Transportation Research Part C 93 (2018) 396–409

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Probabilistic risk analysis of flying ballast hazard on high-speed rail lines

Jieyi Deng[a], Xiang Liu[a,*], Guoqing Jing[b], Zheyong Bian[a]

[a] Department of Civil and Environmental Engineering, Rutgers, The State University of New Jersey, United States
[b] Department of Highway and Railway Engineering, Beijing Jiaotong University, China

ARTICLE INFO

Keywords:
High-speed rail
Flying ballast
Safety
Risk analysis

ABSTRACT

Flying ballast is a significant safety concern for high-speed train operations on ballasted tracks. It is the phenomenon of a ballast particle displaced from the track, due to the aerodynamic force induced by a passing train traveling above a certain speed. Flying ballast can potentially damage tracks and rolling stock, thereby posing a risk to high-speed rail operations. This paper develops a Probabilistic Risk Analysis (PRA) model based on the information available from the field and the literature. The model enables a quantitative assessment of the probability of ballast particle displacement at a particular position on the track, as well as the probabilistic distribution of the total number of ballast particles that are expected to move. The model accounts for various risk factors, such as train speed, ballast gradation, and track position. The model application is illustrated using a ballasted track on the Yellow River Bridge on the Beijing-Shanghai high-speed rail line in China. The analysis finds that flying ballast probability increases when train speed increases, in particular, the problem of flying ballast becomes more pronounced when train speed exceeds 350 km per hour (217 miles per hour). Flying ballast probability might be reduced when the ballast profile is lower, given all else being equal. In addition, flying ballast probability is expected to be higher at the center of the track than in other positions. The proposed risk model can be further developed and ultimately be used to evaluate route-specific flying ballast risk, enabling the identification, assessment, and comparison of risk mitigation strategies in order to support emerging high-speed rail operations.

1. Introduction

High-speed rail (HSR) delivers a safe, fast and energy-efficient means for long distance passenger transportation. Given the development of global HSR systems in recent years, operational safety is of crucial importance.

Flying ballast (defined as displaced ballast particles in this paper) is a primary safety concern for HSR operations on ballasted tracks. Flying ballast can cause damage to locomotives, railcars, and tracks, and may even injure workers near tracks, resulting in significant economic losses and safety hazards. Therefore, understanding and managing flying ballast risk is vital for assuring HSR operational safety.

Ballast flight occurs on ballasted tracks, which can have a range of impacts, from minor to consequential. In addition to ballasted tracks, another common track type in HSR system is called non-ballasted track (also known as Slab Track) (Fig. 1). Non-ballasted track usually provides high longitudinal and lateral stability (Steenbergen et al., 2007). Non-ballasted track has been used extensively, such as on new lines in the Chinese HSR network and Japanese Shinkansen network (Esveld, 2003). Although non-ballasted

* Corresponding author.
E-mail address: xiang.liu@rutgers.edu (X. Liu).

https://doi.org/10.1016/j.trc.2018.06.003
Received 16 December 2017; Received in revised form 9 May 2018; Accepted 7 June 2018
0968-090X/

Fig. 1. Ballasted track and non-ballasted track.

track has been put to use on new HSR lines, many existing HSR lines still use ballasted tracks due to various economic and technological challenges preventing the replacement of all ballasted tracks with non-ballast tracks. In addition, ballasted track has its advantages in terms of lower capital cost and long-term maintenance convenience (Indraratna et al., 2011). Moreover, non-ballasted track cannot be used in certain areas, such as those prone to earthquakes or with softer soil (Saat et al., 2015). For these reasons, ballasted track is still used on many HSR lines; for example, in France, Italy and Spain, dominant HSR track structure remains ballast bed, and thus these tracks are open to the risk of flying ballast.

This paper focuses on evaluating flying ballast risk on ballasted tracks for HSR operations. Although several alternative risk mitigation strategies have been identified in the literature, there is no integrated risk analysis framework through which alternative risk mitigation strategies can be evaluated and compared. The current practice is still mostly reliant on engineering experience. With the aim of advancing both the state of the art and the current practice with respect to flying ballast risk management, this paper develops a Probabilistic Risk Analysis (PRA) model to estimate the probability distribution of the number of flying ballast particles given different operating conditions and at different track positions. PRA is a useful technique for assessing the risk of a rare event (Paté-Cornell and Dillon, 2001). Because of the low occurrence probability of flying ballast, direct statistical analysis is not suitable due to the limited sample size. Instead, PRA decomposes a rare event into a chain of events and influencing factors, and then integrates them using probabilistic methods. PRA has been used in various safety-critical engineering domains, such as space shuttles, nuclear facilities, and aviation (Paté-Cornell, 2002; Paté-Cornell and Dillon, 2001; Vesely and Rasmuson, 1984; Garrick and Christie, 2002; Mohaghegh et al., 2009).

In the context of flying ballast, the mechanism of its occurrence can be described using a mechanistic model accounting for various forces (e.g. interlock force, aerodynamic force, vibration force). The forces leading to a ballast flight can be affected by specified infrastructure factors (e.g. ballast gradation, ballast height) or operational factors (e.g. train speed). When some of these factors are uncertain at the time of risk analysis, PRA can be used as a systematic approach to propagate these factor-specific uncertainties to derive the uncertainty of flying ballast. In this paper, the risk is defined as the probability distribution of the number of flying ballast particles. With the help of the PRA model, the risk analysis methodology is built upon an understanding of the phenomenon and mechanism of ballast flight occurrence, and accounts for a variety of operating and infrastructure characteristics in the field. The general methodology can be adapted to specific routes or networks. The ultimate goal is to evaluate location-oriented flying ballast risk, thereby understanding the effectiveness of potential risk mitigation strategies for HSR safety assurance on specific ballasted tracks.

The remainder of this paper is structured as follows: Section 2 provides a review of previous research in related fields. Section 3 identifies the knowledge gaps that this research aims to narrow. Section 4 estimates flying ballast probabilities under different operational circumstances. A case study of a section of high-speed rail line in China is developed in Section 5, to illustrate model application. Finally, the significant contributions, limitations of this research, and a future research plan are discussed in Sections 6–8.

2. Literature review

Previous studies have focused on understanding the process and influencing factors related to flying ballast in HSR operations. As Table 1 shows, the prior methods include field tests, mechanistic models, risk assessment methods and common risk reduction strategies in practice. Based on these approaches, previous studies identify promising risk mitigation strategies.

2.1. Field experiments

Several field experiments have been performed in order to understand the physical characteristics of ballast flight and relevant aerodynamic factors. For instance, Kwon and Park (2006) conducted a field investigation based on the shape and mass of ballast particles in order to explore the relationship between train velocity and airflow speed underneath the train. The probability of ballast