Re-optimizing ICE Rotations after a Tunnel Breakdown near Rastatt

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Abstract
This paper deals with the situation of re-scheduling railway rolling stock rotations after a major disruption. Disruptions are an all day life problem when operating a railway system. Nevertheless, an unusal example for a disruption is the collapse of a tunnel ceiling near Rastatt in southern Germany due to construction works related to the enlargement of the tracks between Karlsruhe and Basel. As a result the main railway connections Amsterdam-Basel and Berlin-Basel, located on top of the tunnel, had to be closed from August 12th to October 2nd 2017. This had a major impact on the railway network in southern Germany. Hence, all rotation plans and train schedules for both passenger and cargo traffic had to be revised. Since the disruption was very long lasting the revision of the rotation plans was done on a tactical rather than on an operational level which would usually be the case. In this paper we focus on a case study for this situation and compute new rotation plans via mixed integer programming for the ICE high speed fleet of DB Fernverkehr AG one of the largest passenger railway companies in Europe. In our approach we take care of some side constraints to ensure a smooth continuation of the rotation plans after the disruption has ended.

1 Introduction

Planning rolling stock movements in industrial passenger railway applications is a long-term process based on timetables which are also often valid for long periods of time. For these timetables and periods rotation plans, i.e., plans of railway vehicle movements are constructed as templates for these periods. Those rotation plans will gain accuracy the closer the day of operation comes. During operation the rotation plans are affected by all kinds of unplanned events such as natural disasters, technical problems, or man-made impediments. An example for the latter case is the collapse of a tunnel ceiling between Rastatt and Baden-Baden in southern Germany due to construction works related to the enlargement of the tracks between Karlsruhe and Basel. In Figure1 the ICE highspeed train line network is shown with a red mark where the tunnel collapsed close to Baden-Baden on the pink line in the south-west part of the map. As a result the main railway connections Amsterdam-

Basel and Berlin-Basel, located on top of the tunnel, had to be closed from August 12th to October 2nd 2017. This had a major impact on the railway network in southern Germany since this is the direct electrified railway corridor connecting the Netherlands via Germany with Switzerland and Italy. Hence, all rotation plans and train schedules for both passenger and cargo traffic had to be revised. As a side effect many other industry branches suffered from a lack of materials that could not be delivered in time.

In this paper we focus on this concrete case and compute new rotation plans for the ICE high speed fleet of DB Fernverkehr AG one of the largest passenger railway companies in Europe. To bring these rotations into practice the two following conditions had to be considered:

1. Passenger trains operating in southern Baden-Wuertemberg or Switzerland were only operated till Rastatt.

2. The 3rd of October is a national holiday in Germany.

As a result only a limited offer on railway connections exists for this day comparable to the weekend traffic. Nevertheless a seamless connection between the rotation plan for the period covering the construction works, the holiday, and the relaunched regular timetable should be guaranteed. Thus the less differences between the different parts of the rotation plans exist the better.

Constructing new or revised tours of rolling stock vehicles through the timetable after disruptions is a well studied topic in the literature, see Cacchiani et al. (2014) for an overview. Usually, a rescheduling based on a timetable update is done, followed by the construction of new rotations that reward the recovery of parts of the obsolete rotations. We consider a different, more integrated approach with side constraints on the start and end states of the vehicles and a system to reward preserved or similar operated train connections in both periods. The approach is based on the mixed integer programming approach presented in Reuther (2017). The goal is to minimize the operating costs while preparing as best as possible for the relaunch of the regular timetable afterwards. In contrast to the situation this paper deals with most of the research in the literature considers 'ad hoc' rescheduling approaches. For example in Lusby et al. (2017) vehicle rotations have to be revised (almost immediately) for some suddenly occurring reasons. In the case this paper focuses on the disruption is long lasting and therefore changes to the rotations are more on a tactical or strategical level than on an operational.

2 Rolling Stock Rotation Problem with Side Constraints

In this section we consider the *Rolling Stock Rotation Problem* (RSRP) and extend a hypergraph-based integer programming formulation to suit our setting. We focus on the main modeling ideas and refer the reader to the paper Borndörfer et al. (2016) for technical details.

In our computations we distinguish between a cyclical planning horizon of one week and an acyclic planning horizon of two weeks. In the latter case the exact period is from September 27th to October 10th. Let T denote the set of timetabled passenger trips. Let V be a set of *nodes* representing timetabled departures and arrivals of vehicles operating passenger trips of T. In the acyclic case there are additional nodes for start and end positions of vehicles at beginning and at end of the planning horizon. The sets of start and end positions are denoted by $S \subset V$ and $E \subset V$, respectively. Trips that could be operated

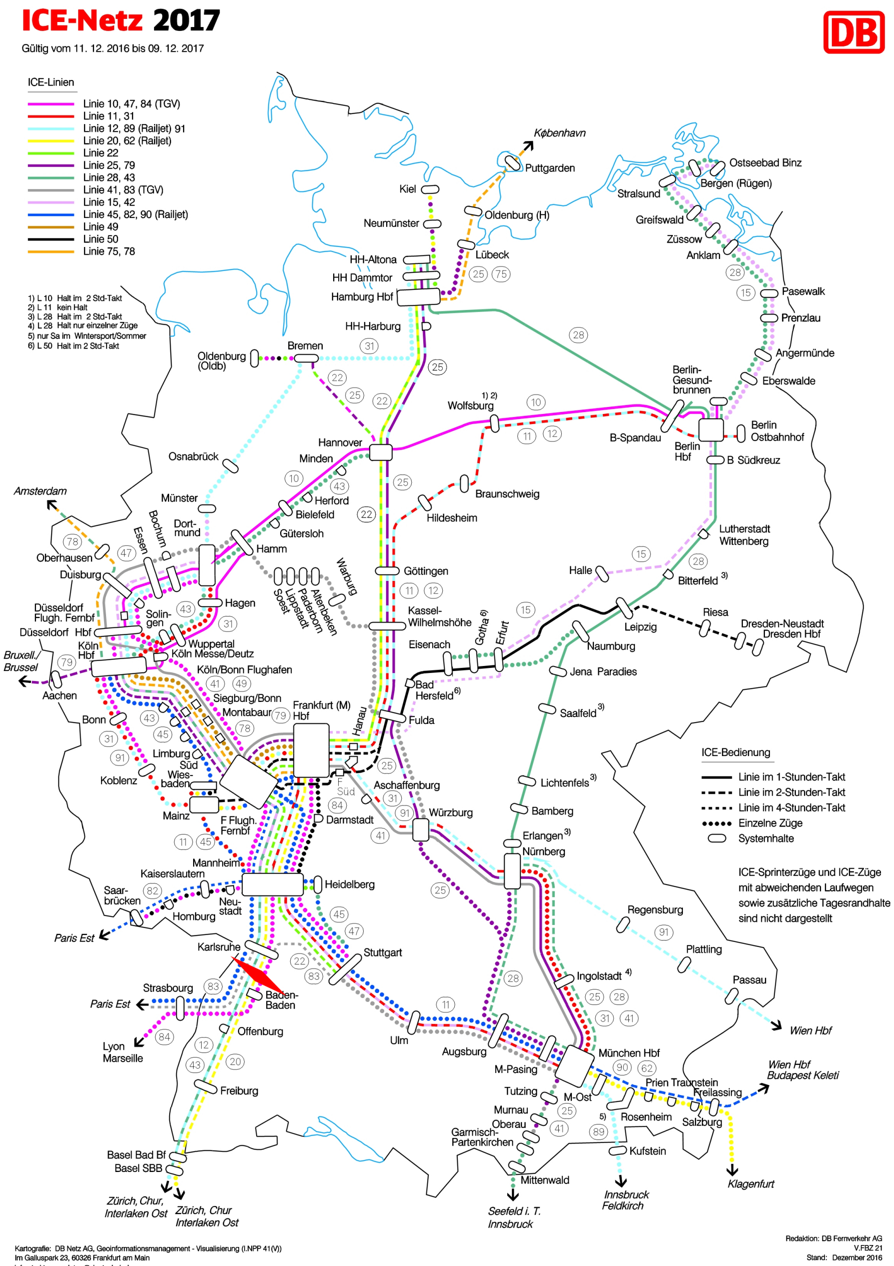

Figure 1: ICE highspeed train line network.

with two or more vehicles have the appropriate number of arrival and departure nodes. Let further $A \subseteq V \times V$ be a set of directed standard arcs, and $H \subseteq 2^A$ a set of *hyperarcs*. Thus, a hyperarc $h \in H$ is a set of standard arcs and includes always an equal number of tail and head nodes, i.e., arrival and departure nodes. A hyperarc $h \in H$ *covers* $t \in T$ if each standard arc $a \in h$ represents an arc between the departure and arrival of t. Each of the standard arcs a represents a vehicle that is required to operate t. We define the set of all hyperarcs that cover $t \in T$ by $H(t) \subseteq H$. By defining hyperarcs appropriately, vehicle composition rules and regularity aspects can be directly handled by the model. Hyperarcs that contain arrival and departure nodes of different trips are used to model deadhead trips between the operation of two trips (or even more if couplings are involved). The RSRP *hypergraph* is denoted by $G = (V, A, H)$. We define sets of hyperarcs coming into and going out of $v \in V$ in the RSRP hypergraph G as $H(v)^{\text{in}} := \{h \in H \mid \exists\, a \in h \,:\, a = (u, v)\}$ and $H(v)^{\text{out}} := \{h \in H \mid \exists\, a \in h \,:\, a = (v, w)\}$, respectively. We call a set $R \subseteq H$ a reference solution if R is a set of hyperarcs that define a set of s-e-(hyper)paths in G such that each $t \in T$, $s \in S$, and $e \in E$ is covered by a single hyperarc. Let $c_R : H \mapsto \mathbb{Q}^+$ denote the cost function of G associated with reference solution R respectively the vehicle movements behind it. Though by $c_R(h)$ all costs for vehicle usage, deadhead trip costs, and energy consumption are given as a weighted sum of the different parameter. Additional a penalty for choosing a different vehicle movement compared to the reference solution is included. In more detail there are penalties for choosing different vehicle types, configurations, or orientations for a trip or choosing different connections between two trips where one succeeds the other. Another important aspect in rolling stock planning and optimization is vehicle maintenance. At DB Fernverkehr AG there are several different maintenance rules for the different ICE fleet that all have to be considered. In this paper we focus on a single maintenance rule that is based on the accumulated kilometers a vehicle is operated between two maintenance services. We denote its upper bound on the total mileage between two maintenance services by U. Maintenance services could only be performed at special maintenances locations $m \in M$. The kilometers a vehicle is moved during an operation modelled by a chosen hyperarc is given by a function $r : V \times H \mapsto [0, U]$. This includes necessary deadhead trips to reach maintenance facilities or turn around trips to change the orientation of the vehicle. To model maintenance services in the RSRP *hypergraph* additional maintenance service hyperarcs were added for each pair of trips if it is possible to visit a maintenance facility and perform the service between the operation of the two trips. The cost for the additional deadhead trip and the cost for the maintenance service is added to the cost of the hyperarc. In this sense a s-e-(hyper)path or a cycle in G is called maintenance feasible, if and only if the accumulated kilometers of all trips and deadhead trips along this path or cycle between each two hyperarcs with a mainenance service is smaller than U. The *Rolling Stock Rotation Problem with Side Constraints* (RSRPSC) is to find a cost minimal, maintenance feasible set of hyperarcs $H_0 \subseteq H$ such that H_0 is a collection of cycles in the cyclic or a collection of s-e-(hyper)paths in the acyclic case and all nodes in V are covered by a hyperarc $h \in H_0$.

Using a binary decision variable x_h for each hyperarc the RSRPSC can be stated as an integer program as follows:

$$
\begin{aligned}
\min \sum_{h\in H} c_h x_h, && && (1)\\
\sum_{h\in H(t)} x_h = 1 && \forall t \in T, && (2)\\
\sum_{h\in H(s)^{\text{out}}} x_h = 1 && \forall s \in S, && (3)\\
\sum_{h\in H(d)^{\text{in}}} x_h = 1 && \forall d \in D, && (4)\\
\sum_{h\in H(v)^{\text{in}}} x_h = \sum_{h\in H(v)^{\text{out}}} x_h && \forall\, v \in V \setminus \{S \cup D\}, && (5)\\
w_a \leq \sum_{h\in H(a)} U\, x_h && \forall a \in A, && (6)\\
\sum_{a\in A(v)^{\text{out}}} w_a - \sum_{a\in A(v)^{\text{in}}} w_a = \sum_{h\in H(v)^{\text{out}}} r(v,h)\, x_h && \forall v \in V \setminus \{D\}, && (7)\\
\sum_{a\in A(m)^{\text{out}}} w_a = \sum_{h\in H(m)^{\text{out}}} r(s,h)\, x_h && \forall m \in M, && (8)\\
w_a \in [0, U] \subset \mathbb{Q}_+ && \forall a \in A, && (9)\\
x_h \in \{0, 1\} && \forall\, h \in H. && (10)
\end{aligned}
$$

The objective function 1 minimizes the sum of the operational cost of all chosen hyperarcs. This includes all cost for operating a trip, deadhead trips, performing maintenances, and costs to penalize irregularities. The first three sets of constraints 2, 3, 4 ensure the covering of each trip, start position or end position. Equations 5 take care about the (hyper)flow conservation. The following four sets of constraints deal with the vehicle maintenance. First, the maintenance variables w were coupled to the hyperarc variables allowing only those to be used for which a hyperarc was chosen. Followed by equations 7 which ensure the correct aggregation of the maintenance resource consumption. The constraints 8 state the possibility to reset the resource flow at maintenance service locations. Finally, the variable domains are given by 9 and 10.

3 Case Study for October 2017

We test our algorithmic approach on real world scenarios of the DB Fernverkehr AG covering the different rotation plans for different sets of ICE-1 vehicles. To do that we use our rolling stock rotation optimizer ROTOR with the modification to the model from section 2. For further information on the implementation and algorithms of ROTOR see Borndörfer et al. (2016); Reuther (2017). All computations were performed on an Intel® Xeon(R) E3-1245 v5 @ 3.50GHz CPU with eight cores and Gurobi 8.1 as LP and sub-MIP solver.

We consider two different scenarios related to the tunnel breakdown. First, we focus on the period between August 12th and October 2nd, i.e., the period where the tracks between Rastatt and Baden-Baden were closed. As this period lasts for roughly eight weeks it was considered as some kind of a regular period comparable to a (planned) longer maintenance period. Therefore new or re-optimized cyclic vehicle rotation plans were computed for each affected vehicle type that were valid from August 12th and October 2nd. We call these instances *period* instances. The second set of instances deals with the situation after the tracks were reopened. Thus, there should be a smooth transition between the rotation plans for the maintenance period and the normal, i.e., undisturbed timetable. Thus, we considered scenarios that optimize the vehicle rotations between September 27th and October 10th. We call them *transition* instances.

3.1 Period Scenarios

As mentioned earlier these scenarios consider a cyclic time horizon of one week, such that the rotations plans could be repeated as long as the tunnel is closed. Thus, we drop all start and end constraints in our model to compute solutions for these scenarios. Additionally, these scenarios arise from the normal timetable that was offered by DB Fernverkehr AG by removing all passenger trips that were operated in Switzerland or south of Rastatt, i.e., all ICE trains going from Karlsruhe to Basel were stopped at Rastatt. Therefore a (maybe non-optimal) solution for these scenarios exists by taking the obsolete vehicle rotation removing all train movements south of Rastatt and connecting the last movement before a removed one to the first one after a removed one. As these scenarios contain less passenger trips, respectively less operated kilometers (roughly 90% of the accumulated trip kilometer of an undisturbed week), it is not clear how good these solutions are. Moreover, there is a maintenance facility near Basel for the ICE fleet which is as a consequence of the tunnel breakdown disconnected from the remaining network where the trains are running. Thus, it is not clear if the heuristically constructed solution is at least feasible. Additionally, planned maintenances at this facility had to be compensated by other facilities.

Table 1: Results for the *period* scenarios.

ID	$\|T\|$	$\|H\|$	Reg. Veh.	DM DM	Rev. Veh.	Heuristic Cost($\times 10^x$)	Optimized Cost($\times 10^x$)	Imp.(%)	CPU(s)	Gap(%)
1	37	0.01m	3	0	3	0.138	0.138	0.0	0.81	0.34
2	258	0.46m	16	1	16	0.918	0.908	1.0	246	0.16
3	582	1.88m	32	1	32	2.285	2.280	0.3	1958	0.64
4	889	18.20m	52	2	50	3.443	3.352	2.7	15053	0.50

Table 1 shows the computational results of the period instances for different sets of the ICE-1 train fleet. The first two columns identify the instance itself by an index and its number of included passenger trips. After that the total number of hyperarcs required to model the respective scenario with our approach is given in column '$|H|$'. The columns 'Reg. Veh.' and 'Rev. Veh.' show the number of required vehicles to cover the regular and the revised timetable in an optimal way. Numbers in column 'DM' mark the number of maintenances of the reference rotation that could not be reached anymore. The two 'Cost' columns list the operational cost of the heuristically constructed solution where trips passing Rastatt were shortened and the best solution found by our approach. The improvement of the latter over the first solution is given in the 'Imp.' column. Finally, the required computation time and LP-IP gap are given by the last two columns. Focusing on the number of vehicles required for this period it is possible to operate the disturbed timetable by the same amount of vehicles. This is not trivial because of the disconnected maintenance facility, but also more expected than surprising. It makes sense to consider the optimized rotations especially if they contain less vehicles as for instance 4, since that frees vehicles for other purposes, even if the heuristically constructed solution is maintenance feasible. The numbers for required vehicles and the cost of instance 1 shows exactly the case where you could not do anything better than shortening the trips passing Rastatt and use the heuristically constructed solution. Keeping in mind that this period lasts for roughly eight weeks, operating a rotation with 1.0 or 2.7% decreased operational cost is highly desired and leads to noticeable total cost savings. The last two columns show that the approach can come up with near optimal solutions in reasonable short computation times. Thus, with an automated approach to re-compute rotations for disturbed scenarios planners have a strong tool at hand to react to the new situation and to qualify their solutions.

3.2 Transition Scenarios

These scenarios model the exact situation between September 27th and October 10th. Thus, we consider an acyclic time horizon of two weeks, with start and end conditions for the vehicles of the fleet. The timetable considered in these scenarios is composed of the disturbed timetable of the disruption period for the first week and the regular timetable for the last week. Additionally, the 3rd of October is a public holiday in Germany. In 2017 this was a Tuesday. Therefore, DB Fernverkehr AG offered a limited number of trips on Tuesday and on Monday, due to a limited demand for train rides on these days. This leads to a somehow irregular period within the timetable. Nevertheless, regularity is always a very desired property in the railway industry. It holds for timetables in the sense of regular, i.e., periodically repeating connections or arrival and departure times. The same holds for rotation plans. To optimize towards regular rotation plans, we consider reference solutions for each of our scenarios. It is composed of two parts the first part is the optimized rotation plan for the respective *period* scenario and the second part is an optimized rotation plan for undisturbed timetable that should be operated again after the 3rd of October. Thus the vehicle locations at the beginning of September 27th and the end of October 10th with respect to the solutions are the start and end conditions for our model. Additionally, there is a penalty for each deviation from any vehicle movement included in the reference solution.

Table 2: Results for the *transition* scenarios.

ID	$\lvert T\rvert$	$\lvert H\rvert$	Veh.	M	Dev.	Dev M.	Cost($\times 10^x$)	CPU(s)	Gap(%)
1	95	0.07m	3	7	6	1	0.314	26	0.00
2	545	1.5m	16	44	52	1	2.053	871	0.84
3	1173	7.1m	32	103	137	2	4.741	7166	1.00
4	1854	74.7m	52	159	175	4	7.223	49311	0.55

Table 2 shows the computational results of the transition instances for different sets of the ICE-1 train fleet. Analogue to the previous table the first three columns identify

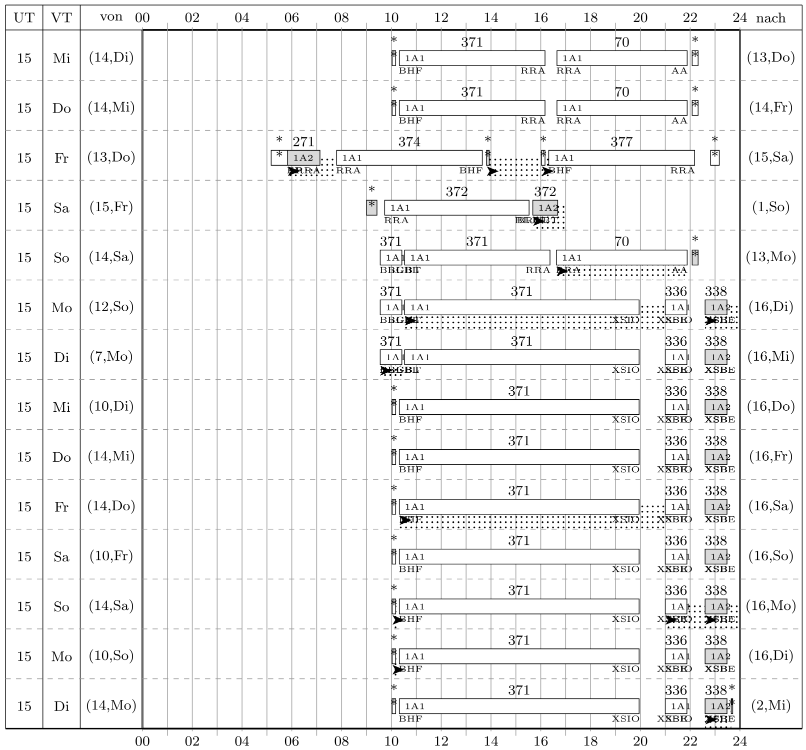

Figure 2: Visualization for a single vehicle contained in the rotation plan of the ICE-1 train fleet.

the respective instance and give the number of included trips as well as the number as required hyperarcs to model the problem. Numbers in columns 'Veh.' and 'M' show the number of required vehicles respectively planned vehicle maintenances for the scenario. Column 'Dev.' marks how many trips of the reference solution have different succeeding trips in the optimized and in the reference solution. A quite similar number is given by 'Dev. M.' as it is the number of maintenances of the optimized solution that deviate from maintenances of the reference solution. The last three columns show again operational cost of the solution, runtime of the approach, and the LP-IP gap. The first observations for the transition instances is that all instances could be solved nearly to optimality. Focusing on the number of trip and maintenance deviations, the optimized solutions keep on average over 90% of all trip connections and over 95% of the planned maintenances of the respective reference solutions. This leads to the conclusion that the vehicles movements during the time horizon of the scenarios are very similar to the movements before and afterwards.

Figure 2 shows a subset of the optimized solution for the ICE-1 train fleet containing trip sequences of a day of operation associated with train 371. In more detail all boxes headlined by a number show a trip with this number. Boxes in the same line succeed or precede the other starting at midnight on the left at ending at the following midnight on the right. The color of a box gives the orientation of the used vehicle, i.e., a white bow shows a vehicle with its first class in front of the second class with respect to the driving direction and gray boxes for the opposite orientation. The abbreviation on the bottom of a box, e.g., 'BHF' (for Berlin Ostbahnhof, in the north-east of Figure 1) gives the arrival and departure stations of the trip. Focusing on trip '371' one can see that the same orientation and vehicle configuration was chosen to operate it over the complete planning horizon although it has different arrival stations in the beginning ('RRA' for Rastatt) and end ('XSIO' for Interlaken Ost, in the south-west corner of Figure 1) of the planning horizon. The vizualization of the optimized solution was done with the techniques discribed in Borndörfer et al. (2019).

4 Conclusions

We presented a case study of a real world scenario of a heavy disruption of the German railway network. This long lasting disruption had a major influence on many parts of the railway system. We presented an approach how to deal with this kind of disruption and how to compensate it. The approach is capable to deal with the size of a nation wide scenario and leads to near optimal solutions in reasonable time.

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