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Review

A tutorial on fundamental model structures for railway timetable optimization

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ABSTRACT

This guide explains the role of railway timetables relative to all other railway scheduling activities, and then presents four fundamental timetable formulations suitable for optimization. Timetabling models may be classified according to whether they explicitly model the track structure, and whether the timetable is intended to be periodic or not (aperiodic). The presentation of models is organized to facilitate the selection of a model by planning objective and available data, regardless of the specific traffic carried or network size.

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1. Introduction

Railway operations involve large sums of money both in infrastructure and direct operating expenses, and their services are valued by both the traveling public and primary industries. A fully defined timetable specifies the paths that trains follow on a railway network including track lines used, junctions or stations traveled, connections between trains for passengers or freight, and various interactions between trains necessary for safe operation, with planned timings for all events. The quality of a timetable determines the utilization of the railway network, the sustainable flow, and the robustness of the service commitments to passengers and freight recipients. For example, Netherlands Railways was the subject of the 2008 Franz Edelman Award (INFORMS), for which they documented a profit increase of € 40 million annually due to improvements to a timetable of 5500 trains [1].

Operation by timetable is frequently confused with the North American term “scheduled railroading”, but North American railroads have not compiled and followed timetables for over fifty years. Instead, they attempt to maintain a homogeneous flow along their networks and rely on experienced human dispatchers to issue orders granting authority for moves directly to train crews. Freight train timekeeping records are measured in hours. This practice, “timetable free” operation, is the result of a legacy of “tonnage” dispatching, where trains only departed when they reached full length or tonnage. This in turn was the result of the elimination of most North American passenger services by 1960 and the simultaneous loss of priority or perishable freight traffic to road carriage. Although increasing network congestion, introduction of intermodal services, and re-introduction of passenger services are apparent throughout North America, for the moment timetable free operation remains standard practice.

Timetable optimization formulations are commonly labeled according to their application: passenger or freight, single or double track, and main lines or junctions. However, frequently the same mathematical structures and capabilities can be found spread amongst these different applications. This leads to a lack of continuity between these conceptual developments and sometimes a lack of recognition as well. From the user’s point

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of view, the originating application is irrelevant so long as the formulation supports the objectives at hand, the available data, and the available computing resources.

This paper addresses timetabling models by their structure and capabilities rather than their prior application. The primary options to consider in selecting a timetabling formulation are whether it explicitly models the track structure, and whether the timetable is intended to be periodic or aperiodic (without regularly sequenced repeating train paths). The four models discussed in this paper are aligned by these characteristics in Fig. 1. Timetables in Europe are frequently periodic. For example, trains leave Manchester for Birmingham, England at seven and twenty-seven minutes past the hour daily, and an ICE train leaves Munich for Nurnberg at sixteen minutes past the hour daily. This means that care is taken to structure the timetable so that passengers may expect a specific service to depart at the same time each hour or half hour. In the United States, intercity or suburban rail passenger services are not offered with periodic timetables, with few exceptions.

All models, regardless of their application, can be segregated according to whether or not they explicitly represent the limitations of the track network. Many managerial questions concern the economic value of a segment of track, or seek to prioritize a limited budget for track investment, and these questions are more easily answered when the track is explicitly considered in the model. The lack of explicit track representation also limits the ability of the model to estimate or forecast line capacity, where capacity is the volume of train paths supported. This is not to be confused with the alternate measure of capacity used in some circles, where capacity is measured as a function of experienced delay or the makespan of trip times. Examples of this measure can be found in the United States, where network performance is frequently measured by the sum of hours of train waiting time [2]. Models that do not explicitly represent the track structure typically require that the initial problem data set supports at least one feasible timetable containing all trains in the data set, whereas models that consider the underlying track resource may return solutions of some subset of the initial train requests.

Note the lack of a entry in Fig. 1 at the intersection of periodic and explicit track features. To date there are no efficient methods of providing both of these features in the same model. It is possible to dimension various aperiodic mixed-integer program models with time scales that “wrap around” to form a periodic decision space [3,4]. Harrod finds that similar problems are more difficult to optimize in their periodic form than in their aperiodic form.

Many of these models may be extended to consider timetable robustness (stability under stochastic delays or incidents), for example using stochastic programming. This tutorial is limited to deterministic timetable optimization, but some brief references are offered here. Kroon et al. [5] determines an optimal periodic timetable from a large sample of stochastic train operation realizations. The objective minimizes a reduced set of “primary disturbances”. Liebchen et al. [6] constrains the feasible range of decision variables to attain a more robust timetable solution in a single optimization step. A significant body of literature describes post analysis of timetable stability, and max-plus system theory is a good starting point [7]. Goerigk and Schöbel [8] consider what timetable robustness expectations are reasonable under two distributions of network delay and four network delay response policies.

1.1. Taxonomy of railway scheduling

Scheduling activities occur at all levels of railway management. At the strategic level, scheduling may determine the frequency of train operations or the origins and destinations served. Interconnections are also a strategic scheduling task. In the case of carload freight, “blocking” is the strategy of grouping cars together to minimize the coupling and uncoupling of individual cars at yards (which may then interact with the choice of route and accumulated distance). For passengers, strategic scheduling determines connections between trains at stations for both variety in destinations served and passenger convenience. All of these activities are frequently collected under the terms “service design”, “network design”, or “strategic operating plan” [9]. The planning of locomotives, rolling stock, and crews also frequently appears under the heading “scheduling” [10].

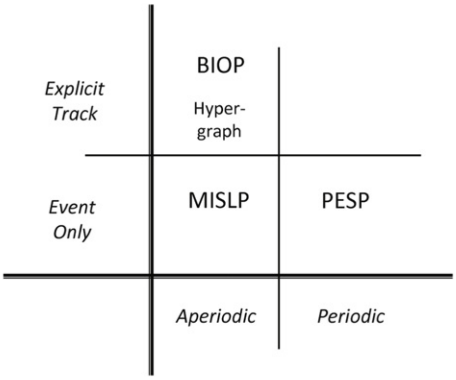

Fig. 1. Model feature distribution.

Timetables are a tactical scheduling activity. As previously described, timetables determine the timings of trains at stations or signal control points. They ensure that a train which departs as scheduled will have a contiguous, conflict-free path to its destination. Conflicts may include trains moving in the opposing direction, slower trains in the same direction blocking the path, or tracks out of service due to maintenance. An iterative cycle may occur between the tactical and strategic scheduling activities. For example, a desired service design may be infeasible at the tactical level, and require either compromises in the service design or changes to the infrastructure. Andersen [11] describes how the Swiss Bahn 2000 service design required changes to the track network in order to attain desired periodic timetables.

Operational scheduling activities include live dispatching of established timetables, and network recovery from delays or incidents. Recovery can take the form of attempting to return trains to their original timetables, or generating new temporary timetables for the remainder of their journeys. There is no conceptual difference between operational and tactical scheduling of trains. Only the solution quality expectations and available processing time differ. Tactical timetable planning seeks a high quality solution and hours or days of processing time are acceptable. On the other hand, operational schedules must be determined in minutes, sometimes seconds, and the first feasible schedule returned may be acceptable.

1.2. Prior references on railway scheduling

A number of prior surveys can be recommended for further reading in railway scheduling research. Lusby et al. [12] presents a comprehensive technical reference to timetabling models organized by track structure (single track, double track, or station tracks). Caprara et al. [13] surveys passenger railway topics in Europe, but specifically excludes freight service topics. Kroon et al. [14] presents a detailed survey and exposition of periodic timetabling, dominated by European literature, with particular emphasis on the periodic event scheduling problem (PESP). Törnquist [15] reviews a sample of 48 timetabling and dispatching papers from both North American and European theaters over