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High-Speed Railway Train Timetable Conflict Prediction Based on Fuzzy Temporal Knowledge Reasoning

He Zhuang [a,b], Liping Feng [a,*], Chao Wen [a,d], Qiyuan Peng [a,c], Qizhi Tang [b]

[a] School of Transportation and Logistics, Southwest Jiaotong University, Chengdu 610031, China
[b] China Railway Corporation, Beijing 100844, China
[c] National United Engineering Laboratory of Integrated and Intelligent Transportation, Southwest Jiaotong University, Chengdu 610031, China
[d] Department of Civil and Environmental Engineering, University of Waterloo, Waterloo N2L 3G1, Canada

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ABSTRACT

Trains are prone to delays and deviations from train operation plans during their operation because of internal or external disturbances. Delays may develop into operational conflicts between adjacent trains as a result of delay propagation, which may disturb the arrangement of the train operation plan and threaten the operational safety of trains. Therefore, reliable conflict prediction results can be valuable references for dispatchers in making more efficient train operation adjustments when conflicts occur. In contrast to the traditional approach to conflict prediction that involves introducing random disturbances, this study addresses the issue of the fuzzification of time intervals in a train timetable based on historical statistics and the modeling of a high-speed railway train timetable based on the concept of a timed Petri net. To measure conflict prediction results more comprehensively, we divided conflicts into potential conflicts and certain conflicts and defined the judgment conditions for both. Two evaluation indexes, one for the deviation of a single train and one for the possibility of conflicts between adjacent train operations, were developed using a formalized computation method. Based on the temporal fuzzy reasoning method, with some adjustment, a new conflict prediction method is proposed, and the results of a simulation example for two scenarios are presented. The results prove that conflict prediction after fuzzy processing of the time intervals of a train timetable is more reliable and practical and can provide helpful information for use in train operation adjustment, train timetable improvement, and other purposes.

1. Introduction

Trains are likely to deviate from train operation plans during their operation and produce headway and route conflicts as a result of the influences of factors such as the weather, geological conditions, and driver and train performance. Therefore, dispatchers often need to make some adjustment to conflicts, on the premise of keeping subsequent operation plans unchanged, and without considering disturbances. Obviously, these assumptions do not align well with the real world. Previous studies on the train delay propagation law [1–3], the dynamic properties of train delays [4,5], and the operation adjustment decision making have proposed adjusting the buffer time as the major way to eliminate headway conflicts or having simulated subsequent train operations by introducing stochastic disturbances [6–10]. Considering that the train timetable is operated periodically and that daily delay information including where, when, and how long can be recorded, we can sum up the delay distribution law and obscure the time interval in a train timetable in order to simulate the subsequent train operation status based on these historical time data.

* Corresponding author.
E-mail address: lipingfeng@my.swjtu.cn

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This approach is much more realistic and valuable than stochastic disturbances.

Murata [11] and Zhou et al. [12] discussed temporal uncertainty and fuzzy timing in a high-level Petri net model with four fuzzy time functions and algorithms for performing the reasoning. This method was applied to check the consistency of temporal knowledge during operation planning by Ye et al. [13] and Liu et al. [14]. Wen et al. [15,16] proposed a method for distinguishing and predicting train operation conflicts based on triangular fuzzy number workflow nets. These studies provide insight into how actual operational data can be used to improve the reliability of conflict prediction results. The aim of this paper is to discuss the following research questions:

- How can the time interval in a train timetable be obscured based on the historical time data?
- What are the decision conditions to headway conflict, and how can the conflict prediction results be presented?
- What is the advantage of the fuzzy temporal knowledge reasoning method in practical application, compared with the current method?

The remainder of this paper is organized as follows: Section 2 models a train timetable based on a timed place Petri net and explains how to obscure the time interval based on historical time data. Section 3 proposes the judging conditions for two different types of conflicts and the evaluation indexes for conflict prediction results presentation. Section 4 takes the Beijing South–Jinan West railway line as an example. Conflict predictions with or without additional perturbations are simulated and the amount of available information in two different reasoning methods is compared, proving the feasibility and effectiveness of the fuzzy temporal knowledge reasoning method.

2. Modeling and pre-processing a high-speed railway timetable

2.1. Modeling a train timetable based on a timed place Petri net (TPPN)

Train timetables have been modeled using different simulation tools and mathematical methods in previous studies. Petri net theory is one of the theories used for timetable modeling, and has been previously applied to train timetable modeling and analysis [2,17,18]. The timed Petri net (TPN) theory is one of the important branches of Petri net theory, and can be divided into the timed transition Petri net (TTPN), timed place Petri net (TPPN), and timed arc Petri net (TAPN) theories, according to the different temporal factor distributions involved [2]. Considering that only the time delay in TTPN is satisfied, and that the state marking of the subsequent places can be changed, the state marking can be easily misunderstood. Therefore, we adopted TPPN as the modeling tool to ensure that the state marking at any time in the model can be explained in an unambiguous way. A high-speed railway train timetable can be modeled based on TPPN as follows:

$$N = \{P, T, Pre, Post, TD, K, W, M_0\} \quad (1)$$

where,

- N is the TPPN model of a high-speed railway train timetable;
- $P = \{p_1, p_2, \ldots, p_m\}$, the finite place set, representing the temporal constraints between adjacent train actions and satisfying the conditions that $P \bigcup T = \varnothing \wedge P \bigcap T = \varnothing$;
- $T = \{t_1, t_2, \ldots, t_n\}$, the finite transition set, representing the train operations at station and satisfying the conditions that $P \bigcup T = \varnothing \wedge P \bigcap T = \varnothing$;
- Pre: $P \times T \rightarrow \{0, 1\}$, the preceding related functions;
- $Post$: $T \times P \rightarrow \{0, 1\}$, the posterior related functions;
- TD: $P \rightarrow time$, the mapping function from the place of the time interval; and
- K, W, and M_0 are the place capacity function, directed arc weight function, and initial identification, respectively. In this model, $K = W = 1$, which means that a train only has one accurate statement at any time.

Fig. 1 is an example of a high-speed railway train timetable for three trains (Tr_1, Tr_2, Tr_3) and four stations (S_1, S_2, S_3, S_4). We build the TPPN model shown in Fig. 2 for this timetable. In this figure, the subscripts using Arabic numerals represent trains or stations and the subscripts using Roman numerals represent sections.

As seen in this example, any train operation plan is a sequence of operational stations and time intervals between adjacent operations. Given these characteristics of a train timetable, its TPPN model has the following features. First, there are three types of transitions, representing train departures, train arrivals, and trains passing through. Two place types exist: the state of a train being at a station, where the delay time is the time interval between adjacent train operations; and the state of a train being in the section between stations, where the delay time is the running time at that interval. Second, a preceding train operation (the preceding transition) imposes restrictions on a train's succeeding operation (the succeeding transition) or on that of an adjacent train. In the meantime, the succeeding transition is restricted

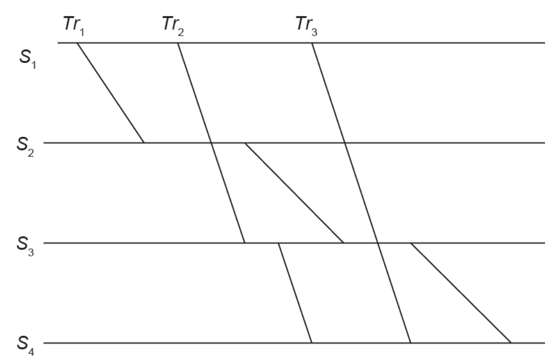

Fig. 1. A sample of high-speed railway train timetable.

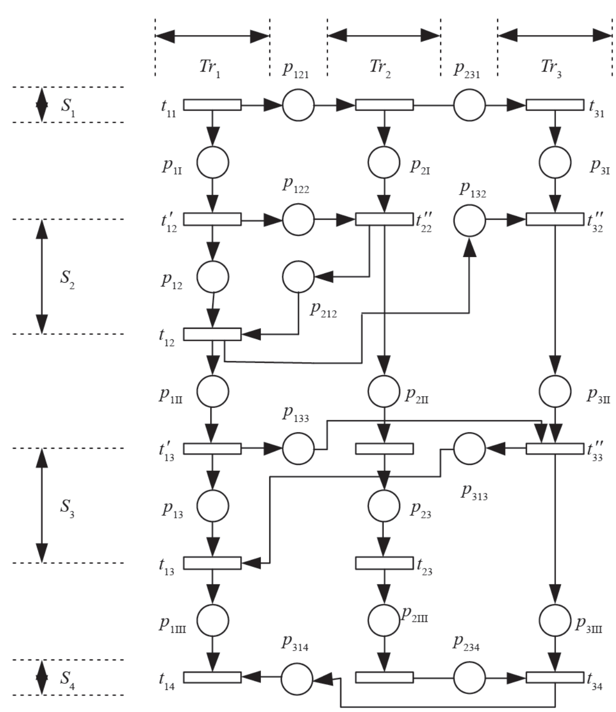

Fig. 2. Model of train timetable sample.