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TAILOR-MADE TRAIN PATH HOMOGENIZATION – A CAPACITY IMPROVEMENT FOR MIXED RAIL TRAFFIC

Summary. This article introduces a novel segmentation of train paths, based on their degree of periodicity and regularity, and, as a consequential measure, a framework process for local mutual homogenization of periodic train paths for a more efficient rail capacity utilization and for energy saving by avoiding an unnecessary stop of a freight or passenger train to be overtaken by a faster train. The framework process is tested in a timetable experiment on the prospective modernized mainline Praha - Plzeň - Domažlice - Furth im Wald. The resulting timetable and distribution of runtime surcharges show that the presented approach has great potential for use in capacity coordination for mixed rail traffic. The types of railway lines and timetables suitable for this framework process, as well as

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specific examples of suitable lines on the current and future Czech railway network, are discussed as well.

Keywords: heterogeneity, homogenization, Integrated Periodic Timetable, interposition, railway capacity, speed bundling, zero symmetry

1. INTRODUCTION

1.1. Strategic and Coordinated Railway Capacity Planning in the EU

The need for more coordinated railway capacity planning both within a particular mixed-traffic mainline, and between the neighboring mainlines (especially subsequent mainlines that form a corridor), requires a novel, holistic, impartial approach that will take into the account technical capacity requirements of all segments of railway transport, but, on the other hand, will maintain the functionality of the (Integrated) periodic timetable for passenger services, due to its undeniable benefit for sustainable traveling both within particular states and through Europe.

Because the below proposed segmentation of railway capacity and a framework process are meant to be guidelines for the railway capacity allocators, rather than exact algorithms, it is necessary to briefly introduce the political context of the EU in terms of railway capacity planning, coordination, and allocation.

The liberalization of the European railway market was first realized in freight transport. Afterwards, the liberalization has gradually emerged in European passenger railways in two forms. The first, more widespread form, is the operation of (often periodic) regional or (sub)urban railway public transport services, but also long-distance services in some countries – see for instance, Bulková et al. [1], ordered as a public service and either periodically tendered or awarded directly, but not always to the dominant national operator. The second form is purely commercial services (long-distance as a rule), using the Open Access to the railway infrastructure in the EU.

After the success of the (at least long-distance and suburban) passenger railway, good-quality capacity for the freight trains (in the sense of frequent time windows for running at maximum allowed speed without stops) became scarce on many European mainlines. The European Commission responded by introducing the Rail Freight Corridors (RFCs), based on the Regulation (EU) No. 913/2010 of the European Parliament and of the Council of 22 September 2010 Concerning a European Rail Network for Competitive Freight [8]. Recently, the initial 11 RFCs have been redesigned into 9 new ones in accordance with European Transport Corridors (ETCs) as a part of the revision of the Trans-European Network [10]. The corridors are administered by RailNetEurope (RNE) – the association of national infrastructure managers and capacity allocators. Particular corridors are then managed by the involved infrastructure managers or capacity allocators [19]. The expectations for RFCs were not fully met, as the European Commission states in paragraph 7 of the Proposal for a Regulation of the European Parliament and of the Council on the use of railway infrastructure capacity in the single European railway area, amending Directive 2012/34/EU and repealing Regulation (EU) No 913/2010 [9]: “The rules and procedures on the management of rail infrastructure capacity should better reflect the needs of all rail market segments. They should, in particular, take into account the necessity of long-term stability of available capacity for passenger services and of short-term flexibility for freight traffic to respond to market demand. Therefore, the process of managing capacity should no longer have a predominantly annual focus but should be arranged in three subsequent phases of strategic capacity planning; rail service scheduling and

capacity allocation and adaptation and rescheduling of capacity. The introduction of better-defined and structured phases that provide for the possibility of long-term planning and short-term adaptation in capacity management would particularly benefit services that are less easy to plan in advance or are more complex to arrange, such as freight trains and cross-border passenger trains.”

The strategy of the European Commission, presented in this proposal, is reflected in a Timetable Redesign (TTR) process, introduced by RNE. The main idea is to fruitfully combine multi-year stability of mostly periodic passenger services and some (partially international) freight trains with the necessary flexibility of daily train path allocation for another (mostly ad hoc freight) trains from the rest capacity. The TTR process comprises several phases with gradually increasing levels of detail. The Capacity Strategy comprises international alignment on large capacity restrictions (extended track closures, etc.). In the Capacity Model, capacity volumes are assigned to the identified market needs. Further, the processes analogous to present capacity allocation and timetabling follow, but with the enhanced IT support that enables better coordination between infrastructure managers and capacity allocators [20].

The authors believe that the Capacity Model can (and should) include the model timetable for the already known demand – mostly periodic passenger services or suitable periodic freight train paths (PFTPs) based on the known freight demand.

1.2. Scope and Structure of this Paper

This paper deals with capacity planning in strategic and tactical phases. Thus, requirements for attractive offers of various segments of (mainly periodic) passenger services and energy-efficient timetabling of freight trains have to be integrated into the planning process. Operative (ad hoc and daily) capacity allocation is considered only in the form of delimitation of time windows for flexible capacity allocation. Punctuality and timetable stability are not directly addressed here – only in terms of sufficient time surcharges and buffer times and their distribution along the mainline.

This paper is organized as follows. In the Introduction, the European strategy for long- and middle-term coordinated railway capacity planning was briefly mentioned. Then, a literature review of the relevant publications is conducted, and the research gap is derived. In Materials and Methods, the authors propose original segmentation of train paths and rest capacity in accordance with the Proposal for a Regulation of the European Parliament and of the Council on the use of railway infrastructure capacity in the single European railway area, amending Directive 2012/34/EU and repealing Regulation (EU) No 913/2010 [9], with symmetrical periodic core, based on degree of periodicity and regularity - both passenger train paths, adhering to the principles of Integrated Periodic Timetable (IPT), and zero-symmetrical PFTPs. Further, the authors propose a novel framework process for coordinated mutual homogenization of train paths in the bottleneck sections for increased efficiency of the capacity allocation and traction energy saving. This section ends with a brief presentation of the mainline chosen for the timetable experiment - the prospectively modernized mainline Praha - Plzeň - Furth im Wald (Germany). Then, the resulting symmetrical periodic timetable, supplemented with PFTPs, constructed as a timetable experiment in accordance with the presented framework process, is presented. In the discussion, the proposed train path segmentation, a framework process, and timetabling experiment are interpreted and then discussed. The conclusion summarizes contribution and major findings of the introduced framework approaches, followed by recommendations for further research.

2. LITERATURE REVIEW

2.1. Timetabling and Capacity Allocation for Mixed Traffic

Due to abundance of research in the field of railway timetabling, the authors basically limited the literature review to mixed railway traffic – scheduling of both passenger and freight traffic on the same line, and to homogenization of train paths.

The first edition of UIC Code 406 Capacity [25] identified heterogeneity of train paths (i.e., different scheduled section runtimes) as one of four key parameters that influence railway capacity. The higher heterogeneity, the lower the capacity of the line. This applies not only to double-track lines, but also to single-track lines – see Dingler et al. [7].

The second edition of UIC Code 406 Capacity [26] clearly displayed limitations of capacity estimation based on the compression of subsequent train paths closely together (with time supplements added to secure quality of operation). This estimation gives various results, depending on the chosen length of the line section.

Krýže [14] in his doctoral thesis highlighted interdependencies between periodic timetables and railway capacity (consumption). Further, he discussed potential usage of the optimization models and finally proposed and demonstrated his own methods for complex construction of periodic timetables. He, however, focused on shorter line sections and did not deal in-depth with overtaking of freight trains by fast passenger trains. In his thesis, he clearly illustrated and explained the influence of train path heterogeneity, i.e., difference in sectional runtime of a train against the most frequent segment of trains – the higher absolute value of the difference, the lower the number of trains can be scheduled through the section – see Fig. 1.

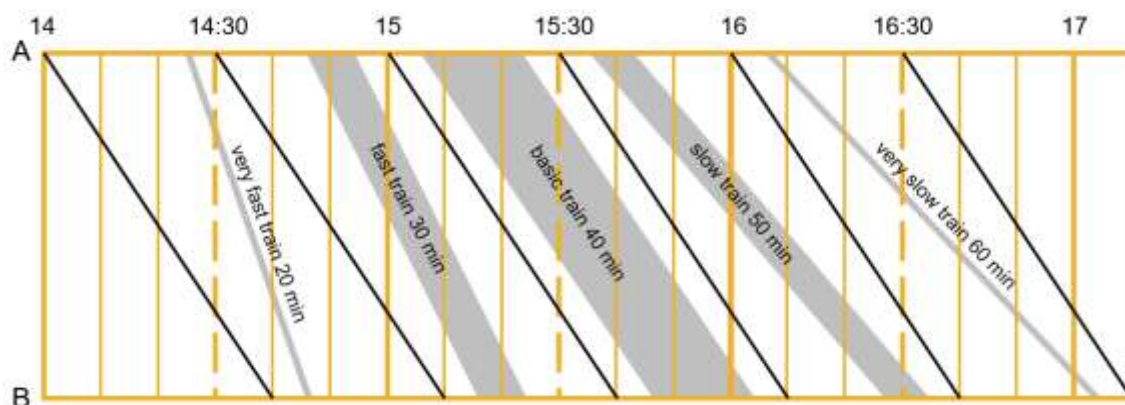


Fig. 1. Usable capacity (sizes of time window) for trains with different section runtimes in the context of periodic timetable on a double-track line [14], translated into English by the authors

Janoš and Kříž [12] proposed to gain additional capacity on a double-track mainline by active overtaking (without stopping any train) a slow regional passenger train by a fast freight train, given the speed ratio of both trains is high enough.

Caimi et al. [3] proposed a mathematical formulation of partially periodic service. Thus, some train paths can repeat periodically, but they can be scheduled in peak times only. Such train paths can then alternate with other ones (e.g., freight train paths), supposing that all such train paths can fit into an all-day, fully periodic timetable.

Smoliner [22] dealt with the coexistence of a nationwide IPT-based timetable, the infrastructure improvements derived therefrom, and commercial (Open Access) passenger services. He proposed System train Paths (STP) in the form of a parallelogram (with fixed departure and arrival times in node stations, nevertheless enabling a variety of stopping patterns in between) that can be either tendered as a public service or tendered to commercial operators.

2.2. Coordination of Periodic Passenger Timetable with Freight Train Paths or Capacity

Lindner and von Redern [15] found that it was necessary to let periodic time windows (“canals”) within the passenger periodic timetable be free for freight trains, giving them sufficient capacity, and that such time windows on neighboring railway lines should preferably be connected together to enable the running of a freight train without stopping. Their conclusion was that periodic capacity rather than a periodic timetable made sense for freight trains.

Stähli [23] considered that planning of through or long-distance freight train paths should be already planned as periodic, in coordination with passenger timetable – not only for the sake of systematization of timetables, but also for better capacity utilization.

Čapek [6] (in cooperation with Swiss rail infrastructure manager SBB Infrastruktur) developed a software tool called FlexFahrplan for planning timeslots for freight trains more rapidly and with better capacity utilization. For this purpose, he developed an algorithm for speed bundling of freight train paths with passenger (or another already allocated) train paths.

Čapek [6] and Klabes [13] used intentional lengthening of train runtime to homogenize the train paths for the sake of more efficient utilization of rail capacity.

Some authors distinguished different capacity consumption of running through and stopping (or acceleration) of a freight train in their research. Opitz [17] formulated “template train atoms” differing in stopping or passing process - later referred to as “snippets” by Pöhle [18]. Vromans [28] saw this variance as flexibility for his model, so the optimal location of overtaking stations for freight trains could be determined. Another aspect to be considered is the difference in (locomotive) power to hauled mass ratios by freight train – see Fig. 2.

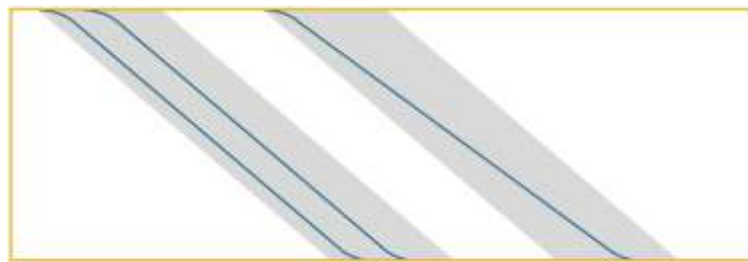


Fig. 2. Illustration of the difference in a practically usable capacity (sizes of time window) for freight trains with higher and lower power to hauled mass ratios that have to stop in both stations that delimit the section

Buschbacher [21] proposed targeted “mini-invasive” infrastructure improvements in the form of adding a short third track or lengthening a station track to enable smoother overtaking of a regional train by an additional long-distance train. He used the same approach for targeted overtaking of freight trains, and, in addition, proposed a systematic rear-end assistance for freight trains to improve their acceleration and, this way, decrease the capacity consumption.

2.3. Research Gap

To the authors' knowledge, there exists no procedure for iterative and coordinated planning of railway capacity with zero-symmetrical, periodic core that takes needs (legitimate interests) of passenger long-distance (with high-speed services, if need be), agglomeration (suburban), regional, and freight railway into account and is based on tailor-made homogenization of train paths for both passenger (long-distance and local) and freight trains.

3. MATERIALS AND METHODS

3.1. Requirements for Train Paths by Various Segments of Railway Transport

A network offer of long-distance railway services should be, at least in the case of a country with polycentric settlement, based on Integrated Periodic Timetable. Of course, in the largest cities, there should be designed efficient interchange connections between relevant long-distance public transport lines. But, in the regional centers, where most railway public transport lines operate hourly, the local IPT-nodes (or "rendezvous" nodes), either around minute zero or around minute 30, have to be respected even by express public transport lines, which use high-speed railway lines for a significant portion of the length of the particular public transport line. Moreover, an exact interposition of two hourly public transport lines (with the same section runtimes and stopping pattern) on a common section is suitable both for the offer of services with a half period, and for efficient utilization of railway capacity – it enables better coordination with agglomeration services, whose period of a public transport line is often 30 min (at least for larger agglomerations with approximately half a million inhabitants or more).

For a network offer of agglomeration (or suburban) passenger railway services, maintaining the principles of IPT is crucial as well. Outside of the center, the services should fit in (long-distance or regional) IPT-nodes (rendezvous nodes). For the services where daily commuting is predominant, a regular period is inevitable – the smaller period, the more attractive for the passengers. Thus, for long parallel sections of two or more public transport lines, their exact interposition into half (or quarter) periods should be strived for. Because a public transport line layout with a majority of diametral lines is both more economically efficient (longer average mileage of the motor units) and more attractive for the passengers, suitable time windows for running on more adjacent corridors have to be found – in the needed period and with zero symmetry, to enable equal timetable offers in both directions. If suitable interoperable (usually tailor-made) vehicles are available, suburban train services can also be directly connected to tram lines in the form of tram-trains – see, for instance, Metelka and Janoš [16].

Regional train services (outside the densely populated areas) on mainlines differ from the agglomeration services in more ways – the trainsets are usually shorter, the service periods longer (60 or 120 min as a rule), and the average distance between neighboring stops should be longer, due to both the lower population density of the served area and for the sake of avoiding too frequent overtaking by long-distance trains.

A special subset of regional or agglomeration trains are regional express services, whose stopping pattern can be zone-specific: in the inner (agglomeration) zone, the service either does not stop at all or only at the most significant stops (in terms of passenger demand and/or network interconnections). On the other hand, in the outer zone, this service stops usually everywhere. This approach gives two benefits: a travel time from the stop to the center mostly does not exceed one hour, and the "fast" part of the train path can be easily bundled with long-distance

or freight services. A model of the system split of passengers (between the everywhere stopping regional train and a regional express) was introduced by Vávra and Janoš [27].

Even though the (Integrated) periodic timetable is mostly not suitable for freight trains, the freight operators need a flexible offer of suitable capacity in the railway network. It means both an all-day regular offer of train paths and their flexible connections in nodes, without unnecessary stops, in more directions. Further, if a freight train has to stop (mostly to be overtaken by a faster long-distance train), it should not be in, or before, an uphill section (for the sake of energy saving), and it should not be in a capacity bottleneck, because braking and subsequent acceleration of a freight train secondary consume a scarce capacity – see Fig. 2.

3.2. Segmentation of Train Paths Based on their Periodicity and Regularity

The authors have deliberately chosen a soft methodological approach, albeit with preservation of basic mathematical rules, that is necessary for Integrated Periodic Timetable. These rules are commonly formulated as follows.

The first mathematical rule is a unified period of services. The basic period is 60 min, and all derived periods have to fulfil the following equation:

$$\forall i, j: p_i = 2^k \cdot p_j; \quad i, j, p \in \mathbb{N}; k \in \mathbb{Z}. \quad (1)$$

where i and j and k are indices, and p is a period.

The second rule is the unified symmetry of all periodic train paths (for all pairs of periodic train paths, for all node stations and directions, the difference between the arrival time from the direction A to the station S and the nearest later minute zero, is equal to the time distance between this minute zero, and the nearest departure time from the station S to the direction A for the same periodic train path in the opposite direction).

The third rule is the arc equation:

$$\forall A, B: t_{run, A-B} = \frac{n \cdot p}{2}; \quad n \in \mathbb{N} \quad (2)$$

where A and B are IPT-nodes, and p is a period.

The fourth rule is the cycle equation:

$$\forall A, B, C: t_{run, A-B-C-A} = n \cdot p; \quad n \in \mathbb{N} \quad (3)$$

where A , B and C are IPT-nodes, and p is a period.

This paper, however, deals with capacity coordination within corridors, so the cycle equation has no practical use here. Except for the abovementioned rules, the methodological approach is soft, suitable more for practical management – planning and allocation – of railway capacity by an infrastructure manager (or a capacity allocating body, if it is a separate entity).

In accordance with the EU strategic approach for railway capacity allocation [9] that emphasizes both multi-year stability for longer-time train services and more flexibility for unpredictable freight (and other) train services, and on the basis of requirements described in the sub-chapter 3.1, the authors propose following segmentation of freight train paths. Assuming that at least in Central Europe there prevail, passenger services based on IPT, the authors propose the all-day (approx. 5:00 to 22:00) strictly periodic and symmetrical core of capacity, which should as well include PFTP – both pre-arranged (PaPs) and further allocated, either for the annual timetable or otherwise (Rolling Planning as mentioned in the TTR processes [20] or daily allocation).

Another segment of train paths should be the edge of periodic capacity consumption – train paths that can be partially periodic (e.g., additional peak passenger services) but are not allocated all-day long, and thus can be alternated in off-peak times by other train paths (e.g., freight) if possible. For a detailed mathematical description of partial periodicity in the timetabling, see Caimi et al. [3].

The third segment is fully flexible train path allocation.

The proposed train path segmentation is displayed in Fig. 3.

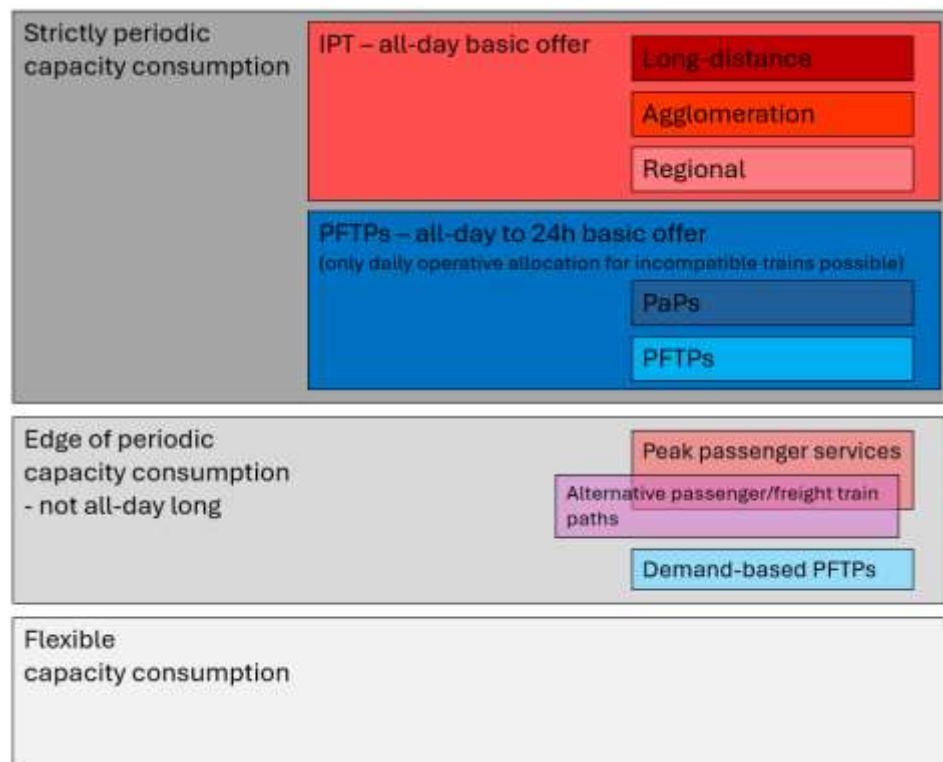


Fig. 3. Proposal for segmentation of train paths, based on their degree of periodicity and regularity

3.3. Tailor-made Local Homogenization of Periodic Train Paths

The aim of the homogenization of the periodic train paths is better capacity utilization – to enable an additional train path between two actual ones, which should help to save traction energy by avoiding the otherwise necessary stop of a freight train. Similarly, a local train path

homogenization can avoid the overtaking of a passenger train by a faster train, that wastes the time of the passengers.

The authors propose the following framework process – a set of measures for the tailor-made local train path homogenization in the sections that emerge as bottlenecks, depending on the type of railway operation and the prevailing (the most frequent) segment of railway transport in a particular section. To the authors' knowledge, this is the first framework process that recommends different measures for train path homogenization in accordance with the type of railway operation. The measures are summarized in Tab. 1 (++ stands for substantial increase of the scheduled runtime, -- stands for reduction of stops of the local trains, + and – stand for slight adjustments of runtime surcharges).

In general, the proposed framework process for tailor-made local train path homogenization can be applied on any line, regardless of the number of tracks, with at least two segments of railway transport whose average speed differs in a particular section. On a single-track line, a full train path homogenization (of long-distance and regional trains, or of passenger trains and PFTPs), complemented by an interposition into a half period, leads to a concentration of crossing (meeting trains in the opposite directions) into only a few stations, and thus to an increase of available capacity for additional (or significantly delayed) trains. For the lines with two or three tracks, the authors estimate that the proposed framework process can bring significant capacity improvements on the lines with a maximum speed of at least 140 km/h (actually regularly utilized by some train segments), which is allowed continuously on the section at least a few tens of kilometers long.

Tab. 1

Proposed framework process (a system of measures) for local train path homogenization

Segment of trains Prevailing trains / type of operation	Long-distance and fast regional passenger trains	Local (agglomeration and/or regional) passenger trains (stopping everywhere)	Freight trains / train paths
Node area – mixed traffic	none	-	none
Hilly terrain, curvy line, mixed traffic (speed limit up to 101approx... 100 km/h)	none	-	none
Mixed traffic, prevailing local trains (speed limit up to 160 km/h)	+	--	++
Mixed traffic, prevailing long- distance trains (speed limit up to 160 km/h)	+	--	-
Single-track, at least 2 segments of railway transport	+	-	-

Freight bypass lines in large node areas	not relevant	not relevant	++
Higher speed, long-distance trains (speed limit 200 to 250 km/h)	none	not relevant	-

3.4. Chosen Railway Lines and Passenger Timetables

For the timetable experiment that should verify the framework approach presented in Tab. 1, two adjoining lines were chosen: Praha - Beroun - Plzeň (Pilsen) and Plzeň - Domažlice - Furth im Wald (Germany). On both lines, partial modernizations are planned – for the first line, a completely new base tunnel between Praha-Smíchov and Beroun stations for mixed long-distance, fast regional and freight traffic for the speed up to 200 km/h is projected. For the second line, partial modernization for the speed up to 200 km/h, that includes doubling of the track, is projected. However, there should remain a single-track section in the middle.

The projected line is schematically illustrated in Fig. 4. The abbreviations of the stations and junctions are explained in Tab. 2. The timetable of passenger trains is taken from the research project Efficient Operational Concept for Rapid Services [4]. Both lines were modeled and the timetable within this project was constructed in the academic/research license of the FBS/iPLAN timetabling software [11]. The same software was used as well for the timetable experiment, that included the construction of a PFTP and slight adjustment of one public transport line of fast trains – R30 – and one public transport line of regional trains – REx40.

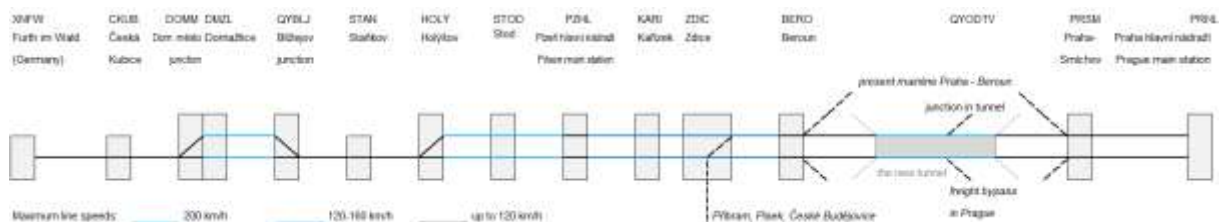


Fig. 4. Layout of the prospectively modernized mainline Praha - Plzeň - Furth im Wald (Germany) with the new tunnel between Praha and Beroun and the modernized sections Plzeň - Holýšov and Blížejev - Domažlice

Tab. 2

Abbreviations of the relevant stations and junctions

Abbreviation	Name	Abbreviation	Name
PRHL	Praha main station	STOD	Stod
PRSM	Praha-Smíchov	HOLY	Holýšov
QYODTV	Tunnel VRT junction	STAN	Staňkov
BERO	Beroun	QYBLJ	Blížejev junction
ZDIC	Zdice	DMZL	Domažlice
KARI	Kařízek	DOMM	Domažlice mesto junction
ROKY	Rokycany	CKUB	Česká Kubice
PZHL	Plzeň main station	XNFW	Furth im Wald

Passenger train paths, especially the long-distance ones, were relatively strictly determined by symmetry times to be achieved in the IPT-nodes. For the express segment (not stopping between Praha and Plzeň), it was the IPT-node Plzeň in the minute 00 (line R32 and regional expresses to Domažlice město) and 30 (line Ex6). The fast train line R30 had to achieve two regional IPT-nodes: Beroun in minute 00 and Rokycany in minute 30. Furthermore, proceeding of all long-distance lines beyond Prague, as designed in the network timetable for the horizon 2050 for the research project Efficient Operational Concept for Rapid Services [4] determined possible time windows for their train paths as well.

Longitudinal and speed profiles of the railway line between Praha and Plzeň are displayed in Fig. 5 and 6. For the railway line to Domažlice, since it is a mix of a present railway line and newly constructed sections, the longitudinal profile is difficult to obtain. The peak of this railway line is in the station Česká Kubice (CKUB).

The runtime surcharges for all passenger public transport lines were chosen within the research project Efficient Operational Concept for Rapid Services [4]. The initial periodic passenger timetables from the abovementioned project are clearly displayed in the form of a netgraph (public transport line scheme with periodic arrival and departure times in the nodes) in Fig. 7. In the Czech Republic, there is right-hand traffic on railways as well, so the arrival and departure times to and from node stations are displayed in this manner. The netgraph clearly shows exact interpositions into the 30-minute period (Ex6+R32, R22+R26 and R30+Rex40 from Praha to Beroun), and the approximate interposition between Ex6 and regional expresses from Plzeň. The times and numbers of stops marked by bold script will be slightly changed in the following timetable experiment, resulting from local homogenization of train paths in bottleneck sections.

For the sake of simplicity, the possible future extension of the P21 public transport line (Nezvěstice - Rokycany) to Plzeň was neglected.

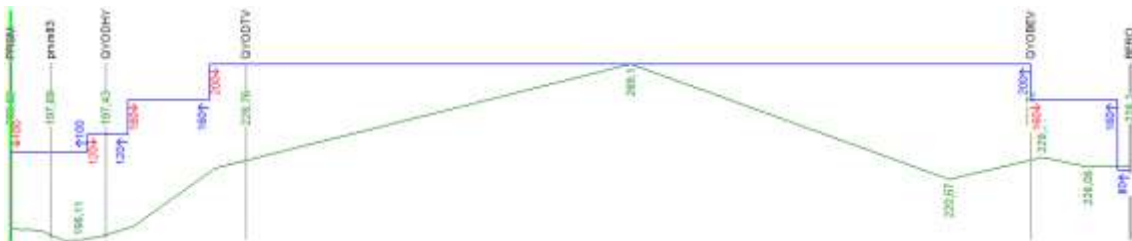


Fig. 5. Longitudinal and speed profile of the prospective new tunnel between Praha and Beroun (data: [4,11])

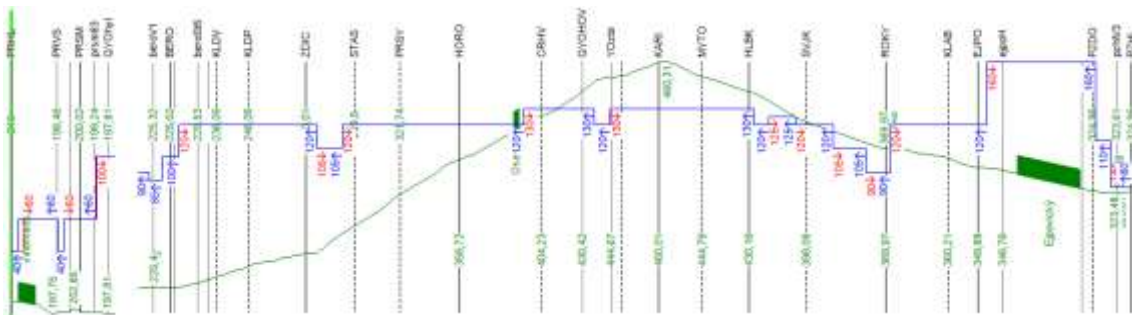


Fig. 6. Longitudinal and speed profile of the already modernized mainline Praha - Plzeň (data: [4,11])

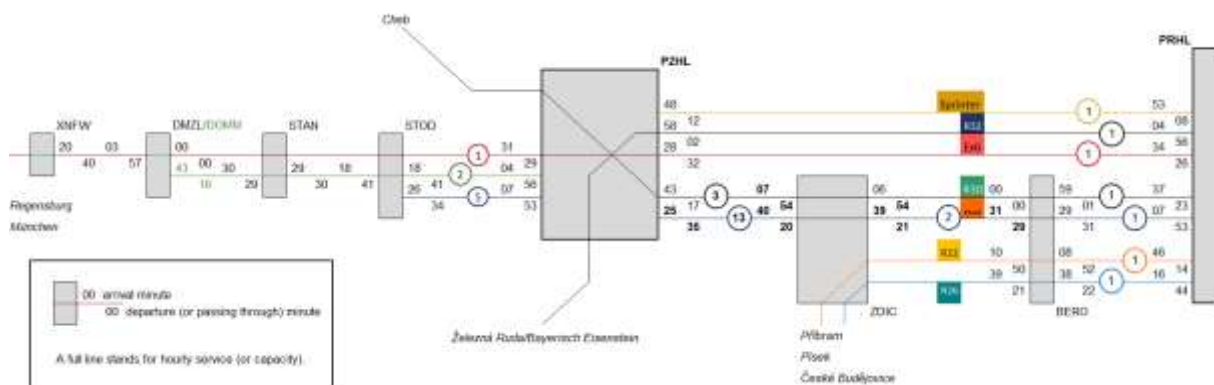


Fig. 7. Netgraph (scheme of periodic passenger services) of the initial timetable on the prospectively modernized mainline Praha - Plzeň - Furth im Wald – adapted from [4]

4. RESULTING SYMMETRICAL PERIODIC TIMETABLE

Due to a lack of available suitable time windows left by the passenger train paths, a pair of stops for overtaking by express trains between Praha and Furth im Wald had to be designed. For the sake of saving the traction energy by freight trains, and for the sake of train path symmetry, the stations for overtaking were chosen so that there was always a small gradient in the relevant direction behind them. According to the modernization project (Update of Feasibility Study Plzeň - Domažlice – CZ/DE border), lengths of the overtaking station tracks should be sufficient: 870 m in Staňkov and approximately 780 m in Stod [24].

For the pair of PFTP, the local homogenization and adjustment of regional train paths were used as follows. Only the direction from Praha to Furth im Wald is described because for the opposite direction, the measures are (almost) zero-symmetrical. The standard runtime surcharge for a PFTP, as used elsewhere in the research project [4], was 10% (of technically minimum runtime, calculated by the iPLAN software [11]).

In the section Praha - Beroun, the runtime surcharge for the PFTP was increased significantly, to fit into a time window after a regional train (regional express line REx40), but before the fast train to Zdice, Písek and České Budějovice (line R26).

Further, up to the station Rokycany, the runtime surcharge for the PFTP was increased significantly as well, for the sake of speed bundling with the (almost everywhere stopping) regional train. The regional train path in this section had to be slightly adjusted by decreasing the runtime surcharge to 6%.

From Rokycany, however, the runtime surcharge for the PFTP was decreased to 3%, so that the freight trains would be able to arrive at Plzeň hl.n. (main station) before the Ex6 express line. The regional train path in this section had to be adjusted as well, at first by decreasing the runtime surcharge to 7%, and then by skipping the stop in Ejpovice. The additional stop there with the R30 public transport line was designed instead.

From Plzeň, the runtime surcharge for the PFTP was decreased to 3%, up to the station Staňkov. Then, to Furth im Wald, standard runtime surcharge of 10% for the PFTP was maintained.

The resulting graphical timetable (train diagram) is displayed in Fig. 8. On the left edge, numbers of line tracks (2 or 1) are clearly graphically marked. The timetable clearly shows the bottleneck sections, where homogenization of passenger train paths was necessary as well: Beroun (BERO) - Hořovice (HORO) and Rokycany (ROKY) - Plzeň main station (PZHL).

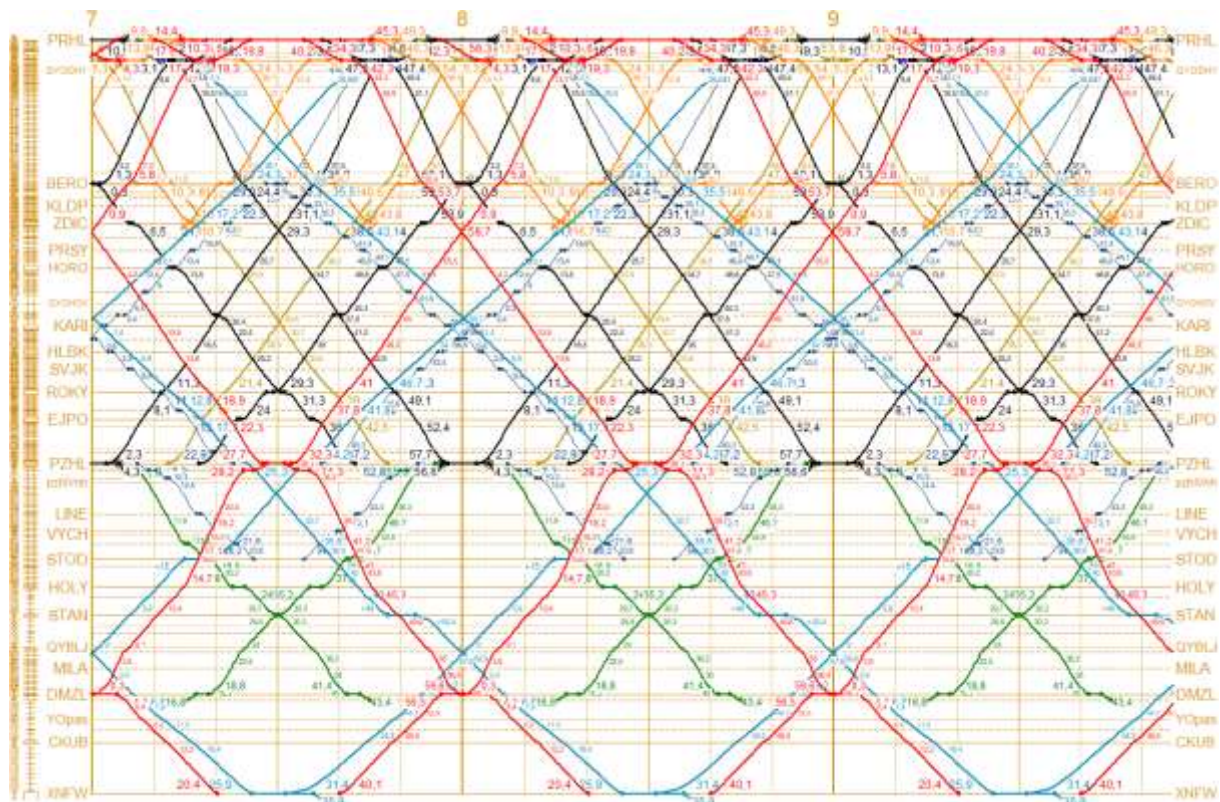


Fig. 8. Proposed graphical timetable for the modernized mainline Praha - Plzeň - Furth im Wald (Germany) with the new tunnel between Praha and Beroun and the modernized sections Plzeň - Holýšov and Blížešov - Domažlice [4]

Tab. 3 shows runtime surcharges by section and for the direction there/back for all periodic train paths in the resulting timetable, except the lines R26 and R32, which were neglected since they occur on a relatively short section. For the proposed pair of PFTP, surcharges were chosen selectively, as proposed above in the sub-chapter 3.3. So, between Rokycany and Stod, the freight train has to run at full speed – 100 km/h, because only a 3% runtime surcharge has been left. For such a distant time horizon as 2050, the authors anticipate automatic Movement Authority for a train and real-time automatic dispatching information for all locomotive drivers even in the Czech Republic, so, in most cases, the driver would be required only to slow down, but not to stop the train fully.

The resulting periodic train paths (PFTPs are displayed in turquoise/light blue) are clearly illustrated in Fig. 9, with the help of the netgraph – a scheme of public transport lines (and PFTPs), where the single solid line stands for hourly service or available capacity (in the case of PFTPs). The departure minutes only by the PFTPs stand for passing through the station without stopping in the particular minute.

The times marked by bold script were slightly changed in the following timetable experiment, as a result of local homogenization of train paths in bottleneck sections (compare with Fig. 7).

Tab. 3

Runtime surcharges of periodic train paths by section (in percents of technically minimum runtime) direction there/back from/to the particular station/junction

From/to the station (junction)	Ex6	R32	Sprinter	REx40	R30	RE PZHL-DOM M	Regio PZHL-STOD	PFTP
PRHL	5/5	5/5	5/5	5/5	8/8			
PRSM/QYODTV	9/9	9/9	13/13	8/8	8/8			8/5
BERO	10/8	7/7	13/13	6/6	8/7			36/30
ZDIC	10/8	7/7	13/13	6/6	8/7			24/30
ROKY	10/8	7/7	13/13	7/7	8/8			3/3
PZHL	9/9					7/7	7/7	3/3
STOD	9/9					7/7		3/3
STAN	9/9					7/7		10/10
DMZL/DOMM	6/6							10/10

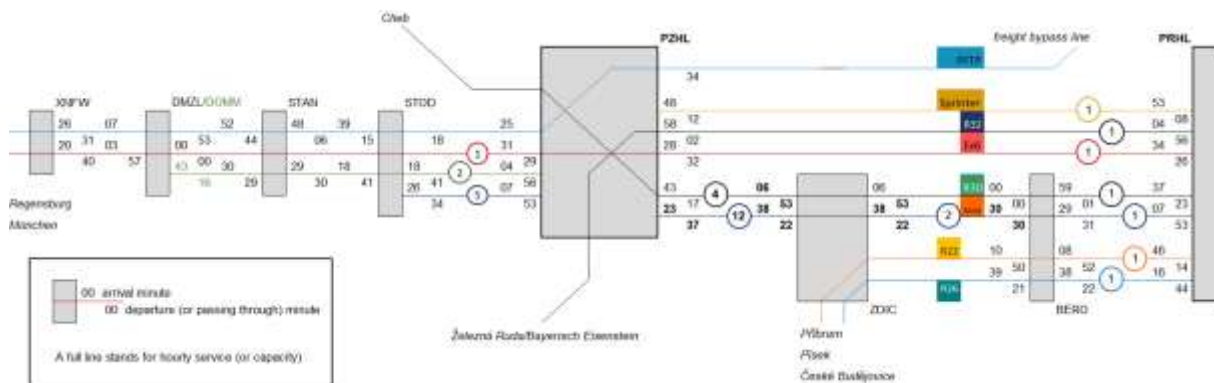


Fig. 9. A proposed netgraph (scheme of periodic passenger services and freight capacity - PFTPs) on the prospectively modernized mainline Praha - Plzeň - Furth im Wald adapted from Fig. 6

5. DISCUSSION AND CONCLUSIONS

To the authors' knowledge, no such holistic approach for such detailed, tailor-made mutual coordination of train paths, considering a proposed symmetrical periodic core (IPT + PFTPs), but soft enough to be universally implementable and to maintain flexibility in the allocation of rest capacity, has been published so far. Because of prevailing strictly mathematical timetabling research with several optimization criteria and necessary simplifications of the real timetables and capacity allocation, there remains a considerable gap between advanced railway timetabling and operation research and practical railway capacity allocation process. The deliberately chosen soft approach (nevertheless respecting mathematical preconditions of IPT), that is based both on previous research and the original authors' findings, is therefore directly applicable for infrastructure managers and other capacity allocating bodies, including the European Network of Infrastructure Managers (ENIM), that should be established by

the proposed related Regulation of the European Parliament and of the Council 2023/0271(COD) on the use of railway infrastructure capacity in the single European railway area [9].

The above introduced timetable experiment has clearly shown that with only slight adjustment of (regional) passenger periodic train paths (1 to 2 minutes and one skipped stop) and with feasible distribution of runtime surcharges, a pair of PFTP's with only one overtaking on an approximately 150 km long, partially single-track, rail corridor with busy passenger traffic, can be designed.

In the present Czech railway network, the authors recommend considering the application of the above presented framework process at least on following sections of present Czech railway lines: Praha - (Poříčany) - Kolín - Pardubice - Česká Třebová - Olomouc - Ostrava, Praha - Benešov, Brno - Břeclav and single-track lines Opava východ - Ostrava Svinov, Nymburk - Mladá Boleslav and Bakov nad Jizerou - Česká Lípa - Liberec. Further, the authors recommend considering the application of the above presented framework process on the following future Czech new or significantly modernized railway lines: Mladá Boleslav - Liberec (a planned new line), new base tunnels Litoměřice - Ústí nad Labem and Ústí nad Labem - Heidenau with planned mixed traffic of (high-speed) long-distance passenger trains and freight trains. However, in such tunnels, any planned slowing of high-speed trains is out of question.

Due to the complexity of the proposed, highly iterative framework process, and the considerable length of the mainline used in the timetabling experiment, the authors had to neglect the assessment of timetable stability and robustness. In general, a periodic timetable leads to locally high consumption of the capacity, or tight scheduling of some trains after each other, with almost zero buffer time (margin) above the minimum headway between subsequent trains. Thus, the authors strongly recommend verification of timetable feasibility for busy mainlines or nodes by suitable simulation tools before their practical implementation – see for instance Čamaj et al. [5].

As part of follow-up research, the authors recommend focusing on the analysis and practical verification of the accuracy of guiding freight trains into a conflict-free time slot, both during timetable design and during operational traffic control. Unlike passenger trains [2,29], freight trains require a longer reaction time – for example, for the braking system – due to their greater length and weight.

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