Conference Paper

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Publication Date:
2015

Permanent Link:
https://doi.org/10.3929/ethz-b-000183297

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Train Delay and Passenger Travel Time Minimization in Real-Time Railway Traffic Management

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Keywords: Delay Management, Train Scheduling, Passenger Routing.

Abstract

Railway service is a key factor to reduce congestion on highways and other means of transport, especially in densely populated areas, and to provide an eco-friendly and sustainable way of transport. In order to attract new customers from other transport modes, European countries defined challenging targets in terms of Quality of Service (QoS) that the railway companies should provide to their customers [2, 16, 20]. However, while the customers of Train Operating Companies (TOC) are the passengers, the customers of Infrastructure Managers (IM) are the trains operated by the railway companies.

This translates to two different views in the problem. This paper addresses the trade-off and the strategic interaction between the objectives of the above-mentioned stakeholders, TOC and IM. While the IM objective relates to train delays, the TOC aims at minimizing the passenger travel time.

Since in heavily used railway networks any small delay easily propagates to other trains, the IM would like to reschedule trains in real time in order to
minimize train delays, taking into account the relative importance of different trains established by the TOC. On the other hand, changing train orders may result in extra delays for those passengers that miss a connection at some station, therefore the TOC would like to keep the connections that are more relevant to the passengers in order to minimize passenger travel times. Therefore, due to the separation of IM and TOC, the actual QoS perceived by the passengers can be viewed as the result of a strategic interaction between IM and TOC, i.e. a game. In this game, the strategy of the TOC consists of defining the relative importance of the different circulating trains, e.g., by specifying a weight for each train equal to the number of passengers that are expected on board the train. The amount of passengers expected on a train can be computed by a passenger routing procedure exploiting common assumption on rationality and information provision to passengers. The strategy of the IM consists of defining a schedule for the trains with minimal total weighted delay of the trains.

This paper presents models and algorithms for the study of the strategic interaction between IM and TOC; we are able to compute a Nash equilibrium of the resulting game, that corresponds to a solution of the problem. We moreover consider other solutions of interest, namely (i) an optimal train schedule from the IM viewpoint, (ii) an optimal train schedule from the TOC viewpoint, (iii) a surrogate for the common practice of railway traffic management, and (iv) two compromise solutions for the combined problem of the IM and TOC companies, both defining a Nash solution of a suitable game. The results are evaluated from the point of view of the IM and TOC objectives.

Background

The state of the art of railway rescheduling problem experienced two main streams of research [1]: train rescheduling approaches focus on the real-time design of microscopically feasible schedules able to minimize train delays, while delay management approaches focus on macroscopically feasible schedules able to optimize passenger flows.

The models for train rescheduling typically tend to incorporate as many practical details as it is necessary to ensure the schedule feasibility, and the objective functions typically focus on train delays. One of the most effective approaches to tackle the resulting computational complexity is based on the combination of blocking time theory [17] and job shop scheduling models achieved through the alternative graph model of [19]. Advanced scheduling approaches based on these concepts are able to quickly solve real traffic flow instances in which train arrival times, orders and routes, are considered as variables (see e.g. [4, 5, 9, 10]). Other promising approaches are based on MILP formulations (see e.g. [3, 18, 21, 24, 25]). All these approaches are able to manage train traffic in limited size networks within a computation time compatible with rail operations; the solutions produced demonstrated remarkable improvement with
One weakness of all these models is the limited consideration of the effects of broken transfer connections, platform changes or routing alternatives on the QoS perceived by the passengers. Among the works trying to enlarge the scope of these approaches, Corman et al. [6] proposes an iterated lexicographic optimization of train delays, given a division of trains into priority classes. The delay of each class is minimized provided that the delay of higher priority classes does not increase. This approach might be applied by defining priority classes according to the estimated importance of particular trains for the overall passenger QoS. A different way to integrate the two objectives involves the bi-objective optimization approach proposed by Corman et al. [7], in which passenger connections are weighted depending on their importance for the passenger QoS, to compute the Pareto frontier of the objectives of train delays and total weight of broken connections.

The other stream of research focuses on the minimization of passenger dissatisfaction [12, 13, 22, 23]. Among this stream of research, the delay management problem [12, 13] decides whether to keep or not transfer connections during operations and/or to reroute passengers between their origin and destination, two crucial decisions for passenger flows. Approaches in this stream are typically based on macroscopic models, considering the arrival/departure events of trains at stations only, and neglecting further infrastructure capacity, or train separation due to the safety system. For this reason, there is a gap between the QoS promised by the solutions delivered and the one that can be achieved when implementing the solutions within the actual limitations and rules of practice. One exception is given by Tomii et al. [23], in which microscopic dispatching is used to forecast more precise QoS. However, since the rescheduling problem is solved heuristically, the gap between the solutions found and the global optimum is unknown.

In conclusion, most of the microscopic train traffic management approaches of the literature still neglect the impact of train rescheduling decisions on the QoS to passenger, while most of the approaches focusing on the passenger perspective miss a detailed description of the rail infrastructure. We are not aware of other papers evaluating the impact of a rescheduling strategy from the viewpoint of both the IM and the TOC.

Research Contribution

This work compares the strategies of TOC and IM by using microscopic optimization models, in order to compute real-time train schedules sufficiently adherent to reality. Algorithms for railway traffic management are also assessed comparing their performance from the viewpoints of TOC and IM. Some algorithms are especially designed to find a compromise solution between these conflicting objectives.

The following research questions are investigated:
Fig. 1 The considered Dutch network

- Which is the impact of passenger travel time minimization on train delay minimization and vice versa?
- At what extent the rescheduling methods commonly adopted in practice can satisfactorily address TOC and IM objectives?
- How good can be a compromise solution computed within a short computation time compatible with real-time operations?

Results

The studied test case is the Dutch railway network of Figure 1. The network is operated by mixed traffic according to a periodic timetable. Tens of thousands of passengers per hour travel between multiple origins and destinations.

We study the following set of instances, based on real-life test case of the Dutch network, and further adapted in order to try different levels of complexity. The network between Utrecht and Den Bosch (a line topology long about 40 km) comprises approximately two hundreds of block sections. There are three major stations, Utrecht (Ut), Geldermalsen (Gdm), and Den Bosch (Ht); we assume all trains stop at those three stations. Furthermore, there are 8 minor stations, as detailed in Figure 1: Utrecht Lunetten, Houten, Houten Castellum, Culemborg, all between Utrecht and Geldermalsen, and Zaltbommel between Geldermalsen and Den Bosch. Only local trains stop at all those minor stations.

The actual timetable used in operations in 2010 is taken as reference, that is periodic with 30 minutes period (see Figure 2). No freight trains are included in the test case. We use the frequency as in the actual timetable, and we also consider lighter timetables with less trains running. Namely, the actual timetable schedules 4 intercity trains per hour per direction between Utrecht and Geldermalsen, 4 local trains per hour per direction between Utrecht and Geldermalsen, and 2 local trains per hour per direction between Geldermalsen and Den Bosch. We note here that those instances describe a part of the network used in [12–15], namely the station of Utrecht.

We also study lighter timetables, obtained from the actual timetable by incrementally removing two intercity trains per hour per direction (yielding
a train frequency of 12 trains / hour) and removing the two local trains per hour per direction going between Utrecht and Geldermalsen (train frequency of 8 trains / hour). The basic hourly pattern of the running trains is reported in Figure 2, for the three variants, (from left to right: 16, 12, 8 trains / hour) , in terms of time-distance paths. Time is on the vertical axis, distance in the horizontal axis. Intercity trains are reported in blue; local trains are reported in green.

We next present the OD pairs. Due to the unavailability of real data about passenger OD flows, we resort to synthetic OD data. We refer to the number of passenger entering/exiting the stations on the line considered as published by the infrastructure manager. The number of passengers traveling on the considered line is estimated and assigned proportionally to the various stations, based on the known number of passengers entering/exiting each station. This is translated to an average rate of passenger generation per OD, per time unit. Availability of more accurate data would allow more precise OD estimation. Out of the theoretically 56 possible combinations of origin and destination stations, we consider the 8 OD pairs with the largest number of passengers.

Entrance delays, for all trains in the network, are generated as in Corman et al. [5,6]. For each configuration investigated, 20 instances are randomly generated according to a three-parameter Weibull distribution, 10 by using the parameters of the Weibull distribution corresponding to normal situations, and 10 corresponding to more heavily perturbed situations. The latter are obtained by using the same scale and shift parameter of the first 10 instances, while the shape parameter is doubled.

We compare the performance of five solution approaches:

- **MDM optimum.** Minimization of the average passenger travel time with the microscopic delay management (MDM) model of Corman et al. [8]. In this paper we assume the results provided by this approach as the optimum for the TOC.
– **TS optimum.** Minimization of the average train delay with the MILP formulation of the microscopic train scheduling (TS) model obtained by formulating the constraints as in D’Ariano et al. [11]. In this paper we assume the results provided by this approach as the optimum for the IM.

– **Nash 1.** First Nash equilibrium achieving a compromise between TOC and IM objectives. In this game the IM strategy is the minimization of a weighted train delay, the weight of each train being equal to the number of passengers onboard the train. The TOC strategy is minimization of average passenger travel time.

– **Nash 2.** Second Nash equilibrium, obtained with a slightly different game. Also in this game the IM strategy consists of the minimization of a weighted train delay, but the weight of each train is equal to the number of passengers disembarking the train. The TOC strategy is the same of Nash 1.

– **Timetable.** With this strategy, the train schedule is simply obtained by keeping the same train sequence of the timetable and delaying each train by the minimum amount needed to achieve feasibility. Passengers then follow the shortest route to their respective destinations. This approach simulates the common practice of railway management in which IM keeps the order of trains prescribed by the timetable, while passengers react individually to delays by choosing the most convenient route in real time.

Figure 4 shows the average performance of the five approaches in terms of the two objectives studied in this work, namely the average passenger travel time and the average train delay, which reflect the different interests of the TOC and of the IM, respectively. All experiments are run on a Intel i5 CPU at 3.20 GHz, 8 GB memory. The commercial solver CPLEX 12.4 is used to solve the problems. All instances of the TS and the two Nash approaches are solved to optimality within a few seconds of CPU time. The timetable approach requires the shortest computation time (about 1 second on average), while the MDM approach may require hours of computation on the largest instances, thus being not compatible with real-time applications.

The computational results reported in Figure 4 suggest the following observations:

– The timetable solutions are of poor quality in terms passenger travel time, while from the viewpoint of the IM this is not the worst solution. This behavior is due to the robustness of the timetable, which is still able to provide acceptable schedules for the IM in perturbed situations, though not optimal. However, since the departure times of the trains do not take into account passenger needs, the individual passengers cannot recover from the perturbations by rerouting.

– As expected, the solutions provided by the MDM model are the best performing for the TOC. However, these solutions maybe unsatisfactory for the IM, due to the increased train delays with respect to the TS solution (and even to the timetable solution).

– The two Nash solutions are both quite effective compromises between the TOC and the IM points of view. None of the two, however, outperforms
Fig. 3 The computational results

the other, Nash 1 being slightly better for the TOC and slightly worst for the IM.

References


