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Aggregation Methods for Railway Networks

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Aggregation Methods for Railway Networks*

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Abstract

This paper presents a bottom-up approach of automatic simplification of a railway network. Starting from a detailed microscopic level as it is used in railway simulation, the network is transformed by an algorithm to an aggregated level, i.e., to a macroscopic network, that is sufficient for long-term planning and optimization. Running and headway times are rounded to a user defined discretization by a special cumulative method. After the transformation we saturate the network with given train requests by computing an optimal slot allocation. Then the optimized schedule is re-transformed to the microscopic level in such a way that it can be simulated without any conflicts between the slots. We apply this algorithm to "macrotize" a microscopic network model of the dense Simplon corridor between Switzerland and Italy. With our micro-macro transformation method it is possible for the first time to generate a profit maximal and conflict free timetable for the entire corridor and for an entire day by a simultaneous train slot optimization.

1 Introduction

Timetabling is one of the major planning tasks in railway traffic. It involves two parts. On the one hand the *railway operators* need to compute a timetable using a small number of vehicles and crews that satisfies passenger demands like short transfer and travel times. On the other hand the *infrastructure companies* must decide about the allocation of train slots to the train requests of the operators. This is especially challenging when conflicts between different requests occur. In such a situation, in particular, in highly utilized networks, manual planning can become very complex and personnel-intensive. Then infrastructure capacity might be left unused or good connections might not be guaranteed for all important points in the network. There is therefore a need for modeling methods that allow for the use of optimization algorithms in timetabling like PESP [35] or TTP [9].

Railway efficiency and the capacity of railway networks are important research topics in engineering, operations research, and mathematics for several

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decades. The main challenge is to master the tradeoff between accuracy and complexity in the planning, optimization, and simulation models. Radtke [31] and Siefer et al. [15] proposed the use of both *microscopic* and *macroscopic models*. They applied microscopic models for running time calculations and the accurate simulation of railway operations, and macroscopic models for long term traffic and strategic infrastructure planning. In a similar vein, Schultz [32] suggested a procedure to insert train slots according to pre-defined priorities in a first step, and to test the reliability of this timetable in a second step by simulating stochastic disturbances. An alternative approach to determine the capacity of a network are *analytical methods*. They aim at expressing the railway efficiency by appropriate statistics, e.g., the occupancy rate. There exist two different approaches: The first is the *handicap theory* by Potthoff [30]; it is based on queueing models. The second uses *probabilistic models* to compute follow-on delays; it is mainly based on the work of Schwanhäußer [33]. He also introduced the important concept of *section route nodes* to analyze the performance of route nodes or stations. Hansen [16] presents a probabilistic model as an alternative to queueing models for a precise estimation of expected buffer and running times. Finally, there is also a substantial literature on discrete optimization approaches to timetable optimization. Due to the complexity of railway traffic, most articles consider only simplified macroscopic models with a simplified routing through the railway infrastructure on simple network topologies, such as corridors, e.g., [7, 5, 9, 23, 4, 14]. On the other hand, routing through individual stations has been considered on a much more detailed level, see [39, 24, 10]. The interaction of both approaches has only recently been studied [8], using a top-down approach.

In this paper a *bottom-up* approach of *automatic simplification* of a complex *microscopic* railway infrastructure model is presented and applied in a case study for the Simplon corridor. The term "microscopic" points out that the input data describes the infrastructure on a very detailed level, that makes it possible to simulate the railway traffic with exact track, switch, and platform assignments of the train paths like it would be in the real world. An aggregation technique condenses this microscopic representation to those data that are relevant for planning and optimization purposes. Transforming the data to a less detailed level makes it possible to compute timetables and optimal slot allocations by methods of linear and integer programming. Of course, the aggregation has to be done in such a way that enough degrees of freedom remain, and in such a way that a slot allocation on the macroscopic level can be transformed back to the microscopic level without creating any conflicts. We describe in this paper a method that does exactly this.

We test our method using real world data for the Simplon corridor from Brig (BR) in Switzerland to Domodossola (DO) in Italy provided by the SBB Schweizerische Bundesbahnen. The Simplon is known as one of the major corridors in the European railway network. It has a length of 45 km and features 12 stations. The microscopic model for this scenario consists of 1154 nodes and 1831 arcs including 223 signals, which is fairly large, see Figure 1. Furthermore the routing possibilities at the terminals Brig and Domodossola and in the intermediate stations Iselle and Varzo, and a rather unusual slalom routing for certain cargo trains through the tunnel lead to complex planning situations.

Before describing our micro-macro transformation in detail, we give a short discussion on the pros and cons of microscopic and macroscopic railway model-

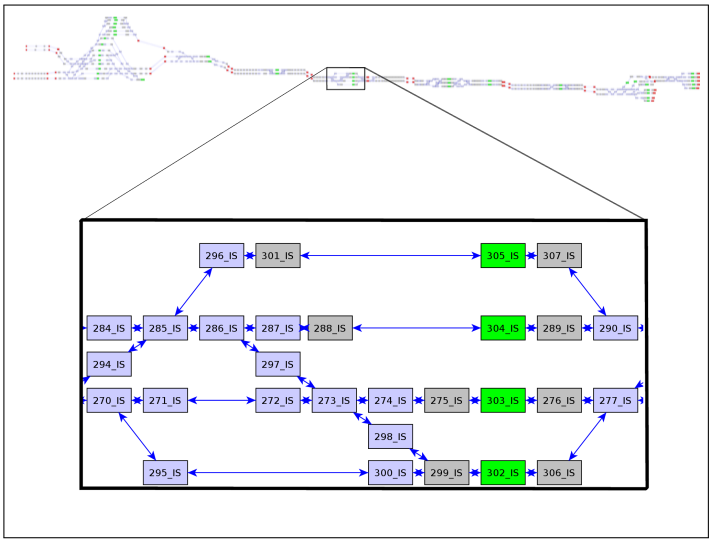

Figure 1: Microscopic network representation of the Simplon corridor and detailed representation of station Iselle as exported by the railway simulator `OpenTrack`.

ing, and why they have to be combined in order to arrive at a method that is both accurate and tractable.

Railway infrastructure and train operations are often modeled using *simulation* programs. In the last 20 years several software programs for simulating train movements were developed [37], [20], [36]. Almost all railway companies use them to support their operations and planning processes. Simulation systems provide a realistic assessment of different options in infrastructure planning. They allow to study the interactions of large numbers of trains in a network, and, in particular, to evaluate the feasibility of a timetable, i.e., if a timetable works in simulation, it can be trusted to be operable in practice. We used in our work the synchronous simulation system `OpenTrack`, that was developed at the ETH Zürich [20], see also [17] for an overview and a comparison of synchronous and asynchronous simulation systems.

A simultaneous *optimization* of a large number of train slots at a microscopic granularity is currently out of reach and would also not be appropriate in many high-level strategic and tactical planning situations. For these purposes, it is better to resort to a *macroscopic model* of the railway system. Such a macroscopic model contains much less information such that the network size can be reduced significantly. In addition to that, a fixed time discretization can be used in order to make the model amenable to discrete optimization techniques. In [13] a standardized format for macroscopic railway models was introduced and a number of test instances that model a part of the German long distance network were made freely available. For line optimization [3] and for periodic timetable optimization [23], simplified macroscopic models of the railway infrastructure and estimates of event times, mostly in minutes, have been used with success.

Our contribution is to present a bottom-up approach to *railway network aggregation* that starts at the microscopic level, goes to a macroscopic model, and ends again at the microscopic level. We present in Section 2 an algorithmic approach thats implements this idea. This approach is tested in Section 3, where we present computational results for different optimization scenarios for the Simplon corridor.

2 Microscopy and Macroscopy, or There and Back Again

Railways are highly complex technical systems, which can be modeled at any level of detail. This modeling effort is no end in itself. Rather, an accurate calculation of running times and precise and unique platform and track allocations are needed to make simulation results match with the real world. The necessary precision can be achieved using microscopic data such as gradients, speed-dependent tractive efforts, speed limitations, and signal positions. However, this type of information is too complex to be handled in a discrete optimization model. Our aim is therefore to work with a *macroscopic model* with the property that the results can be interpreted in and re-transformed to the microscopic world and finally operated in reality. The main contribution of this work is to introduce an algorithm that constructs from a microscopic railway model a macroscopic model with the following properties:

- ▷ macroscopic running times can be realized in microscopic simulation,
- ▷ sticking to macroscopic headway-times leads to conflict-free microscopic block occupations,
- ▷ valid macroscopic timetables can be transformed into valid microscopic timetables.

This section defines the microscopic and macroscopic elements of our approach, and it describes a suitable transformation in detail. It is structured as follows. Subsection 2.1 discusses microscopic railway network models. Subsection 2.2 motivates our aggregation idea and introduces some details concerning the construction of macroscopic networks. The following Subsection 2.3 deals with time discretization. Finally, we propose an algorithm that performs the micro-macro transformation in Subsection 2.4. We remark that although our exposition is based on the simulation tool `OpenTrack`, the methodology is generic.

2.1 Microscopic Railway Networks

The main input for the transformation algorithm is a *microscopic infrastructure network* that is given as a graph $G = (V, E)$. `OpenTrack` uses a special graph data structure in which nodes correspond to so-called *double-vertices*. These consist of a left and a right part, see Figure 2 for examples and [25, 26] for a more detailed description. `OpenTrack` adopts the convention that if a path in G enters a node at the left end, it has to leave at the right end and vice versa. This assures that the direction of the train route is always respected and no illegal turn arounds at switches can be done. Every *track section* between two vertices is modeled as an edge, and every edge has some attributes like maximum speed or length. A double-vertex is introduced at any point where one or more of these attributes change or if there is a switch, a station, or a signal on a track. Figure 2 shows an example of a double-vertex graph in `OpenTrack`.