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Discrete Optimization

# Optimal allocation of buffer times to increase train schedule robustness

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ABSTRACT

Reliability and punctuality of railway traffic are among the key performance indicators, which have a significant impact on user satisfaction. A way to improve the reliability and on-time performance in the timetable design stage is by improving the timetable robustness. In order to increase the robustness, most railway companies in Europe insert a fixed amount of buffer time between possibly conflicting events in order to reduce or prevent delay propagation if the first event occurs with a delay. However, this often causes an increase of capacity consumption which is a problem for heavily utilised lines. A sufficient amount of buffer time can therefore not be added between every two conflicting events. Thus, buffer times need to be allocated carefully to protect events with the highest priority. In this paper we consider the problem of increasing the robustness of a timetable by finding an optimal allocation of buffer times on a railway corridor. We model this resource allocation problem as a knapsack problem, where each candidate buffer time is treated as an object with the value (priority for buffer time assignment) determined according to the commercial and operational criteria, and size equal to its time duration. The validity of the presented approach is demonstrated on a case study from a busy mixed-traffic line in Sweden.



## 1. Introduction

Reliability and punctuality of railway traffic are among the key performance indicators, which have a significant impact on user satisfaction (Hansen & Pachl, 2014). Trains typically run according to a timetable that contains the scheduled departure and arrival times for all trains. A train path in a timetable is represented as a sequence of running times over railway line sections and dwell times in stations. An important constraint of railway traffic scheduling is that the trains which run over the same infrastructure elements (block sections between two signals or station tracks and routes) need to be separated in order to prevent collisions. In real time operations, this task is performed by the safety and signalling systems. However, in order to prevent conflicts, that often result in unnecessary braking and re-accelerating of hindered trains, the conflicting train paths in a timetable need to be separated at least by minimum headway time. Minimum headway times are computed with respect to microscopic train routes using blocking time theory and added between train paths in stations (Hansen & Pachl, 2014).

The inevitable variability of running and dwell times, may cause delays and render a timetable infeasible. Moreover, in busy and heavily utilised networks, a delay of a single train can easily propagate to other trains that share the same infrastructure and/or have a planned passenger transfer, rolling-stock or crew connection (Goverde, 2010; Kecman, Corman, D'Ariano, & Goverde, 2013). In order to increase the robustness of a timetable to delay propagation resulting from the deviations in process times, minimum headway times are often extended with buffer times (Goverde & Hansen, 2013). Fig. 1 shows how buffer times are inserted between train paths. The purpose of a buffer time is to (partially) absorb the deviation of the first train from the scheduled trajectory and prevent delay propagation to the second train (Kroon, Maróti, Helmrich, Vromans, & Dekker, 2008). Therefore, in case of an initial delay of a train, buffer times are essential for keeping the planned schedule of other trains feasible. However, this approach may cause an increase of travel times and infrastructure capacity consumption. Moreover, the unused time reserves represent a direct loss of available capacity (Mattsson, 2007; Vromans, Dekker, & Kroon, 2006). For that reason, finding a well-balanced allocation of buffer times is an important problem in the stage of tactical planning and timetable design.

In this paper we present a knapsack problem based approach for buffering a timetable in a heavily utilised railway network. For

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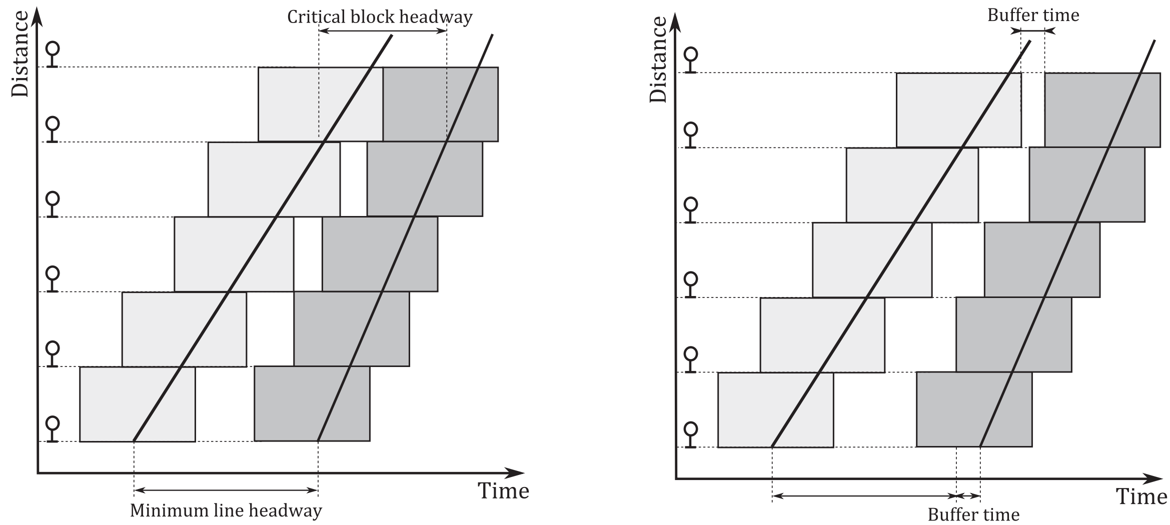


**Fig. 1.** Trains separated with minimum headway (left) and with added buffer time (right).

any given sequence of trains, the available time slack in the schedule can be determined as the time remaining after compressing the timetable so that no time reserves are left between train paths (Landex, 2009; UIC, 2013). The available time slack is often too small to extend each minimum headway time with the recommended value of buffer time determined by a railway company. The objective of this paper is to determine how the available time slack can be distributed among all minimum headway times in a way that maximises the timetable robustness. We model this combinatorial resource allocation problem as a knapsack problem. Each headway time, candidate for buffer time allocation, is treated as an object with a weight equal to its duration. The desired amount of buffer time, as well as the profit for protecting one event with the desired amount, depends on how critical that event is with respect to (i) delay impact resulting from delaying it, and (ii) delay sensitivity, i.e., the impact that other delays may have on that event (Goverde, 2007). We investigate multiple definitions of the knapsack problem for the optimal allocation of the desired amount of buffer time (Martello & Toth, 1990). The approaches are compared based on the quality of solution and computational complexity of the problem. The method was applied on a realistic case study and the obtained results indicate that this method is suitable for optimising the allocation of time reserves in a railway timetable.

This paper is structured in the following way. The next section gives a formal problem description and analyses the applicable approaches in the existing literature. Sections 3 and 4 give a formal problem definition and present the methodological framework, respectively. The case study and results of the computational experiments are given in Section 6. Finally, Section 7 summarises the main findings and gives directions for future research.

## 2. Literature review

In order to increase robustness, most railway companies in Europe suggest assigning a fixed amount of buffer time, possibly dependent on the train and conflict type (DB Netz AG, 2015; ProRail, 2015). However, little empirical proof exists to validate such approach. Numerous research studies therefore aim to determine the indicators of timetable robustness and the ways to improve it (Andersson, Peterson, & Törnquist-Krasemann, 2014; Burdett & Kozan, 2014a; 2014b; Carey, 1999; Salido, Barber, & Ingolotti, 2012; Vromans et al., 2006).

In terms of improving timetable robustness, one direction in the literature was to include the criterion of robustness in the optimisation models for timetable design, which significantly increases the complexity of the timetabling problem (Cacchiani & Toth, 2012). Schlechte and Borndörfer (2010) presented a bi-criteria optimisation problem that focuses on the balance between the efficiency of infrastructure utilisation and schedule robustness. A two-stage stochastic recourse approach presented by Khan and Zhou (2010) modifies the desired timetable computed in the first stage according to the solution for the random disturbance scenario in the second. A branch and bound algorithm coupled with a heuristic beam search were developed by (Shafia, Aghaee, Sadjadi, & Jamili, 2012) to tackle the complexity of the problem. These approaches use starting times, as well as precedence constraints between trains as variables.

In the current practice in railway traffic planning, a timetable for the next year typically evolves from the current timetable (Schlechte, 2012). Feedback information about the realised performance indicators and new requests for train paths are used to define and implement the required changes. Alternatively, the optimal sequence of trains can be computed with respect to minimisation of makespan or cycle time for periodic schedules (Heydar, Petering, & Bergmann, 2013; Sparing & Goverde, 2013). Therefore, traffic planners are often faced with a problem of increasing the robustness of a ‘desired’ timetable with the fixed, pre-determined train orders (sequences).

In previous approaches the aim was to assign a certain amount of buffer times that would increase the schedule robustness with a limited deviation from the desired timetable. A generic formulation of the problem for buffering schedules in cases of known and indefinite demand is discussed by Burdett and Kozan (2015). The applications on robust timetabling include a stochastic optimisation approach for design of robust cyclic timetables (Kroon et al., 2008). Fischetti, Salvagnin, and Zanette (2009) applied the concept of light robustness that was further modified and implemented in a Lagrangian relaxation framework by Cacchiani, Caprara, and Fischetti (2012). Recoverable robustness was proposed as an alternative concept that overcomes the conservative property of robust optimisation (Cicerone, D’Angelo, Di Stefano, Frigioni, & Navarra, 2009; D’Angelo, Di Stefano, Navarra, & Pinotti, 2011; Goerigk & Schöbel, 2014; Liebchen, Lübbecke, Möhring, & Stiller, 2009).

The computational complexity of the robust train timetabling problem motivated the development of the models that exploit the timetable structure (relative train orders) and historical traffic data in order to improve the robustness of given timetable. Vansteenwegen and Oudheusden (2006) first compute the desired