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Quantifying railway timetable robustness in critical points ☆

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ABSTRACT

Several European railway traffic networks experience high capacity consumption during large parts of the day resulting in delay-sensitive traffic system with insufficient robustness. One fundamental challenge is therefore to assess the robustness and find strategies to decrease the sensitivity to disruptions. Accurate robustness measures are needed to determine if a timetable is sufficiently robust and suggest where improvements should be made.

Existing robustness measures are useful when comparing different timetables with respect to robustness. They are, however, not as useful for suggesting precisely where and how robustness should be increased. In this paper, we propose a new robustness measure that incorporates the concept of critical points. This concept can be used in the practical timetabling process to find weaknesses in a timetable and to provide suggestions for improvements. In order to quantitatively assess how crucial a critical point may be, we have defined the measure robustness in critical points (RCP). In this paper, we present results from an experimental study where a benchmark of several measures as well as RCP has been done. The results demonstrate the relevance of the concept of critical points and RCP, and how it contributes to the set of already defined robustness measures.

1. Introduction

A tendency seen for quite some time is a growing demand for railway capacity. During 2011, in total 188 million railway journeys were made in Sweden, which corresponds to 11.4 billion passenger-kilometres (Trafikanalys, 2012). Solely for the last 5 years, this means an increase of the Swedish railway passenger traffic by more than 10% (Trafikanalys, 2012). This trend has led to an increase in the number of operating trains, which in turn has led to a high, at times even very high, capacity consumption and a congested, delay-sensitive network. Frequent delays result in high costs for the operators and the Swedish Transport Administration (Trafikverket) as well as high socio-economic costs for the overall society. Train delays are typically classified as either *primary delays* or *secondary delays*. *Primary delays* are associated with an initial source of disturbance such as a signal failure, or an unusual, lengthy passenger exchange at a certain station. *Secondary delays* (also denoted *knock-on delays* or *consecutive delays*) are caused by the interdependencies between trains where one delayed train may affect the trains surrounding it giving rise to a propagation of the delay. An important objective in railway timetable construction is, thus, to schedule trains so that the risk of delay propagation is limited.

We define a *robust timetable*, as a timetable in which trains are able to keep their original train slots despite small primary delays and without causing unrecoverable delays to other trains.

In order to maintain certain robustness, *margin time* (also referred to as buffer time, slack time or time supplements) is inserted into the timetable. In this paper we distinguish between *runtime margin*, added to a train's shortest runtime between two stations, and *headway margin*, added to the technical minimum time separation between two consecutive trains sharing the same infrastructural resource. The purpose of the runtime margin is mainly to absorb smaller delays enabling the delayed train to recover, while both types serve to limit the risk of knock-on delays. It is also important to mention that the margin provide the dispatchers with certain flexibility when re-scheduling the traffic to prevent delays from spreading further. In a study by Andersson et al. (2011) where the on-time performance of several train services with comparable travel times is analysed, it is concluded that the variations in on-time performance is significantly affected by how the inserted margin can be used operationally by the dispatchers when disruptions occur. The drawbacks, however, of inserting run time margin is the increase in travel time while both types of margin time increase the consumption of network capacity (see e.g. UIC, 2004).

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The challenge in creating robust timetables is twofold: (1) A robustness measure that accurately captures the recoverability properties of the timetable is required, as well as (2) a method that suggests how to modify the timetable in order to increase the robustness in line with other given planning objectives. Before a timetable is actually used in practice, or executed in a simulated environment, it is difficult to predict how the traffic will react to disturbances and to what extent the delays that may occur will spread. Hence, already at this early planning stage, accurate robustness measures are important to use. There is also a need for indicators that point out where the weaknesses in the timetable are located and where margins should be inserted to achieve a higher robustness. In this paper, we focus on robustness measures that serve to assess the sensitivity to smaller delays by identifying specific weaknesses in a draft, or finished, timetable.

Previously proposed robustness measures can e.g. point out trains with a small amount of runtime margins, or sections that are heavily utilised. They are, however, not capturing the interdependencies between different trains sufficiently and do not point out specific weakness in a timetable where margins should be inserted, or which train slots that should be modified at a certain section to increase the robustness. For highly-utilised railway networks with heterogeneous traffic, this is important. To enable this extended weakness analysis, we introduce a new concept referred to as critical points. Critical points refer to very time-sensitive dependencies between different pairs of trains at different locations in the network. In the context, which this paper is focused on, such points typically occur when trains enter a line behind an already operating train, or where trains overtake each other. We also define a measure of the robustness in a critical point, RCP. The critical points are intended to be used in the practical timetabling process to identify weaknesses in a timetable whereas RCP can provide suggestions for robustness improvements.

In the following section we present a summary of related work that describes how robustness in railway traffic timetables is measured in various ways. Then we present the concept of critical points and the proposed RCP measure. This measure, along with a selection of previously proposed measures, is then applied in an experimental study; first on a limited, fictive case for illustrative purposes and later on a real world example. The measures are analysed and the corresponding values are compared in order to study what information each measure provides and how the concept of critical points can be applied when constructing robust timetables. In the final section, we present our conclusions and provide some ideas for future research.

2. Measures of timetable robustness

Robustness in railway timetables can be quantified and measured in various ways. In this section we provide an overview of existing robustness definitions used by the research community. As we will see, many definitions incorporate information on traffic performance, which means that the timetable has to be used, or at least simulated, before its robustness can be evaluated. In our context, focusing on ex-ante measures, no such information is available. Therefore, in Section 2.2, we will narrow our scope to robustness measures that can be computed solely based on information from a timetable.

2.1. Definitions of robustness

During the last decade several approaches have been proposed to investigate, measure, compare, improve, and optimise timetable robustness. Robustness refers to, e.g., "the ability to resist to 'imprecision'" (Salido et al., 2008), the tolerance for "a certain degree of uncertainty" (Policella, 2005) or the capability to "cope with unexpected troubles without significant modifications" (Takeuchi and Tomii, 2005).

According to Dewilde et al. (2011) a robust timetable minimises the real passenger travel time in case of small disturbances. The ability to limit the secondary (i.e. knock-on) delays and ensure short recovery times is necessary, but not enough to define a robust timetable according to the authors.

Also Schöbel and Kratz (2009) have defined robustness with respect to the passengers and as a robustness indicator they use the maximum initial delay possible to occur without causing any missed transfers for the passengers.

Takeuchi et al. (2007) have also defined a robustness index with respect to the passengers. They mean that a robust timetable should be based on the passengers' inconvenience, which in turn depends on e.g. congestion rate, number of transfers and waiting time.

Goverde (2007) on the other hand has defined a timetable as stable (and also robust) when delays from one time period do not spread to the next period. The approaches relies on that the timetable is periodic.

Salido et al. (2008) have presented two robustness definitions. The first definition is the percentage of disruptions lower than a certain time unit that the timetable is able to tolerate without any modifications in traffic operations. A disruption here refers to a delay of one single event in the execution of the timetable. The second definition is whether the timetable can return to the initial stage within some maximum time after a delay bounded in time.

As indicated by the definitions above, robustness analyses are focused on recovering capabilities and how inserted margins can be operationally utilised. Kroon et al. (2008b) describe a robust timetable as a timetable in which initial delays can be absorbed, few initial delays result in secondary delays for other trains and delays can quickly disappear due to light dispatching operations.

In this paper we will use the term robustness as the timetable's ability to handle small delays where a robust timetable is a timetable that can recover from small delays and keep the delays from spreading over the network. In a robust timetable, trains should be able to keep their originally planned train slot despite small delays and without causing unrecoverable delays to other trains.

Measures of railway timetable robustness can be divided in two groups: *Ex-ante measures*, which are related to the timetable characteristics, and *ex-post measures* which are based on the traffic performance. Measures relying on the traffic performance cannot be calculated unless the timetable has been executed in real time or analytically with disturbances, or at least simulated. Measures related to the timetable characteristics can be computed and compared already at an early planning stage without knowledge of the disturbances. Fig. 1 depicts the fundamental difference between the two types of measures.

Robustness measures based on the traffic performance are by far the more common of the two types mentioned, both in research and industry. Typically, measures are based on punctuality, delays, number of missed connections, or number of trains being on time to a station (possibly also weighted by the number of passengers affected). For example Delorme et al. (2009) measure the sum of secondary delays for each train in a timetable, Büker and Seybold (2012) measure punctuality, mean delay and delay variance, Larsen et al. (2013) use consecutive delays and tardiness as performance indicators and Medeossi et al. (2011) measure the conflict probability. All of the examples above are based on perturbing a timetable with observed or simulated disturbances.

In this paper we will only consider ex-ante robustness measures which are applicable at an early stage of the timetable construction