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DOI
10.1109/MTITS.2017.8005686

Publication date
2017

Document Version
Final published version

Published in
Proceedings 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS 2017)

Microscopic Delay Management: Minimizing Train Delays and Passenger Travel Times during Real-Time Railway Traffic Control

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***Abstract*—Optimization models for railway traffic rescheduling in the last decade tend to develop along two main streams. On the one hand, train scheduling models strive to incorporate any relevant detail of the railway infrastructure having an impact on the feasibility and quality of the solutions from the viewpoint of infrastructure managers. On the other hand, delay management models focus on the impact of rescheduling decisions on the quality of service perceived by the passengers, and in the interest of the train operating company. Models in the first stream are mainly microscopic, while models in the second stream are mainly macroscopic. This paper aims at merging these two streams of research by developing microscopic delay management approaches. A variety of solution algorithms are proposed, that compute a solution to the studied problem; the obtained solutions correspond to Nash equilibria of the strategic interaction of the players (train operating company and infrastructure manager). Computational results based on a real-world Dutch railway network quantify the trade-off between the minimization of train delays and passenger travel times, and show that good compromise solutions can be found within a limited computation time.**

***Index Terms*—Rail Operations and Management, Microscopic Delay Management, Train Scheduling, Passenger Routing.**

I. Introduction

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 [10], [11]. 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.

The viewpoint of the different customers translates into different approaches to solve the same problem. This paper addresses trade-off and strategic interactions among 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 of a few trains easily propagates to the 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 some passengers in order to minimize their passenger travel times. Therefore, due to the separation of IM and TOC, the actual QoS perceived by the passengers can be viewed as a game, i.e. the result of a strategic interaction between IM and TOC.

In the studied 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 at scheduled stops during the service. 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 to the studied 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 game.

Computational results based on a real-world Dutch railway

978-1-5090-6484-7/17/$31.00 ©2017 IEEE

network quantify the trade-off between the minimization of train delays and passenger travel times (respectively the IM and TOC viewpoints), and show that good compromise solutions can be found within a limited computation time.

II. Overview of the literature

The state of the art of railway rescheduling problems 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 [11] and job shop scheduling models achieved through the alternative graph model of [13]. Advanced scheduling approaches based on these concepts are able to quickly solve real-time traffic flow instances in which train arrival times, orders and routes are considered as variables (see e.g. [2], [3], [4], [6], [7], [14], [15]). Other promising approaches are based on Mixed Integer Linear Programming (MILP) formulations (see e.g. [12], [14], [19], [20]). 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 respect to the current practice and/or to the basic dispatching rules adopted in most practical applications.

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. [2] 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. [4], 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 [8], [9], [16], [17], [18]. Among these papers, the delay management problem [8], [9] 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 practical limitations and rules. One exception is given by Tomii et al. [18], 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 passengers, while most of the approaches focusing on the passengers 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.

III. The proposed methodology

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 by comparing their performance from the viewpoints of TOC and IM. Some of the proposed algorithms are especially designed to find a compromise solution between the conflicting objectives. The following research questions are investigated: Which is the impact of passenger travel time minimization on train delay minimization and vice versa? To what extent can the rescheduling methods commonly adopted in practice satisfactorily address TOC and IM objectives? How good can a compromise solution be computed within a short computation time compatible with real-time operations?

To address the above questions, this work incorporates the passengers' point of view into an innovative model that includes detailed passenger flows and microscopic train scheduling decisions. A detailed microscopic train scheduling model is combined with a comprehensive assignment of passengers to time-space paths in the network.

A. Train scheduling model

This section recalls the train scheduling model of [6]. The problem of controlling railway traffic with microscopic detail corresponds to a job shop scheduling problem with blocking no-swap constraints [13]. Blocking no-swap constraints model the so-called fixed-block railway regulation that a train on a given block section cannot move forward if the block section ahead is not available or if it is occupied by another train.

We now briefly recall the alternative graph model [13], which is the basis of the train scheduling model of [6]. An alternative graph G is a triple (N, F, A). Nodes in N correspond to operations, each associated to the occupation of a block section by a train, representing either the traversing of a block section or the dwell in a station where a train has a planned stop.

For each node $i \in N$, a continuous variable h_i is associated to the starting time of the corresponding operation. A dummy operation 0, with $h_0 = 0$, is used to represent the starting of the scheduling horizon, and a dummy variable h_* is used to model the objective function. In this paper, a weighted average train total delay minimization would be considered.

Arcs in the set F model time relations between the starting times of specific pairs of operations. For example, if i and j are associated to the traversing of two consecutive block sections by the same train then the directed arc (i, j) models the fact that h_j must be greater or equal to h_i plus the minimum running time of the train on the block section related to node i. In this case the minimum running time p_{ij} is a weight on the arc (i, j).

Fixed arcs can also model a minimum departure time of a train from a block section, which in this case is modelled with an arc $(0, j)$ having weight p_{0j} equal to the minimum departure time. Other examples will be discussed later in this section. In all cases, an arc $(i, j) \in F$ corresponds to the constraint $h_j \geq h_i + p_{ij}$.

Arcs in the set A model potential conflicts between trains on shared resources. Whenever two trains claim the same infrastructure element (block section, platform, etc.) at the same time, a conflict arises and a decision on the order of the two trains on the infrastructure element must be then taken to resolve the conflict. In order to take into account signal status, a minimum time separation between the starting times of the conflicting operations is needed to ensure that the second train enters the infrastructure element sufficiently after the first train has left it (i.e., the first train is occupying the next infrastructure element and minimum time separation constraints are satisfied).

Let i and j be consecutive operations of a train, k and l be consecutive operations of the other train, and let i and k be the two conflicting operations associated to the entrance of the two trains in the same block section. Then, the ordering decision is modeled with a pair of alternative arcs $((j, k), (l, i)) \in A$, representing the alternative constraints $(h_k \geq h_j + s_{jk})$OR$(h_i \geq h_l + s_{li})$, where s_{jk} (s_{li}) is the minimum time separation when i precedes k (when k precedes i). The set A thus contains a pair of alternative arcs for each pair of potentially conflicting operations.

Finding a feasible solution for a given alternative graph G consists of selecting exactly one arc for each alternative pair in A (which corresponds to deciding in which order the pairs of conflicting operations should be performed), thus obtaining a set S of selected arcs from A. The selection S is feasible if and only if the graph $(N, F \cup S)$ contains no positive length cycles. Additional information on job shop scheduling based models for railway traffic control can be found e.g. in [2], [3], [6], [7].

B. Passenger assignment model

The passenger assignment problem (or passenger routing problem) studies the distribution of passengers onto the railway network. We consider a time discrete model for passenger arrivals at each station. Hence, we assume to know the number of passengers willing to reach the same destination $d \in D$ from the same origin $o \in O$, starting their journey at the same time interval w, for a discrete set of arrival times W. The discrete model is justified by the observation that all the passengers with the same destination arriving at a station between two consecutive train departures will move together in the network as a group, under the assumptions that each train has infinite capacity and each passenger aims at reaching his/her destination in a minimum time.

We refer to a group of passengers going from o to d and arriving in o at time w as a triple odw, hereinafter denoted as *demand*, and let ODW be the set of all demands odw. Each odw starts moving in the network at a time π_{odw}. Note that, once the train schedule is fixed, each demand odw moves in the network independently from the other triples, i.e., the choice of a particular routing for a given odw does not influence the routing of any other odw. Moreover, we assume that all passengers in a demand odw will follow the same OD path.

The passenger routing aspect is similar to a multicommodity flow problem on the graph $(N, F \cup S)$, in which a commodity is associated to each odw triple. The only difference is that passengers may change train only at scheduled stops if a connection exists, i.e., only if the connected train departs from the station sufficiently later than the arrival of the passengers. To take into account this difference, we introduce a set of connection arcs C, each associated to a pair (i, j) of operations, where i is the operation associated to the arrival of the feeder train at the station and j is the operation associated to the departure of the connected train from the station. Each arc has a weight c_{ij} equal to the minimum time for transferring passengers from the feeder train to the second one. Each arc in $(i, j) \in C$ is active only if $h_j \geq h_i + c_{ij}$. Passengers are assigned on a straightforward schedule-based principle: they follow the shortest path in the time-distance graph for each origin-destination pair.

C. Solution framework and approaches

We next present approaches to solve the overall problem. A first approach is to directly combine train rescheduling and passenger routing decisions into a single MILP problem. This approach is explained in Corman et al. [5] and briefly sketched hereunder. It requires the introduction of a new disjunctive graph $G^P = (N \cup N^{ODW}, F \cup F^{ODW} \cup C, A)$. N, F and A are the sets defined in the alternative graph for the train scheduling model, while N^{ODW}, F^{ODW} and C are new sets of nodes, fixed arcs and connection arcs that are necessary to take into account passenger routing.

The set N^{ODW} contains two nodes for each demand $odw \in ODW$, namely a source node $start^{odw}$ with supply equal to 1 and a sink node end^{odw} with demand equal to 1. These nodes consider the origin and destination of the flow associated to

odw. Fixed arcs in F^{ODW} link arriving/departing passengers of odw to the first/last train they may take on their journey.

By letting δ^{odw}_{start} be the set of nodes associated to train departures from the origin station of odw and by letting δ^{odw}_{end} be the set of arrivals at the destination station of odw, we have that F^{ODW} is the set of arcs $(start^{odw}, j)$ with $j \in \delta^{odw}_{start}$ plus the arcs (i, end^{odw}) with $i \in \delta^{odw}_{end}$.

The set of connection arcs is the set C as previously defined. An arc $(i, j) \in C$ is given for each pair of nodes i, associated to a train arrival, and j, associated to a train departure, at/from the same station, for all stations. The connection is active if $h_j \geq h_i + c_{ij}$, i.e., if a passenger can transfer from the feeder to the connected train.

The translation of the overall model into a MILP would require the translation of disjunctive constraints into linear equations, that can be done by using the standard big-M technique. The optimal solution to this problem is referred to as a Microscopic Delay Management (MDM) optimum.

Other solution schemes are now investigated to solve the studied problem. In the game-theoretical setting proposed in this paper, the decisions of the two players are successive and reactive on each other's decision. The general structure is a form of iterative game as in Figure 1, where IM and TOC are interacting, each solving the problem pertaining their domain, i.e. minimizing trains' or passengers' delay respectively.

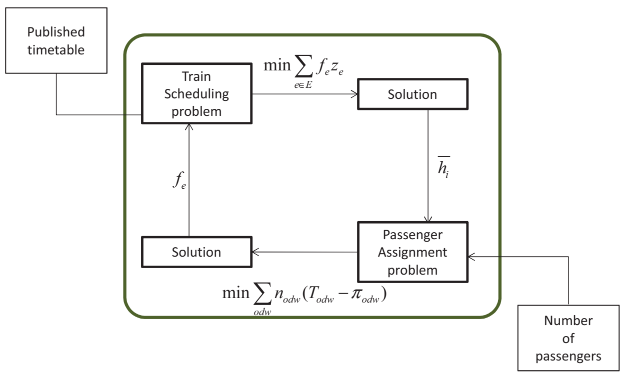

Fig. 1. Iterative setup of the game

The train scheduling problem can be addressed with the minimization of a weighted train total delay, the weights depending on an expected number of passengers loading per train. This is expressed as $\sum_e f_e z_e$ where e are a set of events related to station arrivals, or passage of trains at relevant points in the network; f_e is the amount of passengers related to event e; and z_e is the delay associated to event e compared to the published timetable. A solution to the train scheduling problem delivers a set of $\overline{h}$, that defines the starting time of the train movement in each infrastructure element. The optimal solution to this problem in case each train has the same weight is referred to as a Train Scheduling (TS) optimum.

The passenger assignment problem can be solved by minimizing the total travel time $\sum_{odw} n_{odw}(T_{odw} - \pi_{odw})$, which describes the total travel time as the amount of passengers n_{odw} for each odw, multiplied by their travel time. This latter is expressed as the arrival time at the destination, T_{odw} minus the generation of the group of passengers at the origin station, π_{odw}. A solution to the passenger assignment problem is the amount of passengers assigned per train, and used to compute the weight f_e for the train scheduling model.

The game-based approaches alternate a train scheduling phase, optimizing train orders and times for the computed passenger flows, to a passengers assignment phase, in which passengers' travel time is minimized for the given computed train schedules and network capacity. The procedure iterates until convergence (i.e., until the current overall solution of train scheduling and passenger assignment is equivalent to the one found in the previous iteration), that would correspond to an equilibrium. We compare five solution approaches:

- **MDM optimum.** Minimization of the average passenger travel time with the MDM model of Corman et al. [5]. We assume the results provided by this approach as the optimum for the TOC and a feasible microscopic solution for the IM.
- **TS optimum.** Minimization of the average train total delay with the MILP formulation of the microscopic TS model obtained by formulating the constraints as in Samà et al. [14]. We assume the results provided by this approach as the optimum for the IM.
- **Nash 1.** This is a first Nash equilibrium that achieves a compromise solution between TOC and IM objectives. In this game the IM strategy is the minimization of a weighted train total 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.** This is a second Nash equilibrium, obtained with a slightly different game. Also in this game the IM strategy consists in the minimization of a weighted train total delay, but the weight of each train is equal to the number of passengers disembarking the train. The TOC strategy is as for Nash 1.
- **Timetable.** With this approach, 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.

IV. Test case and computational results

The studied test case is the Dutch railway network of Figure 2. 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.

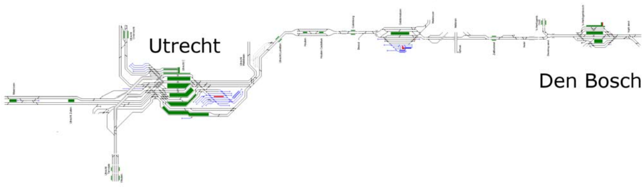

Fig. 2. The considered Dutch network

We perform experiments for a 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.

Entrance delays, for all trains in the network, are generated as in Corman et al. [2]. 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.

All experiments are run on an Intel i5 CPU at 3.20 GHz, 8 GB memory. The commercial solver CPLEX 12.4 is used to solve the proposed formulations. All instances of the TS approach and of the two Nash approaches are solved to optimality within a few seconds of CPU time.

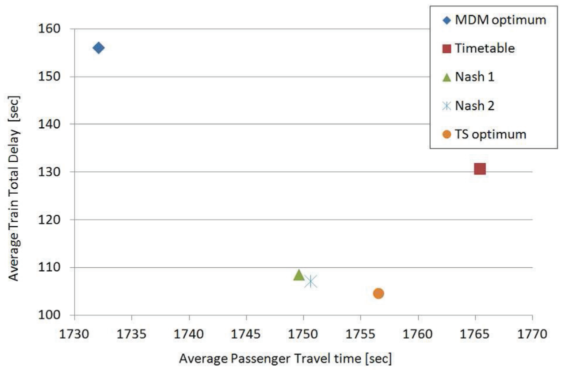

Fig. 3. Trade-off between the two objective functions

Figure 3 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 total delay, which reflect the different interests of TOC and IM, respectively. From the computational results on the practical test case under study, we have the following observations:

- The timetable solutions are of poor quality in terms of 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 may be unsatisfactory for the IM, due to the increased train total delays with respect to the TS solution (and even to the timetable solution).
- The Nash solutions are quite effective compromises between the TOC and IM viewpoints. None of the two outperforms the other. Specifically, Nash 1 is slightly better for the TOC and slightly worst for the IM.

V. Conclusions

This paper integrates train scheduling and delay management visions into a series of models and methods to control railway traffic (Train Scheduling, TS) with the objective of minimizing passenger travel time (directly tackled by Delay Management, DM). Research on TS and DM in the recent years has been very active, with the TS being related to the objectives of the Infrastructure Manager (IM), while the Train Operating Companies (TOC) aim at minimizing the passenger travel time. This paper addresses the trade-off and the strategic interaction between the objectives of the involved stakeholders and represents a first attempt to fully incorporate the passengers viewpoint into a microscopic traffic optimization model.

Several possible directions are open for future research, starting from the obtained results. One could study other ways to reach the Nash equilibria, and possibly determine all of them. The MDM model could be enriched to take into account the finite capacity of each train and/or more sophisticated measures of the passenger discomfort, which would actually need to consider not only the interaction between the IM and TOC, but also the choice of the passengers in the game. Interesting research directions also pertain to studies on other regulatory policies for traffic control and operations, as well as larger networks, further types of service, and different OD flows.

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