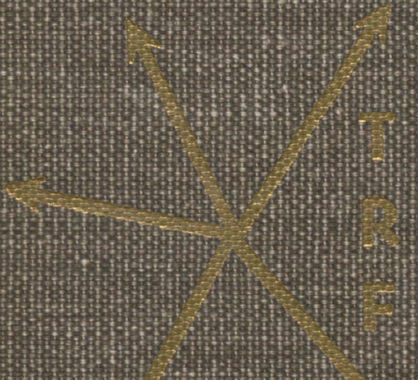
PROCEEDINGS —

Twenty-second Annual Meeting

Volume XXII • Number 1 1981



TRANSPORTATION RESEARCH FORUM

PROCEEDINGS—
Twenty-second Annual Meeting

Theme:

"Opportunities and Challenges in the
New Environment of Transportation"

November 4-5-6, 1981
Golden Gateway Holiday Inn
San Francisco, California

* * *

Volume XXII • Number 1 1981

TRF

TRANSPORTATION RESEARCH FORUM

A Rail Life Costing Model

by E. Roy McIlveen, Michael D. Roney* and Dr. Richard W. Lake**

1. BACKGROUND

THE PROCEDURE presently used in Canada to estimate roadway variability costs is cross-sectional analysis by multiple linear regression of total expenditures for maintenance-of-way and structures (MW&S). Basically, this procedure gives an inference, at some level of statistical significance, of maintenance-of-way unit variable cost.

Recently, there have been misgivings about the use of a single system-average unit-cost for application across a broad array of traffic/truck combinations. Attention has been directed towards possible improvements to both the data base and the methodology. The inherent complexities of an accounting system that could effectively assign track charges directly to even quite aggregated classification of traffic/track combinations would, however, be formidable and hence a pure accounting (data base) solution is impractical. There is more hope for improving the methodology, and in this latter pursuit the engineering approach to costing or more formally the engineering economic cost approach, has generated considerable interest.

Recently, inroads have been made in the development of engineering costing methodologies for maintenance-of-way. Under contract with Amtrak, Rail Systems Research Associates and L. E. Peabody Associates (1973) developed three simple engineering cost functions relating roadway variable costs directly to estimated percentages of annual track component wear. A study by TOPS On-Line Services (1976), commissioned by the Federal Railroad Administration, concentrated on the development of a framework that could be used by all railways to incorporate presently available types of roadway performance information in the costing of rail services for pricing purposes. Some effort was also spent on developing a vector of relative cost factors for each variable judged to exert an important influence on linehaul roadway costs. These were based upon available track research information and tested against the judgment of Southern Pacific Railroad engineering forces.

The procedures developed in these studies depart substantially from the averaging techniques based on historical roadway expense data which are currently used by most of the railway industry. Yet both Peabody and TOPS acknowledged that it was extremely difficult to isolate the effects of any one element or factor. This was attributed to the almost complete lack of control and comparability with which the engineering data were derived. Basically, both methodologies were viewed as a means to begin to utilize presently available types of roadway performance information in the costing of rail services. For example, the TOPS report concludes that:

> "Much more study should be devoted to the entire subject of rail life and the development of procedures to evaluate it, including methods which take into account specific removal criteria and reuse policies as well as the identification of the effects of all significant physical and traffic characteristics."

The Rail Wear Cost Model research reported in this paper is an attempt to overcome the scarcity of controlled experimentation with a more detailed representation of the series of engineering relationships linking cause and effect. The objective is to construct a solid scientific basis for relating the wear caused by a single vehicle passage to the generalization of an incremental track maintenance cost.

The rail wear cost modelling reported here is a stage of a longer term program initiated by CIGGT under contract with Canadian National Railways in 1976. From that time it has proceeded through various stages of development and application supported by contracts with Canadian National (CN), Canadian Pacific, the Canadian Department of Transport and the Association of American Railways (AAR).

2. RAIL WEAR MODELLING

Although most of the project effort was devoted to the modelling of the mechanisms of rail degradation to the point of replacement, it is given only cursory treatment in this paper. This more technical work is reported elsewhere.[1]

The model takes, as input, variables describing the nature of vehicles in the

---

**Canadian Institute of Guided Ground Transport, Queen's University at Kingston, Ontario, Canada.*

traffic mix, operating statistics, track geometry parameters and track quality standards, and uses them to characterize the dynamic wheel/rail interaction for each vehicle type and rail contact location. Estimates are then made of the rates of abrasive/adhesive wear and cumulative plastic deformation on the high and low rail heads, the high rail gauge face and at the joint or weld. Summation of wear rates and cumulative plastic deformation is made at each contact location for all wheels of a single vehicle, and all vehicles in the traffic mix. This is then compared to the specified head, side and rail-end wear allowances yielding an estimated rail service life. An estimate of the rail fatigue life is also made. The service lift estimates are then used to generate a measure of equivalent annual (replacement) cost.

Data input are of three main categories. The first included vehicle and traffic specific data, including train speed, wheel diameter, vehicle total weight and unsprung weight, yearly tonnage of each class, and total yearly tonnage. The second is a set of track specific data including rail weight, rail type, rail mass, rail moment of inertia (second moment of area), track stiffness, curvature, super-elevation and grade. The last category comprises track condition and maintenance data, including maximum vertical and horizontal irregularity over a fixed length, maximum gauge widening, typical dip angle at joint or weld, quality of joint or weld support, use of lubricants and wear allowances.

3. COSTING PRINCIPLES AND ALTERNATIVES

The Road Maintenance Cost Model is designed to generate **avoidable** costs attributable to elements of the system traffic. These costs are an expression of the economic penalty imposed on the track. For rail wear, the cost calculated is the **present value** attributable to the influence the traffic under consideration has or would have on rail replacement cycles. Two concepts—**replacement value** costing and **decremental** cost—are fundamental.

Replacement or **current** value methodologies are gaining acceptance by the accounting fraternity and are starting to receive some consideration from the regulatory agencies.[2] They are now widely used by industry, including some railroads. For the rail wear model and similar procedures, however, a replacement value approach is a fundamental necessity; historical rail investment and replacement data are not available.

The rail deterioration model converts annual changes in rail dimensions and fatigue damage into **rail renewal cycles** by applying the **allowable rail wear and fatigue induced defect** limits specified by the railway for the particular class of track and rail section. Thus, a value equivalent to the **life of new rail** under the current traffic density and mix is calculated. The assumption of constant conditions is important and extends to a wide range of circumstances. Cross-tie condition, ballast, lining, level, train speed, and a myriad of other track-maintenance and train-operating parameters affect rail wear.

By deleting each homogeneous segment of traffic in turn, and calculating the rail life estimate without that segment, the **decremental cost** attributable to that segment can be determined. This cost can be divided by the number of gross tons to obtain **unit cost** (per gross ton mile), or the costs for all segments of the traffic can be added together to obtain measure of **total variable rail renewal cost.** This latter measure, divided by the **equivalent annual rail renewal cost** for the total traffic, provides a measure of **per cent variable.** As could be expected, for high density lines and high curvature trackage most of the cost is variable, while with light density, high track standards and favorable terrain, constant cost predominates.

Alternatively a **marginal cost** approach can be taken. This is similar to the **decremental** approach except that the unit of traffic deleted is ten thousand gross tons per year (it could as easily be a carload). The unit costs computed in this manner have a different meaning, and could not be used to compute **total variable cost** or **percent variable.**

For engineering economy applications, instead of focussing on the penalties imposed by different elements of the traffic mix, one can obtain a measure of the cost impact of any hypothetical change in the track or traffic conditions embodied within the model. Possibilities include addition or deletion of traffic, replacement of a car or locomotive type with alternative equipment, and changes in track standards. Essentially, analogous to the traffic element costing, one starts with the **base** conditions, estimating wear, converting to rail life and thence to cost per year. Then, assuming the change in conditions, wear is re-estimated and rail life and equivalent annual cost recalculated. Subtraction yields the equivalent annual cost impact of the change.

4. CLOSING OPTIONS

The model includes two options for equivalent annual cost computation. Both come from the same **replacement value equivalent annual cost** relationship, but are based on differing assumptions concerning the current condition of the rails.

A replacement value charge is determined by multiplying the installed replacement price of the rails by a charge rate (k^*) that accommodates the expected future replacement prices and, when discounted, yields a nominal rate-of-return equal to the cost of capital. At a cost of capital (k), assuming rail price projections can be described by a constant annual escalation rate (Δ) and for simplicity neglecting taxes,[3], an appropriate **replacement value charge rate** can be shown to be:[4]

$$k^* = \left[\frac{k-\Delta}{1+\Delta}\right]\left[\frac{(1+k)^n}{(1+k)^n-(1+\Delta)^n}\right]$$

This is analogous to a capital recovery factor formulation, for a cost-escalation adjusted, **real** rate-of-return

$$k' = \left[\frac{1+k}{1+\Delta}-1\right]$$

This formulation, however, implicitly assumes that the rail in question is either new or in need of immediate replacement. This may be a realistic approximation of prevailing conditions, but frequently rail exhibits a wide age distribution, with the rail which is being evaluated being part-way into a maintenance/renewal cycle.

The life cycle of the rail under the current conditions is ℓ_1 years. The life cycle with the assumed change in conditions and corresponding change in wear pattern is ℓ_2 years. Because the change in wear patterns only affects the life remaining in the maintenance cycle, the new cycle must start earlier by some fraction of the difference between the length of the two rail renewal cycles (mathematically represented as $p(\ell_1-\ell_2)$ years). Thus the present value cost for the 'new' replacement cycle is

$$(1+k)^{p(\ell_2-\ell_1}\sum_{t=1}^{\infty} M\,(1+k)^{-\ell_2 t}$$

To make the correction to the present values for the difference between the time at which the wear patterns change was introduced and the time from which the present values are to be referenced, both present value streams must be compounded for p times ℓ_1 years. Thus the present value of the difference is

$$PV = M\,[(1+k')^{\ell_1 p}]\,\left[\sum_{t=1}^{\infty}(1+k')^{-\ell_1 t} - (1+k')^{p(\ell_2-\ell_1)}\sum_{t=1}^{\infty}(1+k')^{-\ell_2 t}\right]$$

which reduces to

$$M\left[\frac{(1+k')^{\ell_1 p}}{(1+k')^{\ell_1}-1}-\frac{(1+k')^{\ell_2 p}}{(1+k')^{\ell_2}-1}\right]$$

Assuming an even distribution of track wear, the present value for the mean level of the fraction p is represented by the integral of PV evaluated over the interval $p = [0,1]$, solved as follows:

$$\int_{p=0}^{p=1}\left[\frac{(1+k')^{\ell_1 p}}{(1+k')^{\ell_1}-1}-\frac{(1+k')^{\ell_2 p}}{(1+k')^{\ell_2}-1}\right]dp$$

where $k' > 0$ and k', ℓ_1, ℓ_2 are not functions of p.

$$= \frac{\ell_2 - \ell_1}{\ell_1 \ell_2 \ln(1 + k')} + C \qquad \text{[C here is zero]}$$

This represents the appropriate present value cost savings in perpetuity change rate, and the annual charge is

$$k^* = \frac{k + \Delta(\ell_1 - \ell_2)}{(1 + \Delta)\ell_1 \ell_2 \ln\left(\frac{1 + k}{1 + \Delta}\right)}$$

This formulation, although it provides a superior model for many applications, depends on the assumption of a uniform distribution of rail age. This tends to be unrealistic for low density applications where lives are long. Thus both alternatives are retained as options.

5. INTENDED AND ACTUAL APPLICATION TO DATE

The model was designed to generate route and service specific avoidable costs imposed by the traffic on the track. These unit cost numbers are suitable for the evaluation of engineering alternative such as track maintenance standards, special alloy rails, rail lubrication on curves, axle loadings, speed, truck (bogie) handling characteristics, wheel diameter, and so on. It was also intended to provide unit costs as input to the pricing function.

It has been used for a number of these purposes, and in other (unintended) applications as well. Past and ongoing applications include:

- an evaluation of the potential roadway cost savings accruable through the use of dynamically improved covered hopper cars
- an evaluation of rail wear tradeoffs associated with new equipment acquisitions being considered by London Transport
- an estimation of route- and service-specific benefits accruable through the use of various designs of steerable trucks based upon curve negotiation data obtained in the FRA's Truck Design Optimization Project
- a prediction of expected rail renewal cycles on CN Rail's Ashcroft Subdivision under evolving system parameters
- the development of weighting matrices for the CN system for use in assigning unit costs for roadway maintenance
- the development of a rail life matrix for the Association of American Railroads for use by the U.S. railway industry, with the initial calibration performed using Southern Railway data.

Each of these projects is discussed briefly below.

Analysis of Roadway Benefits of a Dynamically Improved Hopper Car

The roadway benefits evaluation reported here was one facet of a larger study under the auspices of the Engineering Economics Division of the Association of American Railroads' Research and Test Department aimed at identifying the potential total system savings that could be expected to attend the introduction of dynamically-improved cars onto North American railroads. In fact, the question that was asked was **how much should the railways be prepared to pay to obtain freight cars with the loading capacity of the conventional 100-ton car, but with less severe wheel/rail dynamic interactions?**

The analysis avoided any definition of how the dynamic loading performance simulated might actually be achieved. The candidate cars were, in effect, **nondimensionalized** so that it could be applied in a general manner to the evaluation of new generations of freight cars.

To maintain applicability to a large range of North American mainline routings, costs have been estimated for each of four classes of curvature, all on 136 lb. rail.

The characterization of the freight car dynamics was even more general. The estimation of costs was based on vertical/lateral wheel load spectra; a particular load spectrum in either the vertical or lateral plane is the result of some combination of static axle load, dynamic performance, and speed, not car type per se.

The Rail Life Model was used in conjunction with the AAR's Fatigue Life Analysis Program (RFLAP) to examine the impact of:

(1) reductions in the dynamic vertical loadings on variable track costs
(2) reductions in static loading on variable track costs
(3) improvement in curving capabilities
(4) improvements in both vertical and lateral dynamic performance.

Rail life estimates and resulting costs were compared against equivalent results that were predicted to apply for loading spectra typical of a 100-ton covered hopper, called the "base" car.

Sample results are given as Table 1 for an improved vehicle with a dynamic loading that is achievable with current technology. These results show that improvements in vertical response will not greatly reduce track costs, while the effectiveness of lateral response improvements will be highly sensitive to the curvature makeup of the routing. In both cases, a high annual mileage is necessary to pay for improved vehicle vertical response and tracking.

London Transport Study

The Rail Wear Model was employed in the investigation of rolling stock alternatives for the London Transport "Central Line" Subway. With some modifications, the model was used in the comparison of three rolling stock fleets—the 1983 tube stock (which was 32 per cent lighter but which had smaller wheels and required every vehicle to be powered), and the 1989 tube stock with a specially designed steerable axle truck which would maintain radial axle alignment within very close limits. The evaluation of cost-saving benefits of adding steerable trucks to the 1989 stock was examined. It was assumed, for simplicity, that a complete replacement of the stock on the Central Line would be made all at once. Costs and benefits were treated under the categories of energy, vehicle maintenance (available cost and avoidable vehicle inventory), rail wear and lubrication, and curve noise (passenger comfort and regional disturbance) and safety. The rail wear model was used to calculate rail life predictions for the three stock options on the various track sections which were then fed into the calculation of replacement costs.

Truck Design Optimization

Similarly, the Rail Wear Model was used in Phase II of the Truck Design Optimization Program in the comparisons of the standard trucks with five steering axle trucks. The relative impact on rail wear was a major input into the evaluation.

Rail Replacement Cycle Prediction

In a study performed for CN Engineering, the rail wear and rail lives calculated in the Rail Wear Model were used to provide estimates of rail replacement cycles. It was planned to use these site-specific rail replacement cycles to replace the all-purpose set CN presently uses. The model was calibrated to data from the Ashcraft Subdivision and for a given traffic density and traffic mix, on CWR mainline track. Sensitivities were performed for changes in vehicle speed, curvature, gradient, rail weight, tie type and use of lubrication. With considera-

TABLE 1

BENEFITS FROM TYPICAL FREIGHT CAR IMPROVEMENT TARGET

Traffic: 15 MMGT/year
Base Car: 100 ton (263,000 lb)
Trial Car: Vertical dynamics — 25% reduction
Lateral dynamics — 50% reduction

100% Empty Return

Curvature	**Tan**	**0°-2°**	**2°-5°**	**5°-8°**
Rail Life (MGT) Base Car	347.9	347.9	193.6	128.1
Trial Car	399.2	399.2	399.2	375.8
Advantage ($/Mile Present Value [1980])	2,570	2,570	18,509	35,891
Equivalent Annual Benefit $/Mile — Rail	231	231	1,666	3,230

tion of the model's limitations, some investigation into the effects of improved rail steels, and of grinding, on rail life cycles, was also initiated.

CN Weighting Matrices

A particularly interesting application was CN's use of the model's output as weighting factors for their road maintenance costing regression. As illustrated in Figure 3, CN modified the cost function.

Railway Maintenance Expense = Constant
+ Cost/Mile of Roadway (MOR) x MOR
+ Cost/Grade and Curve Unit (G&C) x G&C Index
+ Cost/Switching Minute (YTSM) x YTSM
+ Cost/Gross ton Mile (GTM) x GTM

With weightings derived from the rail wear model and other engineering data to obtain statistically significant results.

Some conceptual difficulties were originally faced in the use of a weighting scheme based on rail life variability to weight all maintenance-of-way costs. On closer examination, it became evident that rail life variability is a reasonable proxy for all variable M/W cost. In actual practice, both timbering and surfacing programs tend to closely follow a rail changeout. This is because this work is most expediently executed when the track is to be disturbed anyway, and also because there are certain similarities between the mechanisms causing rail, tie and ballast deterioration. In particular, spike kill of ties is directly related to the rail changeout cycle. The lives of other track hardware (joint bars, tie plates, frogs, switch points, etc.) are also closely related to rail renewal cycles. Another factor in the decision to use the rail life weighting basis was the dominance of rail replacement costs over all other directly-variable track maintenance costs.

An example of the type of result that was obtained is included as Figure 4.

As shown in Figure 3, the weighting matrix has resulted in a very significant improvement in the ability of the costing regression to explain the variability in the maintenance accounts. Note also that the statistical significance of all the "causal" variables has been increased. To date the levels of unit cost assigned to route- and service-specified traffic have appeared to pass the test of reasonableness.

Industry-Wide Rail Life Costing Matrices

An AAR funded project to perform analysis for U.S. rail conditions has also employed the CIGGT rail wear model. Calibration has been performed using historical traffic, track condition and rail wear data from Southern Railway mainline trackage. Validation of the model with data from track of similar quality and traffic density from other railways, and the extension of the model's range of applicability employing data from railways which operate under substantially different conditions, are necessary. The goal is establishment of the capability, given the relevant line-specific data, to develop rail life costing factor matrices similar to the ones developed for CN.

6. CONCLUSION

Analytical wear modelling improves the accuracy, and scope of the rail life predictions essential to railway system component evaluation and costing. It is particularly attractive in its versatility. In effect, once the complex processes linking wheel/rail interaction to the generation of a cost have been modelled, the resulting tool is sufficiently specific for many cost analyses involving a change in the service environment under which rail must perform. The framework is a particularly valuable one for incorporating the best available results of past and ongoing research into decision-making. The results of future research can also be readily incorporated to increase the predictive capability and timeliness of the model with few changes to the basic model structure.

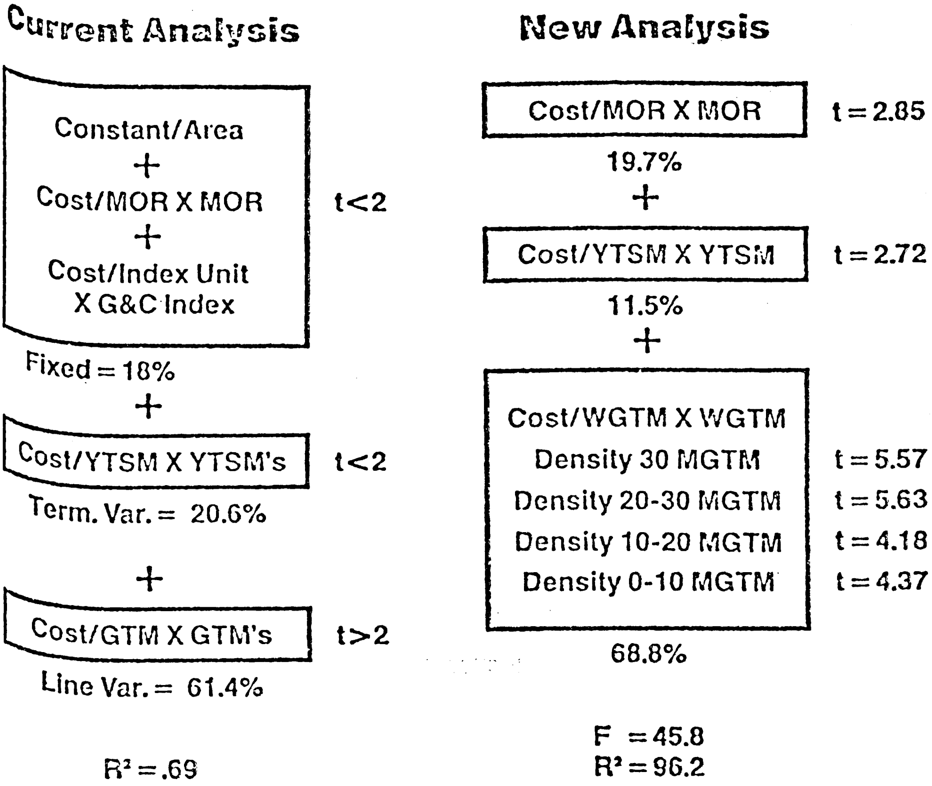
FOOTNOTES

1 Roney, M. D., Turcot, M. C. and Lake, R. W., "A Model of the Physical and Economic Performance of Rail in Main Line Track," Proceedings Heavy Haul Railways Conference, Perth Western Australia, 1978, and McIlveen, E. R., Roney, M. D., Lake, R. W., and Raymond, G. P., The CIGGT Road Maintenance Cost Model, CIGGT Report 80-16, 1981.

2 Railway Costing Study, Report on Phase 2, Volume Four, Canadian Transport Commission 1979.

3 A taxpaying company in Canada would face a more complex formulation. A U.S. company, where Betterment Accounting applies for tax purposes, can be treated with the simpler formulation; with k and adjusted to after-tax equivalents.

4 This charge rate is developed in Schwier, C., and Lake, R. W., "Costing Rail Wear with Replacement Value," from The Eighties: A New Rail Era, CIGGT Report No. 78-5.


WEIGHTED ROAD MAINTENANCE COST REGRESSION — STATISTICAL SIGNIFICANCE

after W.G. Hanks,
Canadian National Railways

FIGURE 3

CIGGT WEIGHTING FACTORS FOR AXLE LOAD AND SAMPLE CURVATURES

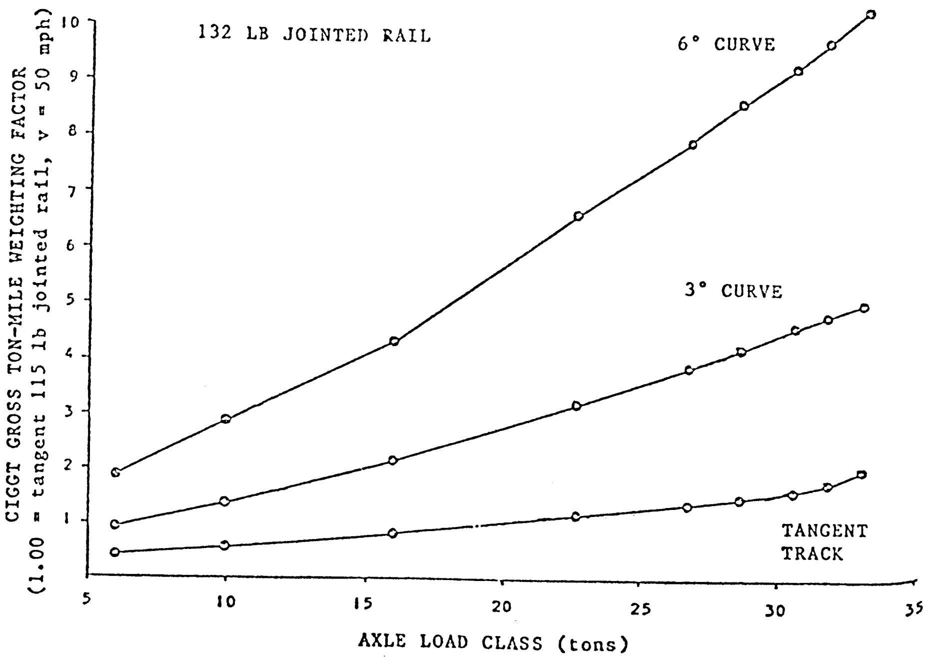


FIGURE 4