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Stability analysis of railway dispatching plans in a stochastic and dynamic environment

Egidio Quaglietta [a,*], Francesco Corman [b,c], Rob M.P. Goverde [a]

[a] Dept. of Transport and Planning, Delft University of Technology, The Netherlands
[b] Center for Industrial Management, KU Leuven, Belgium
[c] Dept. of Transport Engineering and Logistics, Delft University of Technology, The Netherlands

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ABSTRACT

In the last decade simulation models and optimization environments have been developed that are able to address the complexity of real-time railway dispatching. Nevertheless, actual implementations of these systems in practice are scarce. Essential for implementation of an advanced dispatching system is the trust of traffic controllers into a stable working of the system. Nervous systems might change advice suddenly, and even switch back to a solution previously discarded, as time and knowledge of the perturbation progress. To this end, we propose several metrics and a framework to assess the stability of railway dispatching solutions under incomplete knowledge, and report on the evaluation of the state-of-the-art dispatching system ROMA, coupled with the simulation environment EGTRAIN, here considered as a surrogate of the real field. Rescheduling plans calculated at different control stages have been compared for different prediction horizons of the rescheduling tool. This setup has been applied to the Dutch Utrecht–Den Bosch corridor. Results show that the instability increases as stochastic disturbances propagate. Shorter prediction horizons give plans which are more stable over time in terms of train reordering, but tend to manage perturbations mostly by retiming. Larger horizons instead allow to manage traffic essentially by reordering trains but lead to more unstable plans. Enlarging the prediction horizon over a given threshold does not alter neither the structure of plans nor their variation over time.

1. Introduction

Railway traffic is strongly influenced by random disturbances during operations which cause deviations from the original schedule and thereby reducing performances. In order to cope with small perturbations, the design of a robust timetable can be an effective solution. If larger disturbances or service disruptions are observed, it is necessary to adopt real-time dispatching measures to effectively reschedule (reorder, retime or reroute) train services into new updated conflict-free train path plans. In practice, dispatching decisions are taken by traffic controllers based on their own experience or rule-of-thumbs, to solve observed conflicts as soon as possible. The myopic and limited knowledge that dispatchers have of traffic evolution can lead to implement plans that are ineffective or even counterproductive. For this reason, several approaches have been proposed in literature (see e.g. Dorfman and Medanic, 2004; Törnquist and Persson, 2007; D'Ariano, 2009) for the optimal real-time management of traffic perturbations.

Most of the literature refers to a closed-loop rolling horizon framework (e.g. Lüthi, 2009; Corman et al., 2011; Caimi et al., 2012) where at regular time intervals (*rescheduling interval*) current traffic information (e.g. train speeds and positions) is collected from the field. The behaviour over a pre-set time period ahead (called *prediction horizon*) is then predicted according to some mathematical model. If track conflicts are detected a new complete traffic plan is computed and put into operation. This procedure is then iterated over time in a fashion that can be time-driven or event-driven. In real systems, the effectiveness of these plans can be strongly compromised if a large deviation between the actual and the predicted behaviour is observed, due to stochastic and dynamic evolution of traffic. This might lead to a nervous behaviour of continuously changing solutions, which is not acceptable by human dispatchers and practitioners. For this reason, particular attention must be paid to the stability of rescheduling plans. A plan is defined as stable when its (initial) structure is invariant to perturbations occurring on the network within a given time period Δt. In other words, a stable rescheduling plan will remain the same even if computed at Δt later, with respect to updated traffic information. Specifically if at time t trains are following plan P_t, a plan computed at Δt later will differ from P_t if during this time span train services deviate from plan P_t.

Mainly two different factors are responsible for deviating train services from the current plan. The first factor is the

* Corresponding author. Tel.: +31 152782761; fax: +31 15283179.
E-mail address: e.quaglietta@tudelft.nl (E. Quaglietta).

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implementation itself of a new rescheduling plan into operation. This factor is intrinsic to the process of traffic control and leads to deviations from the current plan which are already known to the dispatcher. Indeed the dispatcher knows that at the current time traffic respects the current plan and that after the implementation of the new plan train services will deviate from the current plan to stick to the new plan. In other words this kind of deviation is defined as "controlled" in the sense that the dispatcher knows exactly both the time at which this deviation is triggered (i.e. when he implements the new plan) and the state of traffic after this deviation (i.e. it will follow the new plan). Such a factor is also taken into account by the rescheduling tool which selects the optimal plan based on the prediction of the effects that this plan will produce on traffic when implemented. This means that the rescheduling tool already considers the implementation of the new plan in the computation process of the optimal plan.

The second factor is relative to unplanned events (i.e. extensions of dwell times, breakdown of rolling stock) that stochastically occur during operations leading to uncertain deviations of train services from their scheduled paths. Stochastic disturbances induce train runs to deviate from the current plan and the state of traffic after this deviation is unknown to the dispatcher. In this case we can say that the deviation is "uncontrolled" given that the dispatcher does not know neither the time when it is triggered nor the state that traffic will have after this deviation. The rescheduling tool cannot predict these events in advance (since they are unknown to it) and cannot forecast their effects on traffic until it receives new updated train information from the field.

When we deal with stability of rescheduling plans we refer to their variation over time with respect to uncontrolled deviations induced by stochastic disturbances unknown to both the dispatcher and the rescheduling tool. So far, only little research has tackled this issue (e.g. Lee and Ghosh, 2001; Meng and Zhou, 2011) due to a lack of advanced decision support tools in the railway industry and scarcity of optimal rescheduling models (proposed in the academic literature) interfacing with the real field or with realistic simulation models.

Nowadays railway industry and infrastructure managers are moving towards real-life installation of optimal rescheduling tools. Hence, it is time to investigate how these systems react when interfaced with realistic operations that are subject to unforeseen disturbances. The main scope of this paper is therefore to study how the schedules provided by a tool for optimal rescheduling change over time against stochastic traffic disturbances. It is also investigated how parameters of the rescheduling tool like the prediction horizon influence the stability of plans over time. Outcomes of this study can be useful to: (i) infrastructure managers who need to know limitations and the sensitivity of these systems; (ii) industrial suppliers who necessitate to fine-tune the parameters of these tools in order to improve performances in terms of stability; (iii) dispatchers who must be aware that in some cases these systems can provide plans which vary nervously over time; (iv) academics who need to understand the behaviour of these systems under stochastic conditions in order to develop or fine-tune stable rescheduling models (e.g. based on stochastic optimization) able to cope with the effect of such disturbances.

In this paper an innovative framework is developed which integrates the Alternative-Graph based tool ROMA (D'Ariano, 2009) for computing optimal rescheduling plans with a stochastic microscopic model for simulating railway traffic, EGTRAIN (Quaglietta, 2013). The investigation has been performed by considering a rolling horizon approach and referring to different disturbed traffic scenarios obtained by sampling train entrance delays and dwell times within a typical Monte-Carlo scheme. At regular time intervals updated traffic information is gathered from the simulation model (considered here as the real field) and transferred to the rescheduling tool to compute optimal plans. These plans are only compared among each other but not put into operation in order to keep the stability analysis independent from "controlled" deviations with known effects, induced by the implementation itself of rescheduling plans. In this way the variation of plans is only due to uncontrolled deviations triggered by unplanned events. Plans are compared at three relevant locations with respect to different indicators: (i) the amount of trains in a plan that are reordered with respect to the previous one; (ii) the average amount of time shift compared to the original timetable (retiming); (iii) the total number of reordering instructions that the dispatcher would give to trains, if he implemented all the optimal plans, (iv) the number of trains in the same order that a plan has in common with another plan.

This study has been repeated for different prediction horizons of the rescheduling tool in order to comprehend how relevant this parameter is with respect to the stability of optimal plans. The proposed methodology has been applied to a real case-study in the Netherlands: the railway corridor between Utrecht and Den Bosch. Results show the effectiveness of the developed framework and the usefulness of the proposed methodology to analyse the stability of optimal plans in a stochastic and dynamic environment.

In the following section a literature review on rescheduling methods and stability analysis of dispatching plans is provided. A description of the framework developed is given in Section 3. Section 4 illustrates the methodology adopted to perform the stability analysis, while the application to a real case study and relative results are reported in Section 5. Conclusions are supplied in Section 6.

2. Literature review

In literature, works addressing the stability of rescheduling plans are mostly concerning the management of activities in a job-shop or manufacturing environment. Here the stability is measured by means of the number of rescheduling instructions that must be taken to implement a control strategy (Church and Uzsoy, 1992), or by means of the number of jobs processed on different machines in the initial and the new schedule (Alagöz and Azizoglu, 2003), or also considering the deviation of job starting times (retiming) and job sequences between the original and the revised schedules (Wu et al., 1993; Cowling and Johansson, 2002). Several authors such as Cowling and Johansson (2002), Kimms (1998), and Leon et al. (1994) proposed a method for the dynamic or stochastic scheduling problem addressed to minimize the makespan and the deviation from the initial schedule considering a bi-criteria objective function that simultaneously takes into account the efficiency and the stability of rescheduling plans. Vieira et al. (2000) determined the existence of a conflict between avoiding setups (as a metric of stability) and reducing flow-time (metric of efficiency). The rescheduling interval significantly affects the above objectives, as also concluded in Church and Uzsoy (1992), Leon et al. (1994) and Sabuncuoglu and Kizilisik (2003). In their study, Mehta and Uzsoy (1998) and Cowling and Johansson (2002) indicate that schedules that are robust to stochastic disturbances can be generated without a lot of degradation of system performance. Bidot et al. (2003) conclude that while the length of rescheduling intervals decreases the selected performance metric (makespan) improves.

In the field of railway traffic management most approaches that have been proposed focus on efficiently generating optimal schedules to minimize train delays, through an open-loop optimization process which involves a variety of assumptions on objectives and certain and deterministic conditions. Macroscopic approaches have been proposed by Carey and Lockwood (1995) who developed an iterative decomposition approach for solving the train timetable and path problem in a railway network with one-way and two-