Track-Quality Indices and Track-Degradation Models for Maintenance-of-Way Planning

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An objective measure of railroad track quality and track-degradation models are described and illustrations of how these measurements can be used in maintenance-of-way planning are given. The results presented in this paper are based on the data collected over a period of one year on approximately 290 miles of main-line track. The study was sponsored by the Federal Railroad Administration (FRA) with the participation of the Consolidated Rail Corporation. Track-quality indices (TQIs) are derived from the data collected by automatic track geometry cars. TQIs are figures of merit that objectively quantify the condition of track. It is shown that TQIs can monitor track-degradation and maintenance operations, can summarize and display the condition of large sections of track, and are correlated with both FRA safety standards and values of ride quality. Eleven physical parameters in the areas of traffic, track structure, and maintenance were investigated to determine their contribution to the rate of track degradation. It is shown that a subset of these parameters accounts for more than 80 percent of the change in track conditions as measured by a TQI. Predictive equations are presented that project the condition of track in terms of TQIs.

In 1978, the U.S. class I railroads spent more than \$3.5 billion in maintenance-of-way (MOW) operations and on structures, which amounts to 17 percent of the annual operating expenses. MOW cost is reaching a record high each year. Methods to reduce the high MOW cost or to increase MOW productivity will undoubtedly be of great benefit to the railroad industry.

Traditionally, MOW budgets are established subjectively. Railroad management allocates maintenance funds and sets MOW schedules based on historical data and the justifications provided by division engineers. Because of the decentralized nature of this process and the large variances in MOW capabilities, the productivity and quality of the results are likely to vary from subdivision to subdivision.

Because of the high maintenance costs, railroads are trying to improve the productivity of their maintenance teams through more-effective control of labor and by using mechanized track equipment (1). Some of the railroads have developed computerized systems to schedule and control maintenance (2-6). However, these systems cannot be used for long-term planning of maintenance. Development of a maintenance-planning system involves furthering the state of the art. Such a system requires an objective measure of track quality and track-degradation models.

With the availability of automatic track geometry measurement, the Federal Railroad Administration (FRA) has sponsored research projects to investigate the application of track geometry data in developing long-range MOW planning techniques (7). The most recent study was intended to formulate an objective measure of track quality and to develop track-degradation models (8). This paper describes the results of this study and shows how the objective measure of track quality and the track-degradation models can aid in systematic planning of maintenance that will maximize the effectiveness of the maintenance dollar.

CONCEPTS AND METHODOLOGY

The study was passive in nature; i.e., the track condition was only observed during the study period and in no way was any traffic or maintenance parameter controlled. A test zone [Consolidated Rail Corporation (Conrail)] typical of mixed freight operation was selected for this study. Data on physical parameters were collected in 1978 and 1979 in order to determine their contribution to track degradation. In addition, track geometry surveys were conducted in fall 1978 and fall 1979 by the FRA T-6 survey car to measure the track geometry parameters, i.e., gage, alignment, profile, cross level, and curvature. From the track geometry parameters, figures of merit--referred to as track-quality indices (TQIs)--were computed. The following sections give a detailed discussion of the concept of TQIs and the methodology used to develop the predictive models.

TQIs

TQIs are figures of merit that objectively quantify the condition of the track. The indices are computed from data collected by an automated track geometry measurement vehicle. Track geometry parameters (gage, profile, alignment, cross level, and warp) are measured at 1-ft intervals by the T-6 vehicle; the result is 36 960 individual pieces of information for each mile of track. A TQI is a statistical summary of a track geometry parameter measured over a prescribed length of track and effectively summarizes the large number of measurements of each parameter for a given track segment. Sample statistics such as mean, 99th percentile, standard deviation (SD), and higher-order moments were investigated in this study.

Figure 1 illustrates how a TQI rates the condition of a track segment in a relative manner. In this example, profile is used; however, all track geometry parameters can be applied in a similar fashion. The horizontal dashed line represents the ideal track condition. The solid line represents the actual measurement, and the shaded regions represent the area between the actual line and the ideal line. A figure of merit for profile roughness can be calculated by taking the square root of the average area. A TQI that has a high relative value--for example, 0.5 in--depicts poor track condition, whereas a TQI that has a low relative value--for example, 0.2 in--indicates good track condition. In this example the profile TQI is the standard deviation in a statistical sense and indicates the profile roughness.

Figure 2 illustrates how a TQI can be used in long-range maintenance planning. The track condition at time t_1 is indicated by TQI_1. If the equation of the curve (degradation model) is known, the condition of the track at time t_2 (TQI_2) can be projected as a function of physical parameters such as tonnage and rail type. Railroad management can use this information and the corporate operating policy to allocate resources to maintain a track section at a specified level of performance.

Sixteen TQIs were selected based on the functional requirements of track (8). In the most general sense, the functional requirement of track is to guide and support the rolling stock under prescribed operational conditions in a safe and economical manner. The candidate TQIs considered in

Figure 1. Concept of a TQI.

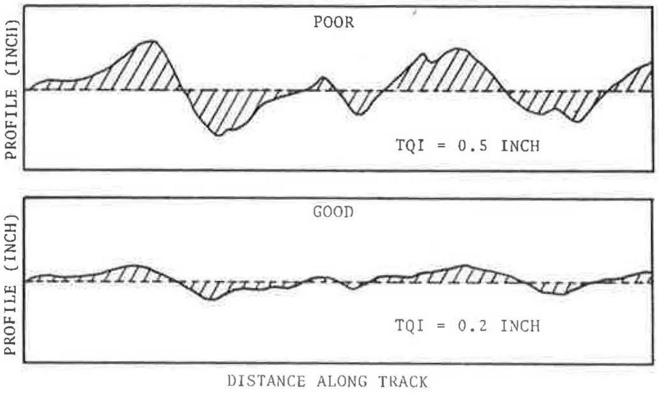
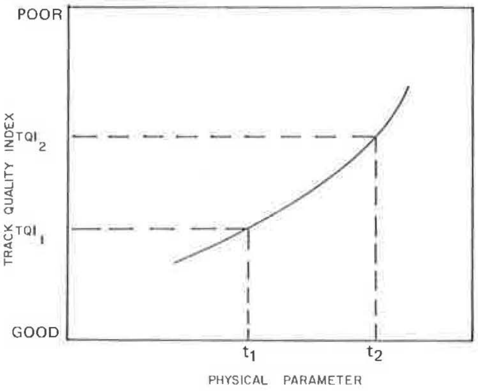


Figure 2. Projection of track condition in terms of a TQI.



this study are listed below (note that they are defined in engineering units to retain their physical significance):

1. For gage: mean gage in inches, SD of gage in inches, 99th percentile of gage in inches, third moment of gage in cubic inches per 1000, fourth moment of gage in inches to the fourth power per 1000;
2. For cross level: SD of mean removed cross level in inches;
3. For warp: SD of 20-ft warp in inches and 99th percentile of 20-ft warp in inches;
4. For profile: SD of profile space curve in inches, SD of 3-ft mid-chord offset (MCO) of profile in inches per 1000, 99th percentile of 16-ft MCO of profile in inches;
5. For superelevation: root-mean-square (RMS) value of cross-level deviation from balanced superelevation in inches; and
6. For alignment: SD of alignment space curve in inches, SD of 2-ft MCO of alignment in inches per 1000, SD of 10-ft MCO of alignment in inches per 1000, SD of 16-ft MCO of alignment in inches.

Only one TQI was selected from each set of TQIs that duplicated each other. The selection criterion for the final TQIs was based mainly on the ability of a TQI to quantify the condition of the track to carry out its functional requirements. In addition, the sensitivity of a TQI to monitor track condition, the computational complexity, the reliability, and the ease of interpretation were considered.

Physical Parameters

Many parameters influence the rate of track degradation. Initially in the program, representatives of FRA, Conrail, and ENSCO, Inc., selected the most feasible set of physical parameters based on previous studies, experience, and cost of data acquisition. Eleven parameters were selected, which are categorized into three areas: track structure, traffic, and maintenance. The parameters for track structure were quantified for each period of observation, and those for traffic and maintenance were quantified between the observations. The parameters are listed below:

Category	Parameter	Descriptive Unit or Term
Track structure	Curvature	Degrees
	Rail weight	Pounds per yard
	Rail type	Bolted, welded
	Ballast condition	Clean, dirty, pumping, fouled
	Rail profile	Percentage bent
	Drainage ability	Adequate or inadequate
Traffic	Track speed	Miles per hour
	Cumulative tonnage	Million gross tons
	Heavy load	Percentage
Maintenance	Basic	Levels 0, 10, 30, or above 30 percent
	Discretionary	Surfacing, tie and surfacing, rail renewal

Of the three traffic parameters, annual tonnage and heavy wheel loads were quantified for the test zone by a seasonal sampling method. Information on track speed was obtained from track charts and Conrail timetables. The heavy loads were determined by adding all the carloads that were more than 90 tons and then calculating the percentage of the total consist load.

Track charts were used to determine the rail weight and rail type. Curvature was quantified by using curvature data collected by the T-6 vehicle. Rail profile and ballast and drainage conditions were quantified by using field observations in accordance with Conrail criteria. Rail profile was defined as the percentage of the surface of the rail that is bent in a bolted-track segment. The ballast conditions were designated as clean, dirty, pumping, or fouled. The drainage condition was designated as adequate or inadequate.

Maintenance practices can be divided into two broad categories--basic and discretionary. The basic maintenance operations considered in this study were regaging, tie renewal, hand smoothing, machine smoothing, and surfacing. Quantification of basic maintenance was accomplished by determining the percentage of the segment that had received maintenance. The discretionary maintenance was categorized into three major operations: surfacing, tie and surfacing, and rail renewal.

Test Zone

A test zone representative of mixed freight operation was selected for this study. The test zone consisted of approximately 290 miles of Conrail main line in the Fort Wayne Division in Ohio and the Lehigh Division located in New Jersey and Pennsylvania. The Lehigh Division consists mainly of class 2 and 3 track and carries annual tonnage of less than 14 million gross tons. A significant portion of the track is curved and has steep gradients. On the other hand, the Fort Wayne Division consists mainly of class 3 and 4 tangent low-gradient track and carries heavy tonnage in the range of 18-25 million gross tons.

The test zone was divided into segments that were homogeneous with respect to the physical parameters. In this case, homogeneous means that a physical parameter such as tonnage is constant throughout the segment. The entire test zone was divided into 676 segments of variable length that ranged from 0.1 mile to a maximum of 1 mile. It should be mentioned that track segmentation is essential in determining the relationship between TQIs and physical parameters because this allows values of physical parameters to be associated with track geometry in a meaningful way.

A significant portion of the test zone received either basic or discretionary maintenance during the study period, which left approximately 200 segments of unmaintained track. In this paper, the degradation models are presented only for the unmaintained track.

The unmaintained segments had a good mix of class 2, 3, and 4 track. The annual tonnage ranged from 5 to 25 million gross tons. Approximately one-half of the segments consisted of tangent track and the other half had curves up to 12°. The rail weight ranged from 130 to 140 lb/yard, and approximately two-thirds of the segments were bolted. The overall drainage condition was good, and the ballast condition was mainly clean or dirty.

Degradation Models

Degradation models were developed to describe the relationship between TQIs and physical parameters. In this study, linear autoregressive techniques were used to develop predictive equations of the following type (8):

$$y = a + b_0\hat{y} + b_1x_1 + \ldots + b_mx_m \quad (1)$$

where

y = current TQI,
$\hat{y}$ = previous TQI,
a = estimated constant term,
b = estimated regression coefficient, and
x = physical parameter.

Predictive equations were developed for the final set of TQIs by using stepwise autoregression techniques (8) to include an optimum subset of physical parameters in the predictive equations. Analyses were performed to determine the contribution of various physical parameters to the change in a TQI. Complete details of the analysis performed are contained in an FRA report (8).

RESULTS AND DISCUSSION

Analysis of TQIs

An analysis of TQIs is provided to show that they provide an objective measure of track condition. This is illustrated in terms of track degradation, the effect of discretionary maintenance, FRA safety standards, and ride quality. Capabilities and potential applications of TQIs are also discussed in this section.

Figure 3 illustrates the manner in which a TQI (in this case the 99th percentile of warp) may be used to monitor track degradation. The 99th percentile of warp for a section of track is shown as measured in 1978 and 1979, during which time no maintenance was performed on this section. Note that all values of the TQI for 1978 lie below their respective values for 1979. If we recall that the higher value of a TQI indicates poorer track condition, Figure 3 clearly illustrates the ability of a TQI to quantify degradation.

Figure 4 illustrates the effect of discretionary maintenance as measured by a TQI. In this section of track, new rail was laid between the 1978 and 1979 surveys. In line with the established convention that low TQI values indicate better track condition, every segment shows improvement due to discretionary maintenance. Note also that the values of the TQI in 1979 are more-or-less uniform. Thus, a TQI may also be used to monitor the quality or uniformity of discretionary maintenance operations.

In order to bring into perspective the value of TQIs, a correlation study was performed between TQI values and federal track safety standards (8). Expected values of TQIs for the different track classes are plotted in Figure 5. The magnitude of the four TQIs consistently decreases as track class increases. It should be pointed out that these values should not be interpreted as thresholds for different track classes. These are the statistical values and provide the nominal range of expected values of TQIs for different track classes.

Figure 6 displays the surface condition of a subdivision of track in the test zone. Expected levels of the gage index for class 3 and 4 track as previously discussed are also indicated in the same figure. A review of the posted track class showed good agreement with the expected track class. Figure 6 also illustrates one of the most important features of the TQI, i.e., the ability to summarize graphically large sections of track, in this case 84 miles. This feature is especially useful to railroad personnel charged with MOW decision-making responsibility.

Track geometry inputs such as alignment or profile perturbations provide the primary means for measurement of vibrations induced in the freight or passenger car. The intensity of these vibrations (acceleration levels) affects lading damage and passenger comfort. The RMS acceleration levels induced in the car body were obtained from the track characterizations (9) and the characteristics of the vehicle suspension system, speed, and the roughness of the track. Vertical accelerations expected at different vehicle speeds for an 80-ton boxcar are plotted in Figure 7 for different TQIs. These vibration levels refer to random track-irregularity inputs of a broad frequency range. If a resonance response, such as harmonic roll, exists due to a periodic input in the track, decreasing the speed may not necessarily reduce the response.

This information may be used in a number of different ways. For example, if freight traffic is being scheduled over class 4 track and it is desired to maintain the lading vibration environment below an RMS acceleration of 0.04 g (a very practical upper limit based on tests of ride quality done by ENSCO, Inc.), the maximum timetable speed should be 42 mph as shown by the intersection of the dashed lines in the lower left-hand corner of Figure 7. Conversely, if the maximum required speed was 35 mph over this same track, it would not be necessary to maintain the track quality to the class 4 value (TQI = 0.14) but to a somewhat lower quality (TQI = 0.17). Thus maintenance allocations would not be used to overmaintain this section of track at the expense of other sections that required more work.

We have shown that a TQI can be used to measure track condition objectively. A TQI can be used to monitor track degradation and maintenance and also to summarize and display the condition of a large

Figure 3. Illustration of the ability of a TQI to monitor track degradation.

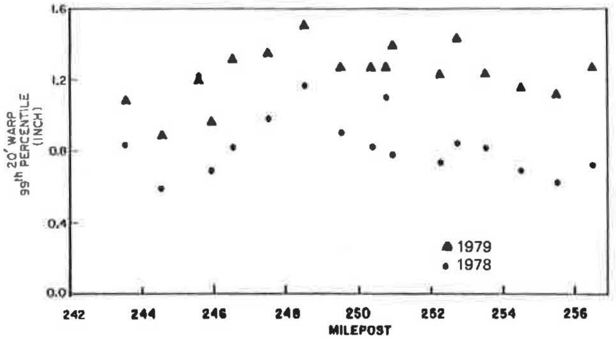


Figure 5. TQI correlation with federal track safety standards.

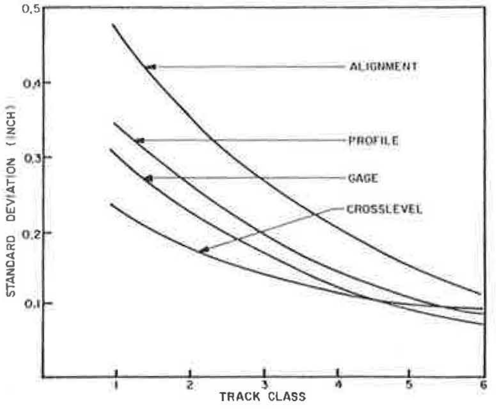


Figure 4. Effect of discretionary maintenance of a TQI.

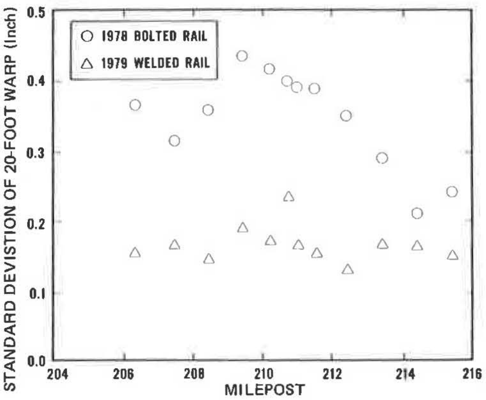


Figure 6. Gage roughness for a subdivision of track.

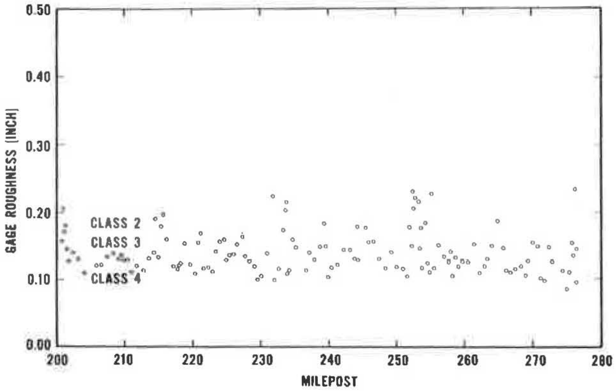
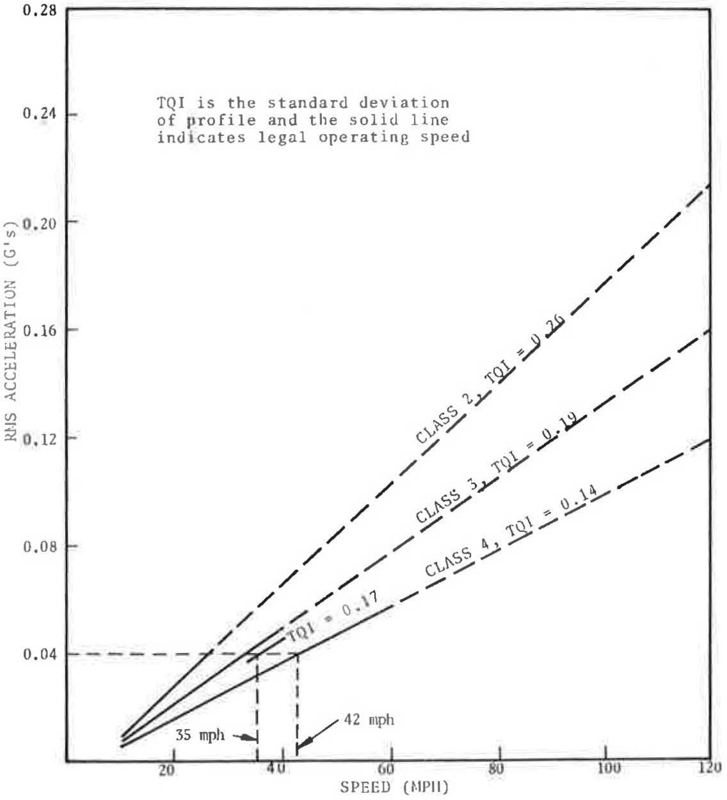


Figure 7. Relationship of TQI to ride quality.


TQI is the standard deviation of profile and the solid line indicates legal operating speed

section of track in a compact form. TQIs are related to FRA safety standards and ride quality and thus can be used in making decisions about scheduling and other train operations.

Final TQIs

Correlation analyses on the candidate TQIs were performed separately for the 1978 and 1979 data. For the purpose of this study, similar results were obtained for the two sets of data. For example, the TQIs that were highly correlated in 1978 were also highly correlated in 1979.

The correlation analyses indicated that indices in the same set (i.e., those calculated from the same track geometry parameter, such as gage, surface, and line) were generally correlated with each other. The final TQIs within a set were selected by using other criteria, as discussed earlier. The final set of TQIs are listed below:

1. Gage-roughness index (y_2): SD of gage in inches,
2. Wide-gage index (y_3): 99th percentile of gage in inches,
3. Surface index (y_7): SD of 20-ft warp in inches,
4. Line index (y_{13}): SD of 10-ft MCO of alignment in inches per 1000, and
5. Superelevation index (y_{14}): SD of unbalanced superelevation in inches.

Table 1. Predictive equations for unmaintained track.

TQI	Predictive Equation[a]	R^2
Gage roughness	$y_2 = -0.036 + 0.84\bar{y}_2 + 0.0007x_2 + 0.0008x_3$	0.89
Wide gage	$y_3 = 13.88 + 0.75\hat{y}_3 + 0.003x_1 + 0.0116x_4 + 0.0526x_6$	0.85
Surface	$y_7 = -0.004 + 0.92\hat{y}_7 + 0.0037x_1 - 0.0032x_4 + 0.069x_6 + 0.0005x_7 + 0.029x_8''$	0.90
Line	$y_{13} = 3.84 + 0.71\hat{y}_{13} + 0.429x_1 + 0.349x_4 + 6.57x_6 + 3.18x_8'$	0.83
Superelevation	$y_{14} = 0.043 + 0.94\hat{y}_{14} + 0.012x_4 + 0.0009x_7$	0.97

[a] $\hat{y}_i$ = previous value of a TQI; x_1 = tonnage; x_2 = percentage of heavy wheels; x_3 = speed; x_4 = curvature; x_6 = rail type (0 = welded; 1 = bolted); x_7 = percentage of bent rail; x_8' = ballast level 1 (mildly dirty); and x_8'' = ballast level 2 (pumping).

Track Degradation

This section describes track degradation for unmaintained track in terms of the final set of TQIs. The equations to predict track condition are described first. This is followed by the analysis of these equations. Finally, an illustration is given to show how these predictive equations can be used to predict track condition.

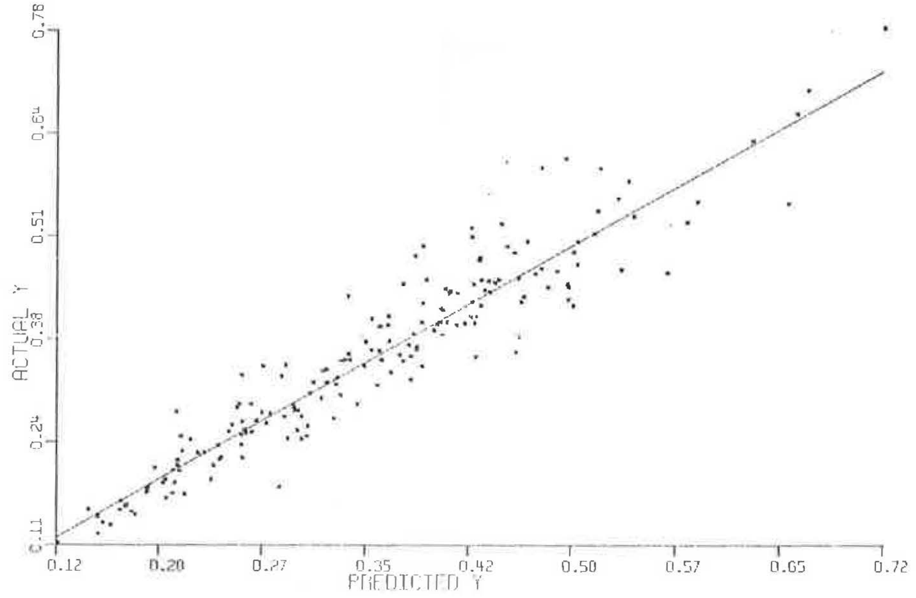
Table 1 lists the predictive equations for the final five TQIs. The predictive equations were developed by using stepwise autoregression (8). The F-value (10) for both the entry and the removal of a variable was set at 3.0. This assures with 99 percent confidence that the variables included in the predictive equations are significant. The predictive equations contain an optimum number of physical parameters from the ones considered in this study. The coefficients of determination (R^2) for all TQIs are well above 0.8, which means that the predictive equations explain at least 80 percent of the variations in TQIs.

The analysis of variance was conducted for the predictive equations. The computed F-values for all TQIs were very significant; in fact, in most cases they were more than 150. Therefore, it can be concluded with a 99.9 percent confidence level (11) that a significant amount of variations in the response variables (TQIs) are accounted for by the postulated models and that there is less than one chance in 1000 that the relationships are due to chance.

The ability of an equation to predict the y-values can be evaluated by plotting the y-values predicted by the equation versus the actual (observed) y-values. In the case of perfect prediction, all the points will be on a 45° line that passes through the origin. Figure 8 shows the plot of predicted y-values versus actual y-values for the surface TQI. The least-squares line drawn through the points was found to have a slope of unity (45° line) and an intercept of zero. Similar results were found for other TQIs. Thus these equations provide good prediction of track condition as measured by TQIs. The spread around the least-squares line can possibly be reduced by including additional physical parameters not considered in this study.

Table 2 shows the effect of adding various physical parameters in the predictive equation for the

Figure 8. Actual versus predicted value of surface TQI.



surface TQI. Note that the previous value of the TQI is the most significant parameter and that rail type and tonnage are the next most important. It should be noted that the addition of successive variables improves the predictability of an equation with diminishing returns. The addition of an extra variable should be evaluated in terms of economic returns, since an extra variable means additional costs for data collection. For example, one might be satisfied with the following equation for the surface TQI to explain 88.6 percent of the total variations:

$$y_7 = -0.033 + 0.98\hat{y}_7 + 0.0045x_1 + 0.067x_6 \qquad (2)$$

where

y_7 = future value of the surface TQI,
$\hat{y}_7$ = previous value,
x_1 = tonnage, and
x_6 = rail type (0 = welded and 1 = bolted).

Figure 9 illustrates how the predictive equations can be used in MOW planning. In this example, the surface condition of 7 miles of a welded-track section is projected by using Equation 2. The solid circles indicate the data points measured in 1978 and 1979. The open circles indicate the track condition projected by Equation 2. Note that the measured condition of track in 1979 is lower (better) than the projected condition. This section of the track received discretionary surfacing during 1978 and 1979. The dashed line then represents the effect of the surfacing operation. The annual tonnage on this section of track was 7 million gross tons during the study period. Based on Conrail historical data, the annual tonnage is estimated at 10 million gross tons for 1980 and 15 million gross tons for 1981. Track condition is projected by using these tonnage values for 1980 and 1981. Note that if no maintenance is performed, this track section is estimated to be within the standards for class 3 in 1981. This ability to project the track condition can help the management to make decisions as to what maintenance (if any) should be performed.

Table 2. Contribution of different physical parameters to predictive equation of surface TQI.

Variable Added	Predictive Equation	R^2
Previous value	$y_7 = 0.014 + 1.16\hat{y}_7$	0.800
Rail type	$y_7 = 0.015 + 0.99\hat{y}_7 + 0.068x_6$	0.846
Tonnage	$y_7 = -0.033 + 0.98\hat{y}_7 + 0.067x_6 + 0.0045x_1$	0.886
Percentage of bent rail	$y_7 = -0.018 + 0.92\hat{y}_7 + 0.065x_6 + 0.0044x_1 + 0.0008x_7$	0.893
Curvature	$y_7 = -0.006 + 0.93\hat{y}_7 + 0.067x_6 + 0.0037x_1 + 0.0007x_7 - 0.0031x_4$	0.897
Ballast level 2	$y_7 = -0.004 + 0.92\hat{y}_7 + 0.069x_6 + 0.0037x_1 + 0.0005x_7 - 0.0032x_4 + 0.029x_8''$	0.899

CONCLUSIONS AND APPLICATIONS

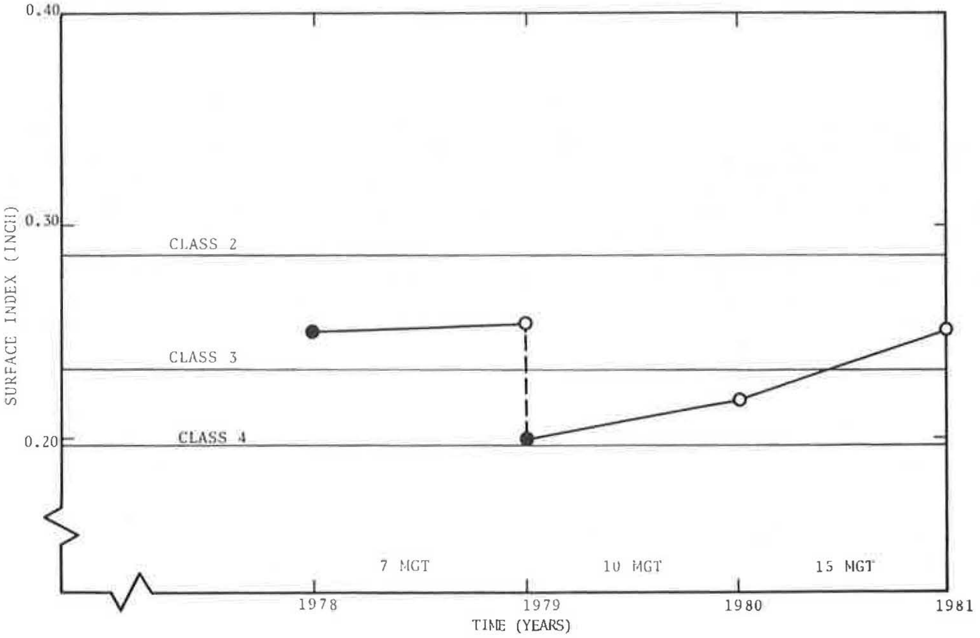
This paper has shown the feasibility of using data from automated track geometry cars along with other track-related data in long-range track maintenance planning. First, it has been shown that TQIs objectively quantify the ability of the track to carry out its functional requirements. Second, it has been found that there exist well-defined relationships between TQIs and certain physical parameters that affect track condition.

It has been shown that five TQIs effectively quantify the condition of track to carry out its functional requirements. The five TQIs are the gage-roughness index, wide-gage index, surface index, line index, and superelevation index.

It has been shown that the track-degradation models can be expressed in terms of TQIs. For unmaintained track, the physical parameters considered in this study accounted for at least 80 percent of the changes in TQIs over the study period. In a number of cases, more than 90 percent of the changes in the TQIs were explained by the physical parameters.

One of the major results of this study is a set of predictive equations that in effect enables the projection of track condition. Furthermore, TQIs can summarize the condition of a large section of track in a clear graphic format on a single sheet of paper. This feature is very valuable, since the railroad management can easily identify those areas of track that may soon require work to remain within posted class standards. The knowledge of the rela-

Figure 9. Projection of track condition.



tionship between TQIs and ride quality can be used to determine the timetable speeds for safe shipment of goods. TQIs offer an additional potential use in the quality assurance of discretionary maintenance.

FRA plans to continue this research to develop analytical techniques for maintenance planning. The major emphasis of the future research will be to develop an analytical technique for planning expenditures for basic maintenance.

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Use of Stabilized Layers in Track Structure

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Stabilization of soils and granular materials by using various admixtures (lime, cement, lime and fly ash, and bituminous materials) significantly improves pertinent engineering properties. Typical effects are increased strength, increased stiffness, improved durability under adverse conditions such as excess moisture and freezing and thawing, reduced plasticity and swell potential, and improved workability. Stabilized subgrade and subballast layers have been successfully used in track structure for various purposes. The effects of stabilized layers on ballast properties, track structure behavior, and performance are considered. Specific topics considered are (a) alleviation of subgrade intrusion, (b) shear-strength conditions at interface between ballast and subgrade, (c) comparative behavior of track sections with and without stabilized layers, and (d) thickness design concepts (based on analyses that use models such as ILLI-TRACK).

Stabilization of soils and granular materials by using various admixtures (lime, cement, lime and fly ash, and bituminous materials) significantly improves pertinent engineering properties. Typical effects are increased strength, increased stiffness, improved durability, reduced plasticity and swell potential, and improved workability. Current stabilization technology and practices have been well summarized in recent publications (1-11).

Stabilized materials, particularly lime and cement, have been successfully used in track structure for various purposes. Stabilization of in situ soils or imported materials is becoming more common in track construction. In a recent article (12), Newby indicated the potential of admixture stabilization for subgrade stabilization.

In this paper, emphasis is placed on the effect of stabilized layers on track structure behavior and performance. Specific topics considered are (a) alleviation of subgrade intrusion, (b) shear-strength conditions at the interface between ballast and subgrade, (c) comparative behavior of track sections that have stabilized layers and those that do not, and (d) thickness design concepts (based on analyses that use models such as ILLI-TRACK).

SUBGRADE INTRUSION

Many engineering properties of granular materials are adversely affected by an increase in the amount of fines. Shear strength, permeability, resilient