Application of Life-Cycle Costing and Demand-Responsive Maintenance to Rail Maintenance of Way

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ABSTRACT

Although rehabilitation and renovation are becoming an increasingly important aspect of construction activity, comparatively little work has been devoted to the development of planning and management tools to evaluate different maintenance policies. In contrast with the design of new construction, the planning and management of maintenance (including routine maintenance, rehabilitation, and renovation) are more concerned with the long-term performance of an existing facility and associated life-cycle costs. Performance and costs are influenced not only by the quality of initial design and construction but also by the magnitudes and frequencies of the actual loads imposed, the actual environmental conditions encountered during service, aging, and the maintenance actually performed on the facility through its life. Because the interactions among these factors are complex, most managers extrapolate maintenance trends and costs from past experience and fail to investigate useful alternatives in maintenance policy through life-cycle costing. In work with the Red Nacional de los Ferrocariles Espanoles (RENFE) (Spanish National Railroad), some new concepts in maintenance management (referred to as a demand-responsive approach) were applied to study several different track maintenance policies. For each alternative not only total program costs, but also the impacts on future system condition, were computed. As a result of this research, a number of key findings emerged for RENFE top management. The analytical concepts of the demand-responsive approach and their application to the Spanish rail network are described.

The rehabilitation and renovation of existing, mature facilities are becoming increasingly important components of construction activity. However, comparatively little work has been devoted to the development of planning and management tools intended specifically for maintenance programs, particularly life-cycle costing of facilities. [For brevity, the term "maintenance" will be used in this paper in a broad sense, encompassing routine maintenance, rehabilitation (i.e., major repair), and renovation (i.e., substantial replacement of ballast, ties, and rail).] Yet, decisions regarding the planning, financing, budgeting, implementation, monitoring, control, and evaluation of maintenance are different from corresponding actions for new construction, in several ways:

1. Mature facilities require an understanding of the concepts underlying their performance, as opposed to their design. Good performance models, which can predict the behavior of a facility and its deterioration as a function of loading history, operating environment (temperature, moisture, soil conditions, etc.), aging, and past maintenance performed are scarce and have not been the focus of much research (in relation to design). Properly developed performance models could be used for design; design procedures cannot always be used for performance.
2. Because rail links rarely fail catastrophically, it is difficult to define the point of failure. This, in turn, complicates the specification of standards governing track performance, safety, and cost. In shifting industry emphasis from new construction to maintenance, engineers may have to rethink the process by which routine maintenance, rehabilitation, and renovation standards are now developed and enforced. This also holds for those facilities that do fail catastrophically (i.e., suddenly and with potentially large loss of life), but the ways in which specific technical and safety issues are addressed analytically will differ.
3. There is a need to understand the role of maintenance itself in influencing track performance. In virtually all performance studies, emphasis is placed on the effects of loads, environment, and aging; in contrast, there is little information about the influence of preventive or corrective maintenance on the subsequent rate of track deterioration.
4. Decisions to repair existing track are complicated by the wide range of activities possible (ranging from minor routine maintenance to major rehabilitation or reconstruction), problems in spatial and temporal allocation of resources throughout a network, and choices between investment and noninvestment policies (e.g., strengthening of track versus imposition of load limits).
5. As a result of Items 1-4, the optimization of maintenance policy is difficult. New concepts and analytic approaches need to be introduced among those responsible for transportation infrastructure, together with complementary support activities (e.g., inspection and monitoring, collection of relevant data, revisions to existing management systems and procedures, introduction of new technology).
6. The management of mature infrastructure implies an ability to evaluate life-cycle performance

and costs. Trade-offs must be measured in economic as well as technical terms to account for impacts to facility owners, users, and nonusers and to provide a consistent basis of measurement for decisions made at different points in a (possibly extremely long) life span.

In addressing these issues, the concepts needed to address facility maintenance itself will be summarized. Then analytic approaches that have been used to implement these concepts within workable procedures will be described. Finally, the application of these procedures to the rehabilitation of the Spanish National Railway will be illustrated.

CONCEPTS OF LIFE-CYCLE COSTING

Analysis of Track Maintenance Alternatives

This work is based on the premise that planning and managing facility maintenance requires a life-cycle approach; that is, consideration of the total costs of construction, routine maintenance, rehabilitation, and use of the facility throughout its service life. There are several reasons for this.

First, as the key component of a rail facility, the track embodies critical trade-offs among the economic costs of construction, maintenance, and rehabilitation (all engineering issues) and of train operation, travel time, accidents, and smoothness of ride (operational and marketing considerations). Furthermore, because these costs accrue in a time span that typically covers several decades, life-cycle costing is a natural and appropriate methodology for analyzing track investment strategies.

Second, for those facilities (such as track) that do not fail catastrophically, it is difficult to define the points at which the facilities require repair or renewal. This, in turn, complicates the specification of design, maintenance, and rehabilitation standards governing track performance, safety, and cost. Life-cycle cost analyses can be used, however, to estimate both the total and the marginal benefits and costs of alternative standards, thereby providing economic as well as engineering guidance on the selection of the appropriate track investment strategy.

Third, life-cycle cost analyses, if properly formulated, help in the understanding of the role of routine maintenance and rehabilitation in influencing track performance. This capability contrasts with, for example, conventional analyses of track design and construction, which emphasize the effects of train loads, environment, soils, and aging but which offer no information relating routine maintenance or rehabilitation policy to the subsequent rate of track deterioration. Where this gap in information exists, policy makers cannot analyze well the impacts of deferred maintenance, nor can they assess effectively potential trade-offs among initial design standards, construction quality, and future maintenance requirements. Such studies are feasible, however, using life-cycle cost analyses.

Fourth, decisions to repair or rebuild track are complicated by the wide range of activities possible (ranging from minor routine maintenance to major rehabilitation or reconstruction), problems in spatial and temporal allocation of resources throughout a network, and choices between investment and noninvestment policies (e.g., strengthening of track versus adjustments in train load or speed limits). Life-cycle analyses can illuminate the long-term costs and benefits of these different courses of action.

Demand-Responsive Approach

The implementation of life-cycle analyses of track required a new approach to looking at track performance and the factors that influence costs throughout its service life. This approach is referred to as "demand-responsive" because routine maintenance, rehabilitation, or reconstruction are viewed as responses to the demand for repair or renewal of the facility. This demand for work arises through both a physical dimension (the condition of the facility, which reflects the quality of initial design and construction; the accumulation of wear and damage from the combined effects of traffic loads, environment, and age; and corrections due to past repairs) and a policy dimension (standards of initial design and construction and the level of maintenance, rehabilitation, or reconstruction to be performed, expressed through quality standards). Furthermore, because the prediction of facility condition is central to the demand-responsive approach, the impacts, as well as the costs, of alternative investment policies can be computed.

Treating routine maintenance, rehabilitation, and reconstruction as demand-responsive activities requires that three additional elements be introduced within existing planning and management models. The first is that estimates of future resource requirements and costs cannot be extrapolated from past trends; they must instead be based on predictions of structural and operational deficiencies caused by use, environment, and age. The second is that, in designing models to be sensitive to the implications of different policies, there must be unambiguous statements of maintenance, rehabilitation, or reconstruction policies that define the types of preventive or corrective actions to be taken and when and where they are to commence. The third is that new relationships must be identified between the as-maintained state of the transportation facility and the impacts to both the transport agency and the traveling public to provide a measure of the benefits or liabilities of each policy at the costs computed. Organization of these ideas within a unified structure is shown in Figure 1; additional details on the demand-responsive approach and its applications may be found elsewhere (1-6).

Analytical Procedures

North American Experience

Many studies of track performance, track life, or track maintenance have been conducted by or for North American railroads. Although the models differ in their scope and approach, in general they attempt to predict the deterioration of one or more track characteristics as functions of several variables, such as annual tonnage (or traffic density), degree of curvature, weight of rail, and velocity of trains. Other factors, recognized on a more limited basis in selected models, include axle or wheel loads, rail age, ballast and tie condition, hardness of rail steel, distinction between jointed and welded rail, superelevation of track, and weight of ties.

Many North American models predict the expected lives of specific track components. Included here are predictions of rail head wear (7-9), rail life due to fatigue (10), overall rail life (11), and tie life (8,12). However, these models do not predict the actual performance of these track components (they predict only the time of useful or safe service), do not include costs, and are not sensitive to changes in maintenance policy. More general

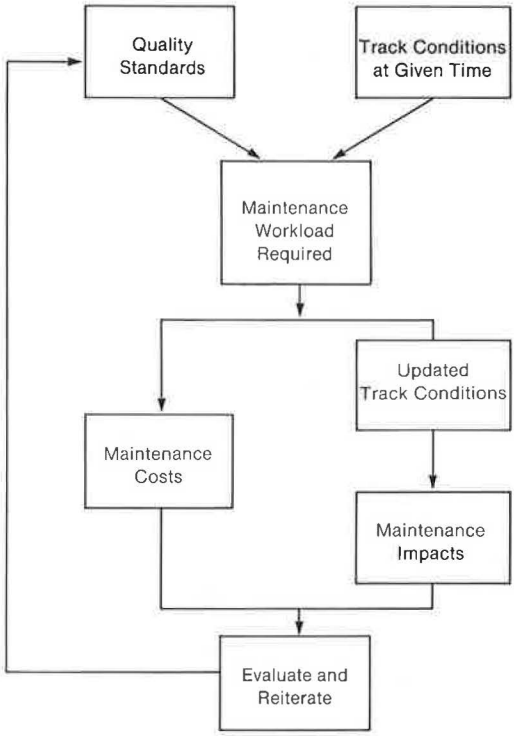

FIGURE 1 Demand-responsive approach to track investment.

models of track performance represent track deterioration or condition using a composite index (13,14). Other models (15) use a profitability criterion to analyze track costs. Although certain models (14,15) do include track maintenance costs within their formulations, these costs are treated as expenditures rather than as responses to demand for repair.

Incorporating the concepts in Figure 1 within analytical models requires an economic as well as an engineering approach. A brief description of how this is done is provided next.

Model Employed in Study

The analytical procedures needed to implement the management structure in Figure 1 are organized within a simulation model, the MIT Intercity Transportation Model (6). Each maintenance policy to be considered is tested by the model, which simulates the performance of the rail network; computes costs of routine maintenance, rehabilitation, and renovation; and predicts policy impacts on preservation of investment and rail operations through a given analysis period. This process is then repeated for several policy options to compare relative costs and impacts, to identify any additional policies that should be investigated, and to decide on a single policy that will form the basis for programming and budgeting future activities. Some examples of typical (but simplified) simulation results follow.

The prediction of track performance for two different policies of maintenance and rehabilitation or renovation is shown in Figure 2. (Track condition is identified in the accompanying figures as Q, a composite measure of several categories of track geometric deviation from the norm. A Q-value of about 100 denotes track in very good condition, whereas Q in excess of 300 reflects poor condition.) Note that, for Policy 1, both the quality standard (Q) and the quality of routine maintenance (denoted by

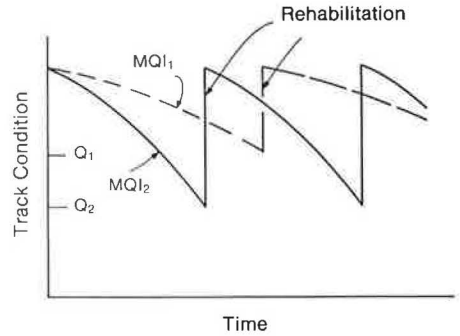

FIGURE 2 Effects of two different routine maintenance and rehabilitation policies on track condition.

the Maintenance Quality Index or MQI) are higher than for Policy 2. As a result, the average system condition is also higher for Policy 1. Predictions of system performance (i.e., histories of track condition) are accomplished using deterioration functions and specifications of routine maintenance, rehabilitation, and renovation policy. Whereas Figure 2 shows only two policies as examples, several policies may be simulated for comparison.

Costs for each policy are computed. The resulting cost histories for the two policies in Figure 2 are shown schematically in Figure 3. Routine maintenance

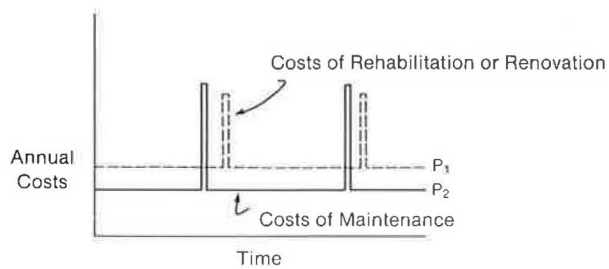

FIGURE 3 Agency costs for two track maintenance policies.

is costed on an annual basis with the better policy costing slightly more. Major repairs are represented by sudden peaks or spikes in the cost history. (Note that, under an inferior rehabilitation or renovation policy, both the magnitude of costs and the time intervals between successive performances of an activity may differ from those of better policies.)

Associated with the condition histories in Figure 2 are changes in impacts on the system, as shown in Figure 4. For simplicity a general benefits measure is shown. In reality several such functions could be developed for trip time and reliability, safety, comfort, and so on. The important thing to note is that the impact bears a direct relationship to the as-maintained condition of the track and is therefore sensitive to maintenance policy.

Results of the simulations in Figures 2-4 can be compared to identify the best policy, with or without budget constraints. To illustrate how this is done, assume that the benefits in Figure 4 can be reduced to monetary terms and thus compared directly to costs. Furthermore, it is assumed that instead of only two policies, as shown in Figures 2-4, several policies have been tested using the simulation model.

The results of each policy may be organized in terms of ascending costs to the transport agency. Because impacts are also in monetary terms (in this

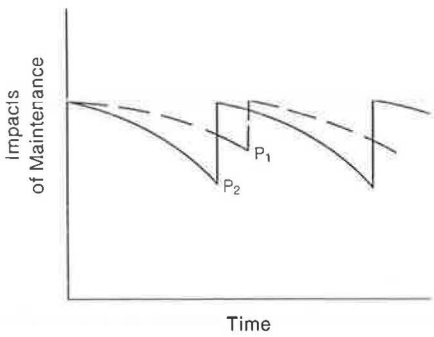

FIGURE 4 Impacts of two track maintenance policies.

example), they can be plotted on the same graph with costs for each policy. If maintenance policies are sensibly defined, more expensive policies (to the agency) should yield more advantageous impacts (i.e., greater reductions in costs associated, for example, with safety, travel time, or trip reliability), leading to the diagram that is Figure 5.

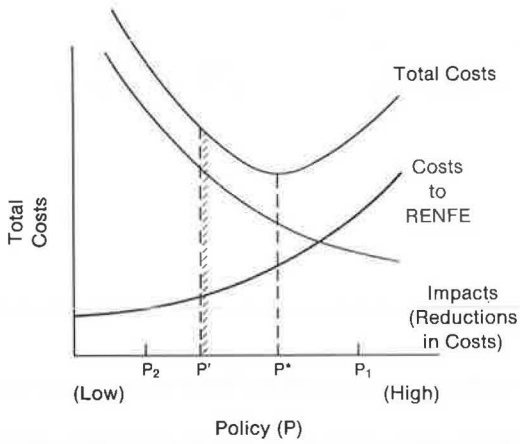

FIGURE 5 Optimization of track maintenance policies or strategies.

Identification of the most advantageous policy now becomes a question of minimizing total transport-related costs for the network configurations and traffic specified. In the absence of budget constraints, the appropriate policy is shown in Figure 5 as P*, because total costs (routine maintenance, rehabilitation, and renovation costs to the agency, plus costs associated with impacts of maintenance) are minimized at this point. If a budget constraint is imposed, the best policy that can be funded lies to the left of P*, perhaps at P'.

APPLICATIONS TO RENFE

The concepts illustrated in Figures 1-5 were applied to analyzing current condition and future maintenance policy on RENFE's track network, using the MIT Intercity Transportation Model. This work was done within the context of a multibillion dollar program proposed by RENFE, extending through the next decade, to upgrade its infrastructure and fleet and to expand and improve the level of transportation service provided.

Several categories of data were collected and analyzed to construct the case:

- Descriptions of the track network, including structural characteristics of each link, daily traffic levels, track classification, and so on;
- Deterioration relationships, developed from statistics on existing track condition provided by RENFE; and
- Routine maintenance, rehabilitation, and renovation policies to be tested, with unit costs to perform work under each policy.

The development of these data, and their relevance to the case, is explained in detail elsewhere (5).

Track Deterioration

In discussion with RENFE engineers, it was concluded that neither the North American models discussed earlier nor European practice reviewed by RENFE applied well to Spanish conditions governing track deterioration; therefore, deterioration models were estimated from data on track condition over time supplied by RENFE. These data were in the form of Q-values, representing composite indices of geometric deviations measured by an instrumental car in several dimensions (e.g., gauge, vertical profiles of both rails, superelevation, warp). At that time, RENFE had insufficient historical data from which to estimate deterioration curves; as an interim measure, cross-sectional data for each track class were used.

Examples of the analysis are shown in Figures 6 and 7 for high-standard and low-standard track, respectively. The change in track geometry (where greater deviations, implying worsening track condition, are denoted by higher Q-values) was found to be correlated with a statistic comprising the age of the track in years (A), traffic in gross tons per day (T), and weight of the steel rail in kilograms per meter (W). A function corresponding to the curves in Figures 6 and 7 was estimated for each of the track classes identified in Table 1 and separately for welded and for jointed rail. It was clearly stipulated, however, that these functions were preliminary and that further research by RENFE would be needed to develop more accurate models based on historical data and including the effects of routine maintenance policy.

Maintenance Policy

Four maintenance policies were tested (Table 2). These policies were sensitive to both Q-value (representing amounts of damage resulting in geometric deviations achieving a certain limit) and track age (to account for damage not correlated with geometric deviations). Note that different quality standards were defined not only for each policy but also for different classes of track. Policy 1 was regarded as the lowest standard and Policy 4 the highest.

The duration of this research project did not allow sufficient time to identify the relationship between maintenance policy and specific operational impacts (e.g., number of derailments, other safety considerations, line-haul travel times, etc.). In lieu of the types of impacts envisioned in Figure 4, the average measure of track condition throughout the network was predicted as an indication of the quality of service, safety, comfort, and speed that would be afforded passengers and freight. (The development of valid impact models relating maintenance policy to safety, operational efficiency, level of service provided, potential market share to be attracted and retained, and preservation of the track investment has been identified as a possible area of future research with RENFE.)

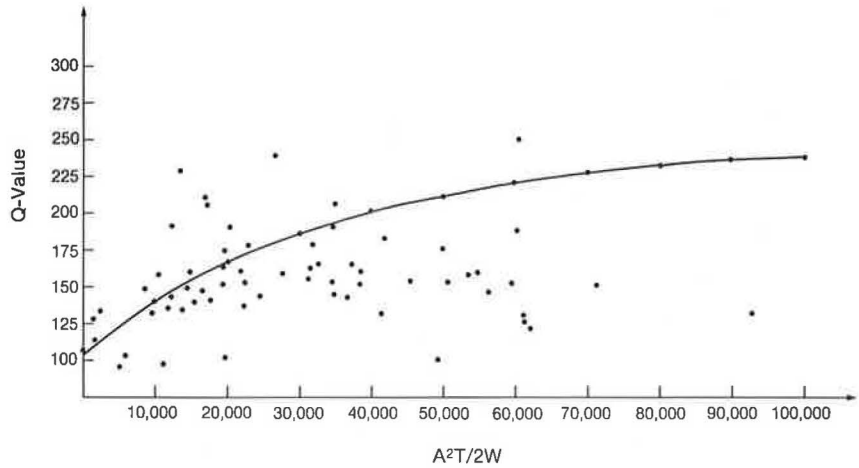

FIGURE 6 Deterioration relationship for arterial track (welded rail).

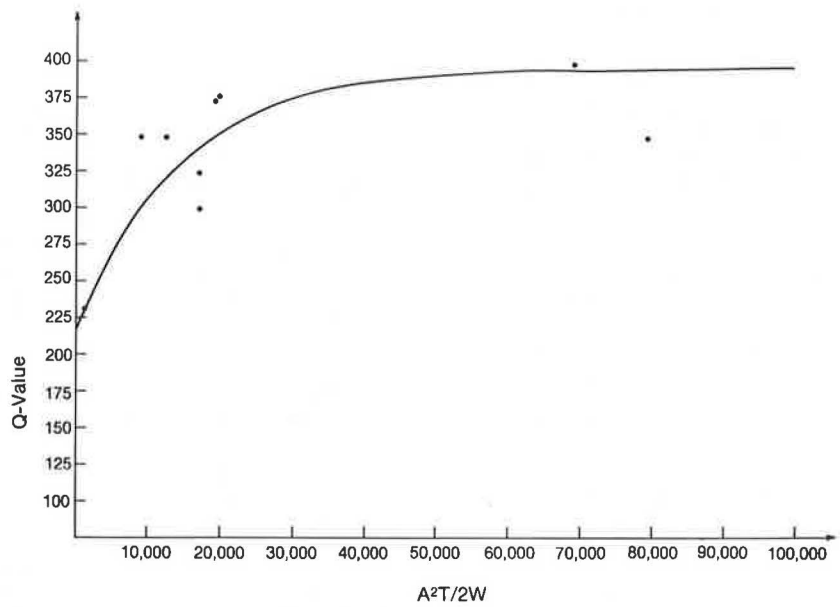

FIGURE 7 Deterioration relationship for secondary track (jointed rail).

TABLE 1 Operational Classes in RENFE Track System

Class	Kilometers	Explanation
Arterial	5534	Main or trunk lines
Principal	6426	Remaining lines serving primary traffic
Potential	2000	Backup system for primary network
Secondary	1137	Secondary lines

TABLE 2 Rehabilitation Thresholds for Four Track Policies

	Policy			
Track Class	1	2	3	4
Arterial	–	0 ≥ 225	0 ≥ 190	0 ≥ 160
Principal	–	0 ≥ 250	0 ≥ 210	0 ≥ 170
Potential	–	0 ≥ 250 or 300 Age ≥ 30	0 ≥ 210 or 275 Age ≥ 25	0 ≥ 275
Secondary	–	0 ≥ 338 Age ≥ 40	0 ≥ 300 Age ≥ 30	0 ≥ 300

RESULTS

Each of the maintenance policies defined earlier was simulated on the RENFE track network for the period 1982-1995. Results were computed in terms of both the costs of each policy to RENFE and the impacts, measured as track condition. This information was obtained (a) for each policy, (b) for each link, (c) for each class of track, (d) for each of seven maintenance zones, and (e) for the entire network. A summary of these results follows.

Figure 8 shows the distribution of costs for each policy for each track classification. The major portion of the budget for each policy is spent on the arterial and principal track classes. The allocation of a greater share of rehabilitation and renovation funds to the principal network does not imply that it is of greater importance. It is a reflection of the higher existing condition of the arterial network and the magnitude of expenditure required to restore the principal network to standard (i.e., to make up for the effects of deferred maintenance).

An analysis was also done of the cost of capital

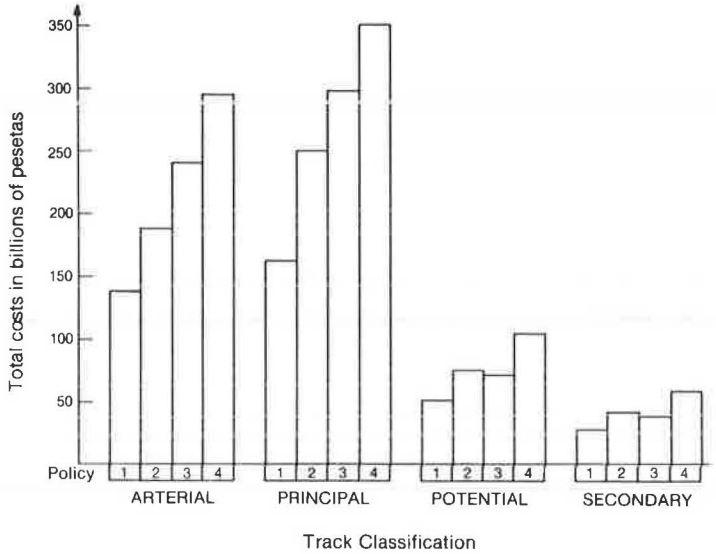

FIGURE 8 Costs versus track class.

repair of track (rehabilitation and renovation) as a percentage of total costs (capital repair plus routine maintenance). The highest such percentages were for Policy 4, which specified the highest standards for the RENFE system. Fifty-three percent of total costs were for rehabilitation and renovation under Policy 4, whereas only 31 percent of total costs were estimated for rehabilitation and renovation under Policy 2. Policy 1, which called for only routine maintenance and no track improvement, had a zero percentage.

Capital expenditures during the first year of the analysis were interpreted as the elimination of backlogged work. Taking the cost of work backlog by policy as a percentage of the overall cost of capital repair (renovation and rehabilitation), the percentage was found to be relatively low for arterial track, from about 20 to 40 percent depending on the policy chosen, indicating that arterial track is currently in good condition. (Track improvement here must be performed later in the 14-year analysis period as the track deteriorates.) Secondary track improvement, in contrast, was totally involved with the elimination of the backlog. When this work is completed, the track will deteriorate slowly due to light traffic volume. Only routine maintenance will be required later in the 14-year analysis period.

Figure 9 shows systemwide values of track condition (Q) averaged over the analysis period for each track class and policy tested. These results support the contention that a better maintenance policy substantially improves track condition. Policy 4 produces relative parity between the arterial and principal networks and provides approximately 12 000 km of premium track. Another significant factor is that Policy 4 is the only one of the four policies investigated that can transform the potential network into another 2 000 km of high-quality track to back up the other two primary networks.

Compared to Policy 4, Policy 3 results in a lower track condition on the arterial and principal networks. However, the harshest penalty in shifting from Policy 4 to Policy 3 is suffered by the potential network, which can no longer (from the standpoint of track condition) fulfill its intended role as a viable substitute for the arterial and principal networks.

A change from Policy 4 to Policy 3 will greatly

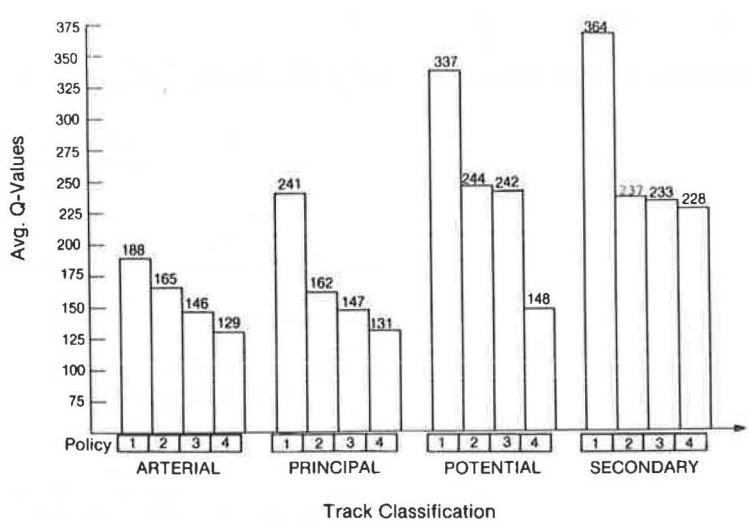

FIGURE 9 Average Q values versus track class.

affect the performance of the two major track classes, arterial and principal. The potential and secondary track classes remain relatively the same.

Policy 1 leaves the entire network in poor condition. The nonarterial classes each exhibit significant rates of deterioration. The only reason the arterial network does not itself exhibit worse conditions is, apparently, its current adherence to standards and that it has not suffered as much deferred maintenance as have the other networks in the past.

IMPLICATIONS FOR RENFE

As a result of this research a number of key findings emerged for the top management of RENFE:

1. For the best policy tested, the average Q-value is still being reduced with reasonable increments of cost. This means that it may be worthwhile to investigate even better maintenance policies.
2. As a measure of track condition, the Q-value is only an approximation of the benefits derived from maintenance. To determine the optimal policy requires at least an economic analysis of costs and benefits. Thus it will be necessary in the future to relate the Q-value of each link to factors such as operational efficiency and reliability, train safety, ride comfort, and so forth. These relationships form a potential topic for future research.
3. The elimination of backlogged work to bring the system up to standard will constitute a substantial percentage of all capital repairs to track during the next 15 years. This significant volume of work to correct deferred maintenance must therefore be accounted for in the definition and scheduling of track renewal projects.
4. The long-term benefits of the renewal program can be protected only if the rail system is maintained adequately and correctly in the future. Past policies of deferred maintenance cannot be continued.
5. The selection of maintenance policy also has strong implications for the operational roles that can be fulfilled by the different classes of track. In light of these considerations, RENFE managers are encouraged to define and test different maintenance policies in their planning of the long-term maintenance program and to include maintenance consideration in their capital budgeting.

CONCLUSION

This project has demonstrated the feasibility of applying demand-responsive concepts of maintenance planning and management to national transport networks. In addition to the case study presented in this paper, the approach has been used extensively in the analysis and evaluation of various surface transportation problems (1-6) and is, in general, applicable to other systems of infrastructure characterized by noncatastrophic failure. Furthermore, the approach addresses analytically many of the fundamental technical, economic, and financial differences between maintenance programs and new construction. This will take on added significance as several segments of the construction industry shift from the building of new facilities to the maintenance and preservation of existing mature infrastructure.

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