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Method of analysis for delay propagation in a single-track network

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ABSTRACT

Delay propagation is a key factor in punctuality of rail services. Propagation of delays reflects the degree of robustness of timetable design and the stability of train operations. This paper studies delay propagation for trains on single-track railways as the Norwegian rail network comprises primarily single-track operations. The analysis is based on real-time punctuality data. We present an algorithm and results from application of the algorithm. The algorithm is a recursive implementation of a set of conditions that (i) detects cases of knock-on delays, revealing dependencies between two trains on single-track railway, and (ii) finds the networks of dynamic delay propagations by tracing the propagation of knock-on delays from one interaction between trains to the next. Finally, we compare our results to delay cause registrations and theoretical calculations of the expected propagation factors. The propagation factors based on our model for a five-month period are typically around two, and over 70% of dynamic delay propagations consist of two trains. This indicates that each delay minute generates an additional delay of 1 min for other trains, which is higher than the present delay registrations. The presented method and analysis can be applied in punctuality improvement work, including timetable analysis.

1. Introduction

Infrastructure managers are working to understand and quantify the influence of individual infrastructure component failures and other delay causes on train traffic in near real-time. This capability will enable smarter and more cost-effective infrastructure maintenance. Successful development of the capability requires a detailed understanding of the occurrence of delays and their propagation through the system. Such insight may also support other efforts to improve punctuality. As the availability of train traffic data increases, there are large opportunities for analytical use of this data to gain an improved understanding of delays and their causes.

The occurrence of primary delays is directly observable and relatively well understood (Olsson and Haugland, 2004; Goverde and Hansen, 2001), although sometimes challenging to quantify accurately. Propagation of delays, from these primary delays, reflects the degree of robustness of timetable design and the stability of train operations (Yuan and Hansen,

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2007). Delays caused by delay propagation are also called secondary or knock-on delays. They have been shown to increase exponentially with capacity utilization (Yuan and Hansen, 2007).

While there are models for the calculation of waiting time and secondary delays on double track lines, few such models for single track lines have been published (Handstanger, 2008). A train suffering a knock-on delay may cause further knock-on delays on other trains, known as dynamic delay propagation (Yuan and Hansen, 2007). While Flier et al. (2009) point to the need to develop algorithms to describe and quantify dynamic delay propagation based on real-time data, we are not aware of previous research to develop such algorithms. Thus, we conducted a study of dynamic delay propagation using real-time train traffic data. Our purpose was three-fold. First, we sought to develop an algorithm that uses real-time data to detect cases of knock-on delays, revealing dependencies between two trains on a single-track railway line. Second, we sought to automatically trace the propagation of knock-on delays from one case to the next, describing and quantifying the dynamic delay propagations. Third, we compared our results to manual delay cause registrations, and to theoretically calculated propagation factors. The algorithm and method is used in a case study to show examples of dynamic delay propagations, and to compare the events of knock-on delays over a period of five months.

2. Literature review

Samuel (1961) highlighted early on the need for statistics in railway management. Several advances have been made since then. Studies of delays, and delay propagation can be based on simulations, empirical data, theoretical approaches, or a combination of these. In our study, we are interested in studies of delay propagation in general, and on single-track lines in particular.

Simulations have been used extensively to study delay propagation (Lindfeldt, 2015; Warg, 2013; Radtke and Bendfeldt, 2001; Goverde, 2010) and it is common to apply simulation techniques when studying the relationship between key factors, such as train homogeneity or capacity utilization and the impact on random primary delays. Lindfeldt's (2015) work is a recent example of such an approach. Warg (2013) has shown that simulation is an adequate method to reveal delay data for future timetabling scenarios. Radtke and Bendfeldt (2001) simulate traffic with introduced primary delays, to be able to compare different scenarios with alternative timetables and infrastructures. Goverde (2010) presents an algorithm that models delay propagation in a large-scale railway network that includes single-track. The model detects the propagation of delays, based on a given railway network, a periodic timetable and a set of initial delays. The results are visualized in the network, and show the magnitude of the delays and how they propagate and die out over time.

Several of the aforementioned papers, use real-time data in their studies. Yuan and Hansen (2007) validate their model by means of train detection data. D'Ariano and Pranzo (2009) use it for the design of a traffic management system. Schwanhausser (1974), Cule et al. (2011), Goverde and Hansen (2001) and Flier et al. (2009) use it in post-evaluation.

Yuan and Hansen (2007) propose an analytical stochastic model which estimates the propagation of train delays at platform tracks and junctions. Their model also adopts recursive substitutions to estimate the dynamic delay propagation. Cule et al. (2011) use real-world data in their search for patterns of delayed trains in the Belgian railway network. The method finds all trains that are frequently delayed for a given time period. Goverde and Hansen (2001) use regression analysis to identify interrelationships between train arrivals and departures. They use real-time data from the Netherlands and time-stamps for events connected to entering and leaving a station. The events correspond to individual train movements along the route.

Flier et al. (2009) uses real-world data to detect two important types of delay dependencies on large-scale railways. These dependencies are knock-on delays caused by sharing of the same infrastructure, and delay caused by late connection between two trains. The algorithmic methods solve maximum optimization problems, and find correlations and patterns in systematic dependencies. Systematic dependencies refer to events (of delay dependencies) that occur on a regular basis. It was suggested that the results could then be statistically analysed, e.g., to assess the significance of the dependencies, and used for timetable planners to detect often-occurring secondary delays and adjust the timetable to reduce the dependencies. As a third step in an evaluation process, Flier et al. (2009) suggested extending their approach to global dependencies, i.e. to trace back the propagation of delays along the route of trains, possibly yielding a network of delay propagations. There are also other examples of articles presenting research on delay propagation on railway tracks (e.g. Conte, 2007; Hansen, 2001; D'Ariano et al., 2007).

Delay propagation can also be reduced through analysis of the operating railway, for instance, for decision support for traffic controllers, as proposed by D'Ariano and Pranzo (2009). The model predicts future evolution of railway traffic based on actual track occupation, characteristics of the signalling system, and train characteristics. The decision kernel of the system is a real-time optimization module, responsible for detecting and solving train conflicts while minimizing the propagation of delays. Others, such as Harris et al. (2013) have also demonstrated the use of structured methods to evaluate and improve performance in dispatching and on station punctuality. While primarily related to studies on multi-tracked infrastructure, Harris et al. (2013) describes a method and explore a case of minor delays incurred on station under the context of major timetable changes.

Schwanhausser (1974) proposed an analytical model to calculate the secondary delay on a railway line. The overall secondary delay is calculated by the summation of the secondary delays multiplied by the frequency of primary delay. Potthoff (1970) provides equations for delay propagation. The propagation factor on single tracks is a function of the initial delay, headway time, buffer time between trains and the number of sections on the single track. The equation is valid for primary