting from surface and alignment errors appears to be responsible for a significant portion of the rolling resistance in the 40-mph range. Results from this study have shown a significant decrease in rolling resistance for a track at the limits of Federal Railroad Administration (FRA) Class 5 alignment and surface errors compared with that of a theoretical track at the limits of Class 4 standards. Although it is recognized that most railroads do not maintain track to the exact limits of FRA standards, the fact that track configured to these limits results in a significantly lower level of fuel consumption must have significance for track maintained to more realistic limits; this could provide justification for maintaining track to much higher standards than required.

The challenge to the industry is clear: in this competitive environment, we must provide a mode of transportation that is as cost-effective as possible. We have the opportunity to optimize a total transportation system because railroads are unique in controlling both equipment and roadway. Certainly, we have done a good job in the past 5 years. In 1984, total railroad operating revenues were only slightly lower than in the record year of 1981; at the same time, railway operating income was the highest of the 5 previous years. Of course, revenue ton-miles were at a 5-year high, but at the same time so were capital expenditures. Clearly, we have done a good job; clearly, we are producing a modern viable system now that partial deregulation has brought us a degree of pricing freedom and the ability to charge different prices for different levels of service.

However, this certainly is not the time to stand back and pat ourselves on the back. Our competitors are busy moving larger, heavier trucks on the nation's highway system. Much effort is being put into the Strategic Highway Research Program, making significant dollars available for highway research, all of which will be used to help make our competitors more cost-effective. We must continue to improve our efficiency. We must continue to make better use of our physical plant. We must continue to determine the best methods of maintaining a quality track structure while consuming a minimum of rail, ties, ballast, machine-hours, and man-hours.

Certainly, a way to achieve the goal of providing quality track at the lowest possible cost is through the intelligent use of planning. The theme of this workshop is cost-effective track maintenance, in other words, making maintenance dollars as effective as possible. It is a timely and well-chosen theme.

You have a unique opportunity to determine how railroads meet the challenge of a free market. If we are able to do better than our competition in service and price, we will all prosper. If we can not or do not, we will be out of work. The days of government, in the form of the Interstate Commerce Commission or FRA, perpetuating money-losing rail lines are gone. Track costs us 25 percent of every revenue dollar. If that percentage is reduced without a sacrifice in track quality, we can compete in more markets; if it goes up, we will compete in fewer markets. The equation is simple.

Many may feel uncomfortable with the idea of maintenance planning. Certainly, no planning system should replace sound on-site engineering judgment. I do not believe that any advocate of maintenance planning believes that either. However, as territories become larger and resources become more precious, we need tools to evaluate the various alternatives--indeed, the multitude of alternatives--that are currently available. We can not afford to waste resources by installing them in less than the best place at the best time in the most cost-effective way.

# Identification of Short-Term Track Maintenance Priorities at CP Rail

**W. C. LIDDELL and M. D. RONEY**

ABSTRACT

The organization of the engineering function at Canadian Pacific Rail (CP Rail) has been dictated largely by geography. A transcontinental system such as CP Rail's is characterized by large variation in the traffic handled and the geomorphology over which it travels. The identification of short-term track maintenance needs and their repair are by and large the exclusive purview of local roadmasters and division engineers who develop an intimate relationship with their territories. The head office engineering function is charged with the responsibility of monitoring the results of these local initiatives and of providing overall guidance on standards and practices. It has been CP Rail's experience that the best way to meet this objective is through strategic interventions into the process that point out potential problem areas while not interfering with or second-guessing the judgment of local people on which CP Rail relies so heavily. Certain of these target areas will be reported on in this paper, specifically, track upgrading, automated track inspection, rail fatigue monitoring, and computer assistance to local offices. Long-range plans are described.

The organization of the engineering function at Canadian Pacific Rail (CP Rail) has been dictated largely by geography. A transcontinental system such as CP Rail's is characterized by large variation in the traffic handled and the geomorphology over which it travels. The identification of short-term track maintenance needs and their repair are by and large the exclusive purview of local roadmasters and division engineers who develop an intimate relationship with their territories. It is just as true today as it was 100 years ago that CP Rail lives and dies on the ability of local supervisors to make good decisions on maintenance needs.

The head office engineering function is charged with the responsibility of monitoring the results of these local initiatives and of providing overall guidance on standards and practices. It has been CP Rail's experience that the best way to meet this objective is through strategic interventions into the process that point out potential problem areas while not interfering with or second-guessing the judgment of local people on which CP Rail relies so heavily.

Certain of these target areas will be reported on in this paper, specifically, track upgrading, automated track inspection, rail fatigue monitoring, and computer assistance to local offices.

## TRACK UPGRADING

A key strategy that is being followed at CP Rail is the progressive upgrading of the track plant. Stated simply, they have found that it makes sense to buy the best they can afford. The ultimate objective would be to achieve a track structure without clearly identifiable weak points, which would enable the optimal utilization of high-production gangs whose activities can be planned well in advance.

Ideally, CP Rail hopes to reach a situation in which the more expensive routine maintenance by basic forces is only required because of local breakdown of the track structure at joints, over problem subgrades, and so forth. In essence, the strategy is to provide a no-surprises track structure that will allow substitution of planned component renewals for firefighting.

The annual replacement of an average of 270 mi of jointed rail with heavier section continuous welded rail is contributing significantly to the elimination of the traditional weak spot in track. A continued program of thermite welding of rail in track combined with the use of prebonded insulated rail joints where isolation of track circuits is necessary has also contributed to reduction in short-term maintenance requirements.

CP Rail has found it economical to use 9-ft hardwood ties in curves in primary main-line territories, and in both curves and tangents between Calgary and Vancouver. In 1976, 14- and 16-in. eccentric tie plates were adopted for high tonnage location in curves of 3 degrees and above. This combination significantly contributed to prevention of plates from nose-diving, or cutting of the ties on the field side, thereby reducing the need for regauging.

In 1982, CP Rail adopted a new ballast specification that is unique in the industry in its attempt to relate measurable characteristics of potential ballast sources to expected service lives in track.

Ballast can be selected to have an abrasion number that is commensurate with traffic levels, minimizing the possibility that premature breakdown will result. The expected service life for ballast for a given source can be assessed using the correlations that have been developed (Figure 1). Ongoing research being conducted in conjunction with CN Rail and Transport Canada is attempting to develop instrumentation to detect problems of weak subgrades due to unfavorable pore-water pressures. Under the same program, guidelines are being developed for the use of geotextiles to protect weak subgrades.

A final area of weakness in track structure that has received some attention is the frog. In 1975, CP Rail introduced explosive depth hardening of rail-bound manganese frogs. Studies have indicated that

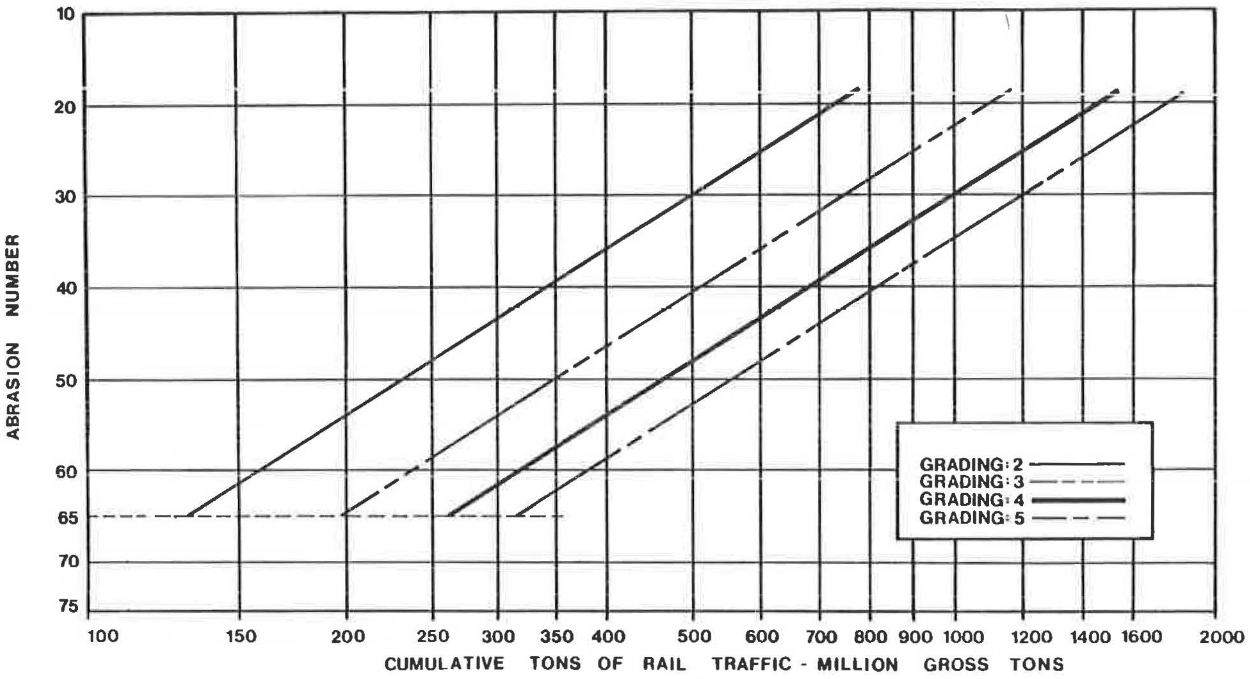

FIGURE 1 Relationship between ballast abrasion number and expected service lives.

this has increased the average life of a frog insert from 60 to 115 million gross tons. CP Rail's ultimate objective is to eliminate the frog as a weak point in the track structure. To this end, research is under way into both use of a moveable point frog and improved alloying and treatment of the Hadfield's manganese steel used in track-work castings.

## TRACK GEOMETRY MEASUREMENT

In the 14 years during which CP Rail's car has been operating, the Track Geometry Car has proven to be an ideal tool for determining short-term priorities for maintenance. Its primary function is to assist the roadmaster in locating potentially hazardous conditions. At the same time, it provides valuable information for both regional and system levels. Comparison of overall deterioration trends guides decisions on when infusions of resources are required to meet standards.

Eleven defect types identified by CP Rail's track geometry car are summarized in Table 1. They are classified as either priority defects or urgent defects. Each roadmaster receives a report of the location and type of track defects found on his territory when he leaves the car. CP Rail's defect definitions have evolved progressively over time in response to their experience of what actually constitutes a track problem. For example, the cross-level defect threshold was recently increased to a minimum level of 3/4 in. over 8 ft, 3 in.

Adoption in 1984 of a new standard for rate of change of superelevation has significantly helped in combatting the derailment problem of empty tank cars. With side bearing clearance just within tolerance, a rate of change of superelevation exceeding 2 in. was found in field tests to cause significant wheel off-loading. A priority-defect classification is now printed out if rate of change of superelevation exceeds either 1 in. in 20 ft or 1 3/4 in. in 55 ft. Concurrent use of two measurement baselines for superelevation measurement, one corresponding to one-half of a rail length and the other corresponding to the wheelbase of a tank car, results in coverage of variation in geometry occurring over a wide range of wavelengths.

A unique feature of CP Rail's defect definitions is the detection of three conditions that could lead to rock-and-roll derailments. Rock-and-roll derailments occur when a periodic pattern of track errors is present at a wavelength that will excite vehicle resonance in one of its possible modes of vibration. The ability of the on-board computer to perform instant pattern recognition is a significant strength of automatic track inspection. Many times, the critical sequence of track errors has been too subtle to be recognized by the track inspector. The geometry car is able to specifically locate errors in surface, cross level, and superelevation that, when occurring at the specified distance apart, will cause unfavorable dynamics. If the resonant condition is not found with their rock-and-roll defect definitions, CP Rail can record all measurements for off-line computer analysis to test the existence of one of a variety of different patterns.

Summary of information from the geometry car is prepared graphically by computer to assist planning of work programs. The current run of the car is plotted against the run made at the same time 1 year previously for indices of surface and cross level, and for comparing total footage of wide gauge. These comparisons show the rate at which track condition is deteriorating or, alternatively, the extent of improvement achieved with a work program. Figures 2 and 3 are sample comparisons. The bold line represents the current year and the past spring is shown as a dotted line. The unit of the gauge graph is number of feet of wide gauge greater than 1/2 in. wide per 1/4 mi.

In the section between mileposts 77 and 93 in Figures 2 and 3, jointed rail was replaced with new welded rail. Both the surface graph (Figure 2) and gauge graph (Figure 3) show marked improvement in track condition. The adjacent section of track, on the other hand, has deteriorated rapidly, indicating the need to extend the program this year.

TABLE 1 Summary of Defects Detected by Track Geometry Car

| EXPLANATION | PRIORITY DEFECT | URGENT |
|---|---|---|
| Wide gauge (Feet/No. occurences) | 3/4" | 1" |
| Surface roughness - left rail | 1" to 1 1/2" | over 1 1/2" |
| Surface roughness - right rail | 1" to 1 1/2" | over 1 1/2" |
| Rock & Roll - Surface Roughness | 6 Surface Defects over 5/8" each | 6 Surface Defects over 5/8" each but averaging 7/8" |
| Cross Level | Rate of change greater than 3/4" over 8'-3" or 1" over 11" | Rate of change greater than 1" over 7'-4" or 1 1/2" over 11" |
| Rock & Roll - Cross Level | N/A | Rate of change of 3/4" in 11" occuring 3 times in 80' |
| Superelevation - actual elevation | elevation of 5 1/2" to 6 1/2" | elevation over 6 1/2" |
| Superelevation - rate of change in 20' | 1" to 1 1/2" in 20' | over 1 1/2" |
| Superelevation - rate of change in 55' | 1 3/4" to 2" | over 2" |
| Rock & Roll - Superelevation | N/A | Change in elevation of 3/4" followed by a reversal of elevation of 3/4" within 62' |
| Alignment | 20 mph:change of curvature of 6°<br>50 mph:change of curvature of 4°<br>all within 62' | N/A |

On the sample comparisons in Figures 2 and 3, a plot of the posted subdivision speeds versus the rated curve speeds as determined with the geometry car are provided. The posted speeds are those listed in the operating timetables. The design speeds are assessed by the car on the basis of the average measured superelevation and curvature, using a CP standard of 2 in. of unbalanced superelevation. In general terms, this gives a picture of how well speeds have been selected for the territory. It indicates the curves that are controlling subdivision speed limits and the factor of safety to be applied when assessing cross-level and gauge deviations measured in the curve. These graphs are also useful for guiding curve realignment programs to reduce rate of change of superelevation because they identify curves with both high rate of change of superelevation and excess superelevation. This enables alignments to be designed to minimize reductions in train speeds.

Track Geometry Car No. 63 has recently been upgraded to better accomplish its objective of assessing maintenance priorities. These upgrades include

- A new superelevation system
- Gradient measurement
- An all-wavelength all-speed profilometer system
- A computer upgrade to a fast HP A900 and the addition of video cameras

The video cameras trained on both wheels of the leading axle of the trailing truck are of particular interest. They visually display to the roadmaster

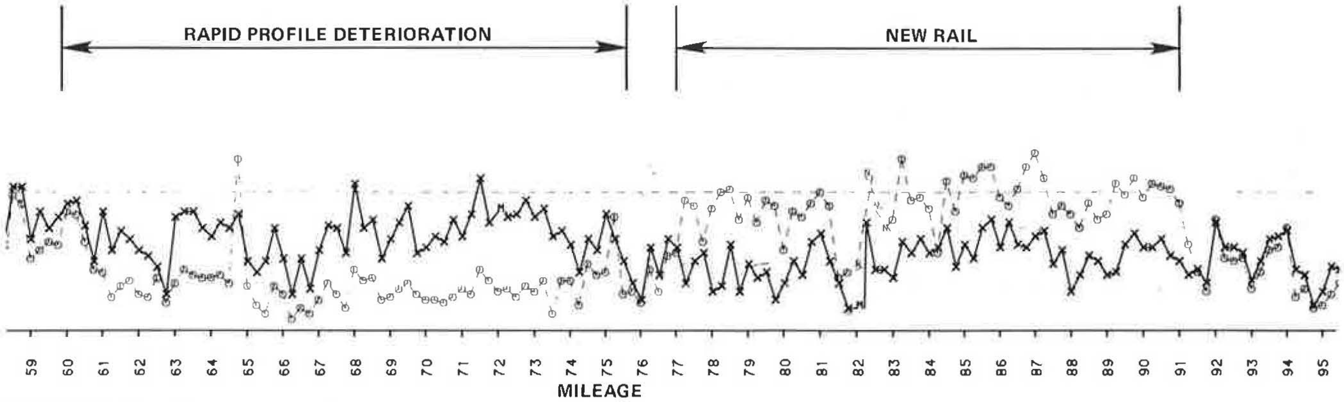

FIGURE 2 Sample comparison of year-to-year surface roughness ratings.

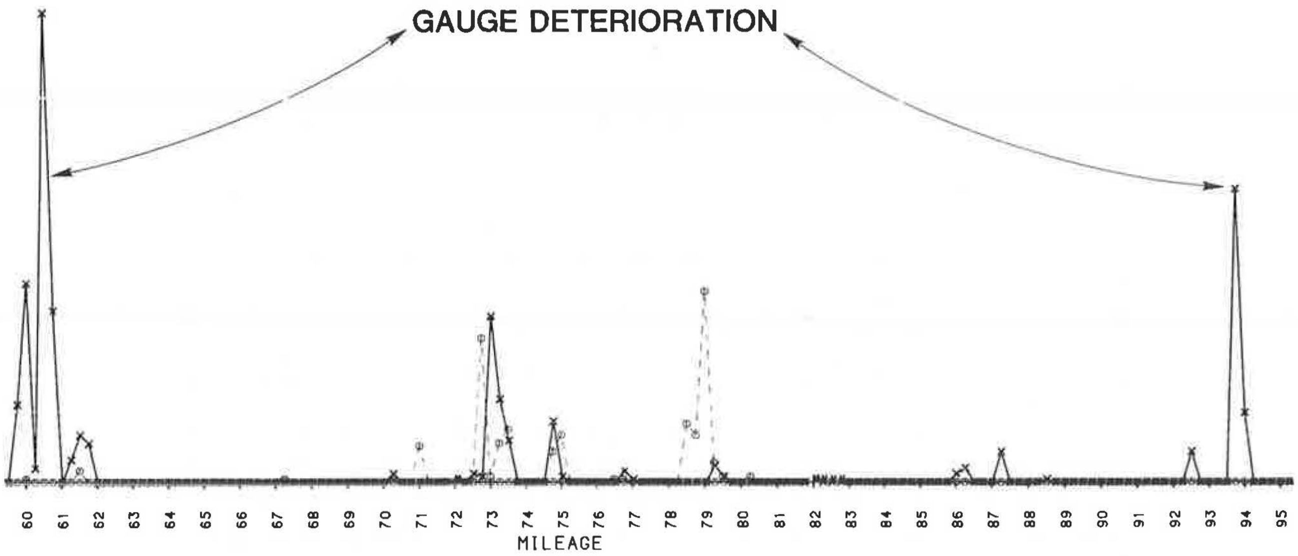

**FIGURE 3** Gauge deterioration: comparison of no. of feet of wide gauge per ¼ mile.

the wheel tracking location as the car responds to unfavorable track geometry. CP Rail is particularly concerned with locations where the false flange of the wheel is able to ride on the field side of the low rails, producing heavy plastic flow and corrugations.

A second track geometry car is currently under development. This two-car consist will emphasize high reliability and high production, enabling CP Rail to increase from three to five times per year coverage of all main lines. This new car will incorporate several additional test parameters, including rail corrugation and rail wear assessment.

CP Rail has a unique requirement for durability in the construction of track geometry measurement equipment because of a policy of operating at the end of regularly scheduled freights under all weather conditions.

## MONITORING RAIL FATIGUE

Monitoring of rail failures receives a high priority as both a problem locator and as a tool for assisting in long-range planning. CP Rail now has a data base containing 15 years of rail failure data, for a total of 230,000 defects. Failures can be grouped according to any combination of mile, subdivision, failure type, track classification, weld or joint area, weight of rail, manufacturer, ingot position, and curve versus tangent.

One of the reports used to locate problems is the rail failure hot list (Table 2), which ranks the 50 worst miles and 50 worst 10-mile sections by mainline versus branchline. This list is used to ensure that priorities for rail programs are properly set and that new rail is distributed over the proper mileages.

CP Rail has recently developed a program for accessing its mainframe files of rail defects, track geometry, and rail failures to analyze rail fatigue trends. This program uses the Weibull statistical analysis technique pioneered at the Association of American Railroads. Historical-defect-occurrence rates can be automatically displayed and analyzed to decide whether rails are exhibiting a mature fatigue process, as indicated by a steadily increasing rate of rail defect occurrences. Constant failure rates over time are considered less of a problem because they indicate random failures of rails that are locally overstressed. Such rails may be part of the infant-mortality segment of the rail population that fails before the general population of rails in the segment.

When it is suspected that a rail is fatiguing, the computer program is used to access the data bases for the section in question, separating tangent sections from curves. A curve-fitting routine is automatically performed to the time series progression of rail failures to test their degree of fit to an equation in the form of the Weibull distribution, which has been found to reflect the progression of fatigue failures in engineering materials. Use of this technique enables the system engineering office not only to test the existence of a mature fatigue process, but also to quantify when critical levels of failures will have been reached. Future failures can be projected to an economic renewal timing of from 3 to 6 defects per year, depending on the level of traffic.

Figure 4 shows sample rates of rail failures in four different lengths of track. An X indicates when the rail was removed. In general, rail is replaced well before its economic fatigue life because of the existence of other wear mechanisms such as gauge-face wear, shelling, and corrugation. As the rail grinding effort is increased, CP Rail expects to increase rail wear limits, leading to more cases of rail renewal due to fatigue. The challenge to extend rail life without incurring heavy penalties in spot rail replacements will put a premium on the ability to track defect trends and recognize the optimal renewal training.

## COMPUTER ASSISTANCE IN PLANNING

Last year, personal computers were installed in all division engineering offices to supplement those already used in the regional offices and some of the maintenance-of-way work equipment and signal shops. Although software has been provided to assist project management, personnel management, and engineering design calculations, perhaps their greatest value is in the promotion of planning.

Initially, personal computers were installed in two pilot divisions for a 6-month period. Both divisions responded by setting up many different kinds

TABLE 2 Excerpt from Rail Failure Hot List

| REGION | NUMBER | SUBDIVISION | BRANCHLINE WHICH TRACK | MP FROM | MP TO | TOTAL DEFECTS |
|---|---|---|---|---|---|---|
| EASTERN | 2147 | WALKELY LINE | SINGLE | 4 | 5 | 10 |
| EASTERN | 2348 | PORT BURWELL | SINGLE | 5 | 6 | 6 |
| EASTERN | 2147 | WALKELY LINE | SINGLE | 1 | 2 | 6 |
| PACIFIC | 4151 | LOMOND | SINGLE | 18 | 19 | 6 |
| ATLANTIC | 1158 | FREDERICTON | SINGLE | 4 | 5 | 5 |
| ATLANTIC | 1142 | GIBSON | SINGLE | 56 | 57 | 5 |
| PACIFIC | 4154 | LANGDON | SINGLE | 36 | 37 | 5 |
| PACIFIC | 4151 | LOMOND | SINGLE | 26 | 27 | 5 |
| PACIFIC | 4151 | LOMOND | SINGLE | 23 | 24 | 5 |
| EASTERN | 2147 | WALKELY LINE | SINGLE | 5 | 6 | 4 |
| ATLANTIC | 1541 | TRURO | SINGLE | 1 | 2 | 4 |
| ATLANTIC | 1541 | TRURO | SINGLE | 2 | 3 | 4 |
| ATLANTIC | 1142 | GIBSON | SINGLE | 55 | 56 | 4 |
| ATLANTIC | 1142 | GIBSON | SINGLE | 52 | 53 | 4 |
| PACIFIC | 4531 | PRINCETON 3B | SINGLE | 158 | 159 | 4 |
| PACIFIC | 4245 | BRETON | SINGLE | 6 | 7 | 4 |
| PACIFIC | 4244 | WILLINGDON | SINGLE | 130 | 131 | 4 |
| PACIFIC | 4241 | HOADLEY | SINGLE | 3 | 4 | 4 |
| PACIFIC | 4154 | LANGDON | SINGLE | 57 | 58 | 4 |
| PACIFIC | 4154 | LANGDON | SINGLE | 53 | 54 | 4 |
| PACIFIC | 4151 | LOMOND | SINGLE | 30 | 31 | 4 |
| PACIFIC | 4140 | ACME | SINGLE | 16 | 17 | 4 |
| PACIFIC | 4140 | ACME | SINGLE | 5 | 6 | 4 |
| PACIFIC | 4134 | EMPRESS 3B | SINGLE | 67 | 68 | 4 |
| PACIFIC | 4134 | EMPRESS 3B | SINGLE | 9 | 10 | 4 |
| PRAIRIE | 3630 | LANIGAN | SINGLE | 47 | 48 | 4 |
| EASTERN | 2540 | TEMISCAMING | SINGLE | 2 | 3 | 3 |
| EASTERN | 2147 | WALKELY LINE | SINGLE | 2 | 3 | 3 |
| EASTERN | 2142 | ELLWOOD | SINGLE | 2 | 3 | 3 |
| ATLANTIC | 1158 | FREDERICTON | SINGLE | 19 | 20 | 3 |

of lists--including records of allocation of machines to territories, accumulated overtime, and eyebolt replacement schedules. Because it was so easy to organize their data, they were keeping more information than before, and, more importantly, they were using it in their planning. The support of personal computing at the divisions was, therefore, seen as a way to assist and promote planning.

Throughout the past year, a project management computer package was implemented at the divisions, based on CP Rail's SPEC planning methodology, which allows local offices to track each individual appropriation in terms of

- Length of critical path
- Effects of delays on project completion
- Estimated project expenditure versus budget

In short, it allows local people to visualize their project, easily make changes to their schedule, and answer questions such as "Do I have enough money in my budget to rent a bulldozer to bring me back on schedule?"

All personal computers are also connected to the mainframe computer, giving them access to CP Rail's excellent electronic mail system. This has speeded up CP Rail's communications and has been invaluable in emergency situations. The Chief Engineer is now afforded the capability to communicate instantly with any engineering office and to view the contents of

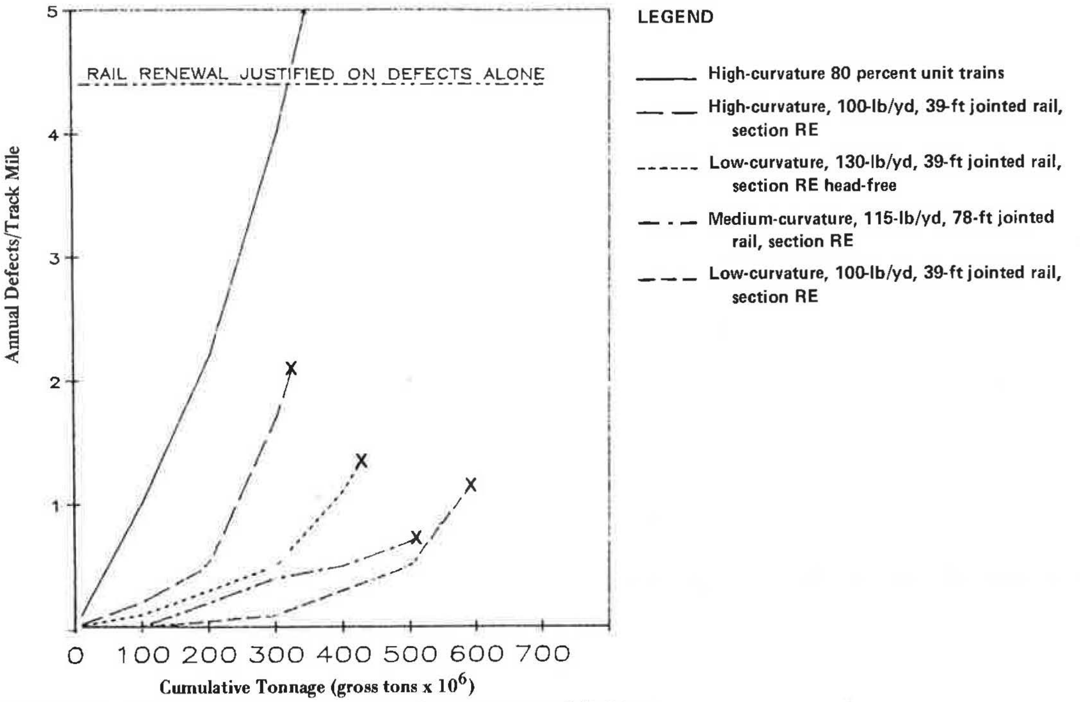

FIGURE 4 CP Rail's rail failure trends on five main line subdivisions.

his in-basket from virtually any office on the system.

The Chief Engineer's office is in the process of implementing full office automation. Files are being kept electronically and many of these will be shared among all engineering offices. For example, a file on the rehabilitation of a bridge could be accessed on the screen and memoranda posted from any office. The elimination of paper is seen as a way to free more time for planning.

## LONG-RANGE PLANS

CP Rail has made a long-term commitment to implement Manufacturing Resource Planning (MRP) at the corporate level. MRP is a management philosophy that emphasizes planning and is run on integrated computer software that guides all aspects of the planning of work, through the ordering of materials and the monitoring of gang progress relative to plan. In effect, it makes 80 percent of CP Rail's current systems obsolete and replaces them with an integrated approach to planning and controlling resources used by all operating departments.

According to the plan, these strategies for improving track structure to eliminate weak links, and development of information systems to assess maintenance priorities, will enable CP Rail to make full use of a long-range integrated planning approach that will reduce firefighting to an absolute minimum.

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# Principles of Maintenance-of-Way Planning

**E. R. TRASK**

ABSTRACT

Doing track maintenance in a planned manner reduces the overall cost of a series of related activities. To obtain optimum results, the planning staff should be experienced and technically knowledgeable. Some of the more important principles to consider when making any plan are establishing the size of the permanent work force, implementing directives from regulatory bodies, establishing standards, measuring rate of plant deterioration, educating staff, communicating effectively, mechanizing gangs, using forecasting material, forecasting future travel levels, creating a plant inventory, establishing a planning period, establishing a logical sequence for replacement of components, coordinating field activities with train schedules, using theoretical degradation models, and reporting progress of work and comparing it with the plan.

After the maintenance requirements for track, roadbed, and right-of-way have been identified, and after priorities have been assigned, the maintenance-of-way activities need to be planned. Almost any good, ambitious individual could fix up a deteriorating piece of track if he was told what to fix and if he had unlimited supplies of money, labor, material, and time. Because there are limitations, planning is required; this is based on the assumption that planning is a method of obtaining maximum benefit for minimum overall cost.

To obtain this benefit, the planning must be done by people who have a feel for how all of the different parts of a track structure relate to each other and what effect a weakness in one component has on other components. Therefore, the first obvious principle of maintenance-of-way planning is as follows: have the planning group staffed with people who have had practical field experience and a basic civil engineering education, and have an ability to do basic economic analyses.

Other principles that will be explained in more detail are

- Establishing the size of the permanent work force
- Implementing directives from regulatory bodies
- Establishing standards
- Measuring plant deterioration
- Educating staff
- Communicating effectively
- Mechanizing gangs
- Using forecasting material
- Forecasting future traffic levels
- Creating a plant inventory
- Establishing a planning period
- Establishing a logical sequence for replacement of components
- Coordinating field activities with train schedules
- Using degradation models
- Reporting progress of work

## ESTABLISHING THE SIZE OF THE PERMANENT WORK FORCE

In the railway industry in Canada, the general trend in track maintenance is to keep track as close as possible to the original construction standards to guarantee an uninterrupted train flow at published timetable speeds. Coupled with this is the need to discover deficiencies and sudden failures, and to protect trains against the hazards they may thereby encounter. Therefore, inspection, decision making, and slow order placing are required.

Because a rail line cuts across large blocks of land and by its very nature separates communities and groups of people, there is a continual call to cross it with items such as roads, wires, and pipelines. Consequently, a permanent, knowledgeable staff must be around to ensure that such crossings are done in away that is safe to both utility personnel and trains and with the least possible interference to railway traffic.

When the time comes to do major rehabilitation, construction, and relocation, it is necessary to have experienced foremen and supervisors to lead these groups. These leaders have to come from an everyday, permanent work force. A few examples of the work done by this permanent force are

- Changing a broken rail
- Regauging
- Lifting joints
- Adjusting rail anchors
- Tightening bolts
- Checking the throw pressure at switch stands
- Shimming
- Removing debris around culverts

The amount of work involved with some of these items is dependent on traffic, while with others it is more dependent on the size of the territory. To ensure a fair distribution of the work among the different groups of maintainers, some system of measuring the traffic, also taking into account the size of the territory, should be implemented.

Canadian National Railways has a mathematical model to help calculate maintenance units for any chosen piece of track. This model is basically dependent on lengths of track but does allow for adjustments based on curvature, traffic density, axle loading, and speed. Therefore, when the total company labor work force has been established by policy, economics, or otherwise, the relative distribution may be done on a fair, impartial basis.

As a typical example, this model might calculate that a crew of 1 foreman, 1 assistant, and 2 track maintainers is sufficient to maintain 18 miles of main track where the level of traffic is 20 million gross tons (MGT) per year, with 15 percent in cars with axle loading of 33 tons and speed of 40 mph and 5 percent of the territory curved to an average of 2 degrees. However, 1 foreman, 1 assistant, and 3 track maintainers would be required for the same kind of territory where the traffic level is 35 MGT per year with 20 percent on heavy axles.

## IMPLEMENTING DIRECTIVES FROM REGULATORY BODIES

Regulatory bodies refers to the Railway Transport Committee of the Canadian Transportation Commission, the Federal Railroad Administration, state legislatures, and agencies that are charged with protecting the public, railway employees, and shippers. One way that they influence the size of the permanent work force in Canada is by having established a frequency of inspection for different classifications of track. This, to some degree, establishes the maximum size of territory that a crew can handle. They also have established a maximum number of hours per day that may be worked and, therefore to some extent, the overall productivity of the large rehabilitation gangs. All of this must be taken into account when planning maintenance-of-way activities.

For example, part of the directive indicates that on busy main tracks, inspection must be carried out so that no more than 2 days fall between inspections. Thus, track inspected on Tuesday must be inspected again, at the latest, on Friday.

## ESTABLISHING STANDARDS

To estimate costs accurately and to ensure safety of operation at chosen speeds, it is necessary to assume a level of quality of a fixed plant; this chosen level of quality should be published as a set of standards. For a plant exposed to a dynamic operating environment, such as a railway, there will be wear. Therefore, it is necessary to have both construction standards and maintenance standards. Construction standards indicate the variation from ideal that is allowable at the completion of a new job. Maintenance standards indicate the amount of wear and the amount of deviation that is acceptable before speeds have to be reduced or rehabilitation has to be undertaken.

If standards are set by the railways, consideration has to be given to the ability to finance improvements as well as to the pure engineering aspects. Therefore, standards set at a chosen level should be estimated for cost purposes, and the ability to finance them should be checked with financial officers and corporate executives. This is of utmost importance because the planning of maintenance-of-way work, as far as the exact timing is concerned, is closely related to the funds available.

At Canadian National Railways, there is an Engineer of Standards who is responsible for checking with other railways, regulatory bodies, research agencies, technical societies, and engineering line officers in order to establish practical standards and modify them in light of changing loads, material developments, and operating conditions. There is also a System Maintenance Engineer who has the responsibility for field inspection to find out if the standards are being followed and for determination of what should be done to ensure that they are. Both engineers meet with senior line officers three or four times a year to decide on new standards and refinements to existing ones. A Chief Engineer negotiates with financial control officers on the level of standards that can be financed without jeopardizing the financial health of the company.

## MEASURING RATE OF PLANT DETERIORATION

Timing maintenance can be done on an analytical basis only if the rate of deterioration of various components is known. If the rate of deterioration is established, the point in time when the components reach their minimum assigned value may be calculated. Some examples of what Canadian National Railways uses to measure deterioration are as follows:

- A physical count of defective wood ties every third year
- Head loss of height and gauge face wear on rail on curves every year
- Quality of ride as measured by a track geometry car that measures surface, alignment, gauge, and cross-level irregularities twice a year

## EDUCATING STAFF

If a company establishes construction standards and maintenance wear limits and has a system of measuring wear and relating it to traffic and thus time, it is necessary to make the company employees aware of them. It is also necessary to teach field workers the best methods of inspecting track and the most effective maintenance techniques to obtain the maximum use out of the track components at the least cost.

For a large railway, it appears that this requires both a formal training program at a center away from the work site as well as on-the-job training. It is also necessary to update the professional technical staff periodically. A company should encourage their people to attend technical seminars and participate in organizations such as the American Railway Engineering Association and local professional engineering organizations.

Canadian National Railways now has a formal training program, which all new track maintainers must take and pass within a 2-year period after being hired. It consists of at least three weeks of classroom instruction from an experienced group of track supervisors. More classroom-type instruction is required if a person expects to be promoted to a higher position, such as Track Maintenance Foreman.

In addition, the training program has several audiovisual information packages aimed at both the field workers and the professional staff; these are meant to provide the latest information on specific techniques such as operating a track motor car safely, maintaining continuous welded rail, and distressing continuous welded rail. They are not meant to be shown only once and then forgotten, but to be repeated at least once a year and more often if there are many new staff or if problems are arising in specific areas.

## COMMUNICATING EFFECTIVELY

For planning to be efficient it must be understood and accepted by the various levels of management, from headquarters to the line supervision. Communication should start before the plans are put together, with discussions out on the track among the various levels. Headquarters staff responsible for final approval of plans should travel over selected portions of track in accompaniment of local engineering supervisors on inspection vehicles, as well as walk a certain percentage. Then there should be continuous discussion among the various levels as plans are prepared and changed.

Unfortunately, in large organizations there is a tendency to require much communication from the field level up to headquarters, but little from headquarters to the field level. This has an irritating effect on the various levels of supervision that participate in the preparation of plans. A determined and specific effort on behalf of senior management is required to overcome this inertia. Finalized plans are then more readily accepted and are generally implemented smoothly and more efficiently.

## MECHANIZING GANGS

Any plans made regarding maintenance-of-way revolve around the amount of machinery available. This not only determines the length of time required to do a job, but also determines the size of work gangs and the split between work to be done by permanent staff and extra or production-style gangs. For example, providing a substantial amount of tie-handling equipment to the permanent maintenance staff could eliminate the large mechanized tie gangs. This, in turn, would reduce the big work blocks that such mechanized gangs require.

## USING FORECASTING MATERIAL

Planning for maintenance-of-way involves the use of materials such as rail, ties, turnouts, tie plates, and anchors. These materials are unique to railways and generally unavailable from nonspecialized vendors. It is usually necessary to have them produced by special order through direct negotiation between a railway and a producer. Therefore, it is necessary to be accurate in predicting what is required and to make predictions 1 or even 2 years in advance.

Canadian National Railways has established a logistics center that has the responsibility of contacting the using functions and obtaining estimates of future material requirements. It then works closely with the Purchasing Department and the engineering supply yards in obtaining the material, coordinating the delivery to the work sites, and making improvements to the overall materials handling systems.

## FORECASTING FUTURE TRAFFIC LEVELS

Planning requires predicting when a component will reach the end of its useful life. When deterioration is dependent on train traffic, the prediction of future traffic levels is called for.

At Canadian National Railways, the Marketing Department has the responsibility of predicting traffic levels and advising the operating departments, such as transportation, equipment, and engineering. Their predictions, which are generally expressed in revenue tons, have to be converted to gross tons before they are used to calculate rail life and the life of other track components. This type of forecasting is essential to planning rail relays, and is very useful for ordinary maintenance, such as transposing rail on curves.

## CREATING A PLANT INVENTORY

To make an overall maintenance plan, it is necessary to know how much of what has to be maintained. This necessitates preparing records of how much track is operated and the location and size of curves, turnouts, culverts, rails, ties, ballast, and many other items.

This information is not a secret to railways. Many of them have kept meticulous records on paper for 100 years or more. What is happening now, however, is that they cannot afford the staff to keep these records or to analyze them in the detail that modern financial constraints impose. Many large companies have found it essential to place their plant inventory on mainframe-type computers, with the proviso that on-line staff have the capability to update as changes occur.

## ESTABLISHING A PLANNING PERIOD

To be cost-effective and to convince financial executives that maintenance-of-way knows where it is going, it is necessary to use planning periods of longer than 1 year. This has logic to it because the nature of track rehabilitation requires dovetailing ballast, tie, and rail renewals. For example, new rail could be seriously damaged if trains operate on it when the ties are in poor shape or if the roadbed is too soft. Also, it is generally impractical to take a busy track out of service long enough to conduct three large rehabilitation programs.

It is recommended that the longest planning period possible be used so that senior officers have the best overall view of upcoming major expenditures. However, there is no sense in choosing a period so far in the future that the marketing forecasts become untrustworthy. Practical experience indicates a 5-year planning period to be both useful and reliable.

## ESTABLISHING A LOGICAL SEQUENCE FOR REPLACEMENT OF COMPONENTS

After a planning period has been chosen, a practical manner in which the various work activities should follow each other can be determined. For example, if traffic predictions indicate that the rail will need to be relaid in 4 years, it would be wise to check the condition of ties, ballast, and embankments, and possibly plan improvements to them as well. If embankment widening is required, it should be done before ballast is added because dumping it later would foul the new ballast. To allow time for the embankment to consolidate, it should probably be constructed 2 years before rail relay and 1 year before ballast restoration.

## COORDINATING FIELD ACTIVITIES WITH TRAIN SCHEDULES

A useful principle of maintenance-of-way planning is coordinating engineering and transportation activities; this can be done when there is a long-term plan plus a detailed construction season plan. If joint meetings are held early enough, detour routes for trains can be planned and work blocks can be chosen so that a minimum number of conflicts arise. Marketing personnel should attend these meetings.

## USE OF DEGRADATION MODELS

Predicting when rehabilitation is to be done may be made more reliable if the rate at which traffic and the environment wears out components is known. This would be fairly easy to calculate if all traffic, wheels, rails, alignments, climate, and so forth were the same. Unfortunately, they are not and there is almost no such thing as a straight-line relationship between wear, tonnage, and time. It varies with axle load, shape of wheel profiles, metallurgy of rail, kind of tie, degree of curvature, and many other factors.

However, with good plant inventory records, traffic records, and much experimental research, it is possible to construct mathematical models that incorporate many of these variables. It is usually necessary to use a computer to do the manipulation because it would be tedious and time-consuming to do otherwise.

Presently, Canadian National Railways has a model for rail and tie degradation and is considering one for ballast.

## REPORTING PROGRESS

While work is progressing, the actual rate should be monitored. This is necessary to take immediate corrective action and to enable more accurate future planning.

Canadian National Railways' Logistics Center contacts each large rehabilitation gang daily and obtains quantities produced on the previous day. This information is then stored on a small computer, average rates are determined, and completion dates are estimated. Senior officers receive a daily report and are thus immediately aware of any serious deviation from accepted rates and can take appropriate action.

## SUMMARY

A brief introduction to some of the principles involved in planning maintenance-of-way activities has been given. There are more such principles, and undoubtedly what is important on one railway is less important on another. However, these principles hopefully will be of some assistance to those charged with the responsibility of planning maintenance-of-way activities.

# Maintenance-of-Way Project Management: Productivity Planning and Control

WARREN B. PETERSON

## ABSTRACT

Cost-effective track maintenance is closely related to and a direct result of a well thought-out plan with effective control procedures for ensuring the attainment of productivity goals and objectives. The application of basic management concepts, including planning, organizing, directing, and implementing, plays an important part in the success of a maintenance-of-way plan and its related management goals. Discussed in this paper are three essential elements of project planning (long-range or multiyear plan, financial evaluation, and line utility level) as well as establishment of production goals by using historical data. Attainment of these goals can only be accomplished through a well-informed project manager having the authority, responsibility, and accountability for crew performance. Specific management activities are discussed.

Cost-effective track maintenance is closely related to and a direct result of a well thought-out plan with effective control procedures for ensuring the attainment of productivity goals and objectives. The application of basic management concepts plays an important part in the success of a maintenance-of-way plan and its related management goals.

## MANAGEMENT CONCEPT

Maintenance-of-way project management includes a wide variety of track-work activity ranging from major track rehabilitation to daily maintenance and inspections. Planning, organizing, directing, and implementing these projects is the responsibility of the engineering line manager in order to ensure their timely completion in accordance with the prescribed quality standards, safe work procedures, and budgetary authorization. It is important to remember that the successful accomplishment of performance objectives and results as part of the planning and organizing functions necessitates the assignment of appropriate management authority, responsibility, and accountability.

As has been indicated, maintenance-of-way planning includes a wide spectrum of activity; however, the management concepts are essentially the same. For this purpose, the planning of projects for rail, tie, and ballast replacement will be used as examples of an effective approach for both planning and control procedures.

## PROJECT PLANNING

Track-maintenance project planning involves three essential elements that are to be considered in the development of an annual program:

- Long-range or multiyear plan
- Financial evaluation
- Line utility level

Long-range or multiyear rail, tie, and ballast replacement programs are a function of the corporate goals and related strategic plan of the company. As is often the case, long-range programs must be continually revised and updated; however, they provide an important threshold for the development of annual programs, related priorities, project plans, and productivity goals. The corporate strategy and goal must be clearly stated to ensure that there is a consistent and compatible long-range plan.

The financial evaluation of the plan will determine whether the multiyear schedule can be sustained or whether modifications are needed to meet annual corporate financial goals. Projected revenues provide the initial benchmark in the financial analysis, with the following factors essential in developing the annual plan:

- Maintenance-of-way ratio
- Gross-ton-mileage maintenance ratio
- Capital funding
- Cost-benefit analysis

The maintenance-of-way ratio, that is, the ratio of maintenance-of-way expense to railway revenue, is a key factor in the attainment of corporate financial goals and therefore an important yardstick in the measurement of the Engineering Department's performance. Expenses must be adjusted in a manner consistent with revenue income to ensure having the prescribed proportionate relationship between transportation and maintenance-of-way activity.

The ratio of maintenance man-hours to operating gross ton mileage is also used as a management control in the definition of the annual plan. Unlike the maintenance-of-way ratio, which is keyed to expense and revenue dollars, the gross-ton-mile maintenance ratio incorporates constant units and a direct comparison of maintenance versus transportation activity.

The availability of cash to be allocated for the funding of capital projects such as rail, tie, and ballast replacement is perhaps the most important factor in establishing the extent of each year's program. With the recent changes in railroad accounting procedures under the new depreciation accounting (DA), these projects are now driven almost entirely by the availability of cash rather than their effect on operating expense, as was the case under the historic retirement-replacement-betterment accounting (RRB).

Finally, each project must be analyzed as to its cost-benefit relationship in order to prioritize projects from the financial viewpoint, taking into account specific track-maintenance concerns such as subgrade instability, tie condition, rail defect rates, speed restrictions, and cycle maintenance requirements.

Track maintenance and rehabilitation must be planned on the basis of that work necessary to safely and efficiently meet the level of service to which the line is subjected. The related utility level of the line includes the following basic elements:

- Maximum authorized operating speed
- Allowable speed restrictions
- Traffic density (present and projected levels)
- Hazardous material density

## PRODUCTION GOALS

The initial step in determining production goals is in the development of historical performance data. Production goals can then be realistically established to form the basis for the management budget plan, cost estimation, and productivity criteria. Obviously, production goals will vary from one system to another, depending principally on crew organization, equipment availability, track time, and so forth, to the extent that goals are somewhat unique to each individual railroad.

Typical productivity goals used to measure crew performance include man-hours per mile for rail and ballast projects, man-hours per tie for tie replacement crews, and miles per day for production tampers. Control parameters including variables such as available track time, weather delays, overtime, and machine downtime must be taken into account when establishing these goals to ensure that there is a consistent performance measure. Quality control requirements must be consistent throughout.

Overall performance goals, that is, departmental productivity, include the maintenance-of-way ratio and the ratio of maintenance man-hours to gross ton mileage. As previously noted, these ratios serve as a basis for the development of the annual project plan as well as performance indicators necessary to ensure adherence to that plan.

## PROJECT CONTROL

The attainment of productivity goals can only be accomplished through a well-informed project manager having the authority, responsibility, and accountability for crew performance. The first line supervisor must have a clear understanding as to the crew organization, production goals, and control parameters in order to effectively manage the project.

Daily crew reporting, typically through call-in reports, is required and must include all pertinent production data. This information is furnished to the project manager, division engineer, and chief engineer. The daily crew production report should include the following data:

- Location and milepost working limits
- Units of work (e.g., number of ties installed, lineal feet of rail replaced)
- Number of men who worked, including foremen, assistant foremen, machine operators, helpers, and laborers
- Total man-hours, including straight time and overtime
- Total crew hours, including on-track time, travel time, train delays, weather delays, and equipment breakdowns
- Delays to trains

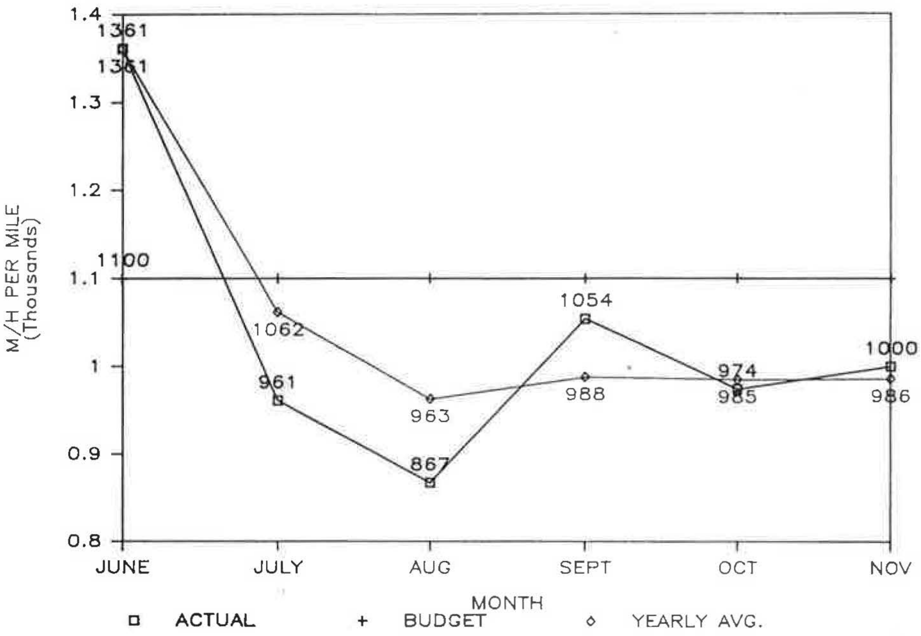


FIGURE 1 Rail relay productivity.

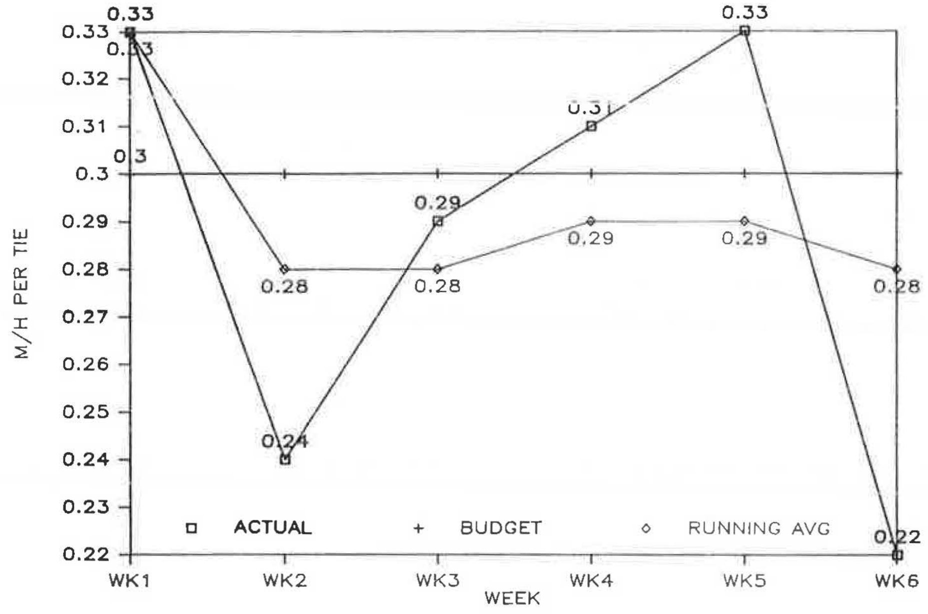


FIGURE 2 Tie gang productivity.

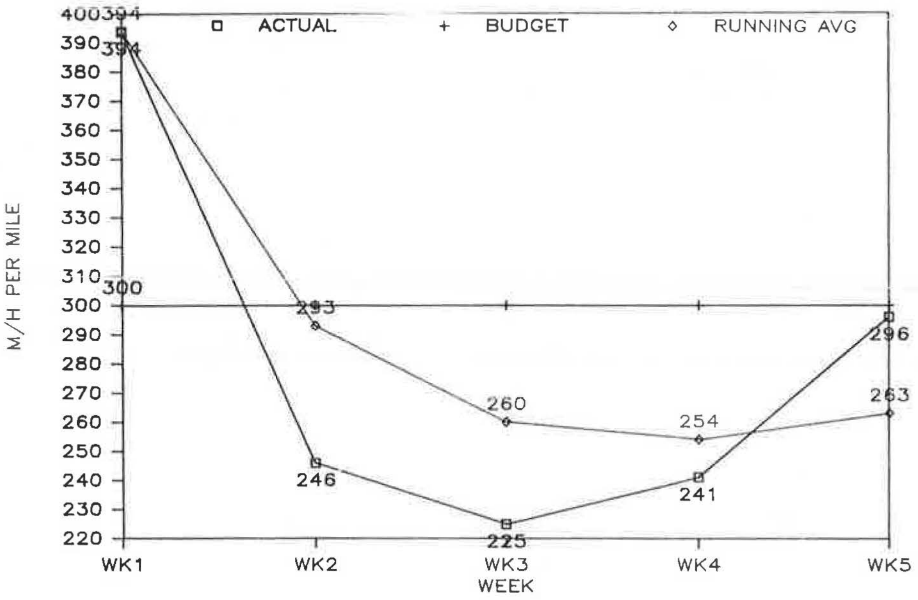


FIGURE 3 Ballast gang productivity.

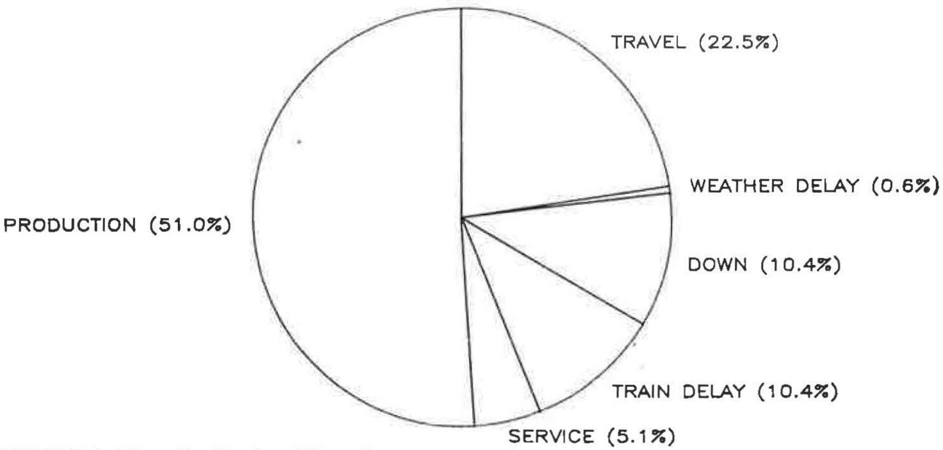


FIGURE 4 Time distribution (all production tampers).

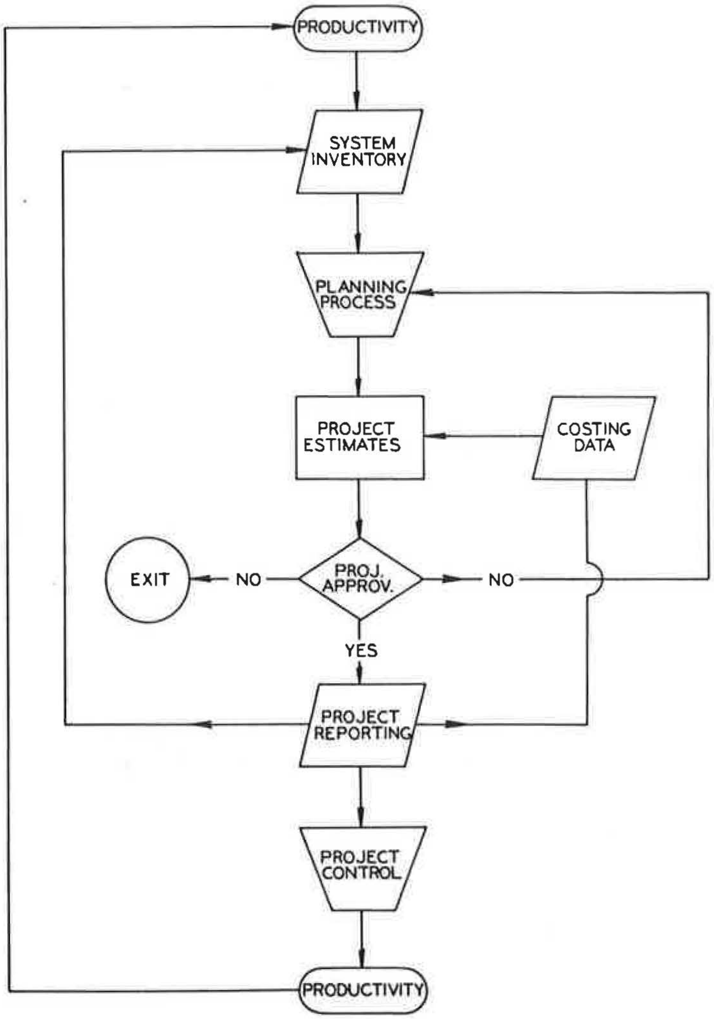


**FIGURE 5 Project planning and productivity.**

The project manager's action plan, that is, the procedures to be followed in taking daily corrective action following substandard crew performance, must be clearly understood by all concerned to ensure prompt, responsive results. Both intra- and interdepartmental contacts should be made directly with those individuals having both the authority and responsibility to take corrective action, thereby avoiding prolonged and costly delays. Specifically, the manager must know who, where, and when to call for help.

Computer processing of the crew production data and the preparation of weekly reports provide updated productivity and project status. Typical summary reports utilizing computer graphics include the following: rail relay productivity (Figure 1), tie gang productivity (Figure 2), ballast gang productivity (Figure 3), and time distribution summary of all production tampers (Figure 4).

## SUMMARY

Establishing basic corporate goals and objectives provides the initial framework for both long- and short-term engineering project planning. Productivity and performance criteria become key factors in the subsequent project plan and related control mechanism. This logic sequence is shown in Figure 5, which indicates the flow through of productivity data used in the planning and control process. As with basic engineering design techniques, keeping the plan simple yet effective will avoid complex sophistication and potential analytic isolation.

# Rail Irregularities and Their Effect on Track Maintenance

P. L. McMICHAEL

## ABSTRACT

Research has shown that the free shape of rails determines the vertical geometry of railway tracks at wavelengths below 5 m. Tracks laid with rails of poor geometry require more maintenance and have a shorter life than tracks laid with good rail geometry. The major rail vertical geometry irregularities occur at welds. Methods of straightening welds and supporting the sleepers around those welds have been investigated. The best results are achieved with a closely controlled overlift of the weld, support of the sleepers by stone blowing, and a machining operation to smooth the running surface of the rail. A new generation of on-track maintenance machines has been designed by using the results of this research. It is anticipated that a significant reduction in track maintenance costs will result from the development of these machines.

Joints in railway track have always presented the railway engineer with a maintenance problem. The maintenance costs of bolted, fishplated joints have been greatly reduced by the replacement, wherever possible, of this type of joint with a weld to form continuous welded rail (CWR). However, the widespread introduction of CWR has not completely eliminated maintenance costs that can be directly attributed to the joints between rails. The reasons these maintenance costs arise and methods by which they can be reduced or possibly eliminated are discussed in this paper.

## RAIL SHAPE AND TRACK GEOMETRY

Measurements of track geometry over a number of years, using British Rail's (BR's) high-speed track recording car, have shown that railway track has an inherent vertical shape to which it returns after a maintenance tamping operation (Figure 1). Measurements have shown that this shape is remarkably persistent in track that is maintained by conventional tamping (Figure 2). It is this inherent shape and the time it takes for its roughness [expressed as its standard deviation (SD) about a mean line] to become unacceptable that determines the frequency of maintenance tamping required (Figure 3). Theoretical studies and practical observation (1) of the inherent shape of track have shown that if a Fourier analysis of the shape is carried out, splitting the track shape into its component wavelengths, faults with wavelengths of less than 5 m show a strong correlation with the free shape of the rail. As the wavelength increases, the correlation is reduced.

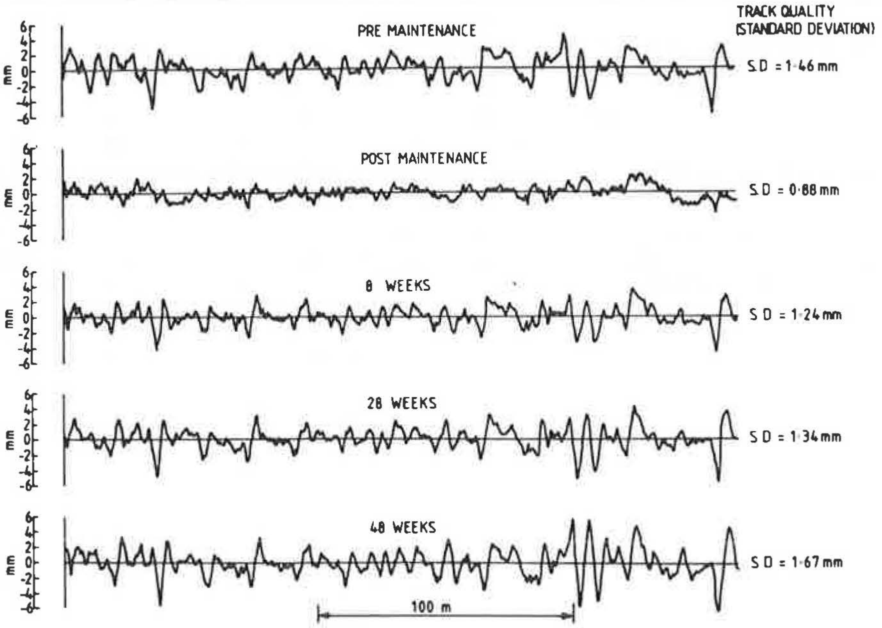


FIGURE 1 Track geometry after maintenance tamping.

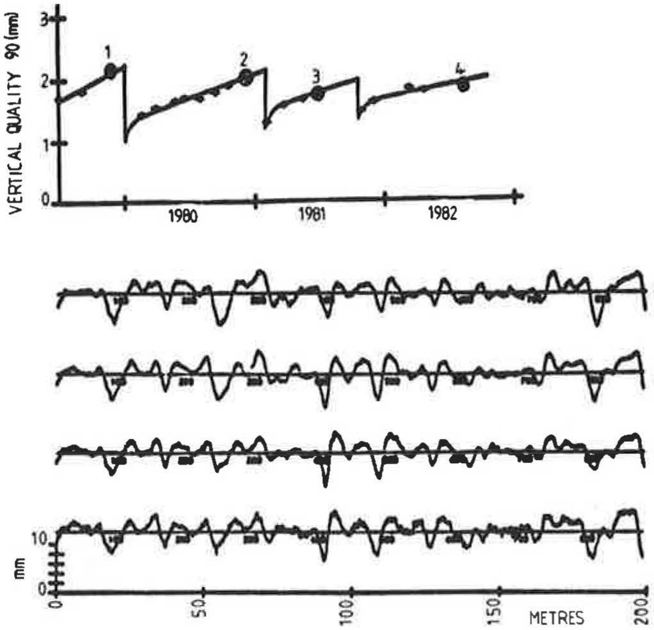


FIGURE 2 Recurrence of vertical profile.

Measurements of both free rail shape and track geometry have shown that the largest short wavelength irregularities occur at welds.

To illustrate the effect of weld shape on track geometry, an experiment was recently carried out on one of BR's tracks (2). In this experiment, the change in the longitudinal vertical profile of a 300-m length of CWR was measured before and after a pair of rails were moved 13.4 m along the track and rewelded into position. The rail was moved and clipped into position without moving any sleepers or modifying the ballast support conditions. The shape of the rail at each weld position before and after moving the rails was measured with a short (1.1-m) versine trolley and, as expected, the shape remained virtually identical over a 5-m length. A sample set of data for welds is shown in Figure 4. The measuring trolley is insensitive to wavelengths of over 5 m.

The geometric irregularity of the weld is determined at the welding depot and depends partly on the straightness of the rails and rail ends as supplied and partly on the effectiveness of the welding machine and press. The principal faults are dips, humps, and steps in the rail profile. The sequence of operations in rail welding depots is that the flash butt welding machine, the flash stripping machine, the straightening press, and the grinding

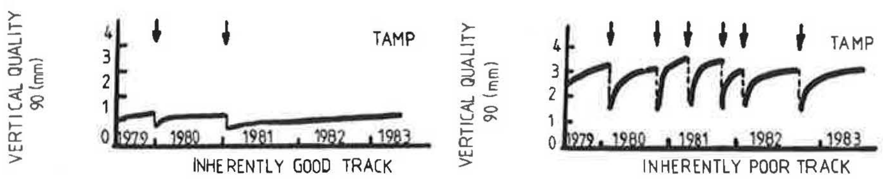


FIGURE 3 Frequency of track maintenance.

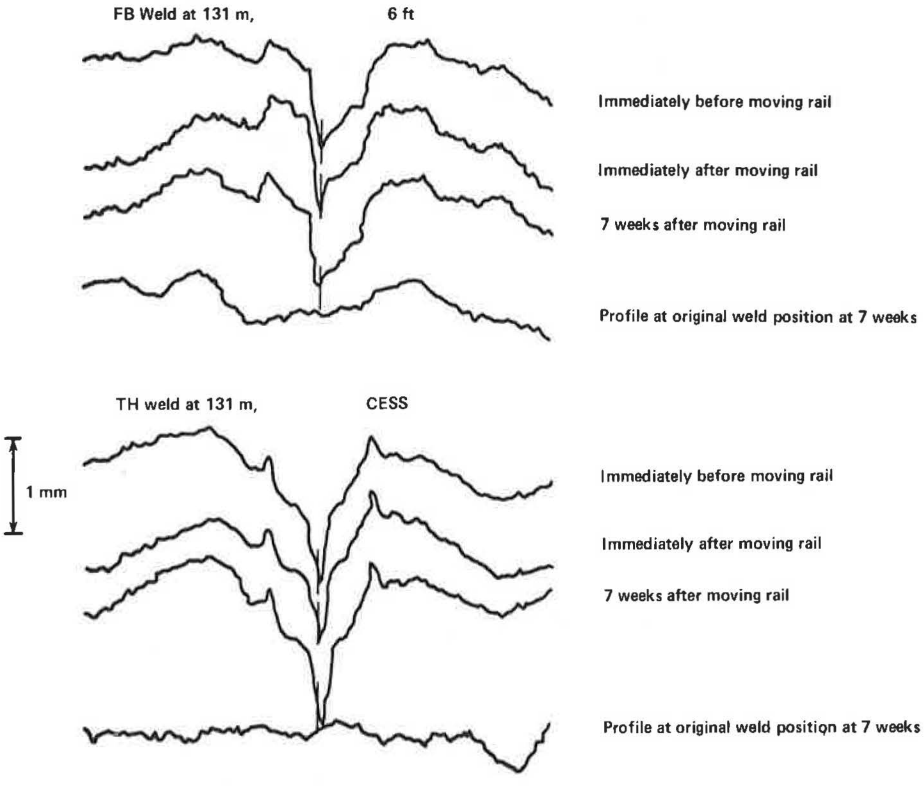


FIGURE 4 Unloaded 1.1-m versine measurements.

process are all located in a sequential line (Figure 5). Constraints of space within the depots lead to these units being one rail length (60 ft) apart. If the depot is producing a weld every 5 minutes, only 10 minutes are left for the weld to cool before reaching the press, at which time the rail is still hot.

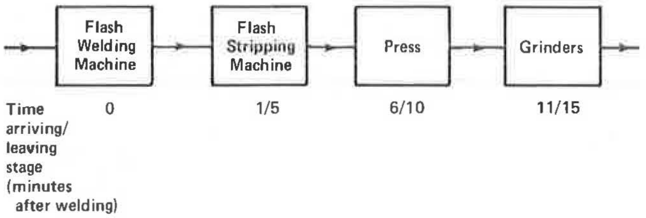


FIGURE 5 British Rail welding depot layout.

Differential cooling leads to the foot of the rail cooling first, causing an initial upward movement of the weld followed by a downward movement as the head cools. If the weld is pressed while hot, an allowance must be made for the movement that will occur after the press. In practice, this is difficult to control because weld temperature distribution varies from weld to weld. To overcome this problem, future welding depots on BR will incorporate a combination of forced air cooling and water spray cooling to ensure that the weld is cool before pressing and that movement following pressing is minimized. It is also likely that one of the control systems described later in this paper will be incorporated into the press. These steps will ensure that in the future, super-straight welds emerge from the welding depots. However, currently nearly two million welds exist on BR's network, produced in earlier depots.

If a rail weld is dipped, as a wheel passes over it the track will accelerate the unsprung mass of the axle upwards after it passes the point of maximum dip. This results in an increased dynamic load on the track, which will cause extra deflection of the track components and ballast support at this position. The constant pounding of the ballast leads to extra settlement of the sleepers in the vicinity of the weld. A theoretical analysis of the effect of 125-mph traffic passing over a 5-milliradian rail dip shows the resulting track profile to be dipped over several sleepers to a maximum of 6 mm (Figure 6). The sleepers around the dip itself may become voided. The wear and attrition of the ballast can in some instances block the drainage pores between the stones and cause a wet or washy spot. This causes a pumping action leading to an abrasive slurry eroding the sleeper (Figure 7). Eventually, the only cure for this situation is to re-lay the track in this area with new components. It is thus imperative that (a) the rails are straight at the moment the track is installed and (b) wherever possible, dipped welds already existing in track (or dips in plain rail) are corrected as part of the maintenance process.

## CORRECTION OF DIPPED WELDS

Several systems for straightening dipped welds are available. The most common method, and that used on BR, is three-point bending. In its simplest form, a rail straightener consists of a beam that rests on the running surface of the rail supported at two points, typically 1 m apart (Figure 8). A hook is located under the rail foot from the center of the beam, and this is loaded hydraulically to bend the rail. This type of rail straightener has the advantage of being inexpensive and simple, but it is crude in its operation and relies on the skill of its operator to achieve a satisfactory result. Before the lift can be applied, some excavation of the ballast is necessary to enable the hook to be located under the rail foot. This restricts the device to operation between sleepers.

British Rail's Research Centre at Derby has carried out a detailed study of the geometrical behavior of track after straightening with this basic equipment (3).

If the dip is merely straightened to leave the three points lying on a straight line, after the passage of a few weeks' traffic some of the rail dip will have returned and there will be only limited

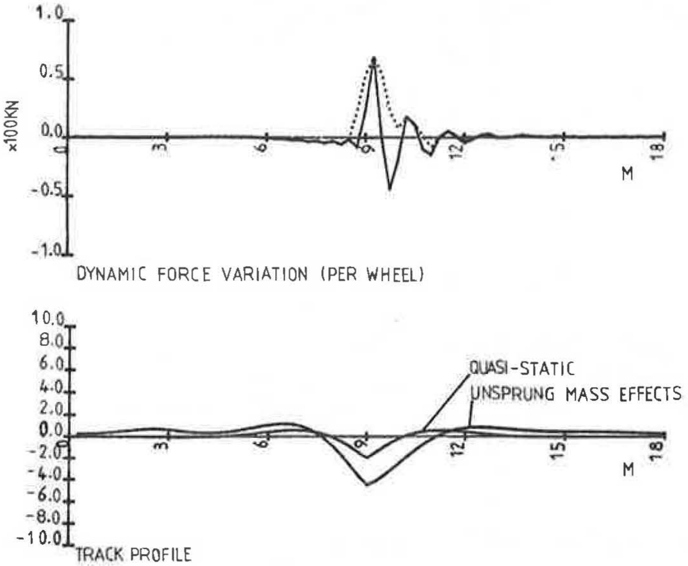


FIGURE 6 Track profile resulting from a 5-milliradian rail irregularity—unsprung mass effects at 125 mph.

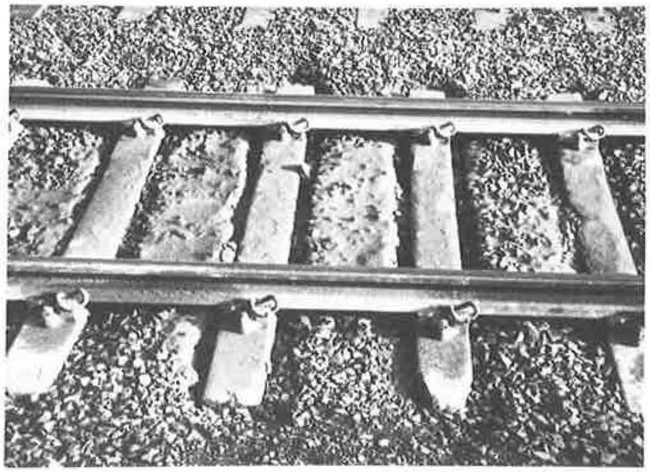


FIGURE 7 Washy spot in track adjacent to a weld.

FIGURE 8 Three-point rail straightener.

improvement in the loaded track geometry. A successful rail-straightening operation clearly needs to devote attention to the ballast support conditions and to the rebending phenomenon.

Rebending occurs because straightening by bending in one direction reduces the yield strength in the opposite direction (i.e., the traffic loading can more easily deform the rail). This reduction in yield strength is known as the Bauschinger effect and is due to the distribution of residual stresses in the rail. The static load of an axle would not, in itself, be enough to cause yield of the rail, but if a significant dynamic load exists because of local roughness in the running surface, the load can be high enough for the rail to yield. As the rail yields in the reverse direction, the yield strength increases and eventually its shape will stabilize. To a greater or lesser degree, this rebending of the rail always occurs, regardless of how the straightening is performed. If the rail is straightened and the sleepers on either side of the weld are squeeze tamped with no additional lift applied, there is again no lasting improvement to the loaded track profile (Figure 9).

An improved result is obtained if a maintenance lift of over 20 mm is applied with the tamping machine (Figure 10) because such a lift is large enough for the tamper to push extra stone under the sleeper. However, even in this case some of the former dip persists in the loaded track profile 1 year after the maintenance.

The best results have been achieved by using the stone blowing technique (4) to support the straightened weld (Figure 11) together with a slight overbend of the rail to anticipate the reverse bending under traffic. By using this combination, a permanent improvement in the inherent track shape can be made.

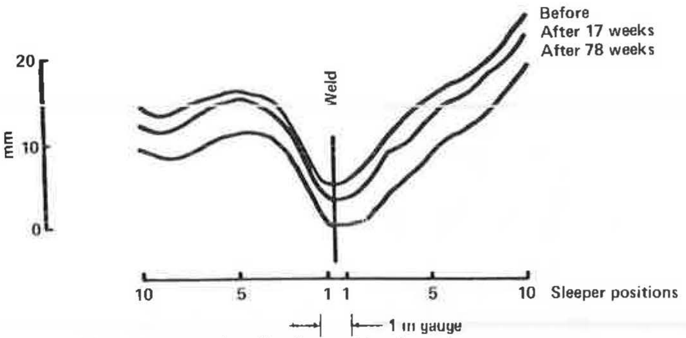
Recent experiments have shown that, to reduce high-frequency impact loads at the weld, the amount of reverse bending can be more closely controlled if the rail surface is ground smooth within a few days of bending. The results of these tests indicate that a suitable rail-straightening system would consist of a machine to straighten the rails in a controlled manner, a machine to smooth the running profile of the rail, and a packing system capable of supporting the sleepers effectively over short and medium wavelengths.

## NEW DEVELOPMENTS IN RAIL-STRAIGHTENING EQUIPMENT

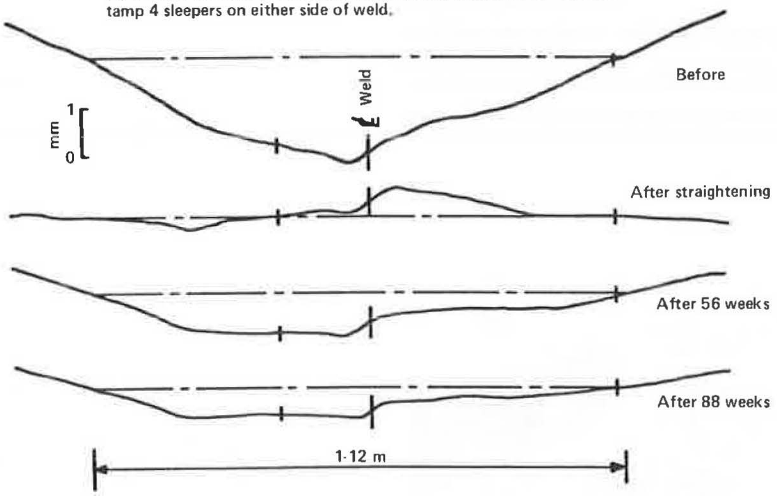
The Austrian firm of Plasser and Theurer in conjunction with the Dutch Railways (N.S.) have developed a system known as STRAIT (STraightening of Rails by Automatic Iterative Techniques) (5). This is a system in which a conventional tamping machine incorporates a three-point rail-straightening device built into its track lifting equipment (Figure 12). The rail bending is done in exactly the same way as with a traditional rail straightener except that the displacement of the center of the rail, where the load is applied with respect to the two reaction points, is monitored by transducers.

A microprocessor using a Newton-Raphson iterative system is used to control the bending process. The rail is straightened in several load applications until a permanent hump of between 0.3 and 0.5 mm has been achieved over the 1.2-m span of the bending beam. While this bend is being achieved, the forces on the rail are such that the track within the wheelbase of the machine is lifted several millimeters. The sleepers surrounding the straightened part of the rail are then squeeze tamped by the machine before it moves forward to the next weld dip along the track. To complete the process, a second machine--a shuffle grinder (Figure 13)--is then used to smooth the surface and remove the slight hump left by the bending process. BR has recently purchased two of these systems, and early results indicate that a permanent improvement in the inherent track shape can be made. The output achieved is around 20 welds per hour.

An alternative system is currently under development by the British firm of Permaquip in collaboration with the Research Department of BR. The system, known as RASTIC (RAil STraightening by Integrated Control), is also a machine-mounted system but is based on a small off-trackable machine weighing under 3 tonnes (Figure 14). The bending heads on this machine apply the load to the rail by gripping it under the railhead (Figure 15), which enables the bending operation to be unconstrained by the position of the sleepers. It also eliminates the need to excavate the ballast under the dipped rail. The bending is controlled by a microprocessor that monitors both the deflection of the rail and the load applied to it. The control algorithm calculates the elastic modulus of the track, detects the yield point of the rail, and predicts the permanent set that has been applied during the bend (Figure 16). This algorithm was developed from an instrumented three-point rail straightener.

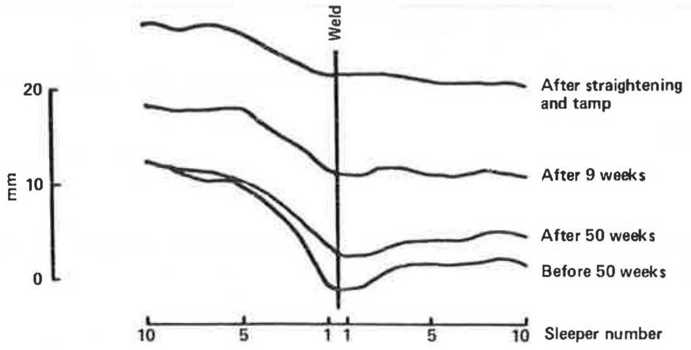


(a) Loaded railhead profile after straightening maintenance—squeeze tamp 4 sleepers on either side of weld.

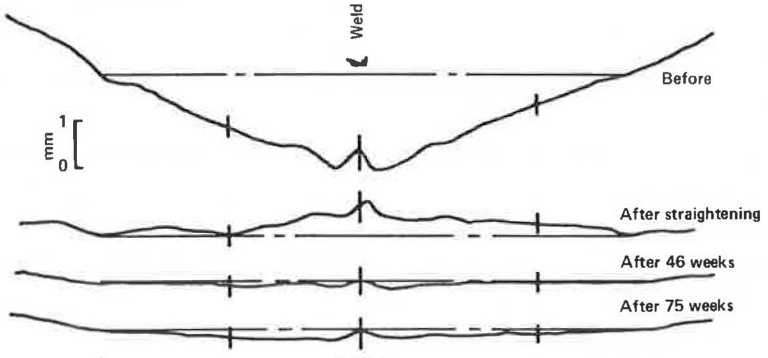


(b) Railhead profile as measured by 1-m gauge.

FIGURE 9 Rail and track profile after straightening and squeeze tamping.



(a) Loaded railhead profile after straightening maintenance—design overlift with single tamp.



(b) Railhead profile as measured by 1-m gauge.

FIGURE 10 Rail and track profile after straightening and design overlift tamping.

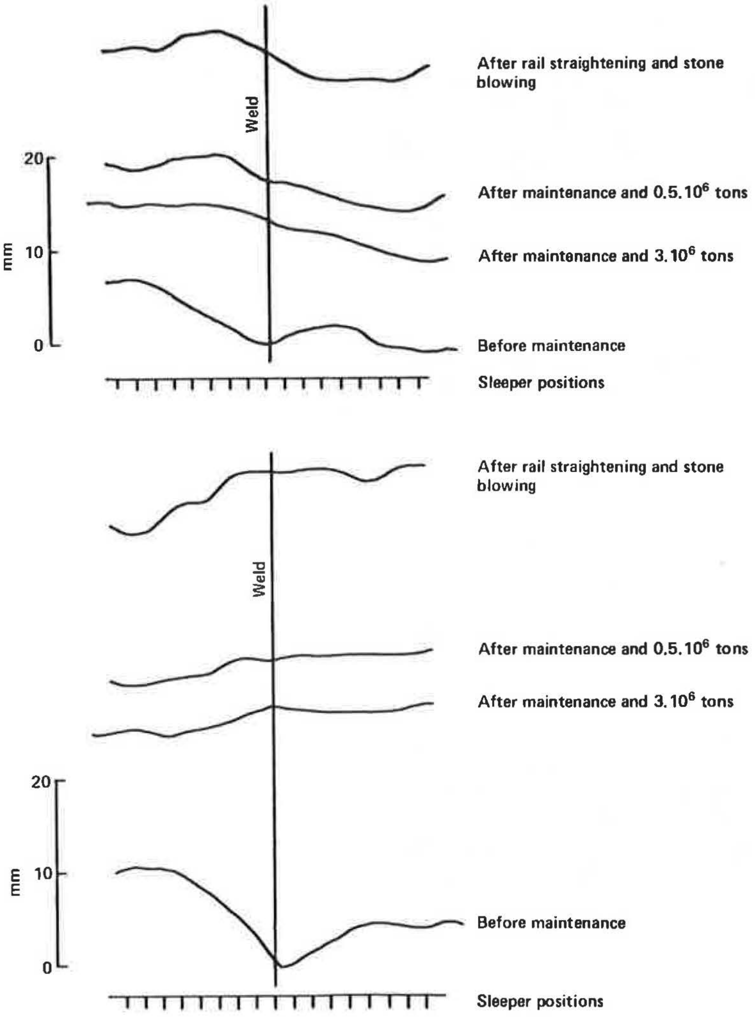


FIGURE 11 Loaded rail profiles of flash butt welds after rail straightening, stone blowing, and trafficking.

The equipment was used to gather load deflection data from a number of bends on differing tracks. Figure 17 shows a typical result obtained by using this equipment. The algorithm is capable of predicting the permanent set of the rail within a standard deviation of 0.2 mm over a 1.1-m span (Figure 18). The machine will therefore be capable of correcting a rail dip with a single lift of the rail, greatly enhancing the speed of the process.

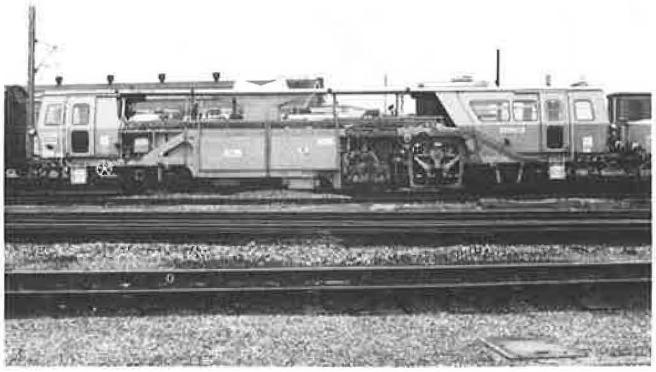


FIGURE 12 STRAIT, Plasser's three-point bending machine.

FIGURE 13 Plasser's shuffle grinder.

In operation, the machine is positioned over the dipped weld. The rail-straightening beam is lowered and moved fore-and-aft until the point of maximum dip is located. The jaws clamp the rail head and the straightening process is carried out. After completion of the bend, the beam is raised from the track.

FIGURE 14 RASTIC's rail-bending machine.

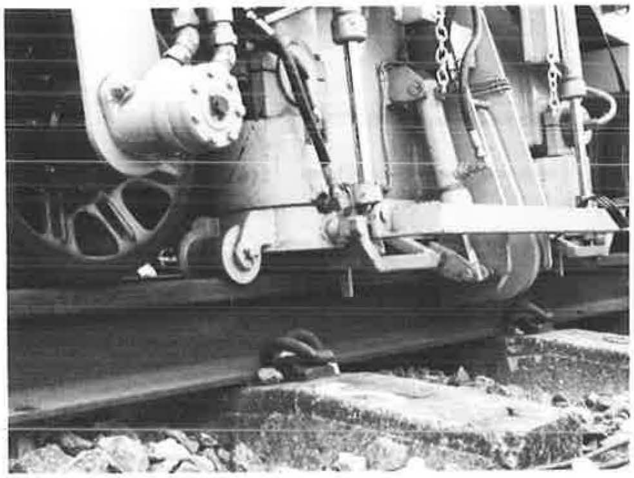


FIGURE 15 Three-point bending head of RASTIC machine.

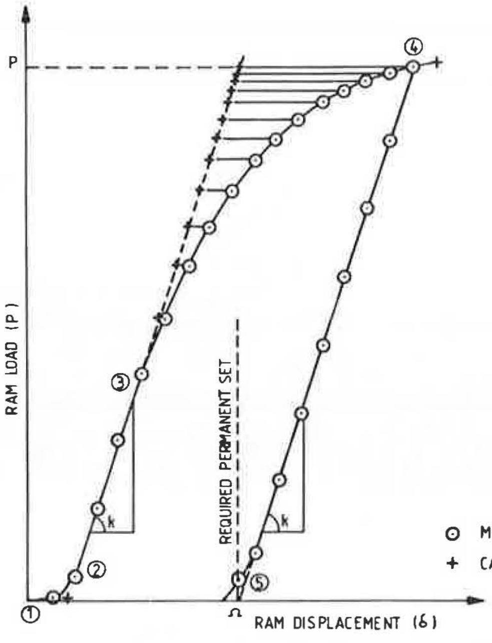


FIGURE 16 Determination of load-permanent rail displacement relationship.

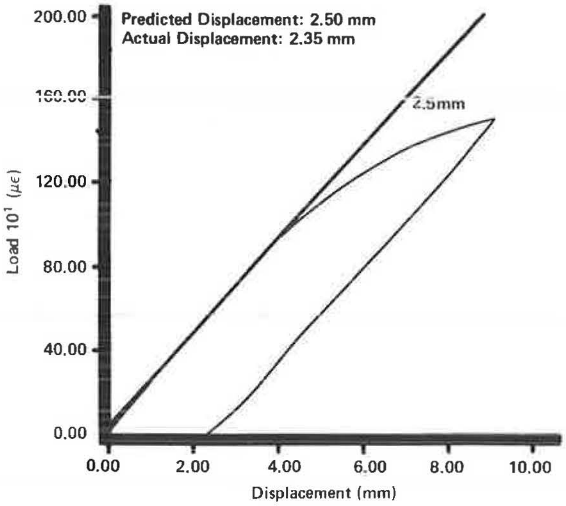


FIGURE 17 Typical result from using instrumented rail straightener.

The process is repeated, if required, on the adjacent weld and the vehicle is then ready to move forward to the next dipped weld. This sequence of operation is totally automatic and is controlled by the microprocessor. A complete bending cycle takes under 20 seconds.

The envisaged output of the machine is over 80 welds per hour, resulting in a working rate of 800 m/hr. At this speed, the machine will be capable of running ahead of a tamping machine that is used in a

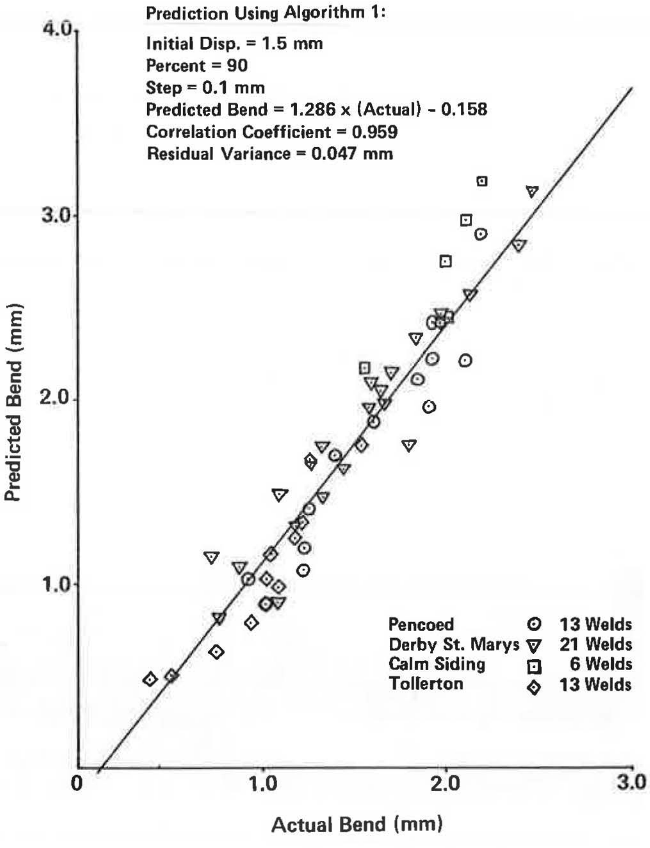


FIGURE 18 Actual versus predicted bend relationship.

normal maintenance operation or ahead of BR's new stone blowing machine. Therefore, it is not necessary to carry out a special packing operation with the straightening operation.

To reduce the high-frequency impacts and to control the reverse bending it will be necessary to smooth the surface of the rail. Conventional grinding machines are too slow to be compatible with the rest of the system, and an in-track rail milling machine (SUPERLEV) is being developed for use in conjunction with RASTIC. This machine is similar to the rail straightener and is also based on an off-trackable concept (Figure 19). The milling heads are arranged to produce a profiled cut of the humped rail. Laboratory trails have shown that an excellent finish of the running rail surface can be obtained by using this technique.

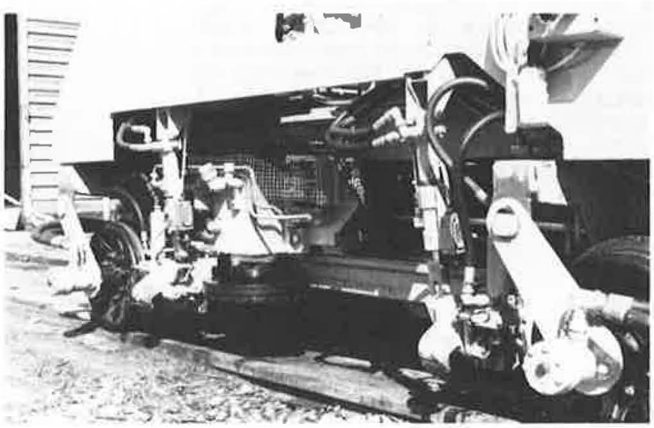


FIGURE 19 SUPERLEV milling machine.

If this system is used selectively on sections of track known to have poor weld geometry, the inherent shape of those sections will be improved. Consequently, less-frequent tamping will be required. Estimates indicate that elimination of all of the dipped welds in BR's track could lead to a considerable saving per annum.

## SUMMARY

Vertical rail geometry has a strong influence on the inherent shape of railway track. The major irregularities in rail shape occur at welds. These should ideally be corrected at the welding depots before the rails are allowed to be made into track. Various machines are available or under development for the correction of dipped welds in track. To achieve a durable improvement in track geometry, a straightening system requires close control of the permanent set applied to the rail and an effective packing system to support the sleepers around the straightened weld. The best results are achieved with a machining operation to smooth the running surface of the straightened rail. It is anticipated that the introduction of a new generation of rail-straightening systems will produce significant savings in track maintenance costs.

## ACKNOWLEDGMENTS

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## REFERENCES

1. D.J. Round. The Effect of Rail Straightness on Track Geometry and Deterioration. Presented at Joint BR-AAR Seminar, Nottingham University, Nottingham, England, Sept. 1981.
2. P.G.S. Carlin. Vertical Longitudinal Rail Profiles of Displaced Continuously Welded Rail. Technical Memorandum TM-TD-20. British Rail Research and Development Division, Derby, England, undated.
3. P.G.S. Carlin. An Assessment of the Effects of Weld Straightening. Note TN SN 155. British Rail Research and Development Division, Derby, England, undated.
4. J.M. Waters. Pneumatic Stone Injection--A Means of Adjusting Track Level. Fourth International Rail Track and Sleeper Conference, Adelaide, Australia, Sept. 1981.
5. C. Esveld. Vertical Rail Geometry--Kinds of Defects, Measuring and Correcting. Rail International, Feb. 1983.

# 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.

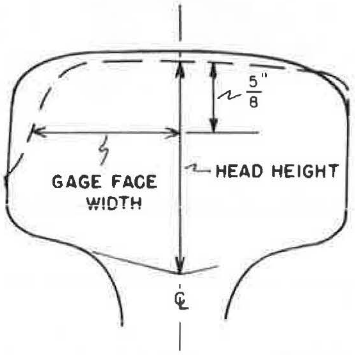
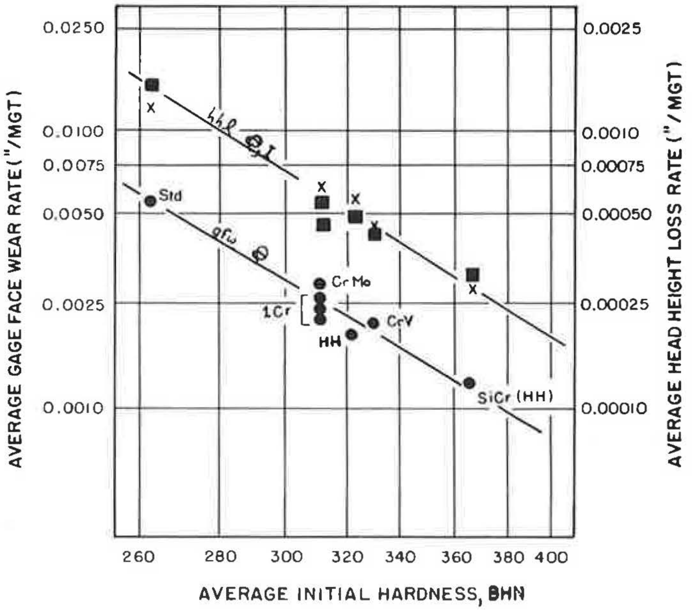


FIGURE 1 Locations of gauge-face and head-height loss measurements.

## WEAR AND RELATED PHENOMENA

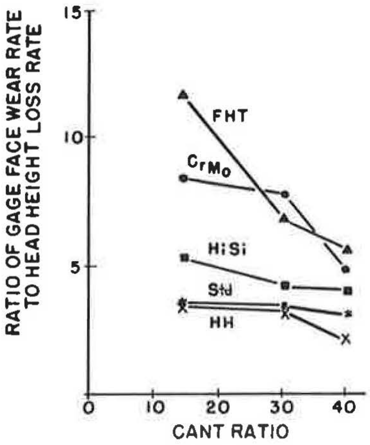
In a narrow sense, rail wear is the loss of material by mechanical action from the running surface and gauge face of the rail in the area shown in Figure 1. However, wear may be thought to encompass all those processes occurring in the immediate vicinity of the wheel-rail interfaces that result from 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, $\phi$); X = head height loss—inside rail (hhl, I); ● = gauge-face wear (gfw, $\phi$); 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.

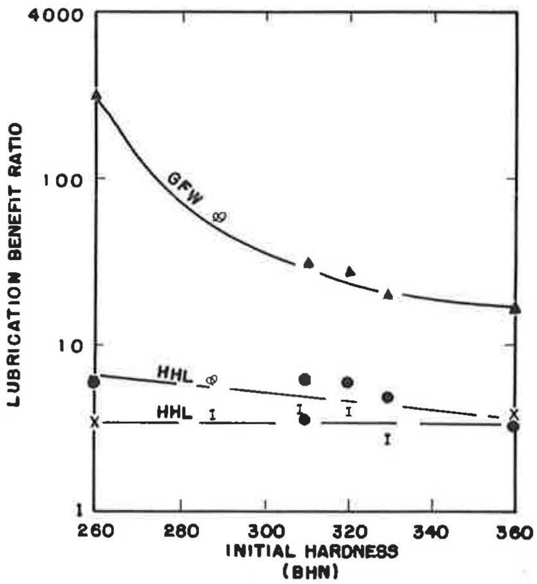


FIGURE 4 Variation of lubrication benefit ratios with hardness.

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 aluminates 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.

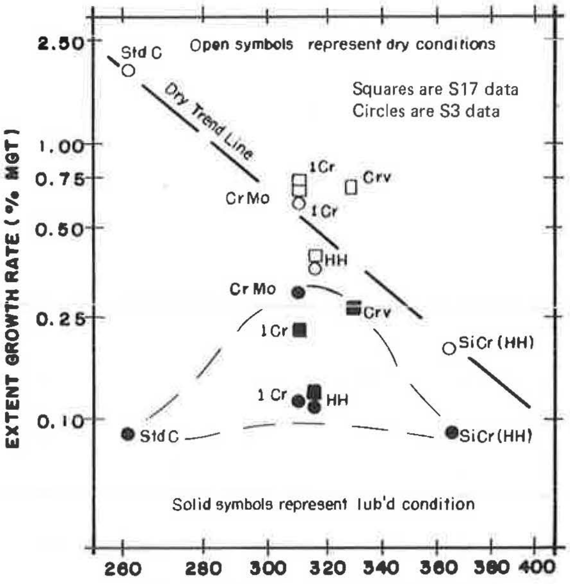


FIGURE 5 Effect of hardness on corrugation extent growth rate.

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 essentially 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.

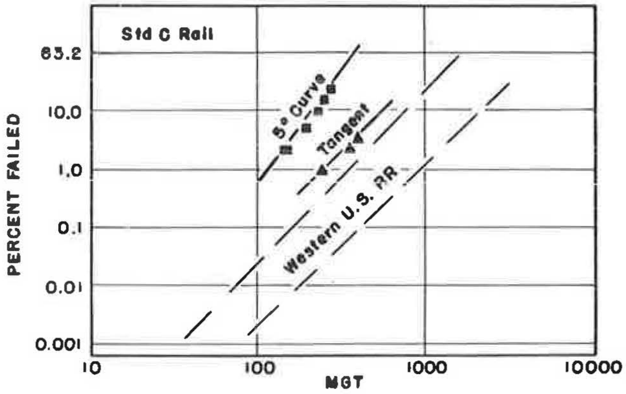


FIGURE 6 Distribution of fast rail failure.

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-

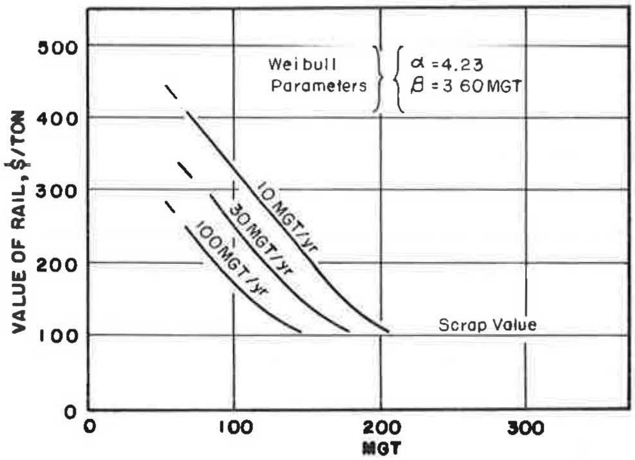


FIGURE 7 Calculated rail value for rail-failure distribution of 5-degree curve.

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.

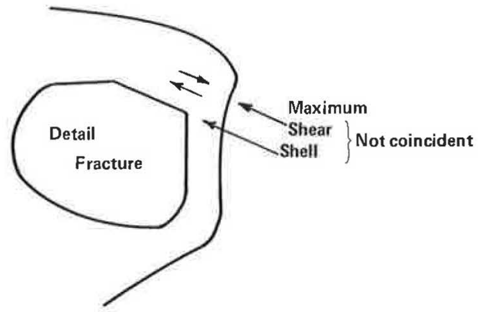


FIGURE 8 Location of shell crack and detail fracture.

The cause of shell initiation at this greater depth within the railhead is the conjoint action of the two predominant stress sytems, 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

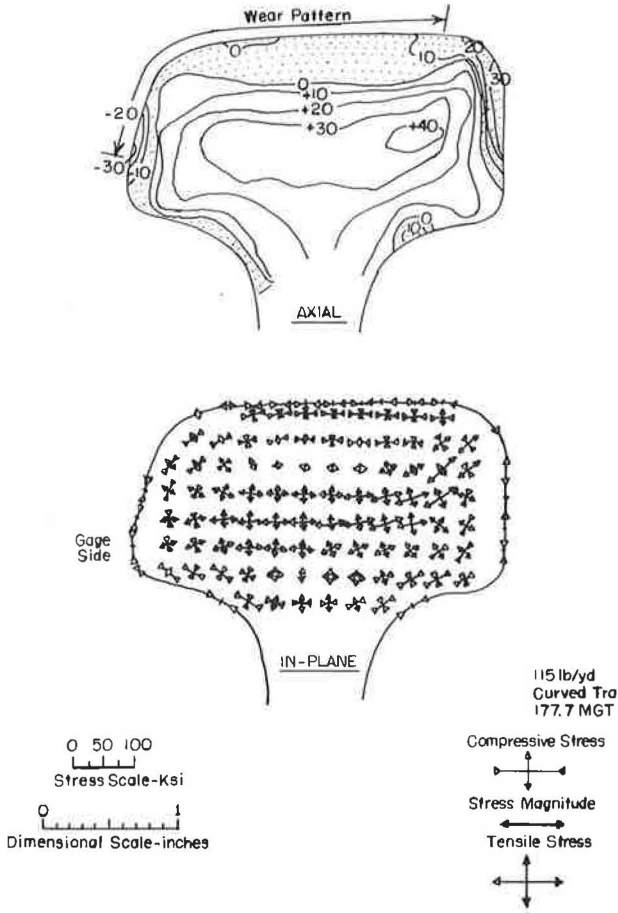


FIGURE 9 Axial and in-plane residual stresses in a service-worn rail.

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

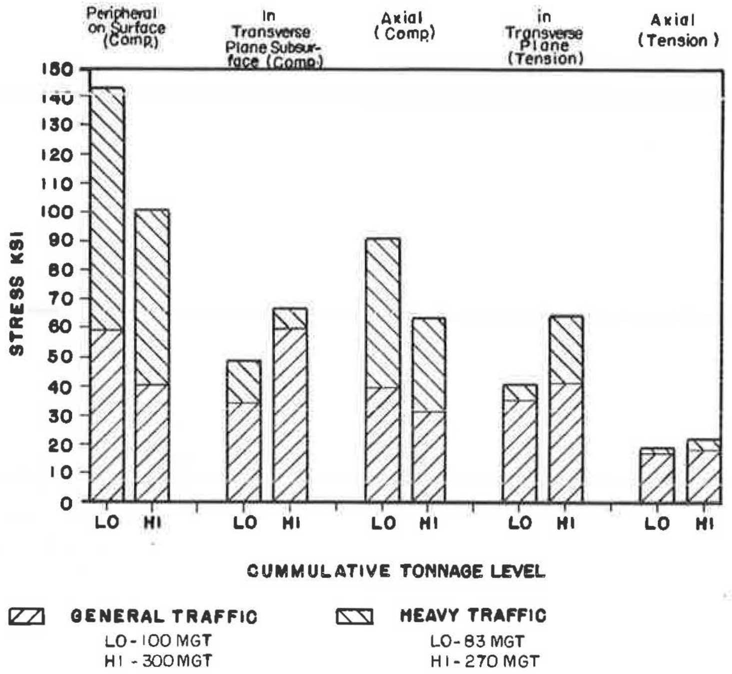


FIGURE 10 Maximum residual stresses measured.

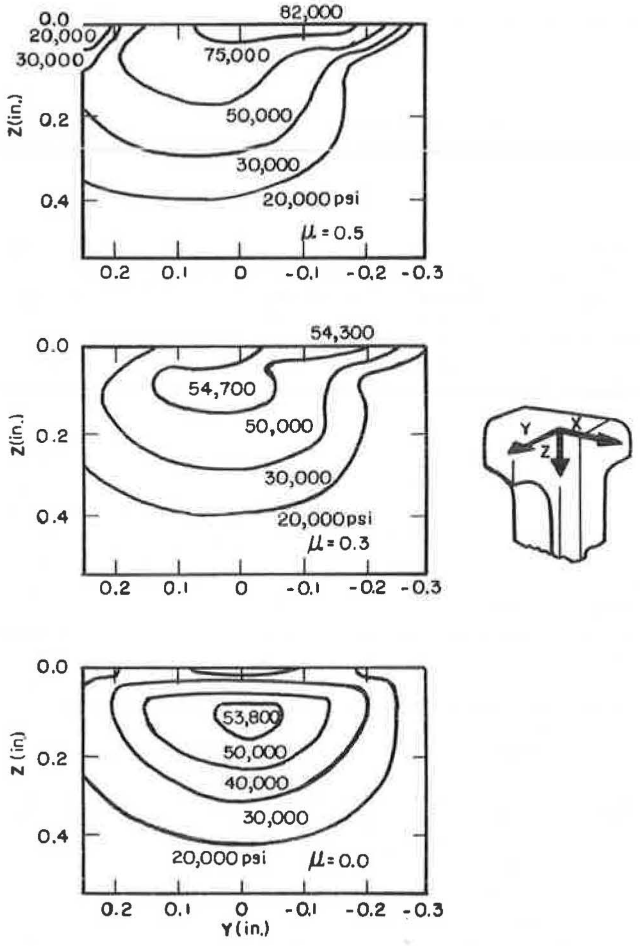


FIGURE 11 Octahedral shear stress contours (combined vertical and lateral loading).

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, $\mu \to 0$) 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 ($\approx 0.3$) 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-

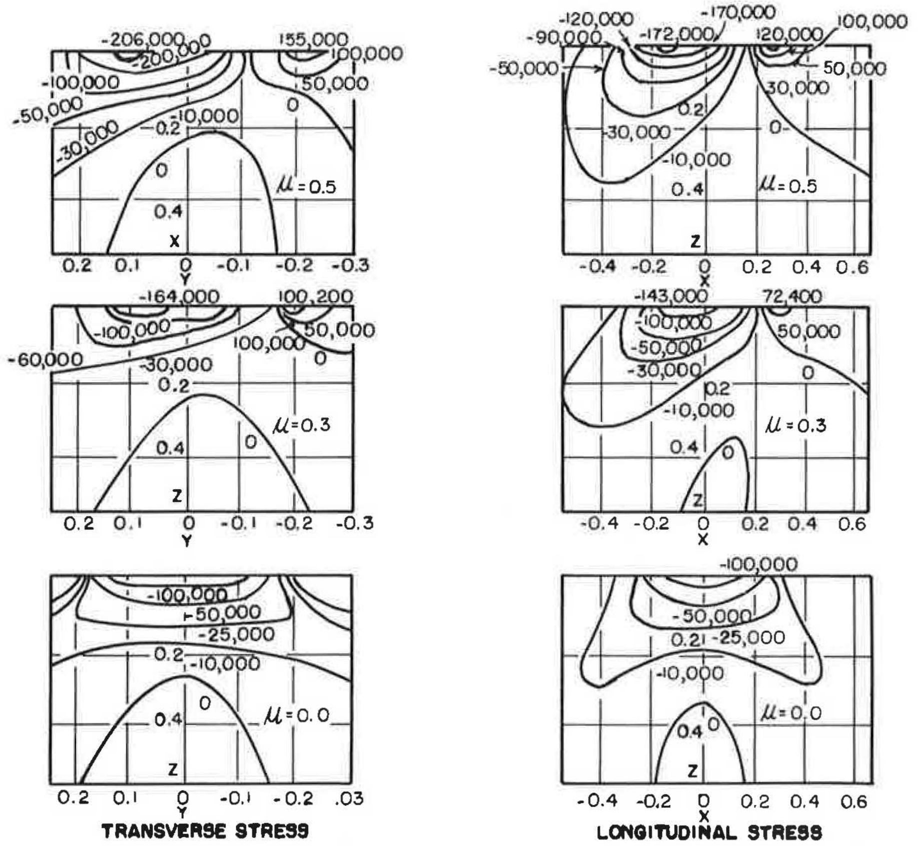


FIGURE 12 Longitudinal and transverse stresses induced by surface contact.

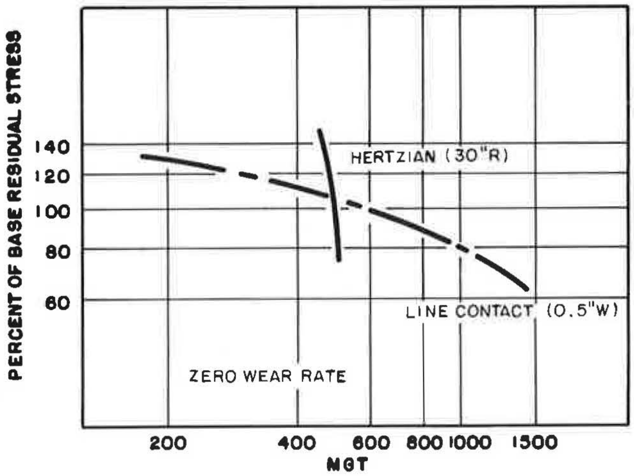


FIGURE 13 Effect of variation in residual stress magnitude on tenth percentile life.

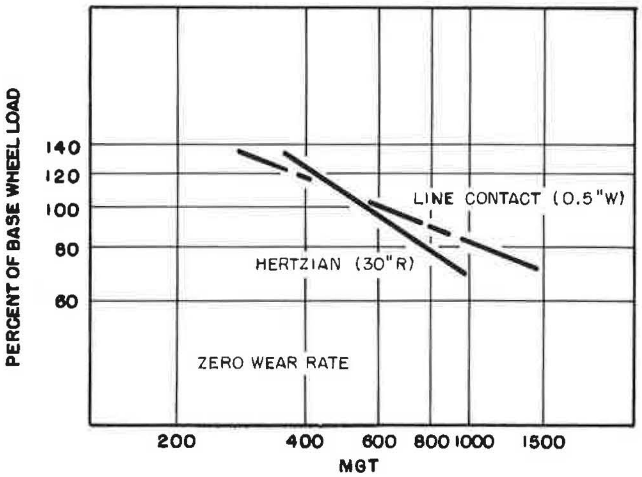


FIGURE 14 Effect of variation in wheel load spectra on tenth percentile life.

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 sheer 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

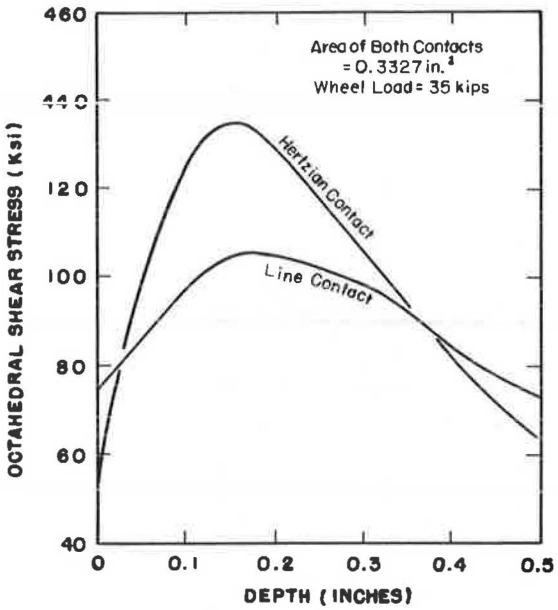


FIGURE 15 Variation of contact stress with depth.

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

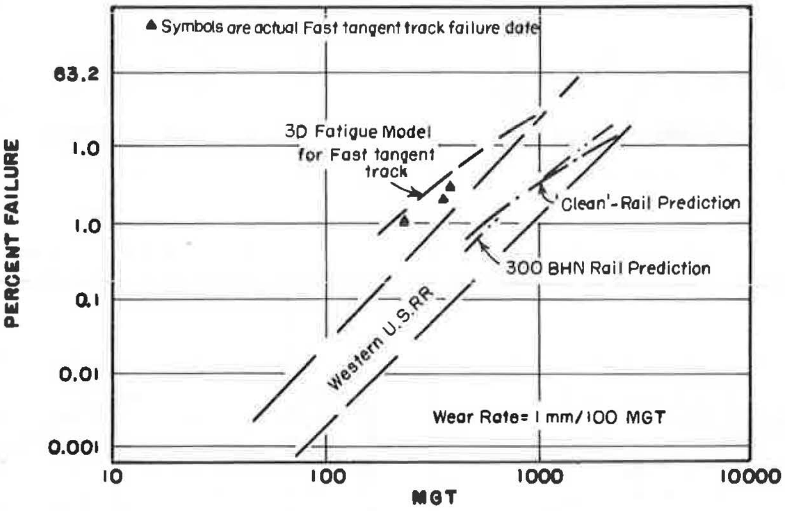


FIGURE 16 Predicted fatigue life distribution for metallurgically clean rails and for 300 bhn rails.

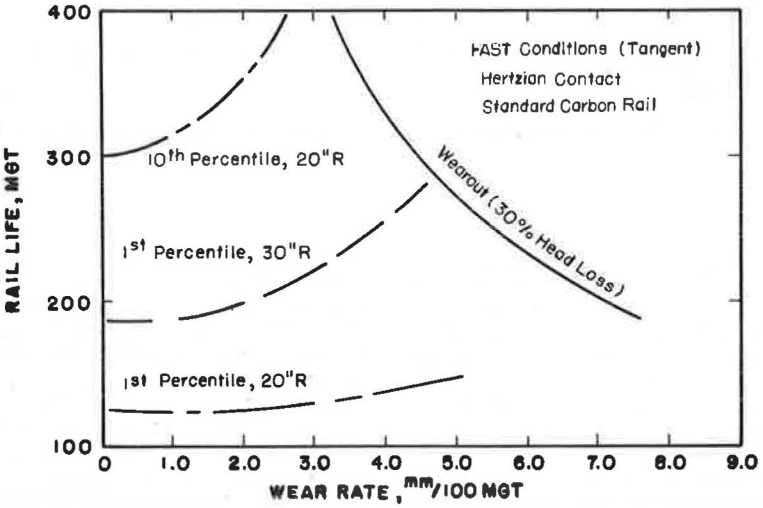


FIGURE 17 Effect of wear on fatigue life.

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 | Avg = 9.85 |
| | 16.9 | 9.7 | |
| | 22.5 | 10.0 | |
| | 22.5 | 9.5 | |
| Lubricated | 16.6 | 18.0 | Avg = 15.0 |
| | 16.6 | 13.9 | |
| | 22.5 | 14.5 | |
| | 22.6 | 13.7 | |

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 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.

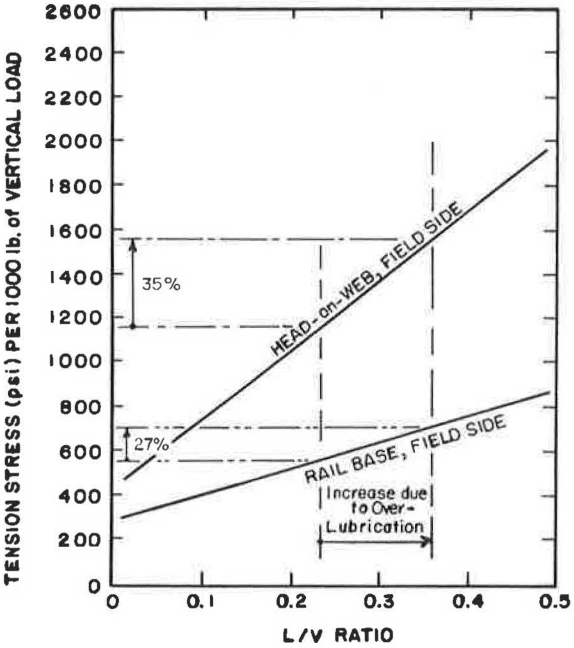


**FIGURE 18** Variation of tension stress at two locations on the rail with increasing lateral-to-vertical ratio.

## 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.

## REFERENCES

1. Effect of Rail Lubrication on Train Operation. Report of Subcommittee 8. American Railway Engineering Association, Washington, D.C., 1940, pp. 151-154, Appendix G, AREA Economics of Railway Location and Operation.
2. I. Fujinawa. Flange and Rail Lubrication. Railway Gazette, Dec. 1, 1967, pp. 899-902.
3. W. Czuba. Rail Lubrication in the Austrian Federal Railroads. OBB in Wort and Bild, No. 4, 1973, pp. 13-16.
4. R.K. Steele and R.P. Reiff. Rail: Its Behavior and Relationship to Total System Wear. Second International Heavy Haul Railway Conference, Colorado Springs, Colo., Sept. 1982, pp. 227-276.
5. P. Mutton, C. Epp, and S. Marich. Rail Assessment. Second International Heavy Haul Railway Conference, Colorado Springs, Colo., Sept. 1982, pp. 330-338.
6. J. Kalousek. Status Report of Ongoing Work. AAR/TDC Joint Research Program on Establishment of Quantitative Wear and Fatigue Model for Railway Rail, National Research Council of Canada, Western Laboratories, Vancouver, Feb. 1984.
7. R.K. Steele and T.J. Devine. Wear of Rail/Wheel Systems. Contact Mechanics and Wear of Rail/Wheel Systems, University of Waterloo Press, Waterloo, Ontario, Canada, 1982, pp. 293-315.
8. L.E. Daniels and H. Blume. Rail Corrugation

Growth Performance. Second International Heavy Haul Railway Conference, Colorado Springs, Colo., Sept. 1982, pp. 294-321.

9. H.B. Hargrove, F.S. Mitchell, R.K. Steele, and R.E. Young. Evaluation of Rail Behavior at the Facility for Accelerated Service Testing. In Transportation Research Record 744, TRB, NRC, Washington, D.C., pp. 6-16.
10. T.R. Wells and T.A. Gudiness. Rail Performance Model: Technical Background and Preliminary Results. Report R474, Association of American Railroads, Chicago, Ill., May 1981.
11. R.C. Rice, R. Rungta, and D. Broek. Third Interim Report on Post-Service Rail Defect Analysis. Contract DOT-TSC-1708. Transportation Systems Center, U.S. Department of Transportation, Cambridge, Mass., July 26, 1983.
12. T.G. Davies et al. Engineering Analysis of Stresses in Railroad Rails. Report DOT-TSC-FRA-81-8. Transportation Systems Center, U.S. Department of Transportation, Cambridge, Mass., Oct. 1981, 397 pp.
13. G. Sines. Behavior of Metals Under Complex Static and Alternating Stresses. In Metal Fatigue (G. Sines and J.L. Waisman, eds.), McGraw-Hill, New York, 1959, pp. 145-169.
14. S. Kumar, D.L. Prasanna Rao, and B.R. Rajkumar. A Wheel Rail Wear Study for Railroad Transit Systems. IIT Trans-80-1. Illinois Institute of Technology, Chicago, Aug. 1980.
15. J.M. Tuten and H.D. Harrison. Wheel/Rail Loads Test, Wayside Date. Battelle-Columbus Laboratories, Columbus, Ohio, Sept. 30, 1980.
16. Lateral Wheel Forces of a Locomotive on a Dry and Over Lubricated Rail. Technical Note TE/RR/067, Transportation Test Center, Pueblo, Colo., Feb. 5, 1985.
17. K. Kho. User's Manual for SAFRAL. K-4A-EM456E/77. Kentron Hawaii, Ltd., Honolulu, June 13, 1977.