Decision Support System for Railway Track Maintenance and Renewal Management

Hakan Guler[1]

Abstract: This paper describes a decision support system approach for railway track maintenance and renewal management system to analyze the track components and to suggest methods for helping the track managers and engineers decide when maintenance is necessary and when is the best time for renewal. In this study, interviews with track maintenance experts, a national survey, and a comprehensive literature survey were used to develop the proposed decision support system. The developed decision support system includes some decision rules. On the basis of these decision rules, the analyses were realized into some stages: first stage, second stage, coherence stage, optimization stage, and evaluation stage. The developed system analyzed the track with its rich database including decision rules developed by the track specialist professionals and finally successful results were obtained. The developed decision support system proved that it is possible to develop planned maintenance and renewal management systems by using advanced computer and measuring systems instead of corrective maintenance and renewal. **DOI: 10.1061/(ASCE)CP.1943-5487.0000221.** *© 2013 American Society of Civil Engineers.*

CE Database subject headings: Railroad tracks; Maintenance; Decision support systems.

Author keywords: Railway track maintenance and renewal; Decision support system.

Introduction

Generally, railways are used very frequently and they play an important role in transporting thousands of people and large amount of goods on a daily basis. The integrity of railway tracks is challenged by the friction forces caused by trains passing over them and corrosive effects of the surrounding environment. Because of that, railway tracks require regular maintenance in order to function properly. There are several maintenance operations that aim to increase a railway's life span, but in some cases, none of these operations is sufficient and the entire railroad section needs to be renewed. Railway organizations generally use different maintenance and renewal (M&R) techniques due to their existing facilities (e.g., technologies, human resources, and collaborations with universities and research institutes). Mostly railway organizations use traditional methods targeting corrective maintenance. Vickerman (2004) stated that the quality, not the volume, of investment and maintenance was the only key factor for railways. Quality means the ability of the infrastructure operator to identify, schedule, and plan capital work, whether routine maintenance or renewals, and then manage its implementation effectively.

Grimes and Barkan (2006) stated that different railways use different proportions of ordinary maintenance and periodic renewal with little consensus as to the best combination. They stated that the cost effectiveness of emphasizing one method over the other has not been analyzed using empirical data. They investigated the cost effectiveness of renewal-based maintenance strategies using high-level financial data from industry sources. Track maintenance and renewal generally covers the operations that are monitoring and maintenance of the track geometry and components and renewal of track components when they deteriorated to such an extent that restoring the geometry and the track itself to achieve the necessary quality is no longer economically feasible. Bocciolone et al. (2007) stated that one of the critical problems was track maintenance activity, requiring a reliable knowledge of the rail status so that a proper intervention can be performed only when necessary. They presented a feasibility study of a foolproof diagnostic tool to get the rail status from the axle-box acceleration measurement for maintenance purposes.

The right time for track maintenance and renewal works must be defined. Track maintenance and renewal works carried out at the right time are crucial to realizing an efficient and optimized maintenance and renewal work plans, thus increasing the life of the track components, whereas carrying out maintenance and renewal works too late is certainly unsafe and as the railway track gets older, the maintenance and renewal costs increase exponentially. Increasing demand for railway transportation requires large amounts of money to be spent on track maintenance and renewal. Cost reduction and better control of maintenance processes therefore increase the efficiency of the railway system. The modern railway infrastructure maintenance management system requires the diagnostic concept, meaning on the condition-based approach as well as criticality and urgency analyses of all the key infrastructure components. Railway organizations can achieve efficient maintenance and renewal management performing an optimization between maintenance and renewal works as well as an optimization for spatial and temporal coherence of the works.

This paper describes a railway M&R planning tool. The developed system is basically a condition-based system using measured data gathered on the track. The system analyzes the track with its rich database including decision rules developed by the track specialist professionals. The developed system is a kind of expert system.

Track Deterioration and Maintenance Models

Railway track and turnouts are subjected to the harshest influences. These influences degrade track geometry and materials in an

[1]Univ. of Sakarya, Dept. of Civil Engineering, Esentepe/Sakarya 54187, Turkey. E-mail: hguler@sakarya.edu.tr

Note. This manuscript was submitted on October 1, 2011; approved on April 9, 2012; published online on April 12, 2012. Discussion period open until October 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Computing in Civil Engineering***, Vol. 27, No. 3, May 1, 2013. © ASCE, ISSN 0887-3801/2013/3-292-306/$25.00.

exponential form. Actually, there are many parameters affecting track deterioration. These parameters cause settlement and lateral displacement of the track; thus railway track components are exposed to fatigue, corrugation, wear, abrasion, defects, and damage. Furthermore, in the small-radius curves, often short-pitch corrugations rise at very high rates. It is very important to determine these degradations in early stages because track condition determines the safety and comfort of rail transport (Bocciolone et al. 2007). There are a lot of researches on railway track deterioration. The researches especially focused on ballast settlement, wear of rails, and wear and surface fatigue of rails. This diversity proves that modeling track deterioration is complex. These models are comprehensively reviewed and discussed by Öberg (2006). Generally, track deterioration models can be categorized under the following titles:

- Models for deterioration due to vertical settlement;
- Models for deterioration due to wear and contact fatigue;
- General deterioration models;
- Models due to changed traffic conditions; and
- Computer-aided planning and prediction tools.

Maintenance policy including modeling and optimization always aims to plan preventive or corrective actions in order to minimize the overall cost of interventions and/or maximize the lifetime of the system (Barros et al. 2002). Generally, the life of railway components can be divided into three characteristic phases: the youth, the middle age, and the old age. Each period of a component life may be linked to a specific type of maintenance action, preventive maintenance, corrective maintenance, or substitution or renewal [Improved Tools for Railway Capacity and Access Management (IMPROVERAIL) 2003].

Decision Support Systems for Track M&R

Decision support systems (DSSs) are technologies that help get the accurate knowledge to the accurate decision makers at the accurate times in the accurate representations at the accurate costs. A decision support system helps asset managers in making the best decision with regard to financial limitations and other dominant constraints imposed on the problem at hand (Rashidi et al. 2010). A decision support system provides managers with a wide range of applications. For example, Karamouz et al. (2005) developed a decision support system for multipurpose reservoir operation. The mathematical models in the system are formulated for monthly operation of hydropower reservoirs. The key components of the system are four main modules: database management, inflow modeling and forecasting, operation management, and real-time operation.

Shen and Grivas (1996) presented the development of a decision support system for the preservation of civil infrastructure. The system aims at providing assistance for decisions concerned with the three main tasks of infrastructure maintenance and rehabilitation: symptom observation, condition diagnosis, and treatment identification.

Jo et al. (2011) presented an integrated decision support framework that helps public agencies identify high-crash locations and develop cost-effective safety improvement projects. State-of-the-art safety concepts, such as safety performance functions, empirical Bayesian method, and potential for safety improvements, are incorporated to identify hazardous highway locations. Cost-effective safety projects are prioritized based on life-cycle safety benefit evaluation and optimal resource allocation models. An efficient solution algorithm to the optimization model is also proposed.

Halfawy et al. (2008) developed a new integrated approach for optimal renewal planning of municipal infrastructure systems. The paper discusses the application of the proposed approach to implement a geographic information system (GIS)—based DSS to support the renewal planning of sewer networks.

A decision support system is a computer-based system that represents and processes knowledge in ways that allow decision making to be more productive, agile, innovative, and/or reputable (Burstein and Holsapple 2008). Over the years, it is seen that the decision-making procedure has been mostly represented as if-then-else rules depending on the nature of the decision support system. The rules are developed by the relevant experts and the working procedure of the system is built on the expert systems, which have been defined as "a system that uses human knowledge captured in a computer to solve a problem that ordinarily needs human expertise" (Turban and Aronson 2001). The quality of the decision support system depends on both the quality and extent of its knowledge (Yehia et al. 2008).

Over the years, considerable development has been made in the developing of railway track M&R planning systems, not only by the railway organizations, but also by specialist institutes and universities. These researches, carried out in the United States, Canada, Japan, and Europe, are presented in Table 1. The more detailed information can be found in European Railway Research Institute (ERRI) (1993) and the maintenance and renewal planning aid system (Mini-MARPAS), track maintenance system (TMS), Shinkansen management information system (SMIS), track maintenance management (GEV), Bovenbouw Informatie en Contoie per Onderhoudsectie (BINCO), rail expert planning, organization and maintenance (REPOMAN), polish abbreviation: Decisions relating to general repairs (DONG), computer-aided works planning (KOMPLAN), Grandes Operations Periodiques (GOP), rail renewal, net present value (RRNPV), and computer-aided system for railway maintenance and renewal (PATER) systems. Most of the track M&R planning systems briefly presented in Table 1 focus on presenting solutions to very precise problems. On account of the wide scope of the objectives considered, they comprise planning aid systems of strategic, operational, or sectorial character. These planning systems are either in the process of development or in the process of evaluation within the railways. The applications and researches of DSS on railway M&R management are briefly described subsequently.

Tew and Twindle (1991) presented the track management model developed by broken hill proprietary research—Melbourne laboratories (BHPR-ML) for use by heavy haul railroads. The model calculated recommended maintenance cycles and associated operating costs and determines the cost-effective track condition in terms of the weighted track quality index (TQI). The TQI was developed by BHPR-ML to indicate the track quality in terms of the effect of various track geometry parameters on damage-related costs.

Hargrove and Martland (1991) presented total right-of-way analysis and costing system, which was a microcomputer-based system that related railroad track and traffic characteristics to the maintenance activities and associated costs of maintaining the track structure.

Uzarski et al. (1993) presented the railroad maintenance management system developed by the U.S. Army Construction Engineering Research Laboratories in conjunction with the University of Illinois. They developed condition indexes for rail, joint, and fastenings; ties; and ballast, subgrade, and roadway component groups. An overall composite condition index for railroad track, as a whole, was also developed. The indexes were based on data obtained from a panel of track experts assessing a variety of track conditions through the use of numerical ratings.

MTR Corporation in conjunction with BHP Research developed an economic/technical rail management model to optimize the rail

J. Comput. Civ. Eng. 2013.27:292-306.

Table 1. Track M&R Tools

M&R tool	Railway organization or developer
System dynamics	German Railways (DB)
Maintenance and renewal planning aid system (Mini-MARPAS)	British Rail (BR)
Track maintenance system (TMS)	Burlington Northern Railroad (BN) (Canada)
Shinkansen management information system (SMIS)	Japanese Railways (JR)
Track maintenance management (GEV)	Swiss Federal Railways (SBB)
Bovenbouw Informatie en Contoie per Onderhoudsectie (BINCO)	Dutch Railways (NS)
Rail expert planning, organization and maintenance (REPOMAN)	BN
Polish abbreviation: Decisions relating to general repairs (DONG)	Polish State Railways (PKP)
Computer-aided works planning (KOMPLAN)	PKP
Grandes Operations Periodiques (GOP)	National Corporation of French Railways (SNCF)
Rail renewal, net present value (RRNPV)	BR
Computer-aided system for railway maintenance and renewal (PATER)	Hungarian State Railways (MAV)
Track management model	Broken hill proprietary (BHP) research (Tew and Twindle 1991)
Total right-of-way analysis and costing system (TRACS)	Association of American Railroads/Massachusetts Institute of Technology (AAR/MIT) (Hargrove and Martland 1991)
Railroad maintenance management system (RAILER)	U.S. Army Construction Engineering Research Laboratory (Uzarski et al. 1993)
Rail management model	BHP Research / Hong Kong mass transit railway (HK-MTRC) (Keefe and Soeleiman 1994)
Economical Track (ECOTRACK)	ERRI International Union of Railways (ERRI 1995)
Track maintenance database system (Micro LABOCS-II)	JR (Yoshimura et al. 1995)
Traitement Informatique du Mauzin et des Operations de Nivellement: Computer processing of the Mauzin data and levelling maintenance (TIMON)	National Corporation of French Railways (SNCF) (Meier-Hirmer et al. 2006)
Railway asset management system (RAMSYS)	MerMec (Jovanovic and Guler 2006)

maintenance and replacement strategies for the MTR system under specific operating conditions (Keefe and Soeleiman 1994)

Uzarski and McNeil (1994) presented an overview of technologies for railroad track condition assessment and decision support systems for track maintenance and renewal. They stated that research and development of technologies for condition data collection and computer-based decision support systems are not widely reported in the literature due to the nature of the industry. They described a variety of systems and issues and consequently stated that decision support systems attempt to move maintenance and replacement decision making from an art to a science.

Yoshimura et al. (1995) presented the design methods and main features of the track maintenance database system (Micro LABOCS-II+) developed for railway track maintenance management. This system was installed and utilized in Japan Railway companies.

European Rail Research Institute and the International Union of Railways (UIC) initiated an innovative decision support system project for railway track maintenance and renewal management. European railway experts pooled their knowledge and experience for the design and development of the mentioned decision support system. The final product, called Economical Track (ECOTRACK), was created in 1998. The main purpose of ECOTRACK was to provide planners and managers with a powerful tool for the purpose of minimizing track life cycle costs (Rivier 1998).

Roberts et al. (2000) described the preliminary results of trials of a decision support system, which forms part of a project titled "A Prototype Expert System for Effective Track Maintenance and Renewal." The objective of the research was to improve the performance of the permanent infrastructure and reduce maintenance costs for railways by encouraging a more consistent approach to the choice of remedial works.

Zoeteman (2002) stated that Delft University of Technology developed and has used a DSS for analyzing the long-term impacts of railway design and maintenance decisions since 1998. The DSS combines data of the construction, maintenance and operating, and financing processes in order to make estimates of total life cycle costs (LCCs). He included infrastructure performance (availability and reliability) in these estimates. DSS design and application, in a revision of the renewal policy for tracks and switches on the Dutch network, were presented. The DSS proved to be a valuable tool for testing the robustness of design and maintenance decisions and focusing the discussion on the important cost-driving factors.

Roberts et al. (2000) stated that modern data collection techniques produced a considerable amount of useful information, which, if made use of, could assist the engineer in the correct diagnosis of failure and to determine the most effective method of remedial action. However, despite developments in data collection and subsequent research into the correct interpretation of this data, little has been done to draw the two together and produce a vehicle to aid the engineer. They considered how this might be achieved through the use of a decision support system and discussed the development of such a system to assist the engineer in making effective maintenance and renewal decisions on the UK rail network.

Jovanovic and Guler (2006) presented railway asset management system (RAMSYS), which was an integrated software platform for the management of all the data related to railway infrastructure maintenance. RAMSYS was designed by railway engineers specifically for the railway industry. It supports the management of all data related to railway infrastructure and rolling stock maintenance (e.g., assets, defects, work history, measurements, and operational data), enabling condition-based and predictive maintenance and renewal.

Technological development enabled railway organizations to develop sophisticated railway track M&R tools integrated with the track recording and measuring systems. Among other tools, Traitement Informatique du Mauzin et des Operations de Nivellement: Computer processing of the Mauzin data and levelling maintenance (TIMON), a computer application using track geometry measurements and maintenance operation data, is currently in use in France. This application illustrates the evolution of track quality indicators. TIMON (Traitement Informatique du Mauzin et des Operations de Nivellement: Computer processing of the Mauzin data and levelling maintenance) that is used for track

J. Comput. Civ. Eng. 2013.27:292-306.

degradation surveillance and for decision making concerning major maintenance interventions. This tool displays information on the track geometry inspections as well as on maintenance operations carried out for each line (Meier-Hirmer et al. 2006).

Developed Decision Support System for Track M&R

The applications and basic techniques of the developed DSS are described in this section. Decision support systems are computer-based systems that represent and process knowledge in ways that allow decision making to be more productive, agile, innovative, and/or reputable (Burstein and Holsapple 2008). As stated in ERRI (1993), an effective decision support system for track M&R must have a knowledge base incorporating the experience and know-how of the railways. The developed DSS is a condition-based decision support system and the system contains a rich M&R rule database to decide on which and what kind of M&R works are necessary for the railway track. In this study, track M&R works of Turkish State Railways (TCDD) were investigated and the most important M&R works were defined by considering Turkish railway experts' knowledge and experience where required data were unavailable. For this purpose, TCDD railway experts shared their knowledge and experience for the design and the development of this DSS.

In the present study, a thorough selection of the experts was important in order to achieve a high-quality DSS on track M&R. The survey experts were carefully selected to guarantee that they acquired the capability needed for the objectives of the study. The survey experts were selected from the TCDD General Directorate, regions, divisions, and subdivisions. The participants were a mixed group of engineers and technicians working at the TCDD track department. Their specialist areas were rails, sleepers, ballast, earthworks, track geometry, measuring systems, and engineering structures. Briefly, the experts were selected based on the following criteria: (1) survey experts were engineers and technicians, (2) survey experts were selected by the head of each organization (TCDD General Directorate, regions, divisions, and subdivisions), (3) survey experts had at least 15 years of work experience, and (4) survey experts joined at least two occupational training programs in the last 2 years.

Based on the expert decisions, the considered track M&R works are given as:

- Integral renewal;
- Rail renewal;
- Sleepers and rail fastenings renewal;
- Rails, sleepers, and fasteners renewal;
- Ballast sieving and/or ballast renewal;
- Sleepers, fasteners, and ballast renewal;
- Tamping (leveling and lining maintenance);
- Rail grinding maintenance;
- General measurements and spot maintenance; and
- Rail lubrication.

The parameters given in Table 2 defined by the expert opinions were used to develop the M&R rules for each type of M&R operation. The developed DSS calculates some of the parameters based on the analytical segments (ASs) mentioned in the following sections. These data, both inputs and outputs, are used within the M&R rule algorithms; however, some further intermediate data may be produced in the process. Simple rules were defined for each type of M&R operation by using the relevant data. For example, IF Track Data (1) $\geq$ Limit value (1) OR Track Data (2) $\geq$ Limit value (2) OR Track Data (3) $\geq$ Limit value (3) ... THEN Work type, Date. Uncertainties arising from the lack of knowledge on threshold values were also eliminated with the help of expert judgement. The system structure of the developed model is illustrated in Fig. 1. Generally, the principle objective is to identify the M&R requirements with a view to classifying them into some categories (ERRI 1993). Similarly, the

Table 2. Parameters Used for Decision Rules

M&R operation	Parameters
Ballast renewal	Type of ballast; Age of ballast and age limits; Tamping history; Tamping frequency; Condition of substructure; Amount of dirty ballast; Track geometry measurements; Deterioration of vertical geometry; Track condition indexes; Minimum ballast depth; and Reference values for ballast.
Sleepers and rail fastenings renewal	Type of sleepers; Age of sleepers and age limits; Loads and cumulative loads; Service index; Gauge value; Gauge narrowing; Gauge widening; Standard deviation of gauge; Condition of sleepers and fastenings; and Number of damaged sleepers.
Rail grinding and lubrication	Track class; Transversal acceleration of bogie; Transversal acceleration of train floor; Vertical acceleration of train floor; Short wave corrugation limit value; Noise limit value; Number of damaged sleepers; Number of trains; Number of rail failures; Track curvature; Cumulative loads; and Weibull distribution parameters.
Rail renewal	Properties of rails; Age of rails and age limits; Loads and cumulative loads; Speeds; Radius of curves; Number of rail defects; Track class; Number of rail faults; and Weibull distribution parameters.
Tamping	Tamping history; Track measurements; Analyzing track geometry; Track geometry limit values; Track condition indexes; Deterioration rate of track geometry; and Number of track geometry faults.
Integral renewal	Sleepers and rail fastenings renewal rules; Ballast renewal rules; Rail renewal rules; Condition of substructure; and Cost analysis.
Rails, sleepers, and fastenings renewal	Sleepers and rail fastenings renewal rules; Rail renewal rules; and Cost analysis.
Sleepers, fastenings, and ballast renewal	Sleepers and rail fastenings renewal rules; Ballast renewal rules; and Cost analysis.
General measurements and spot maintenance	Periodic measurements; Condition of track components; and Cost analysis.

J. Comput. Civ. Eng. 2013.27:292-306.

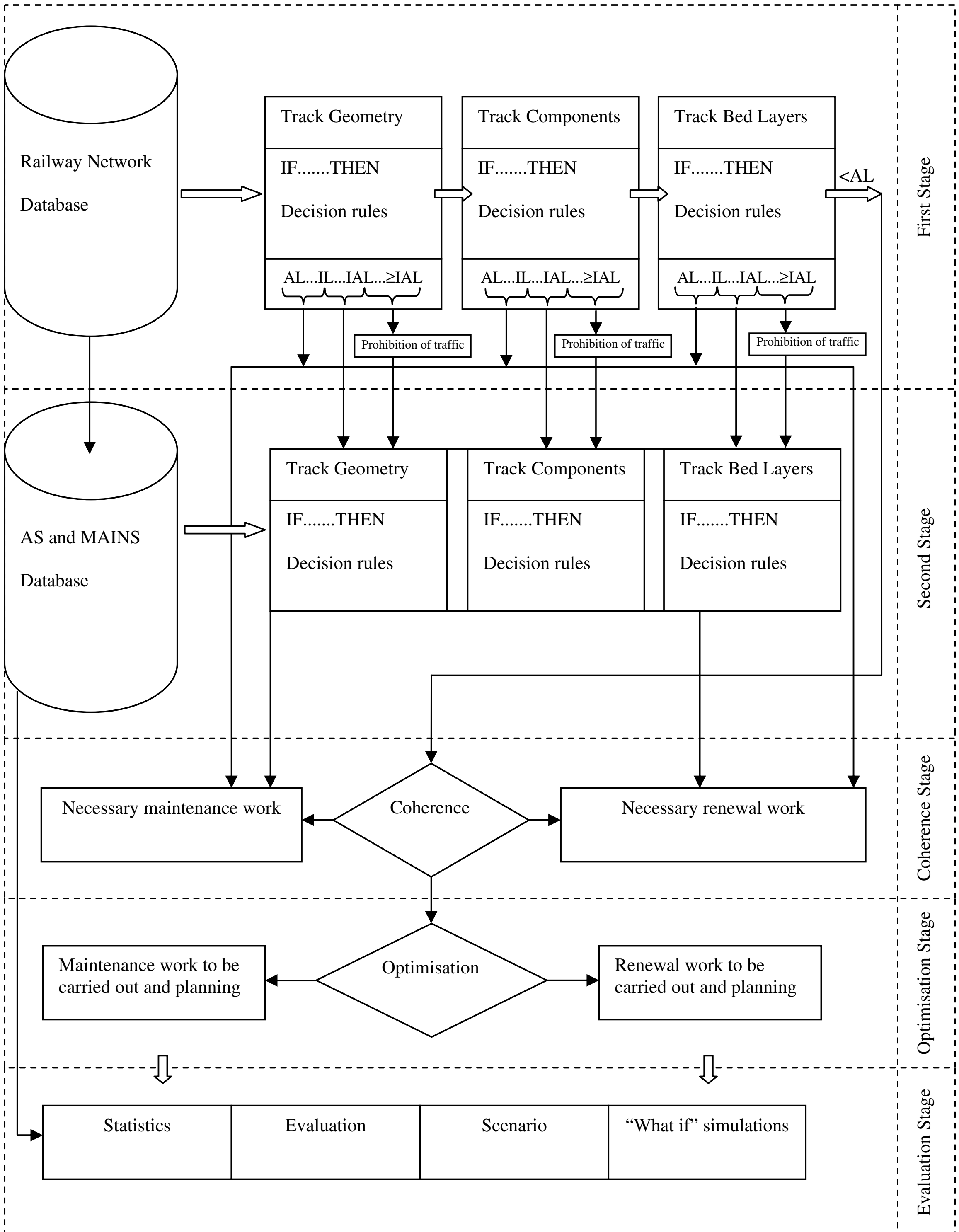

Fig. 1. System structure of the developed model

developed DSS provides the analyses in some stages: first stage, second stage, coherence stage, optimization stage, and evaluation stage.

The first stage of the system is based on a minimum number of data. The railway network data is simply evaluated in the decision support system and the track is effectively classified into four M&R classes:

1. Sections do not require any M&R because threshold values are below the alert limit (AL). These sections are examined at the coherence stage.
2. Sections require regular M&R operations because threshold values are between the AL and intervention limit (IL).
3. Sections may require corrective maintenance and/or renewal operations because threshold values are between the IL and immediate action limit (IAL). These sections are examined at the second stage in detail.
4. Railway is prohibited to traffic. Sections may require corrective maintenance and/or renewal operations because threshold values exceed IAL. These sections are examined at the second stage in detail.

J. Comput. Civ. Eng. 2013.27:292-306.

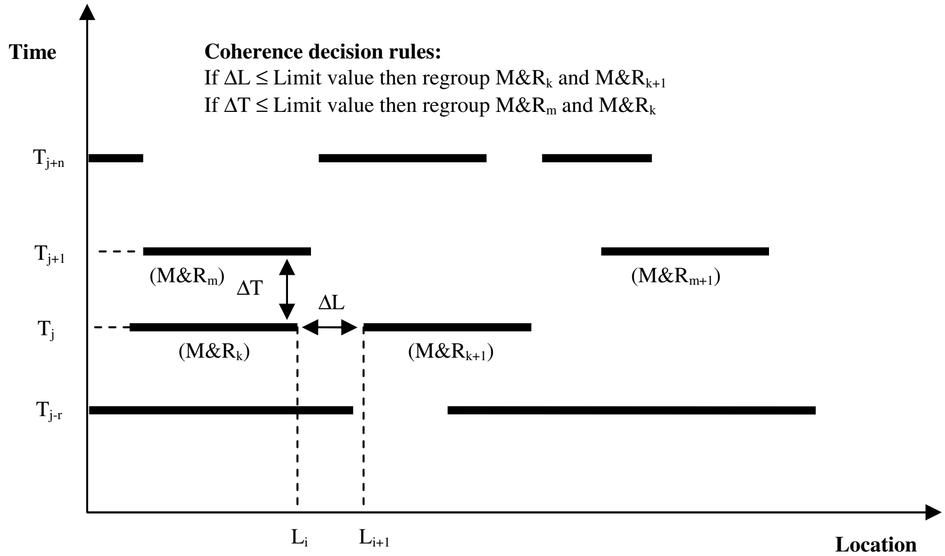

Fig. 2. Coherence rules' procedure

The second stage of the system is based on the detailed data, which are threshold values, decision rules, and deterioration models. The ASs and maintenance sections (MAINs) are comprehensively analyzed to determine the necessary M&R works including their respective urgency. This stage also proposes M&R predictions for medium and long periods.

The coherence stage of the system ensures a coherence analysis based on the decision rules about time and space coherence between the M&R operations during the following and planned years. The maintenance operations are not scheduled before they are about to be renewed. In this study, two main classes of coherence rules were considered, which were time-bounded and location-bounded rules. The time-bounded rules grouped together maintenance or renewal work depending on time. The location-bounded rules grouped together maintenance or renewal work depending on location. These two main classes of coherence rules are illustrated in Fig. 2.

The optimization stage of the system takes the result of the coherence stage and assesses the technical and economic feasibility of the M&R operations taking into account the various managerial and the resource allocation constraints. This stage enables the users to proceed to the final M&R planning based on the technical constraints (machines, staff, and time) and the economic constraints (funds for M&R works) provided by the systems. In this study, the proposed DSS calculates the costs of works considering the equations given in chapter life-cycle costs. The system is also capable of producing calculations on the discounted cash flow method. During the optimization procedure, different types of maintenance and different types of renewals works are regrouped due to some economic constraints (such as sleepers and fastenings renewal work being regrouped with rail renewal or vice versa.). In addition, interaction between M&R works is considered in this stage due to some technical constraints (such as rail grinding being moved just after sleepers and fastenings renewal work).

The evaluation stage of the system provides the users to be used to support the overall management of M&R operations of the railway network. This stage enables making full use of track data and obtained results involved statistical analyses of "What if?" simulations applied to track quality, track life cycle costs, budget, and M&R policies.

Development of Decision Rules for Track M&R

Compared with the other models, the developed model compromises a full rage data of railway track geometry and track components such as track bed layers, rails, and sleepers with their relevant standards.

The decision rules were developed on the basis of these standards, the deterioration models, and the experts' decisions. The development of decision rules for railway track components is presented in this section. Track geometry and track components, which are rails, sleepers, and track bed layers, and their threshold values are described on the basis of analytical segments. Thresholds (limit values) for safety and maintenance reasons are most often standardized. However, all standards use a constant value for a large waveband (Berggren et al. 2008). The M&R system calculates some of the parameters based on the ASs. These data, both inputs and outputs, are used within the systems' rule algorithms, however some further intermediate data may be produced in the process. Simple rules are defined using the relevant data according to type of M&R. For example, IF Track Data ≥ Limit value THEN Work type, Date.

Generally, track data are extracted from basic units of sections, usually called ASs. The segmentation process used in this study is explained in Fig. 3. Track recording cars store the data along the track and then the data are collected into small MAINS.

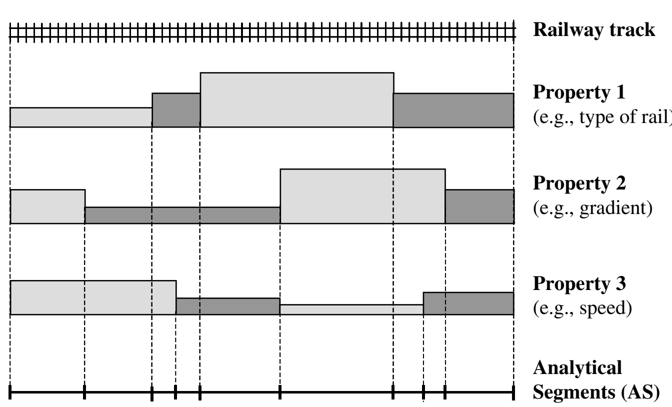

Fig. 3. Track segmentation process

J. Comput. Civ. Eng. 2013.27:292-306.

Measurement, inspections, works carried out, and infrastructures are obtained for every MAINS. Finally, the information needs further aggregating into longer route sections in order to obtain a network-scale assessment of the quality and consequential M&R needs (Guler 2005; Esveld 2001).

Track Geometry

The track geometry assessment is directly performed by the track recording vehicle according to EN 13848-5 (British Standards Institution 2008b; Luber 2009). Track design geometry is described in terms of vertical and horizontal geometry, which are called superelevation (cant), gauge, twist, level, and alignment as functions of distance along the track (British Standards Institution 2008a). Track geometry quality is considered as assessment of excursions from the mean or designed geometric characteristics of specified parameters in the vertical and lateral planes (Guler et al. 2011). In this study, three indicators were taken into account to describe the track geometric quality: extreme values of isolated defects, standard deviation over a defined length (AS), and mean value.

Track indicators relating to comfort, reliability, and safety must be calculated and checked with predefined limit values. Any excess of the limit values must result in an intervention. Therefore, three main levels were considered during the rules development procedures: AL, IL, and IAL:

- Alert limit: If AL is exceeded, then track geometry condition is analyzed and considered in the regularly planned maintenance operations.
- Intervention limit: If IL is exceeded, then required corrective maintenance is carried out so that the immediate action limit shall not be reached before the next inspection.
- Immediate action limit: If IAL is exceeded, then required measures are taken to reduce the risk of derailment to an acceptable level.

Three main levels for track geometry parameters were defined according to EN 13848-5 separately in terms of three indicators. Besides track geometry parameters, the other parameters contributing to vehicle track interaction and ride quality were considered during the M&R rule development. These parameters are obtained by direct measurements or by derived measurements as follows:

- Parameters obtained by direct measurement: horizontal curvature (1/m), vertical curvature (1/m), gradient (mm/m), and acceleration (m/s^2).
- Parameters obtained by derived measurement: change of gradient (mm/m), rate of change of gradient (mm/m^2), cant deficiency (mm), rate of change of cant deficiency (mm/s), cant deficiency variation (mm), rate of change of cant (mm/s), cant gradient (mm/m), cant variation (millimeters), and ride index.
- Supporting data: line speed (km/h) and distance measurement (meters).

Accelerations are important data for rail grinding or rail renewal decisions as well as the running safety and the ride comfort of a railway vehicle. As Yang et al. (2009) stated, forces associated with the train accelerating or breaking could be more than 100 times greater. Table 3 represents the threshold values for the accelerations currently used at TCDD.

Table 3. Accelerations

Accelerations	AL	IL	IAL
Transversal acceleration of the bogie	5.00	7.50	10.00
Transversal acceleration of the train floor	2.50	3.25	3.75
Vertical acceleration of the train floor	2.50	3.25	3.75

Note: All values are given in m/s^2.

Table 4. Condition Indexes

Condition indexes	AL	IL	IAL
QI	<80	<50	<40
C	<80	<30	<10

To define the track geometry condition, a numerical quality index is required to represent the condition of the track geometry. A review of the available literature indicates that railway organizations around the world use different approaches for the development of track geometry indexes (Sadeghi 2010). The main condition indexes are calculated from detailed inspection of car measurements of the track. In this study, the Q-value is calculated as (Patra 2009; TCDD 2009)

$$\mathrm{QI} = 150 - \frac{100}{3} \cdot \left[\frac{\sigma_H}{\sigma_{\mathrm{HLim}}} + 2 \cdot \frac{\sigma_I}{\sigma_{\mathrm{ILim}}}\right] \tag{1}$$

The standard deviation for the interaction is calculated as a combined effect of the cant and the side position of the rail. The C-value is calculated for a longer section of the track and is expressed as (Patra 2009; TCDD 2009)

$$C = \frac{\sum_i u_i}{\mathrm{TU}} \cdot 100 \tag{2}$$

where $\sum_i u_i$ = sum of the track length where all the σ values are below the comfort limits for a given track class (TCDD 2009). The values of QI and C coefficients exceeding the intervention limits are given in Table 4. These condition indexes were considered during the M&R rule development.

Rails

Railway track M&R activities always involve rail renewals because of breakages or damage resulting from traffic loads, time, and/or manufacturing defects. The following data were gathered to monitor the behavior of rails: general information, precise location of defect in the track, date, defect detection method, characteristics of line and track, characteristics of rail, characteristics of welds or resurfacing, code number of defect, action taken, and description of defect.

Three definitions, damaged rails, cracked rails, and broken rails, were used for the rail defects by considering UIC 712 (UIC 2002) rail defect coding system. For M&R operations, the following expressions were used to make the recommendations more easily understandable by the maintenance staff:

- Keep rail under inspection (AL);
- Removal of the rail (IL); and
- Prohibition of traffic and immediate removal of the rail (IAL).

The rail measurements obtained from different resources and the rail failure limit values were transferred into the developed DSS's database. These are rail headwear (millimeters), side wear (millimeters), head profile, gauge corner profile, rail inclination, rail corrugation (millimeters), and equivalent conicity.

Due to the failure evaluation method (e.g., visual testing and ultrasonic testing), the limit values for the rail failures were defined with the appropriate operational interventions (e.g., speed restrictions and operational restrictions) and then transferred into the developed DSS's database.

Previous studies have shown that rail fatigue defects follow a Weibull's law (Zhao et al. 2006). Two-parameter Weibull distribution has been used in this study to analyze the data and to predict the rail failure rate because it has the ability to provide reasonably accurate failure analysis and prediction (Kumar 2006; Evans et al. 2000).

J. Comput. Civ. Eng. 2013.27:292-306.

Table 5. Weibull Distribution Parameters for Rails

Parameter	Value	Decision
Shape parameter (β)	<1	Infant mortality stage
Shape parameter (β)	1	Random failures
Shape parameter (β)	>1	Wear-out stage of the component
Scale parameter (η)	≥1	More than 63.2% of the unit failed

$$F(m) = 1 - \exp[-(m/\eta)^{\beta}] \tag{3}$$

$$f(m) = (\beta m^{\beta-1}/\eta^{\beta}) \exp[-(m/\eta)^{\beta}] \tag{4}$$

Then failure intensity function $\Lambda(m)$ as derived from Eqs. (1) and (2) is given by

$$\Lambda(m) = \frac{f(m)}{1 - F(m)} \tag{5}$$

$$\Lambda(m) = \beta m^{\beta-1}/\eta^{\beta} \tag{6}$$

Then the expected number of failures over period i and $(i+1)$ is given by

$$E[N(M_{i+1}, M_i)] = [(M_{i+1})^{\beta} - (M_i)^{\beta}]/\eta^{\beta} \tag{7}$$

where the total accumulated millions of gross tons (MGT) up to the ith inspection, M_i, is given by

$$M_i = \sum_{j=0}^{i} m_j \tag{8}$$

From the values of η and β obtained, the mean time to failure (MTTF) can be calculated as

$$\mathrm{MTTF} = \eta\Gamma[(\beta+1)/\beta] \tag{9}$$

where $\Gamma[(\beta+1)/\beta]$ = gamma function with argument $(\beta+1)/\beta$. The shape parameter β has an effect on the failure rate of a component. The scale parameter η is also known as the characteristic life of the component. The decisions rules were developed due to the β and η parameters given in Table 5 (Kumar 2006).

Reddy et al. (2007) stated that lubrication at wheel flange and rails on sharp curves was considered as an effective solution for reducing wear loss of material from an effective cross section of rail and wheels. Annual grease consumption for rail lubrication varies between 0.7 and 2.5 kg/km for different countries (Larsson 2000). In this study the following parameters were considered to constitute the decision rules for rail lubrication: number of trains, track curvature, number of rail failures, cumulative loads, and Weibull distribution parameters.

Sleepers

Railway sleepers are an important element of all railways. In the course of track maintenance, sleeper replacement represents the most significant cost for railways. Many sections of railways in Turkey are constructed with concrete and wooden sleepers that have been in position for many years. In this study, decisions related to sleepers are based on data stored in the database (e.g., age, type, and tonnage), geometry measurements made by track-recording cars, and results of a visual assessment of sleepers. Railway sleepers' visual inspections in Turkey are currently performed manually by a human operator. A railway worker walks along the track visually examining each sleeper (Yella et al. 2009; TCDD 2009).

There are two main possibilities of defects for concrete sleepers, cracks and surface defects (TCDD 2009). The wooden and concrete sleepers' condition data from TCDD in the analysis section are presented in Tables 6 and 7, respectively. The studies carried out on different track constructions showed that wear and damages of both wooden and concrete sleepers was very small within a relatively long time, but grow very fast in the final period. Thus, this phenomenon is a strongly nonlinear one.

Table 6. Inspection Criteria and Determinations for Wooden Sleepers

Damage level	Damage status	Decision
1	Widely cracked, metal plate is sunken	Replacement within 3 weeks
2	Not widely cracked, metal plate is sunken	Replacement within 12 weeks
3	Presence of cracks, metal plate is not sunken	Condition monitoring
4	No cracks, metal plate not sunken	No action

Table 7. Inspection Criteria and Determinations for Concrete Sleepers

Damage level	Damage status	Decision
1	Severe damage (widely cracked)	Replacement within 3 weeks
2	Severe damage (long cracks) Longitudinal ≥ 0.3 mm At dowel ≥ 0.1 mm At head ≥ 0.3 mm Transverse ≥ 0.3 mm	Replacement within 12 weeks
3	Damage	Condition monitoring
4	Light surface damage	No action

Probability distributions are used to model random events for which the outcome is uncertain; therefore, the distribution of the probability of failure at different times can be modeled by a probability distribution. A probability density function (PDF), represented as $f(t)$, is any function that is always positive and has a unit area as follows (O'Connor 2011):

$$f(t) = \int_{-\infty}^{\infty} f(t)dt = 1 \tag{10}$$

The cumulative density function (CDF), represented by $F(t)$, is the probability of the random event occurring before t, $P(T \leq t)$.

$$F(t) = P(T \leq t) = \int_{-\infty}^{t} f(x)dx \tag{11}$$

The reliability function, known as the survival function, is denoted by $R(t)$. It is the probability that the random event (time of failure) occurs after t.

$$R(t) = P(T > t) = 1 - F(t) \tag{12}$$

The exponential distribution is a frequently used distribution in reliability engineering and it is used to model the behavior of units having a stable failure rate. Mathematically, the one-parameter exponential PDF is given by

$$f(t) = \lambda e^{-\lambda t} \tag{13}$$

The one-parameter exponential CDF is given by

$$F(t) = 1 - e^{-\lambda t} \tag{14}$$

J. Comput. Civ. Eng. 2013.27:292-306.

The one-parameter exponential reliability function is given by

$$R(t) = e^{-\lambda t} \tag{15}$$

The general state of sleepers may be defined as a present serviceability index (PSI). In this study, the one-parameter exponential CDF was modified and the following equation was used to determine the PSI of the sleepers (TCDD 2009; ERRI 1993):

$$\mathrm{PSI}(M) = 1 - \exp\left[k_f\left(\frac{M}{M_L} - 1\right)\right] \tag{16}$$

The PSI values were also taken into account during the M&R operations for the sleepers. The PSI values were obtained from statistical analyses and expert decisions. The limit values of the PSI are given in Table 8, including the required parameters to calculate the PSI. Fig. 4 represents the developed decision rules' flow chart of algorithm for sleeper M&R activities considering the PSI values.

Table 8. Railway Sleepers: PSI Values with Required Parameters

Type of sleepers	Traffic load (MGT/year)	Coefficient (k_f)	Life time (years)	Decision (all type of sleepers)
Concrete	>15	5.2	35	
Concrete	≤15	5.2	40	0.6 < PSI ≤ 1.0:Only maintenance
Hard timber	>15	5.2	25	0.4 < PSI ≤ 0.6:Partial replacement
Hard timber	≤15	5.2	30	0.2 < PSI ≤ 0.4:Planning of renewal
Soft timber	>15	5.2	18	0.0 ≤ PSI ≤ 0.2: Renewal
Soft timber	≤15	5.2	21	

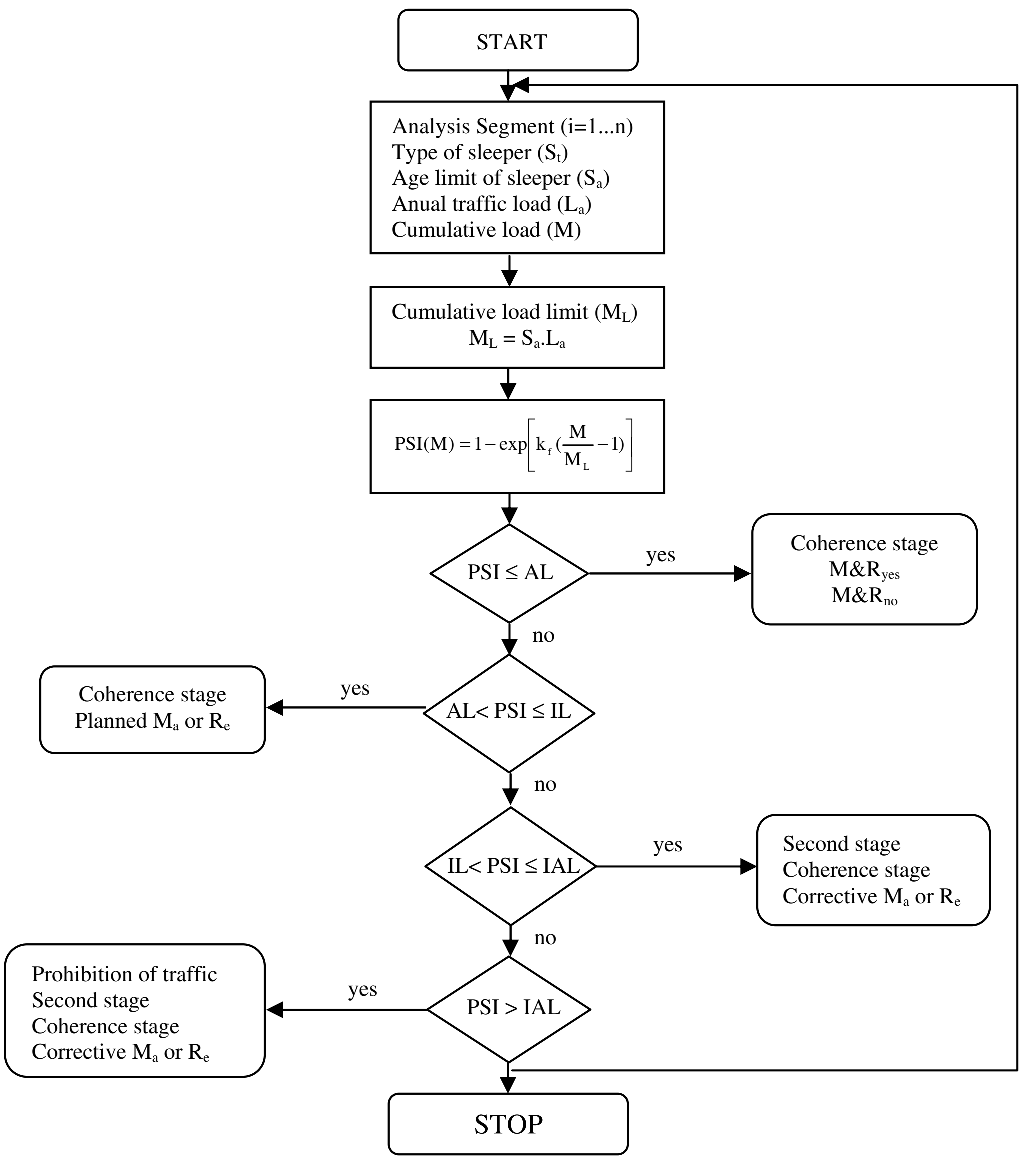

Fig. 4. Flow chart of sleeper M&R algorithm

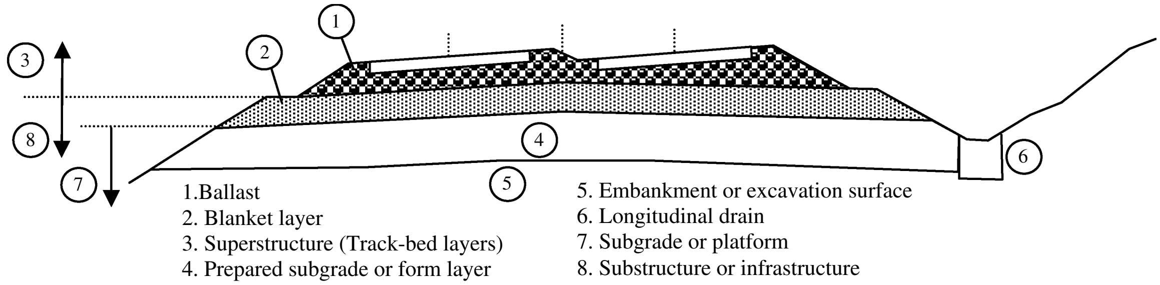

Fig. 5. Schematic cross section of railway track

Track Bed Layers

Track bed layers have an important role in track performance with respect to track support stiffness, maintenance of track geometry, and drainage. The general term for track bed layer refers to both ballast and subballast layers. In this study, Fig. 5 was considered for track structure during the data collecting process.

Terms such as general maintenance, renewal, routine maintenance, remedial works, strengthening, and improvements of railway track bed were used to define maintenance of earthworks and track bed on existing lines. Earthwork is a general term applied to cuttings, embankments, and composite cross sections. In this study, the substructure was classified according to following terms: geotechnical classification of soils, classification of soils according to bearing capacity, and frost susceptibility of soils (UIC 2008).

Ballast is formed from crushed stone and consists of particles in the size range 20 to 63 mm, and the characteristics of ballast material are explained in EN 13450 (British Standards Institution 2003). Good quality ballast must have well-graded aggregates, but the existence of a high amount of fines in ballast can rapidly result in track settlement and drainage problems (Bonnett 2005). The reference values for ballast and subballast are given in Table 9. These values were considered during the M&R decisions.

The annual average number (ℓ_m) of tamping operations can be statistically calculated as a function of track age for a given category of traffic. Thus a curve describing the annual average number increasing in time is obtained (Fig. 6).

$$\ell_m = f(T) \tag{17}$$

The number of tamping operations (ℓ) for a given age may differ from the annual average number (ℓ_m) of tamping operations. In this situation, on a particular track section, the track bed maintenance coefficient is defined as (Fig. 6)

$$k = \frac{\ell}{\ell_m} \tag{18}$$

When ℓ exceeds a certain threshold value $\ell_S = 6$, track geometry standards can no longer be fully maintained; it will then be necessary to carry out other work so as to try to reduce the k value (UIC 2008, 2009). The track bed maintenance coefficient k is known at any time by keeping detailed records of the leveling operations. If the foundation is very poor, factor k reaches to higher values; however, this coefficient equals 1 in the average case. This value and other observations made during the line inspections determine the measures required for routine maintenance, any localized operations, and renewals. The limit values for k and the decisions are given in Table 10.

Table 9. Reference Values for Ballast and Subballast

Material	E (MPa)	ν	c (MPa)	φ (°)	γ(kN/m^3)	Minimum depth (mm)
Ballast	130	0.2	0	45	15	300
Subballast	120	0.3	0	35	19	150

Life Cycle Costs

LCC takes into account all costs associated with the lifetime of the system, such as operating costs, maintenance costs, energy costs, and taxes, apart from capital costs (Patra et al. 2009). LCC is an effective engineering tool for providing decision support in the design, procurement, and maintenance of major systems, thus LCC analyses were included in the developed system.

In this study, curves with different radii and engineering structures (e.g., tunnels and bridges) were considered to associate maintenance

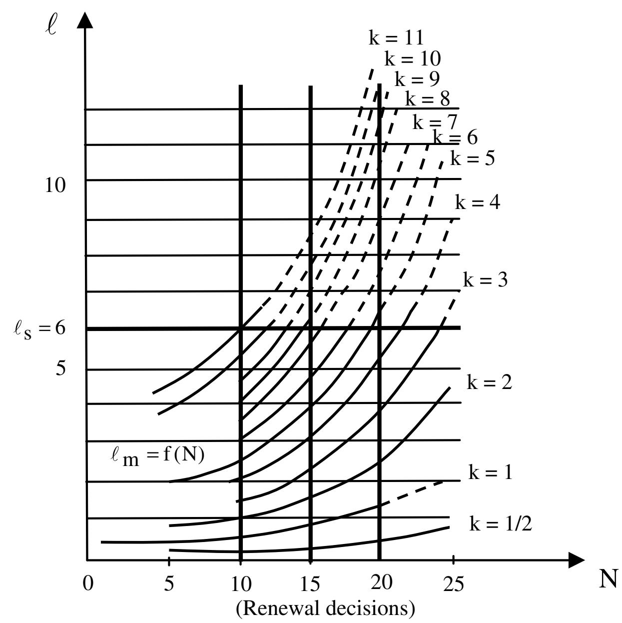

Fig. 6. Annual number of tamping operations with track bed coefficient

Table 10. Track Bed Maintenance Coefficient

Limits (k)	Decision
$k < 1$	Correct track bed layers
$1 < k < 2.5$	Track bed layers slightly underdimensioned
$2.5 < k < 5$	Underdimensioned track bed layers, subballast layers of poor quality and poor functioning of drainage
$k > 5$	Track bed layers underdimensioned, subballast layers of poor quality or nonexistent, and poor functioning of drainage

J. Comput. Civ. Eng. 2013.27:292-306.

costs with railway track. Railway tracks expose lateral forces in curves. Consequently, the deterioration rate is higher in sharp curves and the replacement of track components occurs too frequently. Thus, the railway track was divided into different maintenance sections due to the curve radius, i.e., 0–200 m ($R_c = 1$), 200–400 m ($R_c = 2$), 400–600 m ($R_c = 3$), and so on. Curves with radii greater than 1,800 m were considered as straight track. In this study, the number of each M&R activity in a defined period was calculated considering cumulative traffic loads and interval values defined by the expert decisions. For instance, $M/M_{\mathrm{RG}i}$ corresponds to the number of rail grinding in a period. In this equation, M is cumulative load (or time) and $M_{\mathrm{RG}i}$ is the interval for grinding of the ith curve in MGT. In this equation, $M_{\mathrm{RG}i}$ was defined considering some parameters such as geographic condition, weather, and curvature, which were playing different roles of formulating LCC equations.

While the railway track components are in good condition, engineering structures may be partially or completely damaged by various things such as leakage, cracks, and fatigues. In this situation, it is necessary to repair the damaged engineering structure during the required M&R activity. So an additional cost was added to the total cost due to the engineering structure on the relevant maintenance section. The M&R costs were determined according to simplified TCDD calculations and the calculations are illustrated as follows (Patra et al. 2009; TCDD 2009):

Rail grinding cost:

$$\mathrm{RGC} = \sum_{s=1}^{S}\sum_{i=1}^{R}\sum_{j=1}^{N-1}\frac{[C_{\mathrm{RG}s} + (T_{\mathrm{RG}i}\cdot C_L \cdot L_i \cdot n_{\mathrm{RG}i}) + (T_{\mathrm{RG}i}\cdot C_{\mathrm{ERG}}\cdot L_i \cdot n_{\mathrm{RG}i})]\cdot(M/M_{\mathrm{RG}i})}{(1+r)^j} \tag{19}$$

Rail lubrication cost:

$$\mathrm{RLC} = \sum_{s=1}^{S}\sum_{i=1}^{R}\sum_{j=1}^{N-1}\frac{[C_{\mathrm{RL}s} + (T_{\mathrm{RL}i}\cdot C_L \cdot L_i) + (T_{\mathrm{RL}i}\cdot C_{\mathrm{ERL}}\cdot L_i)]\cdot(M/M_{\mathrm{RL}i})}{(1+r)^j} \tag{20}$$

Rail renewal cost:

$$\mathrm{RRC} = \sum_{s=1}^{S}\sum_{i=1}^{R}\sum_{j=1}^{N-1}\frac{[C_{\mathrm{RR}s} + (C_R\cdot L_i) + (T_{\mathrm{RR}i}\cdot C_L \cdot L_i) + (T_{\mathrm{RR}i}\cdot C_{\mathrm{ERR}}\cdot L_i)]\cdot(M/M_{\mathrm{RR}i})}{(1+r)^j} \tag{21}$$

Tamping cost:

$$\mathrm{TC} = \sum_{s=1}^{S}\sum_{i=1}^{R}\sum_{j=1}^{N-1}\frac{[C_{Ts} + (T_{Ti}\cdot C_L \cdot L_i) + (C_{Ti}\cdot C_{\mathrm{ET}}\cdot L_i)]\cdot(M/M_{Ti})}{(1+r)^j} \tag{22}$$

Ballast renewal cost:

$$\mathrm{BRC} = \sum_{s=1}^{S}\sum_{i=1}^{R}\sum_{j=1}^{N-1}\frac{[C_{\mathrm{BR}s} + (C_B\cdot L_i) + (T_{\mathrm{BR}i}\cdot C_L \cdot L_i) + (T_{\mathrm{BR}i}\cdot C_{\mathrm{EBR}}\cdot L_i)]\cdot(M/M_{\mathrm{BR}i})}{(1+r)^j} \tag{23}$$

Ballast cleaning cost:

$$\mathrm{BCC} = \sum_{s=1}^{S}\sum_{i=1}^{R}\sum_{j=1}^{N-1}\frac{[C_{\mathrm{BC}s} + (T_{\mathrm{BC}i}\cdot C_L . L_i) + (T_{\mathrm{BC}i}\cdot C_{\mathrm{EBC}}\cdot L_i)]\cdot(M/M_{\mathrm{BC}i})}{(1+r)^j} \tag{24}$$

Sleeper renewal cost:

$$\mathrm{SRC} = \sum_{s=1}^{S}\sum_{i=1}^{R}\sum_{j=1}^{N-1}\frac{[C_{\mathrm{SR}s} + (C_S\cdot L_i) + (T_{\mathrm{SR}i}\cdot C_L \cdot L_i) + (T_{\mathrm{SR}i}\cdot C_{\mathrm{ESR}}\cdot L_i)]\cdot(M/M_{\mathrm{SR}i})}{(1+r)^j} \tag{25}$$

Fastener renewal cost:

$$\mathrm{FRC} = \sum_{s=1}^{S}\sum_{i=1}^{R}\sum_{j=1}^{N-1}\frac{[C_{\mathrm{FR}s} + (C_F\cdot L_i) + (T_{\mathrm{FR}i}\cdot C_L \cdot L_i) + (T_{\mathrm{FR}i}\cdot C_{\mathrm{EFR}}\cdot L_i)]\cdot(M/M_{\mathrm{FR}i})}{(1+r)^j} \tag{26}$$

Track inspection cost:

$$\mathrm{TIC} = \sum_{s=1}^{S}\sum_{j=1}^{N-1}\frac{[C_{\mathrm{TI}s} + (T_{\mathrm{TI}}\cdot C_L \cdot L) + (T_{\mathrm{TI}}\cdot C_{\mathrm{ETI}}\cdot L)]\cdot(M/M_{\mathrm{TI}})}{(1+r)^j} \tag{27}$$

J. Comput. Civ. Eng. 2013.27:292-306.

Implementation of the Model

The developed DSS was successfully implemented into TCDD with the help of local personnel for both general management and for planning purposes. The required data were transferred into the system database from the existing databases and the data collection systems. The general properties of the implemented railway tracks are presented in Table 11. The implemented railway track is between Arifiye and Eskisehir, Turkey, which is a conventional railway approximately 180 km in length (Fig. 7).

The data that are measured along the track are generally considered in two main blocks, on-line system and off-line system. Measuring vehicles or portable measuring devices are periodically used to collect the data along the track in time. Appropriate systems are very important to build a model on an on-line database. Track M&R systems are basically used at the off-line system stage, although some analyses could be realized at the on-line stage. In the case of considering the technological developments, it is easy to transfer the measured data to off-line database systems with wireless technology or removable disks for detailed analyses. In this study, the recorded track geometry data performed by noncontact and contact track recording cars were used. The self-propelled recording cars are designed for the measurement of track geometry and/or other parameters of the rail, the track, and its infrastructure. The noncontact track recording car, named Pirireis by TCDD, is capable of measuring rail profile and accelerations as well as track geometry. For the historical track geometry data, the noncontact track recording car's measurements were used. The recorded track geometry data, consisting of profile in the left and right rail, alignment in the left and right rail, twist, and gauge, were recorded by the recording cars every 25 cm with a chord length of 18.9 m. TCDD has been using portable measuring devices to collect the data of rails and sleepers. TCDD also has a geotechnical laboratory to test the materials for the track bed layers.

This study showed that TCDD has been using traditional methods targeting corrective maintenance similar to most of the railway organizations around the world. Traditional approaches require more resources according to planned M&R management systems. The developed DSS proved that it is possible to develop planned M&R systems by using advanced computer and measuring systems. One of the most important findings for the railway track produced by the system was that TCDD had a renewal policy in time. In case of efficient life cycle management, the renewal policy must be replaced by a policy representing an optimal balance between M&R. The system has proven itself and is becoming an essential tool in the decision-making process on track M&R management. The developed prototype planning system is in the process of evaluation within the TCDD. The system is going to be improved with new rules and limit values on the base of outputs and measured data over the track.

Table 11. Properties of Implemented Railway Tracks

Track properties	Arifiye–Eskisehir, Turkey
Maximum speed (km/h)	120
Total length (km)	180
Minimum curve radius (m)	256
Maximum axle load (tons)	22
Maximum gradient (%)	27.55
Rail type	S49
Sleeper type	Wooden and concrete
Rail length	Jointed and continuously welded rail

Future Work

The developed DSS system comprises conventional ballasted railway tracks with an all-granular layered track bed. This system has been in use for years around the world, offering excellent results although requiring certain M&Rs as mentioned in this paper. Due to the low M&Rs, a slab track system requiring much higher investments is an alternative to ballasted railway track. Some countries prefer using a slab track system, especially for high-speed lines in preference to ballasted track, mainly in tunnels and on elevated structures. TCDD is also planning to use a slab track system in tunnels and on elevated structures for both conventional and conventional high-speed lines. For street-running systems, light

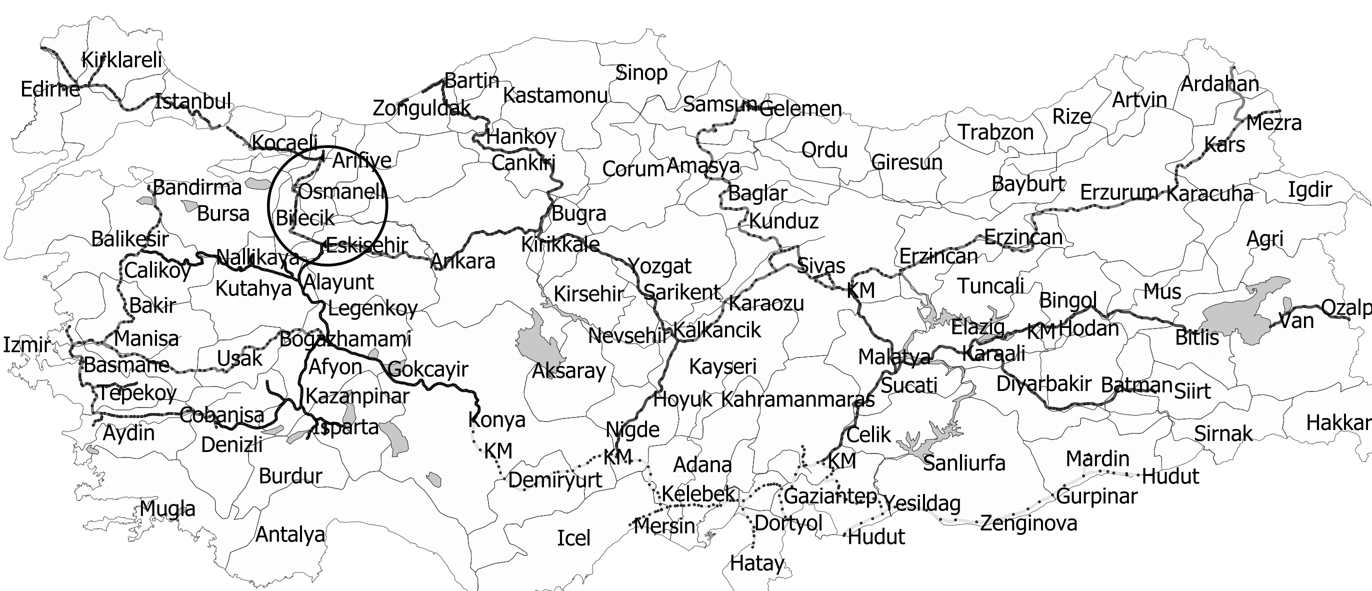

Fig. 7. TCDD railway network and Arifiye–Eskisehir, Turkey, railway line

J. Comput. Civ. Eng. 2013.27:292-306.

rails, and metro systems, slab track has been in widespread use in Turkey. The metropolitan municipalities and TCDD are planning to combine conventional and light rail systems for tram-train purposes. This aim is going to require combined M&R plans including different types of traffics (e.g., high-speed railways and light rail systems) and different types of superstructures (e.g., slab tracks). Thus, the developed DSS is going to be adapted to the new decision environment.

Consequently, future work will include the following:

- The system is going to be improved with new rules and limit values on the base of outputs and measured data over the track.
- The developed DSS system may be easily exported to conventional high-speed ballasted railway tracks only by changing the threshold values with lower ones. For this purpose, technical specification for interoperability (TSI) for high-speed and expert decisions are going to be used as a guide as well as the expert decisions. TSI for high speed has been revised and came in force 2008 [European Association for Railway Interoperability (AEIF) 2008].
- In comparison with ballasted track, slab track is a maintenance-free system. This system doesn't need the typical well-known maintenance works such as tamping, ballast cleaning, and track lining. On the other hand, increases in noise level and local track settlements are the main disadvantages of the slab track system. It is possible to develop some decision rules on noise level and track settlement. The developed DSS system is going to be improved considering the slab track system's requirements to adapt the system to the new decision environment.
- The developed DSS may be easily adapted to light-rail systems having mixed superstructure types such as ballasted and ballastless. Simply, the threshold values are going to be replaced by the new ones considering the existing specifications and the expert decisions.

Conclusion

The proposed model was implemented as a decision support system for the maintenance and renewal management of the railway track. The developed DSS completely supports the condition-based M&R management system and uses all necessary data of the track. The system has mostly fulfilled the expectations by providing a solution to the difficult problem, which is maintaining track at the required quality level for the minimum cost. The proposed DSS model provided advanced decision support rather than a simple schedule optimization. The initial input for the system is the track condition data collected directly on the line, which, once it is aggregated, takes the form of a database. The system then works as an expert system, configured as a group of decision rules, to analyze this information and provide useful criteria applicable to the planning of M&R programs. The developed DSS has a capability to renew itself in time. The system is going to produce some outputs and the users will have a chance to change some rules or include some new rules to fit the system into the reality.

Notation

The following symbols are used in this paper:

A_{FRCs} = additional fastener renewal cost due to the sth engineering structure in Turkish liras;
C = condition index;
C_B = cost of ballast in kilometers/Turkish lira;
C_{BCs} = additional ballast cleaning cost due to the sth engineering structure in Turkish liras;
C_{BRs} = additional ballast renewal cost due to the sth engineering structure in Turkish liras;
C_{EBC} = equipment cost for ballast cleaning in Turkish liras/hour;
C_{EBR} = equipment cost for ballast renewal in Turkish liras/hour;
C_{EFR} = equipment cost for fastener renewal in Turkish liras/hour;
C_{ERG} = equipment cost for grinding in Turkish liras/hour;
C_{ERL} = equipment and material cost for lubricating in Turkish liras/hour;
C_{ERR} = equipment cost for rail renewal in Turkish liras/hour;
C_{ESR} = equipment cost for sleeper renewal in Turkish liras/hour;
C_{ET} = equipment cost for tamping in Turkish liras/hour;
C_{ETI} = equipment cost for track inspection in Turkish liras/hour;
C_F = cost of fastener in kilometers/Turkish lira;
C_L = average labor cost in Turkish liras/hour;
C_R = cost of rail in kilometers/Turkish lira;
$C_{\mathrm{RG}s}$ = additional grinding cost due to the sth engineering structure in Turkish liras;
$C_{\mathrm{RL}s}$ = additional rail lubrication cost due to the sth engineering structure in Turkish liras;
$C_{\mathrm{RR}s}$ = additional rail renewal cost due to the sth engineering structure in Turkish liras;
$C_{\mathrm{SR}s}$ = additional sleeper renewal cost due to the sth engineering structure in Turkish liras;
C_{Ts} = additional tamping cost due to the sth engineering structure in Turkish liras;
$C_{\mathrm{TI}s}$ = additional track inspection cost due to the sth engineering structure in Turkish liras;
c = cohesion;
E = modulus of elasticity;
e = Euler's number;
$F(m)$ = cumulative rail failure distribution;
$f(m)$ = density function;
k = track bed maintenance coefficient;
k_f = age (or cumulative load) adjustment factor;
L = total length of track section in kilometers;
L_i = total length of maintenance section in kilometers;
ℓ = annual number of tamping operations;
ℓ_m = annual average number of tamping operations;
ℓ_S = threshold value of annual number of tamping operations;
M = cumulative load (or time);
M_a = maintenance;
$M_{\mathrm{BC}i}$ = interval for ballast cleaning of the ith curve in MGT;
$M_{\mathrm{BR}i}$ = interval for ballast renewal for the ith curve in MGT;
M_{Fri} = interval for fastener renewal for the ith curve in MGT;
M_L = cumulative load (or age) limit;
$M_{\mathrm{RG}i}$ = interval for grinding of the ith curve in MGT;
$M_{\mathrm{RL}i}$ = interval for lubricating of the ith curve in MGT;
$M_{\mathrm{RR}i}$ = interval for rail renewal for the ith curve in MGT;
M_{Sri} = interval for ballast renewal of the ith curve in MGT;
M_{TI} = interval for track inspection in MGT;
M_{Ti} = interval for tamping of the ith curve in MGT;
m = millions of gross tons;
N = life period of track in years;
$n_{\mathrm{RG}i}$ = number of grinding passes on the ith curve;
R = curve radius;
R_c = number of class of curve;
R_e = renewal;
r = discount rate;
S = number of engineering structures;
$T_{\mathrm{BC}i}$ = average time to clean ballast of the ith curve in hours/kilometer;

$T_{\mathrm{BR}i}$ = average time for ballast renewal of the ith curve in hours/kilometer;
T_{Fri} = average time for fastener renewal for the ith curve in hours/kilometers;
$T_{\mathrm{RG}i}$ = average time to grind the ith curve in hours/kilometer;
$T_{\mathrm{RL}i}$ = average time to lubricate the ith curve in hours/kilometer;
$T_{\mathrm{RR}i}$ = average time for rail renewal of the ith curve in hours/kilometer;
T_{Sri} = average time for sleeper renewal for the ith curve in hours/kilometer;
T_{TI} = average time to inspect track in hours/kilometer;
T_{Ti} = average time to tamp the ith curve in hours/kilometer;
β = shape parameter;
γ = specific weight;
η = scale parameter;
λ = scale parameter (hazard rate);
ν = Poisson coefficient;
σ_H = average standard deviations of the height;
σ_{HLim} and σ_{ILim} = comfort limits for a given track class;
σ_I = average standard deviations of the interaction; and
φ = friction angle.

References

Barros, A., Grall, A., and Berenguer, C. (2002). "Maintenance policies for a two-units system: A comparative study." *Int. J. Reliab. Qual. Saf. Eng.*, 9(2), 127–149.

Berggren, E. G., Li, M. X. D., and Spannar, J. (2008). "A new approach to the analysis and presentation of vertical track geometry quality and rail roughness." *Wear*, 265(9–10), 1488–1496.

Bocciolone, M., Caprioli, A., Cigada, A., and Collina, A. (2007). "A measurement system for quick rail inspection and effective track maintenance strategy." *Mech. Syst. Sig. Process.*, 21(3), 1242–1254.

Bonnett, C. F. (2005). *Practical railway engineering*, 2nd Ed., Imperial College Press, London.

British Standards Institution. (2003). "Aggregates for railway ballast." *BS 13450*, London.

British Standards Institution. (2008a). "Railway applications. Track. Track geometry quality. Characterisation of track geometry." *BS 13848-1*, London.

British Standards Institution. (2008b). "Railway applications. Track. Track geometry quality. Geometric quality levels." *BS 13848-5*, London.

Burstein, F., and Holsapple, C. W., eds. (2008). *Handbook on decision support systems 1*, Springer-Verlag, Berlin, 21–54.

Esveld, C. (2001). *Modern railway track*, 2nd Ed., MRT Productions, Zaltbommel, The Netherlands.

European Association for Railway Interoperability (AEIF). (2008). "Trans-European high-speed rail system, technical specification for interoperability (TSI), infrastructure subsystem." Official Journal of the European Union, Rep. No. *2008/217/EC*, Luxembourg.

European Rail Research Institute (ERRI). (1993). "Decision support system for permanent way maintenance and renewal (specification for a prototype based on expert system)." *Rep. RP1*, Specialist Committee D 187, Utrecht, The Netherlands.

European Rail Research Institute (ERRI). (1995). "ECOTRACK—Decision support system for permanent way maintenance and renewal." *Rep. RP2*, Specialist's Committee D 187, Utrecht, The Netherlands.

Evans, M., Hastings, N., and Peacock, B. (2000). *Statistical distributions*, 3rd Ed., Wiley, New York.

Grimes, G. A., and Barkan, C. P. L. (2006). "Cost-effectiveness of railway infrastructure renewal maintenance." *J. Transp. Eng.*, 132(8), 601–608.

Guler, H. (2005). "Modelling railway track geometry deterioration: An information system based study." Ph.D. thesis, Univ. of Istanbul Technique, Istanbul, Turkey.

Guler, H., Jovanovic, S., and Evren, G. (2011). "Modelling railway track geometry deterioration." *Proc. ICE Transp.*, 164(2), 65–75.

Halfawy, M., Dridi, L., and Baker, S. (2008). "Integrated decision support system for optimal renewal planning of sewer networks." *J. Comput. Civ. Eng.*, 22(6), 360–372.

Hargrove, M. B., and Martland, C. D. (1991). "TRACS: Total right-of-way analysis and costing system." *Int. Heavy Haul Railway Conf.*, International Heavy Haul Association, Virginia, 244–251.

Improved Tools for Railway Capacity and Access Management (IMPROVERAIL). (2003). *Competitive and sustainable growth programme*, TIS.PT, Lisbon, Portugal.

International Union of Railways (UIC). (2002). *UIC 712: Rail defects*, 4th Ed., UIC, Paris.

International Union of Railways (UIC). (2008). *UIC 719: Earthworks and track bed for railway lines*, 3rd Ed., UIC, Paris.

International Union of Railways (UIC). (2009). *UIC 714: Classification of lines for the purpose of track maintenance*, 4th Ed., UIC, Paris.

Jo, J. H., Lee, J. H., Ouyang, Y., and Peng, F. (2011). "Integrated decision support for roadway safety analysis." *J. Comput. Civ. Eng.*, 25(1), 50–56.

Jovanonic, S., and Guler, H. (2006). "Railway infrastructure assets management by using appropriate systems." *7th Int. Congress on Advances in Civil Engineering*, Yildiz Technical Univ., Istanbul, Turkey.

Karamouz, M., Zahraie, B., and Araghinejad, S. (2005). "Decision support system for monthly operation of hydropower reservoirs: A case study." *J. Comput. Civ. Eng.*, 19(2), 194–207.

Keefe, R., and Soeleiman, S. (1994). "The development and application of a technical/economic rail management model to Hong Kong's mass transit railway." *10th Int. Rail Track Conf.*, Rail Track Association, Cherrybrook, Australia, 131–143.

Kumar, S. (2006). "A study of the rail degradation process to predict rail breaks." Ph.D. thesis, Luleå Univ. of Technology, Lulea, Sweden.

Larsson, P. O. (2000). "Lubricating parameters for wheel—Rail interface." *ELGI AGM Proc.*, ELGI Spokesman, Athens, Greece.

Luber, B. (2009). "Railway track quality assessment method based on vehicle system identification." *Elektrotechnik & Informationstechnik*, 126(5), 180–185.

Meier-Hirmer, C., Senee, A., Riboulet, G., Sourget, F., and Roussignol, M. (2006). "A decision support system for track maintenance." *Comprail—10th Int. Conf. on Computer System Design and Operation in the Railway and Other Transit Systems*, WIT press, Wessex, UK.

Öberg, J. (2006). "Track deterioration of ballasted tracks—Marginal cost models for different railway vehicles." M.Sc. thesis, Royal Institute of Technology, Stockholm, Sweden.

O'Connor, A. N. (2011). "Probability distributions used in reliability engineering." *Reliability information analysis center (RIAC)*, Univ. of Maryland, College Park, MD.

Patra, A. P. (2009). "Maintenance decision support models for railway infrastructure using RAMS & LCC analyses." Ph.D. thesis, Luleå Univ. of Technology, Lulea, Sweden.

Patra, A. P., Söderholm, P., and Kumar, U. (2009). "Uncertainty estimation in railway track life-cycle cost: A case study from Swedish National Rail Administration." *Proc. Inst. Mech. Eng. Part F*, 223(3), 285–293.

Rashidi, M., Lemass, B., and Gibson, P. (2010). "Decision support system for concrete bridge maintenance, ISCM II and EPMESC XII, PTS 1 and 2." *AIP Conf. Proc.*, 1233, 1372–1377.

Reddy, V., Chattopadhyay, G., Larsson-Kraik, P. O., and Hargreaves, D. J. (2007). "Modelling and analysis of rail maintenance cost." *Int. J. Prod. Econ.*, 105(2), 475–482.

Rivier, R. E. (1998). "ECOTRACK: A tool for track maintenance and renewal managers." *Comprail—6th Int. Conf. on Computer System Design and Operation in the Railway and Other Transit Systems*, WIT press, Wessex, UK, 733–742.

Roberts, C. M., Chan, A. H. C., Stirling, A., and Madelin, K. A. (2000). "UK orientated decision support system for effective track maintenance and renewal." *Comprail—7th Int. Conf. on Computer System Design and Operation in the Railway and Other Transit Systems*, WIT press, Wessex, UK, 903–912.

Sadeghi, J. (2010). "Development of railway track geometry indexes based on statistical distribution of geometry data." *J. Transp. Eng.*, 136(8), 693–700.

J. Comput. Civ. Eng. 2013.27:292-306.

Shen, Y. C., and Grivas, D. A. (1996). "Decision-support system for infrastructure preservation." *J. Comput. Civ. Eng.*, 10(1), 40–49.

Tew, G., and Twindle, K. (1991). "Track maintenance planning using computer analysis." *Proc., 1991 Heavy Haul Workshop*, International Heavy Haul Association, Virginia, 158–184.

Turban, E., and Aronson, J. E. (2001). *Decision support systems and intelligent systems*, 6th Ed., Prentice Hall, Upper Saddle River, NJ.

Turkish State Railways (TCDD). (2009). "TCDD annual maintenance and renewal report." TCDD Permanent Way Dept., Ankara, Turkey.

Uzarski, D., and McNeil, S. (1994). "Technologies for planning railroad track maintenance and renewal." *J. Transp. Eng.*, 120(5), 807–820.

Uzarski, D. R., Darter, M. I., and Thompson, M. R. (1993). "Development of condition indexes for low-volume railroad trackage." *Transportation Research Record 1381*, Transportation Research Board, Washington, DC.

Vickerman, R. (2004). "Maintenance incentives under different infrastructure regimes." *Util. Policy*, 12(4), 315–322.

Yang, L. A., Powrie, W., and Priest, J. A. (2009). "Dynamic stress analysis of a ballasted railway track bed during train passage." *J. Geotech. Geoenviron. Eng.*, 135(5), 680–689.

Yehia, S., Abudayyeh, O., Fazal, I., and Randolph, D. (2008). "A decision support system for concrete bridge deck maintenance." *Adv. Eng. Software*, 39(3), 202–210.

Yella, S., Dougherty, M., and Narendra, K. G. (2009). "Condition monitoring of wooden railway sleepers." *Transp. Res. Part C*, 17(1), 38–55.

Yoshimura, A., Yoshida, Y, Hosokawa, T., and Kamiyama, M. (1995). "Development of database system, Micro LABOCS-II+, for railway track maintenance management." *Railway Technical Research Institute, quarterly reports*, Vol. 36, Railway Technical Research Institute/ Tetsudo Gijutsu Kenkyujo, Tokyo, Japan, 95–101.

Zhao, J., Chan, A. H. C., Roberts, C., and Stirling, A. B. (2006). "Assessing the economic life of rail using a stochastic analysis of failures." *J. Rail Rapid Trans. Part F*, 220(2), 103–111.

Zoeteman, A. (2002). "Computer assisted revision of infrastructure maintenance policy." *8th Int. Conf. on Computers in Railways*, WIT Press, Wessex, UK, 345–354.

J. Comput. Civ. Eng. 2013.27:292-306.