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Modeling cascade dynamics of railway networks under inclement weather

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ABSTRACT

Understanding the cascade dynamics of delay propagation under inclement weather is crucial to proactive railway management. In this paper, we proposed a Switching Max-Plus System (SMPS) to model the delay propagation on railway networks, which extends the conventional MPS by incorporating multiple system matrices to capture the dynamic impacts of inclement weather. An algorithm based on the All-Paired Critical-Path (APCP) graph was developed to solve the SMPS, which calculates secondary delays without backtracking the precedent events. The proposed model and its solution algorithm were validated using discrete-time simulations on both artificial and empirical networks. The robustness of railway services was also analyzed using the concepts of vulnerability and diffusivity.

1. Introduction

Recently, with the rapid development of rail infrastructure, the railway system is becoming one of the busiest transportation modes in China with over 1.4 billion trips taken every year (Chou et al., 2011; Zheng, 2010). As China's railway network spans through numerous diverse climate regions, its operation is always subject to inclement weather, such as strong rainstorms and blizzards. Under such conditions, the operating speed is constrained by the Rail Transportation Weather Index (RTWI) and relevant safety regulations (China Meteorological Administration, 2007). The reduction in operating speed may result in severe primary and secondary delays over the entire railway network (Cui and Zhang, 2010; Ma et al., 2011; Zeng et al., 2012). For example, on February 4th 2013, due to snowstorms in northern China, three major railway services among Beijing, Tianjin, Shanghai, and Guangzhou suffered from severe delays; some services were even canceled, leaving thousands of passengers stranded in Shanghai Station for over three hours. On December 15th 2012, more than 10 high-speed rail services from Beijing Station were delayed for nearly 2 h in the morning due to heavy fog and snowstorms. The operating speed was reduced from 300 to 100 km per hour (km/h), resulting in severe primary and knock-on delays over the network.

Although the delay caused by severe weather is inevitable, understanding the underlying cascade dynamics of delay propagation is crucial for the effective management of a railway network. Due to the shared infrastructural resources, the primary delay of an arrival or departure may propagate to its subsequent events. Such propagation of train delays at the

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network scale could be rather complicated and often exhibits a cascade pattern, where the delay of a single service may lead to a catastrophic cascade of delays over the entire network (Zhou and Zhong, 2007).

Usually, train delays are grouped into two categories: the primary delay and the secondary (knock-on) delay. The primary delay is directly caused by incidents such as the malfunctioning of the infrastructure and inclement weather. The secondary delay, on the other hand, is due to the propagation of delays incurred by other services because of track sharing, operational constraints, and safety regulations such as the minimum running headway and speed limit (Kliewer and Suhl, 2011).

To capture the propagation of primary delays, several stochastic delay models have been developed with the objective of estimating stationary distributions of secondary delays. For instance, Carey and Kwiecinski (1994) investigated multiple train services on single-track lines with stochastic running and dwell times. Probability density functions of successive arrival and departure times were derived in a recursive way. Higgins and Kozan (1998) presented another stochastic delay model of urban railway networks, where they assumed that source delays were due to frequent random events (e.g., long dwell times) and followed certain distributions (e.g., the Erlang distribution). An implicit expression was proposed to derive the expectations of secondary delays. Recently, Meester and Muns (2007) extended the model by using phase-type distributions. The objective of these stochastic models was to derive the stationary distributions of train delays given the primary delays that follow certain probability distributions. Since inclement weather is a type of small probability event, these stochastic models can only provide statistical properties of train delays in the long run. They are unable to predict train delays when the network is affected by inclement weather with a specific spatial–temporal coverage. Therefore, it is unfeasible to compare these stochastic models with the proposed method due to the different modeling objectives and applicable scenarios.

In contrast to stochastic models, the deterministic approach applies the max-plus algebra, wherein movements of trains are depicted as a discrete-event system. For example, Braker (1993) developed a recursive system using the max-plus algebra for periodic timetables of the Dutch railway network. Subiono (2000) extended Braker's model to accommodate networks with mixed train types. Based on these Max-Plus System (MPS) models, De Schutter et al. (2002) and van den Boom and De Schutter (2006) proposed several control models to reschedule train services for mitigating secondary delays.

However, these static MPS models (Braker, 1993; De Schutter et al., 2002; Goverde, 2007; Subiono, 2000) can only be applied in situations when initial delays are known and their propagation is governed by static constraints in normal conditions. When railway networks suffer from inclement weather that changes in both temporal and spatial scales, the constraints are no longer static; instead, they evolve accordingly to time. Delay propagation exhibits a more intricate pattern. On the one hand, additional primary delays may be coupled into the system while earlier primary delays are still propagating. In this case, the propagation of earlier delays no longer follows normal regulations, and therefore, a single system matrix with normal constraints is insufficient. On the other hand, even if the weather condition is assumed static, primary delays still cannot be readily obtained as dependencies may exist among primary delays themselves.

In this paper, we present a Switching Max-Plus System (SMPS) to model the delay propagation under the dynamic impact of inclement weather. In contrast to existing MPS methods, the SMPS introduces a system matrix for each operation scenario, describing the impacts of the inclement weather at different stages. The railway network is switching between different operating modes with the dynamics of hazardous weather. An algorithm based on the All-Paired Critical-Path (APCP) graph is developed to solve the SMPS and has two main advantages: first, it enables a direct calculation of the delay of a certain event without the need of backtracking its precedent events; second, measures of service robustness, such as vulnerability and diffusivity, can be readily determined from the APCP graph. For a comparison, an iterative algorithm is also presented based on the precedence graph of the slack time matrix. Case studies on both artificial and empirical networks are conducted to validate the model and its solution algorithm.

The proposed model contributes to the state-of-the-art railway operation research in two ways: (1) it successfully modeled the delay propagation through an SMPS approach. SMPS is a significant extension of MPS, in which the structure of SMPS is not constant but rather evolving with time. To the best knowledge of the authors, very few, if any, studies have taken into account the dynamics of constraints (inclement weather, in this study) in modeling the delay evolution in railway networks; and (2) an APCP graph based algorithm was developed to replace the iterative approach for improving the computational efficiency. More importantly, robustness measures of railway services, i.e., the vulnerability and the diffusivity, can be derived from the APCP graph.

The rest of the paper is organized as follows. Section 2 presents the SMPS model for delay propagation under inclement weather. Section 3 proposes the APCP algorithm for solving the SMPS model, as well as robustness measures derived from the APCP graph. Section 4 presents cases studies on both artificial and empirical railway networks. Section 5 concludes the paper.

2. Model formulation

In this section, we first define the problem and introduce the basic notation. Then, the fundamentals of the max-plus algebra are presented. We demonstrate how operational constraints of a railway system can be expressed using the max-plus algebra. Then, we propose a Switching MPS (SMPS) approach for modeling the cascade dynamics of railway networks under the impacts of inclement weather.