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Applied analysis for improving rail-network operations

Avishai (Avi) Ceder *, Stephan Hassold

Transportation Research Centre, Department of Civil and Environmental Engineering, University of Auckland, New Zealand

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ABSTRACT

In times of recession with local authorities being forced to minimize their expenditures and having quite a few budget cuts, it is getting more and more important for public-transport operators to implement an efficient operation in order to be competitive. This work examines the operations of a rail operator in Auckland, New Zealand, and shows options to improve it. It is twofold. First, the crew scheduling component is analyzed by a column generation approach. The results show that efficiency of operations can be improved by more than 9% using different crew schedules. Moreover, this efficiency measure can be further improved by more than 15% when additional driver training is provided to allow for the crew to operate all trains. Second, a detailed reliability analysis is demonstrated to identify and evaluate the sources of unreliable service and develop remedies to resolve observed problems. It is shown that the outcome of the crew-scheduling problem can have a significant impact on the reliability of the rail network. One of the main causes for delays and unreliability problems is heavy passenger load, which increases dwell times. Accurate passenger demand estimation is crucial in resolving these issues and improving the on-time performance of the rail network.

1. Introduction

In times of recession with local authorities being forced to minimize their expenditures and having quite a few budget cuts, it is getting more and more important for public-transport operators to implement an efficient operation in order to be competitive. At the same time the customers desire a reliable and punctual service. This work is divided into two parts: one is related to scheduling issues and one to operational issues. The first part examines the crew-scheduling component of a rail operator in Auckland, New Zealand, and develops options and modeling to improve it. The second part provides a detailed operational-reliability analysis, demonstrating the problems and possible remedies not only to the rail provider of Auckland, but to the general community of rail-transport providers.

At first sight it seems that scheduling-related and operational-related themes cannot be under the same roof of research. However, if the two subjects are studied at the same rail-service provider then there is an opportunity to examine a few interrelated issues between the two themes. That is, the outcome of the crew-scheduling problem can have a significant impact on the reliability of the rail network, as is explored further in Section 5.

1.1. Background of crew scheduling solutions

The crew-scheduling problem (CSP) has been discussed abundantly both in and out the transportation literature; relevant papers are found in journals related to mathematics, computing, operations research, and specialized scheduling resources

* Corresponding author.
E-mail address: a.ceder@auckland.ac.nz (A.(A.) Ceder).

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(Ceder, 2007). CSP is often formulated as a set covering problem (SCP). The SCP requires defining a large set of driver-workdays; then a subset of this set is chosen so as to minimize costs, subject to constraints that make sure that all the necessary driving duties are performed. Most CSP formulations also verify that the labor-agreement rights of all drivers are maintained. A full, classic CSP normally includes the generation of the feasible workdays as a first, separate stage, and then the choice of a subset that best satisfies all needs as a second stage. In most practical transit networks, there can be thousands of driving duties to be carried out, and hence the need for millions of possible workdays. It is, therefore, common to construct in advance only a limited number of feasible workdays (Ceder, 2007). In what follows is a brief overview of some of the crew-scheduling approaches.

Desrochers and Soumis (1989) presented an approach based on SCP, but with a column-generation-solution procedure. The first stage of the column-generation process seeks a subset that best covers all duties within the range of the feasible workdays, which are already known. A second stage follows, in which new feasible workdays that improve the existing solution are generated iteratively.

Lourenco et al. (2001) bring a multi-objective CSP, led by the concept that in practice there is need to consider several conflicting objectives when determining the crew schedule. The multi-objective problem is tackled using meta-heuristics, a Tabu-search technique, and genetic algorithms. Banihashemi and Haghani (2001) formulate a CSP as a duty-based network-flow problem. First, minimum cost is sought in a binary programming problem that is a relaxed version of the original, omitting labor-rights constraints. Then, an iterative column-generation procedure using two sets of constraints is performed: ''hard'' constraints restricting the building of specific workdays (e.g., too long), and ''soft'' constraints penalizing non-efficient workdays, but not strictly forbidding their inclusion in the solution.

Freling et al. (2001) discuss differences between bus and train CSPs and propose a methodology for the scheduling of train crews. The problem, formulated as an SCP with additional constraints, is solved using a heuristic branch-and-price algorithm. Branch-and-price is a special application of branch-and-bound, in which a column-generation technique is used to solve linear programming relaxations with a huge number of variables. Feasible workdays are generated in a network, in which each node corresponds to a duty piece, and each path through the network to a feasible duty; the optimal solution is sought through dynamic programming, that of a resource-constraint, shortest-path algorithm.

Borndörfer et al. (2001) start with an optimal solution of the LP-relaxation of the master problem and suggest, thereafter, an algorithm using a variable fixing technique to stepwise enforce integrality of the solution.

Kroon and Fischetti (2001) present an SCP for railway crew that allows some flexibility in specifying penalties for undesirable types of workdays. A dynamic column-generation procedure is used; hence, duties are not generated *a priori* but in the course of the solution process. Regeneration and re-selection of workdays are carried out in each iteration. Generation is preformed in a network in which trips are represented by arcs. To solve the SCP, a Lagrangian-relaxation method and sub-gradient optimization are used instead of the common linear programming.

Methods to accelerate the generation of duties are discussed by Barnhart et al. (1995) and Lübbecke (2005). The methods consider restricting the underlying network and calculating lower bounds on the reduced costs during the generation process. An alternative heuristic is proposed by Lan et al. (2007) combining a greedy approach with random features and a neighborhood search strategy.

Alefragis et al. (2000) decomposed the problem instance using graph coloring techniques. Because the decomposition procedure is based on trips that are known to be performed by separate duties, it does not affect the quality of the column generation process. Another decomposition approach is proposed by Abbink et al. (2007) who heuristically decompose the problem instance based on criteria such as geographical and line-based information.

Chen and Shen (2013) propose an improved column generation algorithm for crew scheduling problems using a large set of ''good'' potential shifts which is precompiled using problem-specific knowledge. Shifts from this shift-pool are added dynamically to the master problem until no more promising columns exist. Only then new columns are created using a resource-constrained shortest path algorithm.

The general approach used for developing a solution to the crew planning problem follows a methodology which is fairly traditional in the literature. The problem is decomposed into three phases as follows (Caprara et al., 1999):

(i) *Pairing generation*: A very large number of feasible pairing is generated. A pairing is defined as a sequence of trips which can be assigned to a crew in a short working period. A pairing starts and end at the same depot and can have various characteristics (e.g., with/without intermediate rest period outside the depot, night working period, etc...) which determine its cost.

(ii) *Pairing optimization*: A selection is made of the best subset of all the generated pairings so as to guarantee that all the trips are covered at minimum cost. This phase follows quite a general approach, based on the solution of the set covering or set partitioning problems (SCP/SPPs), possibly with additional constraints (e.g., lower and upper bounds on the number of pairings selected for each depot).

(iii) *Rostering optimization*: The pairings selected in the previous phase are sequenced into rosters, defining a periodic duty assignment to each crew which guarantees that all the duties are covered for a certain number of consecutive days (e.g., a month). Furthermore as the duties are assigned to individual crews, the rostering phase needs to consider work regulations involving safety constraints, enterprise bargaining agreements and potentially also individual preferences. Rosters are generated separately for each depot.