The effective residual capacity in railway networks with predefined train services*

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Abstract. In this paper we address a variant of the freight train routing problem to estimate the residual capacity in railway networks with regular passenger services. By ensemble averaging over a random temporal distribution of usable slots in the network, bounds on the number of additional freight trains on predefined relations are established. For the solution, a two-step capacitated routing approach based on a time-expanded network is used. The approach is applied in a case study to freight relations in the railway network of North Rhine Westphalia.

Keywords: Railways, residual capacity, freight train routing

1 Introduction

Railway timetabling of passenger and freight traffic is usually performed on different time scales. Whereas passenger services are scheduled in the annual timetabling process, the majority of freight services are requested on relatively short notice within the timetable period. As a result, freight traffic has to be routed according to the spare residual capacity in the timetable, a problem commonly referred to as the *freight train routing problem* [1].

In long-term planning of network and line concepts, the question how many additional trains can effectively be routed is generally more important than the generation of a specific timetable. This is why an understanding of the usability of the residual network capacity as a function of the passenger traffic load is required. In particular, the analysis has to deal with the problem that residual capacity is temporally bound and may not allow for coherent freight train routes.

In this paper, an adaptation of the freight train routing problem for network capacity planning applications is discussed. To assess the number of routable freight trains, a time-expanded network is considered, where train path requests and spare capacity for different network segments are randomly distributed throughout the day. The solution consists in a two-step approach: In the first step, the number of trains is maximized, in the second step traveling times are minimized. The model is applied in a case study to North Rhine Westphalia and compared to successive and static routing approaches.

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2 Related Work

Various studies of the freight train routing problem have been performed in the literature. In the scheduling context, Cacchiani et al. [3] present an ILP problem for scheduling extra freight trains in an existing passenger timetable. The model is based on a time-expanded network graph that only contains links compatible with the predefined passenger services. The problem is solved using a Lagrangian heuristic where line capacity constraints are relaxed. A related, continuous scheduling approach, has been described in [2]. Here, each train is attributed with a time window and the objective is to minimize penalties resulting from time-window violation. Predefined passenger services can be allowed some flexibility based on the penalization of time windows.

Borndörfer et al. [1] present an approach which abstracts from the timetable to a more general routing setting. The problem is also set on a time-expanded network graph. Capacity constraints imposed by passenger traffic are not considered, explicitly. Instead, they are accounted for by a nonlinear *capacity restraint function* in the objective function, which measures the congestion effects as a function of the local traffic load. Another timetable-independent routing approach is dicussed in [4], where a static network routing problem including line segments, station areas, and route nodes is considered. Parametric queuing-based delay evaluation procedures currently used by DB Netz AG [6] are applied to calculate the residual capacity of each component. An iterative solution approach accounting for the nonlinear coupling between train routing and capacity constraints, which explicitly depend on the routing of freight trains, is introduced.

Similar to [1] and [4], the focus of this work is on the identification of residual network capacity in long-term planning, regardless of the specific timetable concept. The model we propose can be seen as an extension of [4] to time-dependent routing. From a methodological point of view, however, our approach is most closely related to the one described in [3], including strict capacity constraints in the network graph.

3 Model

3.1 Capacitated Railway Network Model

On a macroscopic level, railway networks are composed of lines, junctions and stations. In Germany, the capacity utilization and spare capacity of these elements is presently assessed using aggregate queuing-based approaches [6]. Waiting times as a function of the traffic load ρ are compared to an empirical *level of service* (LoS), which denotes the economically optimal utilization of capacity and depends on the share of freight trains (p_{frt}). The admissible number of trains during a time frame T for a given traffic mix is obtained by setting (also see [5])

$$T_W(\rho) \stackrel{!}{=} c \cdot e^{-1.3\cdot(1-p_{\mathrm{frt}})} \cdot T =: \mathrm{LoS}(p_{\mathrm{frt}}), \tag{1}$$

where the constant c depends on the type of element (see [6]).

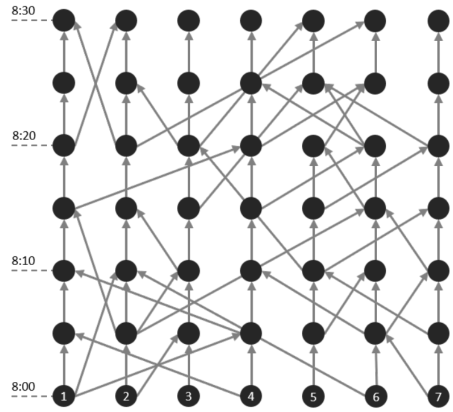

Fig. 1. Illustration of a 30 minute time slice of the network with randomly distributed slots for freight trains. Station/yard capacity restrictions are not depicted in the figure.

In the present work, residual capacity is calculated based on Formula (1) for each component and distributed randomly over the time frame F for all components, independently. For macroscopic network routing on the station/yard-level, correlations between infrastructure segments are relatively small due to a large number of merging and starting or ending train services. An example for the resulting time-expanded residual network graph, where residual capacity translates into usable links is given in Figure 1.

3.2 Demand Modeling

Freight traffic demand is assumed to be independently uniformly distributed over the time frame F for all freight relations. It is assumed saturating, i.e. the number of train path requests is higher than the residual capacity. This allows to determine the number of additionally marketable slots in a capacity analysis setting.

3.3 Routing Approach

In the following, we adopt the notation and build on [3] for the routing problem. Let (V, E) denote the network graph, T denote train runs, and σ_j and $\{\tau_j\}$ the start and the (time-expanded) destination node of train run $j \in T$. $\delta^-(v), \delta^+(v)$ are the sets of in- and outgoing arcs in node v. Let further c_v denote the node capacity, i.e. the number of additional freight trains trains that can simultaneously be acquainted in a station at the given time. It is assumed the start node has infinite capacity – which is reasonable, as it often refers to a shunting yard. t_{je}, $t_{j,\min}$ refer to the running time of train j along $e \in E$ and the minimum running time of train j on its designated route. q is a factor specifying the maximum admissible running time prolongation.

The freight routing consists of a two-step approach, where the number of additional freight trains subject to time constraints is maximized in the first step and running times for this train number are minimized in the second step.

Step 1 – Constrained Flow Maximization

$$\max \sum_{j\in T,\ e\in\delta^+(\sigma_j)} x_{je}, \qquad s.t.$$

$$\sum_{e\in E} t_{je}x_{je} \leq q\cdot t_{j,\min} \qquad \forall j\in T, e\in E \tag{2}$$

$$\sum_{e\in\delta^+(v)} x_{je} \leq 1 \qquad \forall j\in T, v\in V \tag{3}$$

$$\sum_{e\in\delta^-(v)} x_{je} = \sum_{e\in\delta^+(v)} x_{je} \qquad \forall j\in T, v\in V\setminus\{\sigma_j,\{\tau_j\}\} \tag{4}$$

$$\sum_{e\in\delta^+(v)} x_{je} = z_{jv} \qquad \forall j\in T, v\in V \tag{5}$$

$$\sum_{j\in T} z_{jv} \leq c_v \qquad \forall v\in V \tag{6}$$

$$x_{je}, z_{jv} \in \{0,1\} \qquad \forall j\in T, e\in E, v\in V, \tag{7}$$

Constraint (2) imposes a running time restriction and constraint (3) ensures that each train visits each node at most once (no cycles). (4) is the standard flow conservation and constraints (5)-(7) ensure the capacity limits of stations are satisfied. Infrastructure restrictions such as lack of electrification or narrow curves can be accounted for by setting $x_{je}=0$ in case train j cannot be operated on this line.

Step 2 – Running Time Minimization

Let n be the maximum number of additional freight trains obtained in the first optimization step. The second, running time minimization step provides insights into the quality of the routing concept in terms of the running times of the trains. The two-step approach allows to decouple flow maximization and running time minimization, which is computationally more efficient if additional fairness constraints between different train relations (cf. [4]) are to be considered.

$$\min \sum_{j\in T}\left(\sum_{e\in E} t_{je}x_{je} - \sum_{e\in\delta^+(\sigma_j)} x_{je}t_{j,min}\right), \qquad s.t.$$

$$\sum_{j\in T}\sum_{e\in\delta^+(\sigma_j)} x_{je} = n$$

$$\text{Constr. (2)--(8)}$$

4 Results

The freight routing capacity is analyzed in a case study for the network of North Rhine Westphalia, which consists of 51 nodes and 148 links (see Fig. 2). For the analysis, the three relations Oberhausen-Troisdorf, Oberhausen-Siegen and Aachen-Münster are considered, which are amongst the relations with the highest demand or have been discussed to mitigate capacity shortages.

The results presented in the following are calculated for a 8h time frame without running time restriction (2). For time resolutions of 3 to 5 minutes and train demands of the order of the *static* residual capacity, almost all instances could be solved to optimality using Gurobi in $60 - 600s$. The paths of 6 additional freight trains are visualized in Figure 2.

A major question in the context of residual freight capacity is whether trains should be routed simultaneously (pre-planned freight slots in the timetable) or successively (which refers to the current construction practice). To investigate this problem, we analyze 500 realizations of the network with random demand and usable slots on lines. It is found that simultaneous planning yields approximately 2 trains more than successive routing (cf. Fig. 3), on average. Running time drops by about 20 min ($264.8/244.9$ min), also see Fig. 3. The difference will probably get stronger in case of higher overlap between freight relations.

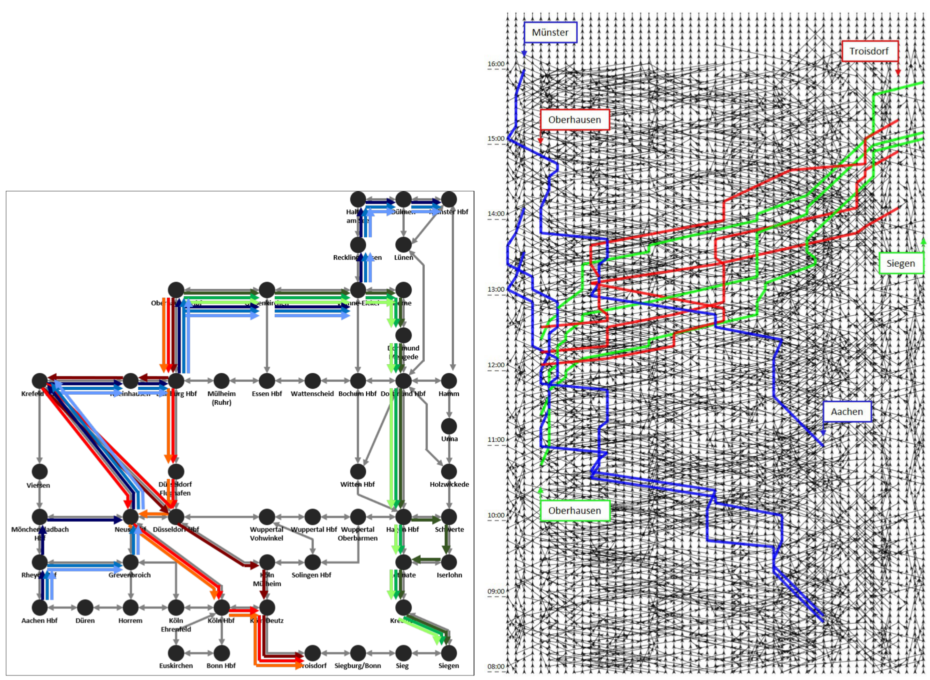

Fig. 2. Visualization of freight train routing results for three freight train relations in North Rhine Westphalia. Train routes (left) and time-expanded network (right).

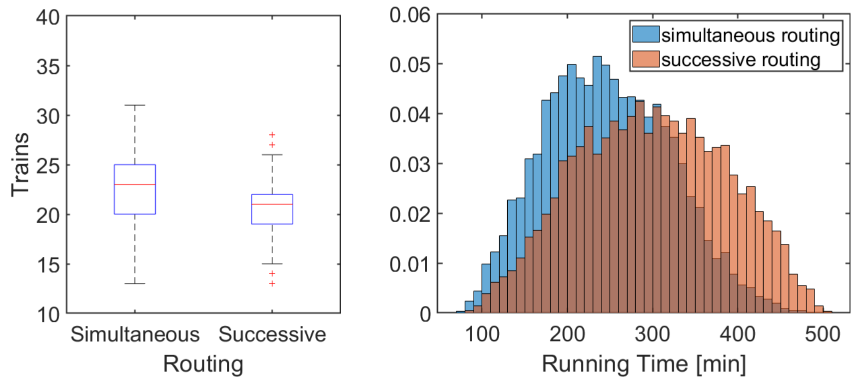

Fig. 3. Results freight train routing for simultaneous and successive routing (500 real.). Number of additional freight trains (left) and running time statistics (right).

In a static routing setting for the same network, a total of 56 trains can be supported at an average running time of 115 *min*. We therefore conclude that connectedness of slots in the network is a major factor and that it seems advisable to harmonize slots for entire freight relations in the timetabling process.

5 Conclusion and Outlook

In this paper we have discussed an approach to assess residual network capacity for freight train routing in an existing passenger timetable concept based on stochastic demand and residual capacity. We have demonstrated its applicability in a case study for North Rhine Westphalia. In future, the approach is to be extended by coupling it to a more detailed demand and capacity modeling.

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