Development of Railroad Track Degradation Models

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Maintenance of railroad tracks is both costly and difficult to manage effectively. The track geometry measurement car allied to modern data processing techniques is a valuable tool that can be used to improve railroad safety and the cost-effectiveness of track maintenance. An approach to using track geometry data in maintenance management being developed under a joint FRA-Consolidated Rail Corporation (Conrail) cooperative program is outlined in this paper. The functional requirements of track are to permit the safe and economic movement of rail traffic. The definition of track quality indices (TQIs) derived from track geometry data to reflect the ability of track to meet functional requirements and progress in the development of track deterioration models are described. The models predict how track quality, as measured by TQIs, changes as a function of causal parameters, such as traffic, track type, and maintenance. Preliminary track deterioration models have been developed by using a combination of empirical statistical analysis and engineering analysis, and the uses of deterioration models in track maintenance planning are discussed. The statistical analysis is supported by a data base of track quality and causal parameter information for 350 miles of Conrail freight trackage obtained during a 4-year period.

One of the major railroad operating expenses is for maintenance of way (MOW), which covers the maintenance of track, roadbed, buildings, bridges, tunnels, signals, and communications. In 1980 U.S. railroads spent approximately $4.75 billion on MOW, approximately 70 percent or $3.3 billion of which was spent on the maintenance of the track and roadbed (1). For the well-being of the industry track maintenance funds should be spent effectively and accidents and train delays due to inadequate track should be minimized. In addition to being costly, track maintenance is difficult to manage. A large railroad may have up to 20,000 route miles and cover a geographical area of 2,000 miles from end to end. Quantitative data on track conditions must be available to management to ensure that maintenance is planned and executed as effectively as possible.

The track geometry car, linked to modern data processing and management techniques, provides management with quantitative data on track condition. FRA, in cooperation with the Consolidated Rail Corporation (Conrail), is sponsoring a research program to develop an approach to using track geometry data to improve safety and maintenance planning. The key elements of the approach are as follows:

1. Define the functional requirements of track,
2. Select track geometry statistics [called track quality indices (TQIs)] that relate to the ability of track to meet its functional requirements,
3. Use empirical and engineering analysis to develop models that predict the change in track quality (as measured by TQIs) as a function of key causal factors, and
4. Develop a methodology for using the track deterioration models to improve safety and maintenance effectiveness.

The FRA research program was initiated in 1978. Initial empirical track geometry degradation models were developed from 1 year of data over 250 miles of Conrail tracks (2). A comparison of actual and predicted track degradation over a portion of this trackage indicated that partial success had been achieved and that further development was desirable. Progress to date in refining the track degradation models and the related data acquisition and reduction techniques is reported in this paper.

USES OF TRACK GEOMETRY DATA

Although track geometry cars have been used in the railroad industry for more than a century, their use has greatly expanded during the last 10 years in response to developments in instrumentation and data processing. Most major railroads and FRA have now acquired track geometry cars for track inspection and have been developing data reduction and analysis techniques to improve safety, maintenance planning, and track quality control.

The three basic approaches to using track geometry data in maintenance planning follow. The traditional use of track geometry data is track inspection to locate exceptions to railroad or federal track standards. The objective is to identify track defects that need immediate correction. An example of this type of use is the FRA's automatic track inspection program, where track geometry is analyzed to provide printouts of exceptions to federal track safety standards.

A more recent devlopment is to use the data to provide a characterization of the overall present track condition. The normal approach is to divide the trackage into segments, typically between 0.25 and 1 mile in length, and to compute track geometry statistics for each segment. The geometry statistics can be summed to arrive at a measure of overall segment track quality, which is used as an input to maintenance planning. This approach is typified by that developed by Tuve and his colleagues (3) on the Southern Railway, where a track geometry rating (TGR) is used to characterize track. TGR is statistically related to the incidence of slow orders and derailments and is used to recommend maintenance priorities.

The most recent development in the use of track geometry data is to use track deterioration models to predict future track quality. This approach is currently at the research and development stage and is the subject of the remainder of this paper. Estimates of future track quality can be used to assist maintenance planning and in the selection of the most economical maintenance practices and track structure to meet safety and service requirements. The track deterioration models quantify the influence of the factors that affect track deterioration, called causal parameters, on track quality. These typically include traffic, track type, and maintenance parameters.

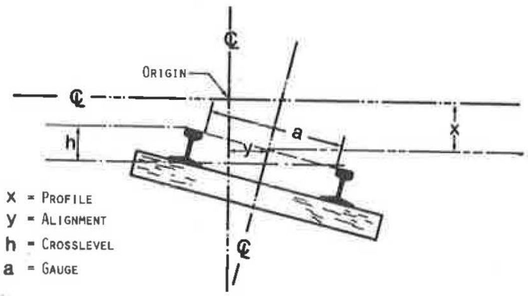
MEASUREMENT OF TRACK GEOMETRY AND CALCULATION OF TQI

The function of a track geometry car is to measure the four basic parameters that define the position of the rails relative to fixed reference axes in the ground (Figure 1). These parameters are as follows:

1. Profile (x): Vertical deviation of track centerline measured level with the top of the rails,
2. Alignment (y): Lateral deviation of track centerline, measured at a reference height (usually 5/8 in.) below rail head,
3. Gauge (a): Distance between rails measured at a reference height (usually 5/8 in.) below rail head, and
4. Cross-level (h): Vertical height difference between railheads.

The measurements are made at discrete intervals, typically 1 ft, along the track. Track geometry cars also measure distance along track, curvature,

Figure 1. Track geometry parameters.



and car speed and have some system for locating car position along the track. Ta-Lun Yang et al. have given a detailed description of a modern track geometry car, FRA's T10, that is similar to the FRA T6 car, which provides the data used in this project (4).

TQIs are statistics calculated from the raw track geometry data for a track segment. To be useful in maintenance planning TQIs should relate to the ability of track to perform its functions. The functional requirements of track can be stated as follows:

1. To support the movement of traffic with an acceptably low risk of track-caused derailments, and
2. To permit a quality of service (speed and ride quality) to be offered that suits the needs of the railroad's customers.

Proper quantification of the relationship betweeen possible TQIs and the functional requirements is a complex task; however, some guidelines are available to assist TQI choice. This project is primarily concerned with general mixed freight. For this type of freight, safety or derailment risk is the prime factor influencing TQI choice, and ride quality has a secondary influence.

Apart from the social responsibility of a railroad to run a safe operation, derailments affect direct and indirect operational costs and decrease revenue by reducing service reliability and harming a railroad's reputation with shippers. Accident-risk considerations also drive decisions to place slow orders on track, which also increase operational costs and reduce the quality of service to the shipper.

Ride quality can affect costs by damaging shipments, which leads to loss and damage claims. A brief review of these claims, however, suggests that this is a comparatively small factor. A more significant effect of poor ride quality may be the added cost associated with the wear and deterioration of freight cars and locomotives and fuel consumption (5).

TQIs chosen for this track deterioration analysis were standard deviation and 95th percentile of the filtered track geometry measurements. The raw measurements are filtered to remove long wave length irregularities that do not affect derailment risk or ride quality significantly. The filtering process involved first calculating a 50-ft running mean of track geometry measurements and then taking the difference between the running mean and the original measurements to give the filtered measurement. The choice of the 50-ft running mean was based on freight cars that have suspension natural frequencies in the range 1.5 to 5.0 Hz and run at speeds up to 45 mph. A longer base for the running mean calculation would be appropriate for vehicles that have softer suspensions or operate at higher speeds. TQIs for an individual segment are the standard deviation and 95th percentile of all measurements within the segment. The 95th percentile is that value exceeded by 5 percent of the filtered measurements in the segment.

Initial analysis has been concentrated on five surface-related TQIs:

1. Standard deviation of filtered cross-level,
2. Ninety-fifth percentile of filtered cross-level,
3. Standard deviation of filtered profile,
4. Ninety-fifth percentile of filtered profile, and
5. Standard deviation of 20-ft warp (differences in cross-level).

Although similar to cross-level standard deviation, the warp TQI was included to provide continuity with earlier phases of the program. Study of alignment and gauge TQIs was deferred for future study.

TRACK DEGRADATION CAUSAL PARAMETERS

The basic track deterioration modeling process involves the use of engineering and empirical statistical analysis to produce an equation that shows how TQI or change in TQI is influenced by the causal parameters. The causal parameters selected for this analysis are listed in Table 1 and discussed in the following sections.

Traffic Data

Traffic consists of tonnage in the time slice between track geometry measurements and train speed data. Two parameters have been used to quantify tonnage--total gross tons, and percentage of high axle load (>45,000 lb) tonnage. Two speed parameters have been used, posted speed and estimated actual speed. The estimated actual speed is calculated from the posted speed modified by slow orders and acceleration and braking distance. Speed will also be affected by power to weight ratio, but this was not considered at this stage.

Track Structure Data

Track charts and maintenance records are used to quantify rail weight, age, type (welded or jointed) and time since production surfacing. Curvature is provided by the T6 car track geometry records. Ballast type, ballast condition, and drainage condition are quantified by field observation to specified

Table 1. Track degradation causal parameters.

Category	Causal Parameter	Units
Traffic	Tonnage in time slice	Million gross tons
	Heavy axleloads	Percent
	Equivalent tonnage	Million gross tons
	Posted speed	mph
	Estimated actual speed	mph
Track structure	Curvature	Degrees
	Rail weight	lb/yd
	Rail type	Welded-jointed
	Rail age	Years
	Ballast type	Aggregate index
	Ballast index	Coded
Maintenance	Time since surfacing	Months
	Basic maintenance	Fraction
	Production maintenance	Segment affected
	Surface	Fraction
	Tie renewal	Segment affected
	Rail renewal	Segment affected
Other	Frost damage index	Coded

Table 2. Significant causal parameters in surface deterioration from engineering analysis.

Causal Parameter	Significance
Present surface TQI	High
Annual tonnage	High
Axle load mix (percentage heavy wheel loads)	High
Train speed	High
Ballast type	High
Track modulus (function of ballast type and condition)	High
Ballast and drainage condition	Moderate
Time since surfacing	Moderate
Freeze-thaw cycles	Moderate
Curvature	Moderate

criteria. Overall roadbed condition was quantified by a ballast index derived from an aggregate index of the ballast material, modified by factors for ballast and drainage condition.

The aggregate index is determined from the results of Los Angeles abrasion and millabrasion tests, as described by Raymond (6). Ballast index (BI) is given by the formula:

$$BI = AI(BC + 1)^{1/3} + DF \qquad (1)$$

where

AI = aggregate index (typically 40 for granite and 65 for limestone),
BC = ballast condition on a scale of 0 (excellent) to 3 (poor), and
DF = drainage factor (10 = good; 20 = bad).

The factors for ballast condition and drainage were based on limited tests on degraded ballast. Ballast index values range from 40 (excellent) to 120 (very poor).

Maintenance Data

Maintenance performed (both basic and production) is recorded by nature and quantity of work performed (e.g., ties replaced or track-feet surfaced), date, and location. They are summed to give the total work performed on each segment between track geometry surveys.

Other Parameters

Geographical factors such as climate and soil type are expected to affect track deterioration rates. Probably the most important is the effect of frost. A frost damage index (FDI), made up of terms to represent freezing degree days, number of freeze-thaw cycles, and winter precipitation has been quantified for each test zone and year.

Summary

All these parameters have been quantified for a selected portion of the Conrail test trackage and time periods for which track geometry data are available. These have been combined with corresponding TQI data into a comprehensive data base for statistical track degradation analysis.

TRACK DEGRADATION ANALYSIS

Two basic approaches can be used in track degradation analysis. The engineering approach (7) consists of establishing, by theory and testing, the mechanical properties of all the elements that make up the track structure and the railroad vehicles. Then engineering mechanics analysis is used (a) to determine the loads that the vehicle will impose on the track as a function of vehicle type, track mass, stiffness, and speed and (b) to predict the track permanent deformation under these loads. The advantage of this approach is that it provides a good engineering understanding of how track responds to vehicle loading. The disadvantage is that the mechanical properties of vehicles and track are variable and difficult to quantify. This means that absolute predictions of track degradation, particularly of how track roughness changes, are difficult.

The statistical approach involves the analysis of many observations of actual track performance and the corresponding causal parameters. The track performance, as measured by TQI or change in TQI, is the dependent variable, and the causal parameters are the independent variables. Correlation analysis, analysis of variance, and regression analysis are used to develop track degradation models. The advantage of this approach is that, because actual observations are used, it can give absolute predictions of track performance. The disadvantage is that, without the engineering understanding, inappropriate model forms may result. These may fit the set of observations used for analysis but give misleading results for different combinations and values of causal parameters.

A combined approach has been adopted in the FRA research program to develop track surface deterioration models. First, an engineering analysis was performed that suggested the form of the relationship between the causal parameters and change in TQI and the likely importance of each parameter. Statistical analysis is then used to calibrate the engineering model. In practice, model form is a compromise between that suggested by engineering analysis and that which lends itself to statistical analysis.

The significant causal parameters for deterioration of surface are given in Table 2. Note that only the causal parameters that vary significantly on the Conrail test trackage are given. This excludes, in particular, tie type, spacing, and condition; rail weight; and vehicle type. Equation 2 is a highly simplified form of an engineering degradation equation.

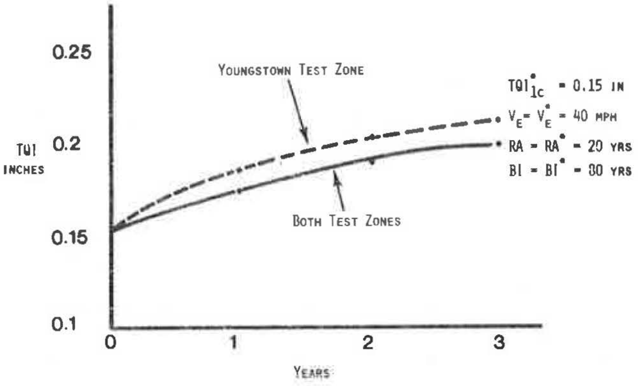
$$\begin{aligned} TQI = {} & K_0 + K_1 \text{ (vehicle loading term) (ballast settlement term)} \\ & + K_2 \text{ (weathering term, FDI)} \\ & + K_3 \text{ (maintenance term)} \end{aligned} \qquad (2)$$

The vehicle loading term is a function of tonnage, axle loads, speed, existing track quality, and track modulus and is basically multiplicative. The ballast settlement term is a function of BI. K_0, K_1, K_2, and K_3 are coefficients.

The statistical analysis relies on 460 observations of actual performance of the Conrail trackage. The trackage used is situated in two test zones on the Conrail system, one in the Youngstown division and one in the Lehigh division. Each observation consists of the five TQIs at the beginning and end of a 1-year period and the corresponding causal parameters. These data were first analyzed for correlations among the TQI, among the causal parameters, and between change in TQI and the causal parameters. The results from this showed the following:

1. The two profile-related TQIs and the three cross-level-related TQIs correlated strongly with each other. Standard deviation of filtered profile and standard deviation of filtered cross-level were chosen for model development, as representative of the two groups.
2. Some strong correlations among causal param-

Figure 2. Predicted cross-level standard deviation TQI.



eters existed in this data set, which limits the ability of statistical analysis to separate the influence of such parameters.

3. A preliminary indication of which causal parameter appeared to influence track degradation was obtained.

After some preliminary analysis a basically multiplicative form of model was chosen. This is shown in Equation 3.

$$\begin{aligned}TQI_2/TQI_1 = {} & \alpha_1 \exp [\alpha_2(TSS)] \, (V_E/V^*_E)^{\alpha 3} \, (RA/RA^*)^{\alpha 4} \\ & x \, (TQI_{1p}/TQI^*_{1p})^{\alpha 5} (TQI_{1c}/TQI_{1c})^{\alpha 6} \\ & x \, (BI/BI^*)^{\alpha 7} \, (1 + FS)^{\alpha 8} \, (EMGT \\ & \div EMGT^*)^{\alpha 9} \end{aligned} \qquad (3)$$

where

TQI_1 = Initial track quality index in time period (in.),
TQI_2 = Final track quality index in time period (in.),
TSS = Time since surfacing (months),
V_E = Equivalent train speed (mph),
RA = Rail age (years),
BI = Ballast index,
EMGT = Equivalent million gross tons in time period = total tonnage + heavy axle load tonnage,
FS = Fraction of segment surfaced, $\alpha_1 \cdot \cdot \cdot \alpha_9$ are determined by statistical analysis,
V^*_E and RA^* are arbitrary fixed reference values of each parameter. These were chosen to be representative of typical track, and
Suffixes c and p refer to cross-level and profile TQIs.

This model represents a compromise between the engineering model, with its combination of multiplicative and additive terms, and a form that is convenient to handle statistically. Equations 4a and b give examples of the resulting models and Figure 2 is an example of a degradation prediction by using the model. Terms without statistical significance were omitted.

For the Youngstown division test zone,

$$\begin{aligned}TQI_{2c}/TQI_{1c} = {} & 1.25 \, (TQI_{1c}/TQI^*_{1c})^{-0.58} \, (V_E/V^*_E)^{-0.18} \\ & x \, (RA/RA^*)^{-0.11} \, (BI/BI^*)^{1.04} \\ & x \, (1 + FS)^{-0.44} \end{aligned} \qquad (4a)$$

For the combined Youngstown and Lehigh division test zones,

$$\begin{aligned}TQI_{2c}/TQI_{1c} = {} & 1.18 \, (TQI_{1c}/TQI^*_{oc})^{-0.46} \, (V_E/V^*_E)^{-0.053} \\ & x \, (RA/RA^*)^{-0.21} \, (BI/BI^*)^{0.53} \\ & x \, (1 + FS)^{-0.39} \end{aligned} \qquad (4b)$$

$R^2 = 0.49$.

Note that the model predicts annual degradation with approximately 18 million gross tons.

The absence of a significant relationship between tonnage and degradation is disappointing but is apparently caused by a limited range and number of tonnage values in the data and correlation with other causal parameters.

Some shortcomings both in model form and in the statistical techniques used have been recognized, and further model development is in progress. This will be followed by an analysis of the impact of production surfacing on the surface TQIs.

Many uses for an ability to predict track deterioration can be suggested. By predicting track quality over future years, the time at which track quality reaches a minimum acceptable standard can be determined and used to order the priority for maintenance, plan maintenance, and set inspection schedules. If the cost and relative impact on track quality of different maintenance operations is known, then optimization analysis can be used to indicate the most economical approach to maintaining track to a desired standard. The relative performance of different track components and materials can be quantified and the information can be used to support purchase decisions.

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Rehabilitation of Amtrak Baltimore and Potomac Railroad Tunnel in Baltimore, Maryland

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Rehabilitation of the National Railroad Passenger Corporation (Amtrak) Baltimore and Potomac (B&P) Railroad Tunnel in Baltimore, Maryland, built between 1871 and 1873, was undertaken by Amtrak and funded by the Northeast Corridor Improvement Project (NECIP). Planning of the project was undertaken jointly by Amtrak, FRA, and De Leuw, Cather/Parsons and Associates (DCP). Construction management services were provided by DCP. The tunnel rehabilitation effort, planned improvements, and problems encountered and action taken to overcome them are described. The double-track tunnel is a vital link in the Washington to New York freight and passenger main line and its deteriorated condition made its rehabilitation a primary goal of NECIP. After field inspections and engineering analyses were completed, the repairs agreed on were to (a) rehabilitate the existing invert, (b) repair the tunnel lining, (c) rebuild the gunite casing of the arch and walls, (d) install 140-lb continuous welded rail, (e) install a new gantlet track, (f) grout the invert, and (g) clean and improve the drainage system. The work was designed to be accomplished by contractor forces and Amtrak employees. To date three new sumps have been installed. Work on one track has been completed and work on the second track was scheduled to begin early in 1983.

The Baltimore and Potomac (B&P) railroad tunnel is located immediately south of the Baltimore passenger station and is within the heavily used Washington to New York passenger and freight main line known as the Northeast Rail Corridor. In 1980 a major rehabilitation of the tunnel was undertaken by the National Railroad Passenger Corporation (Amtrak) and funded by the Northeast Corridor Improvement Project (NECIP). Planning of the project was undertaken jointly by Amtrak, FRA, and De Leuw, Cather/Parsons and Associates (DCP). Construction management services were provided by DCP.

INTRODUCTION

The B&P Tunnel was built in 1871-1873 at a cost of about $2.3 million. Constructed in three sections, it spans a distance of 6,948 ft and has an inside height of 22 ft and a width of 27 ft (with slight variance at curves) to accommodate two tracks (Figure 1). The north section (approximately 1,150-ft long) is known as the John Street Tunnel; the center section (approximately 3,650-ft long) is known as the Wilson Street Tunnel; and the southern section (approximately 2,200-ft long) is called the Gilmor Street Tunnel. The largest gap between sections (approximately 300 ft) is between the Wilson and Gilmor Street Tunnels. The ruling grade is 1.34 percent through the Wilson and John Street Tunnels.

Original construction was cut and cover, except for a 1,057-ft section that required boring through rock. Side walls generally were made of masonry 4- to 6-ft thick and the arch was made of five rings of brick with masonry rubble. Quicksand and shifting earth were encountered in several locations during construction, and serious water problems resulted from underground springs and heavy rains. Water has continued to be a serious problem; water and sewer lines running along, over, and under the tunnel have deteriorated as the result of age and train vibrations.

By the turn of the century rail traffic through Baltimore had become so great that the Pennsylvania Railroad gave serious consideration to ways of relieving the congestion. The problem was compounded because evolving railroad technology had produced larger and higher locomotives and cars that required greater clearance. The floor of the tunnel was lowered approximately 2.5 ft in 1916-1917 to accommodate larger trains. The track was reconstructed on block ties fastened directly to a new concrete invert, and drainage was provided by a 10-in. pipe embedded in the invert in the center of each track with drop inlets at 100-ft intervals. The base of the walls was chipped away to improve horizontal clearance, with the result that the original wall thickness of 4 to 6 ft was reduced to a thickness of 1 ft 10 in. in some locations.

By 1923 the tunnel had become so badly damaged by constant leaks and locomotive exhaust blasts that lining repair became a continuing operation. The tunnel was subsequently closed to train operations on at least two occasions because of flooding. Major renovations were performed in 1935-1936 to install an oilostatic power line and catenary for electrification and in 1959 to improve clearance and install a gantlet track for freight trains.

As early as 1915 the Pennsylvania Railroad considered building new tunnels parallel to the existing Union and B&P Tunnels to provide additional capacity and alleviate traffic congestion. By 1928 railroad authorities were characterizing Baltimore as the bottle neck of north-south rail traffic. Debate on this subject continued for many years and, during the early stages of planning for NECIP, consideration was given to either outright replacement of the present B&P Tunnel or the construction of a parallel tunnel. The cost of building a new tunnel, estimated to be $200 million in 1974 dollars, when ranked against NECIP requirements and funds available and when coupled with the possibility that con-