Evaluating disturbance robustness of railway dispatching measures

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ABSTRACT
Railway traffic is operated according to a detailed (off-line) schedule of operations, specifying for each train its path through the network plus arrival and departure times at its scheduled stops. During daily operations disturbances perturb the plan and dispatchers take actions in order to keep operations feasible and to limit delay propagation.

This paper presents a dispatching tool to handle the management of railway traffic during infrastructure disruptions in a large network. Due to its capabilities, the tool can also be used to evaluate draft timetables. This work evaluates the delay robustness of timetables that follow a “shuttle principle” to be more robust than regular timetables against wide-spread disturbances, as adverse weather and other operational disturbances. A test case is presented on a large Dutch railway network with heavy traffic, for which we compute quickly efficient train schedules at the level of block signals. When comparing the schedules, a trade-off is found between the minimization of delays, due to train conflicts and due to disturbed rolling stock and crew duties, and of the generalized travel time for passengers at given origins and destinations.

Keywords: Railway Traffic Management, Delay Propagation, Timetable Assessment, Microsimulation

INTRODUCTION
Railway operations follow detailed train plans, defining several months in advance the train order and timing at crossings, junctions and platform tracks. A robust timetable is able to deal with minor perturbations (i.e., few minutes of delays) occurring in real-time by using smart planning rules, and distributing time reserves along the train paths. However, no reasonable railway plan is robust or reliable enough in case of large delays or the blocking of some tracks. Despite the big effort spent, technical failures and other disturbances (such as train delays, reduced operating speeds, bad weather, temporary unavailability of some routes) result in disruptions that require multiple adjustments to the traffic plan and result in longer travel times.

Due to the interaction of trains along open tracks and in station interlocking areas, delays propagate widely in heavily loaded networks, causing delays to other trains with a relevant impact on service quality. In an on-line perspective, the train operating companies adjust, in short time, the personnel and rolling stock plans to comply with the actual traffic situation, while experienced dispatchers foresee simple route conflicts due to perturbed operations and to take compensatory control actions based on local information.

Advanced approaches have been recently proposed to update rolling stock, crew and passenger plans during various traffic situations (see, e.g., the recent works of Jespersen-Groth et al. [7], Nielsen et al. [10] and Vansteenwegen and Van Oudheusden [11]). The main assumption is that a feasible train timetable for the disrupted operations exists when a solution to crew rescheduling or, respectively, rolling stock scheduling is computed. The main focus of those tools is on the macroscopic level, to deal with disturbances in an approximate way at global level. A drawback is the imprecise modeling of capacity constraints at stations and along open tracks, even though disruptions may result in heavy limitations of the available railway capacity.

Systems supporting the task of the dispatcher have been proposed to compute quickly detailed train schedules (see, e.g., the literature review regarding models, methods and test cases in [3, 8, 12]). Anyway, most of the existing approaches for on-line rescheduling lack of a thorough computational assessment, limit the analysis to simple networks or simple perturbation patterns, are often simplified and do not capture entirely the consequences of delays and other disturbances, limited capacity, potential conflicts and deadlocks.

The main contribution of this paper is the assessment of advanced dispatching measures for managing

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railway traffic in a large network with dense traffic. We refer to exceptional situations for which “shuttle timetables” are defined to increase robustness of operations in case of severe disruptions, in addition to timetables designed to manage regular traffic conditions. To our knowledge, this work is the first approach to compare regular versus shuttle timetables. We study the effects of these two types of timetables in microscopic detail for large networks. To cope with a network composed of multiple dispatching areas, we incorporate the single-area dispatching support system ROMA (Railway traffic Optimization by Means of Alternative graphs) [3, 4] in a novel optimization framework that addresses the management of disrupted traffic conditions over multiple local areas. Graph theoretical models plus exact and approximate re-timing, re-ordering and re-routing solution algorithms for single-area and multi-area dispatching problems are described in [3, 5] and [1, 2], respectively. In the computational experiments, we analyze a complex and busy part of the Dutch railway network, generate multiple delayed trains and compute feasible schedules by detecting and solving conflicts between trains. We evaluate the solutions from two points of view that are the minimization of train delays and travel times. As a result, suitable dispatching actions can be found for specific disturbance situations, or draft timetables can be thoroughly evaluated against disturbances. The computational assessment can also help railway companies to show the advantages and disadvantages of shuttle timetables in case of heavy weather or major disruptions.

PROBLEM DESCRIPTION

To cope with severe disturbances that may result in delay propagation and infeasibility, fast and efficient management of railway traffic during operations is required. A microscopic model of railway networks and train movements at the level of block sections and signals is required to detect potential conflicts and avoid deadlocks, find suitable dispatching actions in terms of updating train routes, orders and times, and for a detailed evaluation of the multiple objectives characteristics of the different actors involved (dispatchers, train operating companies and passengers).

A block section is a track segment between two main signals and may host at most one train at a time. The passage of a train through a particular block section is called an operation. A train route is a sequence of operations to be performed in a railway network during a service. Each operation requires a given running time which depends on the actual speed profile followed by the train while traversing the block section. The minimum time separations among the running trains translate into a minimum setup time between the exit of a train from a block section and the entrance of the subsequent train into the same block section.

A set of trains cause a deadlock (i.e., circular waiting) when each train in the set claims a block section ahead which is not available, due either to a disruption or to the occupation/ reservation for another train in the set. Instead, a potential conflict arises when two or more trains claim the same block section simultaneously. A decision on the train ordering has to be taken and one of the trains involved has to change running, departure, passing times according to the constraints of the signaling system.

The total output delay is the difference between the calculated train arrival time and the scheduled time at a relevant point in the network, and is divided into two parts. An initial delay is caused by disturbances (e.g., blocked tracks, rolling stock or infrastructure failures, entrance delays) that cannot be recovered by rescheduling train movements (i.e., changing their sequence). A consecutive delay is caused by the interaction between trains running in the network, i.e., trains that are held in front of a red signal or brake for a yellow signal, in order to solve a potential conflict.

During disruptions (such as a train malfunction or an infrastructure failure) the capacity is strongly reduced for a long period of time. The time reserves in the timetable are not sufficient to prevent delay propagation and a new plan of operations is required. Trains may be scheduled along a different route, with a different stopping pattern, or even canceled or short-turned between some stations. To reduce the impacts of delay during exceptional conditions, shuttle timetables are considered in the Netherlands. These timetables are designed to improve reliability of the railway system during wide-spread disruptions (for instance, heavy snowfall or similar adverse weather). Most of the traffic is short-turned at major stations and trains provide shuttle services going back and forth between two consecutive major stations and serving all local stops. In this case, rolling stock circulation plans might require a significantly different number of train units in order to keep the same service frequency on a disrupted network. Alternatively, a reduced service frequency would be available for a fixed number of train units. The following measures are combined for generating shuttle timetables: (i) keeping train paths short, so that the propagation of delays cannot exceed regional boundaries, (ii) keeping only limited passengers connections for the trip that is interrupted and (iii) keeping drivers and rolling stock together so as to avoid any inconvenience due to repositioning trips, or further knock-on effects between train lines.

METHODOLOGY

Figure 1 shows a schematic view of the optimization framework proposed for scheduling trains in large networks in case of disturbed traffic conditions. To react to disturbances, a set of (off-line) draft timetables is provided. The real-time variability of train position and speed defines a delay instance that represents the current status of the network (based on the actual position and speed of trains running in the network). The output of the dispatching tool is a set of detailed micro-
scopic schedules that are proposed to the dispatchers, and evaluated by multiple solution indicators.

**Fig. 1:** Scheme of the optimization framework for the disruption handling process in large networks.

In order to study the network-wide effects of dispatching actions and alternative timetables, we consider train operations over a large network decomposed on multiple local dispatching areas. Figure 2 shows the adopted distributed system architecture, the actors involved and the information flows. We consider a network divided into $n$ local areas with a dispatcher for each area. Each dispatcher is supported by a local scheduler, while a network coordinator system supervises the global schedule and takes scheduling decisions at the borders between areas.

**Fig. 2:** Scheme of the large scale microscopic scheduler.

We consider the ROMA tool, described in [3, 4], to schedule trains in each dispatching area. A job shop scheduling problem with additional constraints is used to model the railway operations microscopically. The formulation is based on alternative graphs [9] and uses the blocking time theory [6] to compute time separations between operations at the level of block sections and various signaling technologies, as for ETCS. This approach also models train movements within the interlocking area, as well as shunting movements.

The decomposed approach of [2, 1] is adopted to manage traffic flow in overall network. Feasible schedules are found for each local area by the train scheduling procedure of D’Ariano et al. [5]. The solutions of the local schedulers are then driven by a coordination heuristic toward globally feasible solutions.

**COMPUTATIONAL EXPERIMENTS**

This section presents preliminary computational results. The optimization framework is implemented in C++ and run on a 4-processor PC running at 2.8 Ghz. We study a trafficated and complex railway network in the South-East of the Netherlands that spans over ten dispatching areas of the Dutch railway network, including the main stations of Den Bosch, Nijmegen, Arnhem and Utrecht. The general network layout has a circular shape with a maximum distance between borders of about 100 km. In total, there are more than 1200 block sections and station platforms.

**Fig. 3:** Lines frequency for the reference timetable.

The regular periodic timetable has a cycle time of one hour and schedules around 150 trains. Figure 3 reports schematically the frequency of the train services along a schematic network layout. Every solid line indicates that there are two trains running per hour per direction on a specific line. Light green lines are local services and dark blue lines are intercity services. The dotted line represents an international service scheduled once per hour.

In the experiments two types of timetable are tested: the one actually in operations, and a given shuttle timetable. In this latter, train services, train units and crews follow a special pattern, going back and forth between the major stations of Utrecht, Den Bosch and Arnhem, as shown in Figure 4. The circulation of train units and crew has been considered by including minimum turnaround times between the services.

An important aspect for the railway undertaking is to consider the additional crew and train units needed. In fact, the shuttle timetable keeps the same service frequency and the same scheduled departure and arrival times at stations as in the normal timetable. While local trains are operated mostly within a single shuttle area, long-distance lines are actually interrupted. With the shuttle principle, those lines are operated with 2 trains per hour per direction, while the average turnaround time considered for the crew and rolling stock plan is 15 minutes, a quarter of the cycle time of the timetable. For each line, one train/crew unit is always standing at a side of each border station between two shuttle zones, waiting to operate the next service. For the whole area, additional resources are required by 4 train/crew units at Utrecht Central Station, 3 units at Den Bosch, and 3 units at Arnhem. From an operational point of view, a different choice could be made.
to cancel trains and to reduce the service provided to passengers, with no need of additional train/crew units for the railway undertaking.

**Fig. 4:** Plan of the rolling stock and crew circulation in the shuttle areas. The path for the OD pair Amsterdam-Den Bosch is highlighted.

A time horizon of traffic prediction of 90 minutes is considered, after a warm-up period of 60 minutes. We assess 50 delay cases introduced in the first hour of traffic prediction. For all trains in the network, input delays are generated according to Weibull distributions fitted to realistic data. For the proposed instances, the maximum and average input delays are 890 and 190 seconds; around 32% of the running trains are delayed by more than 3 minutes. We evaluate a simple retiming procedure, that keeps the order scheduled in the timetable. This is a common practice to assess robustness of draft timetables. The advanced dispatching framework of [2] is also assessed. This approach uses the train rescheduling algorithms of [5] to solve conflicts and deadlocks efficiently.

For each delay case, the dispatching tool delivers microscopically feasible operational plans, including circulation of train/crew units within the stations at the borders of the shuttle zones, where trains are turned back according to a simplified shunting plan. The implementation of pure retiming strategies is straightforward and requires always less than 15 seconds. The advanced rescheduling algorithms compute a solution in less than three minutes.

Figure 5 shows the combined effects of the shuttle timetable against the regular one, and the possibility to adjust the timing of trains or to reschedule them.

The top plot represents a dispatcher point of view, by showing the average consecutive delay (in seconds) for the trains running in the overall network. The use of rescheduling measures allows to reduce delay propagation greatly, with more than 80% delay reduction against pure retiming strategies. The shuttle timetable increases robustness to delay propagation against the normal timetable by 8% when using retiming actions only; and up to 22% when rescheduling is applied.

The bottom plot focuses passengers traveling on the OD pair connecting Amsterdam to Utrecht and Den Bosch, as highlighted in Figure 4. For this assessment, we consider a “generalized travel time” (in seconds) for the given OD pair, that weighs waiting times in station platforms twice as much as travel times (to penalize more a long waiting time at a station rather than a long travel time on trains). The shuttle timetable does not include passenger connections, resulting in additional waiting times at stations. For this reason, rescheduling compared to retiming leads to minor differences. The bottom plot shows how the higher delay robustness of the shuttle timetable is complemented by a generalized travel time about 25% longer, with a large effect on passengers attractiveness. In general, accurate data about the passenger flows over all routes would allow a network wide evaluation of multiple OD pairs, improving the evaluation of passengers’ discomfort.

From the two plots of Figure 5, the results obtained for the regular and shuttle timetables can be compared in terms of the two performance indicators. In case of both retiming and rescheduling measures, the average consecutive delay is larger for the regular timetable while the generalized travel time is larger for the shuttle timetable. The counterintuitive result obtained for the shuttle timetable is due to the additional waiting time at Utrecht station for passengers traveling on the studied OD pair. More general conclusions regarding the selection of the best timetable from the passenger’s point of view would require a detailed analysis of a number of factors including the specific OD pairs, the network structure, the location and duration of disruptions, the train delays and their impact over increasing time horizons of traffic prediction and multiple areas.
SUMMARY AND NEXT RESEARCH

This paper applies innovative dispatching procedures to support the railway rescheduling process during disturbed operations ranging as far as exceptional situations that may need an alternative timetable to deliver attractive and robust services. We refer, in particular, to shuttle timetables that ensure feasible and stable operations with the drawback of reducing railway capacity or requiring additional train units to keep the same level of service. Multiple performance indicators assess the negative effect of disruptions on the quality of the railway services, so that the dispatchers can choose the most effective resolution scenario and the corresponding microscopic plan of operations for dealing with the disrupted traffic situation.

The next step of our research will be focused on a thorough assessment of the combined effects of the selection of alternative disruption resolution scenarios and the evaluation of dispatching measures (i.e., retiming, re-ordering, re-routing and canceling train services) in case of various disturbances: an increasing number of delayed trains, a set of dwell time perturbations and various infrastructure disruptions.

An interesting direction for future research could be dedicated to apply the proposed optimization framework to support real-time dispatching decisions. The local dispatcher may choose a single train schedule associated with a pair timetable and dispatching solution. The final output would include blocking time graphs, the evaluation of train delays and travel time for passengers, and measures of robustness against possible traffic perturbations. For the development of an on-line for dispatching support, the dispatching measure should be evaluated in a stochastic environment. Other research could address the implementation of dispatcher user interfaces, enabling fast and simple communication of key indicators.

Another use of the large scale microscopic scheduler could be for the off-line evaluation of draft timetables. Currently, timetables are mostly evaluated by considering limited stochastic factors, by neglecting capacity constraints in complex areas and by assuming fixed train orders during perturbed operations. With the proposed tool, variability of operations are modeled by random distributions of delays and other inputs characteristic in a Monte Carlo scheme. Further study of the combined effects of input variability, different timetables and dispatching policies would represent a step forward for the assessment of timetables during the planning stage. When computing train schedules, the circulation of rolling stock and crew could be evaluated on a more granular level of investigation in order to better evaluate passengers’ discomfort and robustness against network-wide delay propagation.

REFERENCES


