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# New alternative graph models and methods for the real-time railway traffic management problem

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**Abstract** Due to the increasing traffic demand and the limited availability of infrastructure, railway managers are seeking methods to better use the already existing one. Utilization plans are carefully designed; however, disturbances may arise, creating time-overlapping conflicting request done by multiple trains on the same resources that the dispatchers are required to manage. Limited automated system aid is provided to the dispatchers which, due to the limited time available, are not able to fully evaluate the effects of the recovery decisions taken by them. Some decisions may lead to future delays, which in turn may create new conflicting requests, in a snowball effect. Optimization is thus necessary to minimize the delay propagation and the consequential worsening of the quality of the service offered.

The paper focuses on the real-time Railway Traffic Management Problem (rtRTMP) which can be defined as follows: given a set of trains travelling in a network within a certain time window, and given for each train its default and possible alternative routes in the network, its current position, its minimum running time in each block section it requires to traverse, solving the rtRTMP consists of assigning a passing time to each train in all the block sections of its chosen route in such a way that each block section is used by at most one train at a time and no deadlock exists in the network.

The study of the rtRTMP received increasing attention in the literature in the last years. Early approaches tend to solve very simplified problems that ignore the constraints of railway signalling, and that are only applicable for specific traffic situations or network configurations (e.g., a single line or a single junction), see, e.g., the literature reviews in (1; 2; 4; 6; 7; 8; 10; 11).

The *alternative graph* of Mascis and Pacciarelli (9) is among the few models in the literature that can be used to model both macroscopic and microscopic levels of detail. At the state-of-the-art, the microscopic level of detail is

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achieved on a block-section granularity, which is necessary to ensure the fulfillment of traffic regulations. This model generalizes the job shop scheduling model in order to deal with additional constraints. The alternative graph can be described as a triple $G = (N, F, A)$ where:

- $N = \{s, 1, ..., n, t\}$ represents the set of *nodes*, where $n$ nodes are related to each operation, i.e. the traversal of a resource (block/track section or station platform) by a job (train), while the nodes $s$ and $t$ represent the start and the end of the schedule. By definition, the start time of the schedule is a known value, e.g. 0, and the end time of the schedule represents, eventually, the objective function, e.g, the minimization of the maximum or average train delay;
- $F$ is the set of *fixed directed arcs* that are used to model the sequence of operations regarding the pre-defined set of routes for each train in terms of minimum/maximum running and dwell times, plus additional constrains such as connections, minimum departure and maximum on-time arrival;
- $A$ is the set of *alternative pairs*, each composed of two alternative directed arcs. Each pair models a scheduling decision between two trains requiring to use the same resource, considering minimum sequence-dependent headway times. There can be multiple types of alternative arcs between the nodes.

A feasible schedule is represented by a *complete selection* $S^c$, where an arc for each alternative pair of the set $A$ is selected and the connected graph $(N, F, S^c)$ has no positive weight cycles. A so-defined connected graph represents a *conflict-free* schedule where, given the timing related to each operation, the minimum time separation constraints are satisfied on each resource.

A big-$M$ Mixed Linear Integer Programming (MILP) formulation of the rtRTMP can be obtained from the alternative graph model by introducing a binary variable for each train sequencing decision and a binary variable for each train routing decision (12). The resulting problem is strongly NP-hard and may often require high computation time to reach good quality solutions.

In order to achieve better quality solutions in a short computation time, to quickly solve the alternative graph model, we consider the optimization solver AGLIBRARY, a software developed by the Operations Research group of Roma Tre University for dealing with complex scheduling and routing problems. AGLIBRARY works on the following framework: initially, a good quality solution for the scheduling problem with fixed routings is computed by using heuristics and a (truncated) branch-and-bound algorithm (5); afterwards, a new improved solution for the scheduling problem with flexible routings is computed by applying meta-heuristics such as tabu search and variable neighbourhood search (3; 12).

This paper reports on recent improvements in the alternative graph formulations and in the AGLIBRARY optimization solver. In particular, the original contributions of this paper are the following:

- We reach a higher lever of detail in the rtRTMP model by using the alternative graph in order to deal with complex interlocking station areas and the typical multiple track-incompatibility characterizing them through new arrangements of the alternative pairs;

- We better manage the modelling of train route alternatives, thus lessening the number of variables and constraints in the alternative graph and in the MILP formulation. We achieve this by introducing the concepts of *common* and *alternative operations*. We call a common operation the traversing of a block section by the train which takes place independently from the actual route chosen. We call an alternative operation an operation between two common resources representing the traversing of alternative (sequences of) block-sections which depends on the route of the trains in order to traverse the network. In order to obtain a feasible solution, for each alternative operation, one among the alternative (sequences of) block-sections available for it needs to be chosen;
- While a speed-up in the solution process can already be reached by the implementation of the new management of the train route alternatives, the changes produced in the alternative graph model, in particular the ones due to the new arrangements of the alternative pairs, need to be taken into account. We thus study new properties on the alternative graph model. We then use these properties to develop and improve the algorithms in the AGLIBRARY solver. For example, the use of common and alternative operations allows the computation of a lower bound for the rtRTMP considering both routing and scheduling decisions. In particular, this is computed by solving the problem considering for each train a *fictitious route* in which for each alternative operation the shortest path among the available alternatives is considered and no scheduling decision is modelled.

Computational experiments are performed on practical-size railway instances with simulated disturbed traffic conditions and the results obtained are shown to be promising for real-time application.

**Keywords** Real-Time Railway Traffic Optimization · Job Shop Scheduling · Disjunctive Programming

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