Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Reliability Engineering and System Safety 92 (2007) 1303–1314
RELIABILITY ENGINEERING & SYSTEM SAFETY
www.elsevier.com/locate/ress

Importance measures-based prioritization for improving the performance of multi-state systems: application to the railway industry

Enrico Zio, Marco Marella, Luca Podofillini*

Department of Nuclear Engineering, Polytechnic of Milan, Via Ponzio 34/3, 20133 Milano, Italy

Received 19 July 2006; accepted 24 July 2006
Available online 30 November 2006

Abstract

The railway industry is undertaking significant efforts in the application of reliability-based and risk-informed approaches for rationalizing operation costs and safety requirements. In this respect, importance measures can bring valuable information for identifying the actions to take for most effective system improvement.

In this paper, the railway network is modelled within a multi-state perspective in which each rail section is treated as a component, which can stay in different discrete states representing the speed values at which the section can be travelled, depending on the tracks degradation and on the traffic conditions. The Monte Carlo method is used to simulate the complex stochastic dynamics of such multi-state system.

A prioritization of the rail sections based on importance measures is then used to most effectively improve the performance of the rail network, in terms of a decrease in the overall trains delay. High-importance sections, i.e. with highest impact on the overall delay, are considered for a relaxation of their speed restrictions and the proposed changes are then verified, from the risk-informed perspective, to have negligible impact on the risk associated to the rail infrastructure.

Keywords: Multi-state systems; Importance measures; Risk-informed optimization; Monte Carlo

1. Introduction

Operation and maintenance procedures in the railway industry have been traditionally based on the knowledge and experience of each individual company and applied with the primary goal of providing a high level of safety to the infrastructures [1]. Nowadays, the competition from other forms of transportation has forced the railway industry to produce significant efforts for the application of reliability-based and risk-informed approaches to maintenance optimization, with the aim of reducing operational expenditures while maintaining high standards of safety [1–5].

In risk-informed decision-making, a key role is played by the importance measures (IMs), which provide information about the importance of the components constituting a system with respect to its performance [6–9]. This piece of information can be of great practical aid to system designers and managers: the identification of which components mostly determine the overall system performance allows tracing system bottlenecks and provides guidelines for effective actions of system improvement.

The risk-informed decision-making process for system improvement can be generally thought of as a three-stages procedure. First, a comprehensive, realistic model of the system behaviour is built. Then, IMs are computed and used to select the components to be prioritarily addressed for effective system improvement. The final stage is the demonstration that the system improvement proposed is actually acceptable from the risk-informed perspective, i.e. that the value of risk associated to the system after the improvement is under control and in accordance with the safety regulations [8].

Abbreviations: MSS, Multi-state system; MC, Monte Carlo; IMs, Importance measures

*Corresponding author.
E-mail addresses: enrico.zio@polimi.it (E. Zio), luca.podofillini@psi.ch (L. Podofillini).

0951-8320/$ - see front matter
doi:10.1016/j.ress.2006.07.010

Notation

τ	mission time
n	number of rail sections
j	index associated to the generic rail section, $j = 1, 2, \ldots, n$
φ_j	length of rail section $j = 1, 2, \ldots, n$
n_b	number of branches in the rail network, connecting hypothetical cities
b	index associated to the generic branch, $b = 1, 2, \ldots, n_b$
n_l	number of lines in the rail network
l	index associated to the generic rail line, $l = 1, 2, \ldots, n_l$
σ_l	length of rail line l, $l = 1, 2, \ldots, n_l$
s_l	number of sections constituting rail line l, $l = 1, 2, \ldots, n_l$
$t_{sc,l}$	scheduled time for a train to cover line l, $l = 1, 2, \ldots, n_l$
f_l	number of trains per day travelling through the rail line l, $l = 1, 2, \ldots, n_l$
$X_j(t)$	random train speed through section j at time t
$\overline{X}_l(t)$	average of the train speeds $X_j(t)$ belonging to rail line l, $l = 1, 2, \ldots, n_l$
T_l	random time a train takes to cover line l, $l = 1, 2, \ldots, n_l$
k, r	indexes associated to the generic state of section j, $k, r = 0, 1, \ldots, m_j$
$m_j + 1$	number of states of section j
x_{jk}	train speed through section j in state k
$\lambda_{j,k\to r}$	transition rate of section j from state k to state r, $k, r = 0, 1, \ldots, m_j$
δ_j	number of degradation levels of section j
h_{jk}	degradation level associated to state k of section j
h, g	indexes associated to the generic degradation level of rail section j, $h, g = 0, 1, \ldots, \delta_j$
p_{jh}	probability of section j having degradation level h, $j = 1, 2, \ldots, n$, $h = 0, 1, \ldots, \delta_j$
$\gamma_{j,h\to g}$	transition rate of section j from degradation level h to degradation level g, $h, g = 0, 1, \ldots, \delta_j$
$p(x_{jk}\|h)$	probability of train speed x_{jk} in section j given the degradation h
α	generic level of train speed
c_α	multiplicative factor to modify the transition rates according to the speed α
$d(t)$	expected overall delay over the network at the time t
$d_j^{>\alpha}$	expected overall delay of the network when the speed in section j is always kept above level α, $j = 1, 2, \ldots, n$
a_j^α	generalized performance achievement worth of section $j = 1, 2, \ldots, n$

In this paper, the use of IMs for risk-informed application is demonstrated with reference to a sample rail network system which is described as a multi-state system (MSS) [10,11] whose components are the rail sections, each one characterized by different environmental and traffic load conditions. The performance of each rail section is measured in terms of the speed at which a train can travel through it: realistically, different speeds are possible so that the multi-state perspective becomes mandatory. The travelling speed of a train in a section is assumed to depend on:

- *Track quality*. If a rail section has bad track quality, the rail managers can decide to impose restrictions on the travelling velocity in order to further reduce fatigue and stress conditions on the tracks so as to keep under control the probability of undesired events such as rail breakage or, eventually, derailment.
- *Traffic load*. The speed reduction in a section can either cause traffic congestion on the whole line or, alternatively, can be compensated by increasing the travel velocity in the adjacent sections so that trains are on schedule on the overall line.

The performance of the rail network is measured in terms of the delay accumulated by the trains over the entire network in 1 day of operation. To properly describe the complex dynamics associated with the rail system, a Monte Carlo (MC) simulation approach is embraced [12]. This approach was adopted for its modelling flexibility, which provides for further potential of adherence to reality. In particular, it allows modelling of the dependencies considered. Numerical solutions of Markov and Semi-Markov models could be alternatively used [13].

MSS–IMs [14] are computed to identify which sections are the most responsible for the overall delay on the network. The sections identified as most responsible can then be addressed, e.g. in terms of a relaxation of the speed restrictions, for effective improvement of the rail network performance, i.e. a decrement in the overall delay. Within a risk-informed perspective, the possible negative impact on the risk associated to the rail infrastructure is then verified to be negligible.

It is believed that this paper is a first contribution towards filling the gap between the extensive theoretical work on MSS–IMs [14–18] and their practical application.

2. Problem description

The definition of inspection and maintenance procedures in the railway industry has always aimed at assuring the highest possible level of safety to the infrastructure whereas economical issues have been of less concern. However, nowadays the competition from other transportation industries has increased the need for a rationalization of the expenditures for safety [1–5,19].