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Planning of railway infrastructure development in combination with the construction of an integrated periodic train timetable

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Abstract. The article analyses the importance of combining rail infrastructure development planning with the introduction of integrated periodic timetables. In the context of rising investment and operating costs for transport infrastructure, adequate planning is crucial for the optimal use of public funds. The article aims to show how railway infrastructure development planning can be effectively linked to implementing integrated periodic timetables, with examples from Germany and Austria. The author analyses studies from these countries to show how an integrated periodic timetable can improve the attractiveness of rail transport by ensuring regularity and ease of interchange. The studies provide a comparison of different timetables and their impact on the operation of railway systems. Case studies from Germany and Austria were also analyzed, where theoretical assumptions were applied in practice. In both cases, timetable construction and infrastructure development planning were iterative processes with several steps. Extensive consultation processes with industry stakeholders and central and local authorities played an important role. The results show that implementing an integrated periodic timetable reduces journey times and increases passenger numbers, as observed especially in Switzerland in the 'Bahn 2000' project. The strategic analyses focused on identifying necessary infrastructure investments, particularly eliminating and preventing bottlenecks on the railway network. The article's conclusions suggest that infrastructure development planning and constructing a strategic integrated periodic timetable is vital to optimizing railway systems and increasing their attractiveness and competitiveness. An equivalent methodology should be used in railway infrastructure development planning.

Keywords: railway infrastructure, integrated periodic timetable, transport planning, railway development, capacity of the railway network

1. Introduction

Transport infrastructure development involves huge capital expenditure followed by high operating costs. Generally, these funds are public money. Therefore, their expenditure should be as well thought out and planned as possible. The specific nature of rail

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infrastructure and the organization of rail traffic means that the ability to create a transport offer is closely linked to the available railway infrastructure. Effectively linking these two aspects is a significant planning challenge.

At the same time, for rail to be the mode of choice for travelers, it is necessary, among other things, to create an attractive timetable that meets passengers' needs. From this point of view, one of the most advantageous types of timetables is the integrated periodic timetable (IPT). It is easy for passengers to remember thanks to the repeated departure times. The well-thought-out and planned integration of different train paths to enable convenient interchanges increases comfort and reduces overall rail travel time.

Exciting approaches to the organization of rail traffic in the context of the development of rail infrastructure and, therefore, the introduction of an IPT in combination with the planning of new investments have been introduced by some European countries such as Switzerland, Germany, and Austria. For example, the periodic timetable was first introduced in Switzerland in 1982. This was followed in 1987 by the "Bahn 2000" project to expand the Swiss rail network. The aim of this project was, among other objectives, to increase the railway network's capacity, introduce half-hourly frequencies on the main railway lines, and reduce journey lengths, including transfer times. This required a series of investments in railway infrastructure.

The project was implemented in several phases, as more sections of railway lines were opened to the traffic. The first stage, consisting of 130 projects, was completed in December 2004. According to data [17], long-distance passenger transport volumes increased by almost 30% between 1996 and 2005 and 7% in 2004-2005 alone. Significant growth was also achieved in regional transport.

The success of the "Bahn 2000" project also depended on factors not directly related to IPT but essential for the attractiveness of rail transport. These factors include the tariff system or the replacement of rolling stock.

To give further insight into this problem, the author describes in detail the introduction of an IPT in connection with the development of railway investments in the example of two countries, Germany and Austria. Therefore, the article aims to present a method of planning the development of railway infrastructure based on an IPT using the examples of studies carried out in Germany and Austria. For the analysis, the article is divided into five parts. The first section introduces the topic and the article's structure. Section 2 presents selected issues related to the design of periodic timetables and a more comprehensive literature review. Sections 3 and 4 discuss the studies developed in Germany and Austria, respectively. A discussion of the results and conclusions is include in the last section.

2. Selected aspects of the construction of regular train timetables

2.1. Introductory remarks

A train timetable is a plan according to which train runs are to take place on a given railway network or part of it during the time it is in force [25]. The classification of railway timetables can be made based on various aspects, such as, for example, the duration of validity, the form of presentation, the purpose, the process of construction by railway infrastructure managers [7], and the regularity. This last criterion is crucial from the passenger's point of view and the quality of the transport service. Considering the above, the following types of timetables can be distinguished [21]:

1) Ordinary (with independent routes) – a timetable that does not consider the regular periodic intervals between trains. Routes are individually planned, often leading to irregular departure and arrival times. This type of timetable may be less predictable but allows greater flexibility in adapting the transport offer to changing demand.
2) Periodic asymmetric – a timetable where trains run at regular intervals, but these intervals may vary according to the direction of travel or time of day. This type of timetable can better adapt services to changing traffic volumes, such as during peak or off-peak hours. Although they provide some regularity, the lack of symmetry can introduce complications in planning transfers.
3) Periodic symmetric – a timetable with equal intervals between trains running in both directions. This type of timetable is easy for passengers to remember because the departure and arrival times are the same at each hour. Symmetry in scheduling also facilitates the organization of transfers and coordination with other modes of transport.
4) Periodic integrated – a periodic symmetric timetable that also considers the optimization of connections with other lines and modes of transport. In practice, this means that trains and different modes of transport are coordinated to minimize waiting times for transfers, improving travel convenience.

As seen from the presented classification of timetables, only IPT considers optimizing connections with other lines and modes of transport. This means that this type of timetable is strongly passenger (customer) oriented. Therefore, this article will analyze the IPT in more detail.

2.2. Integrated periodic train timetable

An IPT is a timetable with the following essential characteristics:

- integrated – integrates different train lines (transport lines) at specific nodes (hub stations), providing transfer possibilities in a coordinated and planned manner,
- periodic – train departures take place at equal intervals (e.g., every 30 minutes, 1 or 2 hours).

Integration takes place at node stations, understood as nodes from the point of view of the timetable rather than their function on the railway network. The model layout realizes it by the almost simultaneous arrival of trains from different directions at the station. The stopping times of these trains are primarily determined by providing adequate transfer times. Departures from the interchange station also occur as simultaneously as possible.

This situation is only possible at larger interchange stations with extensive track systems where several railway lines meet. In the case of smaller stations, trains of a lower category (e.g., regional) arrive at the station first. They are also the last to depart. The shortest stopping times are expected for higher category trains – e.g., long-distance (Fig. 1.).

In addition, a periodic timetable can be characterized by additional symmetry. As defined by the author in the article [21], the train paths of all lines are characterized by symmetry about the same axis, e.g., a full hour. Therefore, the position of one train path determines the position of the other paths in a given direction and the paths in the opposite direction. In the case of a symmetrical timetable at node stations, train arrivals occur n minutes before the hour, representing the axis of symmetry (e.g., a full hour or 30 minutes after a full hour), while departures occur n minutes after that hour.

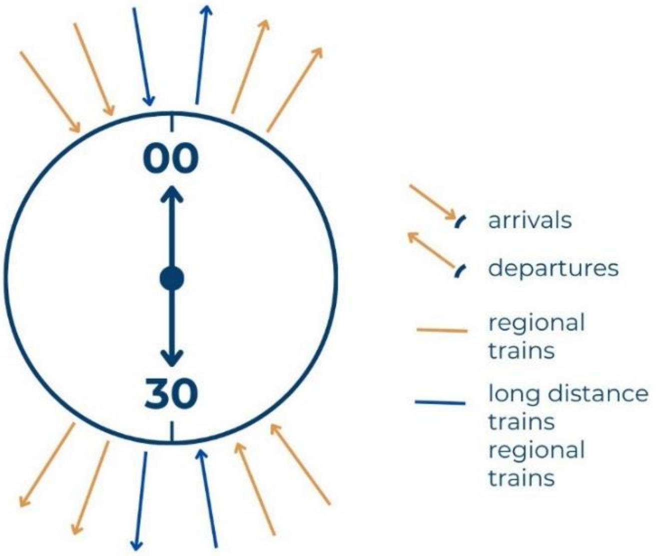

Fig. 1. The idea of IPTT (source: own elaboration)

The optimum journey times between node stations are fundamental to the periodic symmetric timetable. For an hourly cycle, the optimum times between node stations are under 30 minutes or a multiple of this value. These times include the travel time between nodes and the necessary stopping time at the station related to passenger transfers and all operational activities (Fig. 2.).

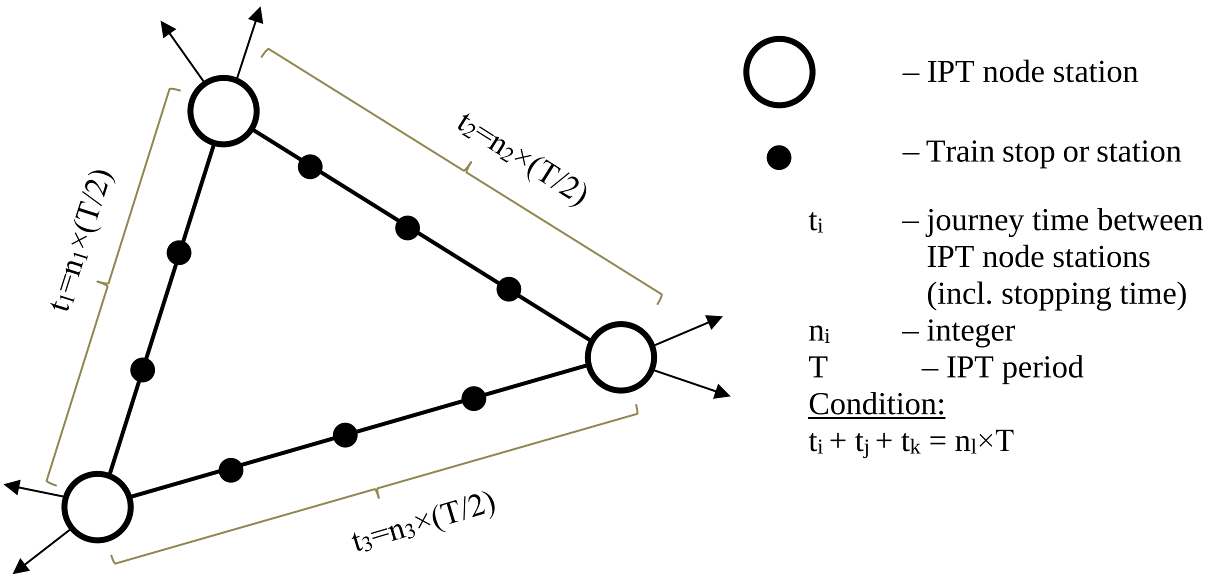

Fig. 2. Principle of the nodal network model for periodic timetables (source: own elaboration based on [24])

3. Literature review

IPTs are an essential factor in optimizing and improving attractiveness and competitiveness, as well as increasing the efficiency of rail transport systems. They are the subject of numerous research studies, which, in particular, indicate the advantages of such timetables [15]. Their implementation increases passenger satisfaction and facilitates journey planning thanks to easy-to-remember departure and arrival times. They contribute to an increase in demand for transport [5]. According to a transport model for selected railway lines in the UK, introducing such timetables could increase passenger numbers by up to 77%. Another effect of introducing IPT is to minimize transfer times and improve the attractiveness of public transport, including rail transport.

They can be introduced, for example, only on a particular line, in a specific transport segment, or on the scale of a more extensive railway network. The article's authors [4] compared different operational concepts of high-speed lines in several European countries, pointing out the widespread use of IPT and recommending the implementation of such a timetable on Czech high-speed lines. The approach using nodal points of the transport and logistics network is also used in freight transport [19].

A similar proposal for implementing a periodic timetable was presented for several railway lines in the Karlovy Vary region in the Czech Republic [9]. The social and economic role of public transport and the need to reduce travel times, including transfer times, for the attractiveness of this system was emphasized. It is also reflected in the method of evaluating public transport systems, including timetables on a regional scale [20].

Periodic timetables can also contribute to reducing CO2 emissions. This effect can be achieved by increasing the share of rail transport in total passenger traffic [15,31] and reducing traction energy consumption. A method for adjusting timetables to consider increased traction energy recovery is presented in [18]. Additionally, implementing energy storage in rail transport systems may have great potential [28].

Attempts are also being made to automate and optimize the construction of periodic timetables. For example, a mixed integer linear programming (MILP) approach was used to develop a timetable for a section of the Dutch rail network [2]. A similar approach was used in a study of the busiest central section of the Brussels railway node [3]. The proposed method creates a periodic timetable and proposes specific routes for the assumed track layout. The algorithm optimizes infrastructure occupancy and resilience to delays. In the first step, the model assigns a path for each train to minimize infrastructure occupancy without considering the timetable. Then, a second model responsible for timetable construction assigns infrastructure occupation times to each train. The authors note that in this approach, the occupancy of the railway infrastructure is analyzed before the timetable is constructed. The timetable developed using this method improved delay resilience by 11% compared to the reference timetable produced by the Belgian railway infrastructure management company. Another model based on the developed SMT (Satisfiability Module Theories)-Solver tool [11] was also used to construct a timetable based on a mesoscopic infrastructure model.

The optimization and coordination of timetables in complex railway networks require sophisticated modeling and optimization tools. In the literature, there are proposals for approaches that do not require the development of train timetables, e.g., using a queueing network model that also allows the calculation of parameters concerning, for example, potential delays [10]. In another approach [14], the capacity of the railway network is determined, also without a developed timetable. Two methods are used: an exact branch-and-bound algorithm and tabu search.

A hybrid approach to periodic timetables is also proposed in the literature, combining the advantages of periodic and non-periodic timetables to increase the flexibility and sustainability of railway systems [27].

A significant barrier to implementing IPT might be the high investment costs. At the same time, independent of the type of timetable, the costs of building and upgrading the railway infrastructure are very high, so they should be well-planned. For this reason, it seems necessary to develop strategic timetables [26], which differ from operational timetables due to their specific characteristics. Instead of introducing direct constraints on the synchronization between train runs (as is the practice in most timetable models), the authors proposed to include the departure time at the origin station as a function of the destination to ensure the periodic nature of the services.

However, to some extent, the research gap is the strategic planning of railway infrastructure development. There are different approaches to planning infrastructure development. They can use transport models [13], focus on environmental effects and the reduction of pollution and greenhouse gases [12], or highlight issues related to the organization of rail traffic. In a developed model [29], the authors analyzed how the existing railway infrastructure could be upgraded to reduce the overall delay of existing and scheduled trains while minimizing the costs incurred. Another paper [6] formulated the problem of designing a rail network under capacity constraints and uncertain timetables, also paying particular attention to the reliability and resilience of the transport system.

The problem is formulated similarly in [30] – the aim is to find a rail infrastructure network that meets given traffic (line capacity) requirements at the lowest possible total design cost. The infrastructure is represented by a network consisting of nodes and arches. The nodes represent stations, and the arches represent railway lines between stations. The demand is represented by traffic flows consisting of the number of trains, source nodes, and end nodes. To simplify the calculations, the stations are assumed to have unlimited capacity. The network topology and capacity of the individual lines are therefore designed.

In addition, maintenance costs and capacity are factors worth considering when planning rail infrastructure development [8]. These could also be considered more widely in the early design phases. There are also examples of fuzzy logic as a decision-support tool in transport development planning [16], making it possible to consider criteria that are difficult to describe with precise indicators.

The literature review shows that periodic integrated timetables have the potential to improve the efficiency and attractiveness of rail transport. Studies show benefits in better coordination of transfers, optimization of resources, and reduction of emissions.

4. Analysis of railway infrastructure development in Germany

4.1. General remarks

The railway timetable in Germany has already been implemented mainly as a periodic timetable, while on a regional scale, it also has the character of an integrated timetable. To implement a federal IPT, the German Ministry of Infrastructure contracted a pre-feasibility study in 2014. It demonstrated the feasibility of such a timetable.

Consequently, a model timetable covering all long-distance and regional train services and the so-called "system freight services" (discussed in more detail later in this article) was contracted in 2016. The study is known as "Deutschlandtakt" ("German tact") [1]. One of the results of this study is the so-called 'target timetable after 2030'. This concept for passenger and freight railway services is based on an IPT.

Within the framework of this study, a list of necessary investment tasks for the construction, enhancement, or modernization of the railway transport infrastructure was analytically determined based on the target timetable. This reflects the principle: "First the timetable, then the construction and expansion of new railway infrastructure".

It is assumed that implementing this concept will improve the accessibility of the railway system, increase the offer of rail passenger transport, reduce journey times and travel times through coordinated transfer connections, reduce freight transport times, and improve the competitiveness of rail freight relative to road transport.

4.2. Basis for the study, background data and assumptions

The 'Deutschlandtakt' timetable is a timetable that takes into account many factors that contribute to the attractiveness of the German rail service. This includes, in particular, good train connectivity for passengers using different commuting zones and competitive travel times to destinations, enabling them to continue their journey by other means of transport. The starting point for the analysis was the existing infrastructure of the federal infrastructure administrator (DB Netz AG) and selected non-federal railways relevant to the entire network, the investment projects of the government's railway program 2030 and the federal states, as well as other smaller tasks implemented or planned by the railway infrastructure administrators.

Regarding traffic, the starting point was the passenger transport offer under the Government Railway Programme 2030, the long-term concept of the regional transport offers in accordance with the declarations of the federal states, and the concepts of the railway operators and industry organizations. The entire transport offer in freight and passenger transport is arranged in so-called system lines. The core line network partially included individual train connections (e.g., the fastest express trains or additional round-weekend supplementary trains). Trains not included in this regular network, such as those to tourist destinations, were not included in the developed timetable.

In principle, the study does not define specific technical solutions for train control systems, as planning takes place at the level of macroscopic analysis. For routes with exceptionally high rail traffic volumes, the requirements for signaling technology were formulated in terms of the necessary minimum follow-up times. If an increase in the capacity of a line is required in the target timetable, such tasks are included in the list of investments.

4.3. Supply and demand determinants of the concept

The development of the Deutschlandtakt target timetable was an iterative process. The entire process included three main iterations presented to the public: October 2018, May

2019, and June 2020. The primary objective was to develop a nationwide IPT. The following features characterize the concept presented:

– fixed line frequencies,
– half-hourly or 15-minute frequencies where lines overlap in corridors with high traffic volumes (Fig. 3.),
– a relatively constant service throughout the day,
– transfers with identical hourly or half-hourly times and clear directional connections at major nodes,
– short transfer times for interchange connections with high traffic volumes,
– repetitive traffic and technical-operational schemes for rail operators.

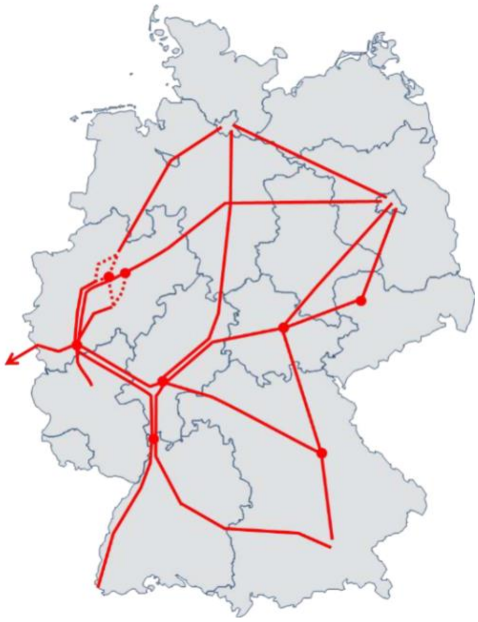

Fig. 3. Corridors with 30 min frequency in long-distance traffic (Source: [29])

The proposed concept of an IPT Deutschlandtakt assumed the achievement of three essential milestones:

– timetable to the Government Railway Programme 2030,
– complementary studies for the main railway nodes according to the Government Railway Programme 2030,
– target timetable Deutschlandtakt (2030+) realized in three iterations.

A detailed description of the individual project milestones is presented in Table 1, while Table 2 shows additional results from the second and third iterations.

4.4. Methodological conditions for the construction of the passenger train timetable

The construction of the target timetable concept was carried out based on system routes based on the characteristics of the model trains. The system routes are used to determine the necessary infrastructure changes. They can be implemented in stages in the operational timetable once the necessary investment tasks have been completed. The target timetable defines the investment tasks and does not constitute an operational timetable.

Table 1. Deutschlandtakt project milestones

Milestones	Description
Timetable for the government's rail programme 2030	Objective: Develop a timetable for the Government's Railway Programme 2030 based on planned investment projects to visualise timetable opportunities resulting from planned infrastructure projects and the traffic forecast 2030. This timetable is the baseline for the construction of the target timetable.
Supplementary studies for major rail nodes under the Government's Railway Programme 2030	Objective: To detail the scope of the investment projects included in the government's railway programme 2030 in several major nodes (Hamburg, Hanover, Cologne, Frankfurt am Main, Mannheim and Munich) – Completion of the 2030 timetable with additional regional and local connections declared by the federal states. – Adopt assumptions for freight train lines and compare them with existing forecasts. – Developing models and carrying out microscopic simulations of rail traffic. – Identification of bottlenecks using macroscopic and microscopic simulations with a proposal of investment tasks to eliminate them.
Target timetable Deutschlandtakt (2030+) in three iterations, with the 1st iteration (October 2018)	Objective: Further development and optimisation of railway nodes for timetable 2030 – Supply-oriented adjustment of the transport offer – Additional infrastructure tasks, – Recommendations resulting from previous expert studies, – Feedback from the federal states, – Feedback from railway operators.

Source: own elaboration based on [1]

Table 2. Implementation of the second and third iteration of the project

Phase	Description
Target timetable Deutschlandtakt (2030+), 2nd iteration (May 2019)	The second iteration of the Deutschlandtakt timetable aimed at defining investment projects to improve the quality of passenger and freight transport, considering the results of consultations on the transport offer with the industry, freight and passenger operators, and the federal states.
Preliminary economic assessment	The implementation of the concept of the Deutschlandtakt project also involved the identification of infrastructure tasks that may not be economically efficient (taking passenger and freight traffic into account), whereby: – Examination of whether the transport offer concept corresponds to demand (comparison of projected passenger flows with the number of seats in long-distance traffic). – Identifying elements of the transport offer that are not balanced by increased passenger flows.
Target timetable Deutschlandtakt (2030+), 3rd iteration (June 2020)	Consideration of additional lines that can be operated by more economical (and slower) rolling stock: – 3rd iteration based on a participatory process on the assumptions of the transport offer – Considering the results of the preliminary economic assessment.
Evaluation	The evaluation was developed based on the Traffic Forecast 2030 and under the current evaluation methodology for the government's rail programe.

Source: own elaboration based on [1]

The first planning step was to analyze the shapes of the railway nodes and the dependencies in journey times in the 2030 timetable and to analytically identify the railway line sections and node elements that do not allow the traffic assumptions to be implemented. The specific work stages in the context of creating an IPT were as follows:

- analysis of journey times between node stations based on the railway network 2030 (Fig. 4.),
- determination of the nodes of the network based on the travel times between the nodes for long-distance and regional transport, with priority given to relations served with low frequency to optimize interchange connections,
- further development of the transport offer on routes with higher frequencies,
- planning the shape of the railway network,
- creation of connections,
- definition of transfer links,
- identification of infrastructure bottlenecks or time constraints resulting from the timetable concept,
- determination of infrastructure needs for the target timetable.

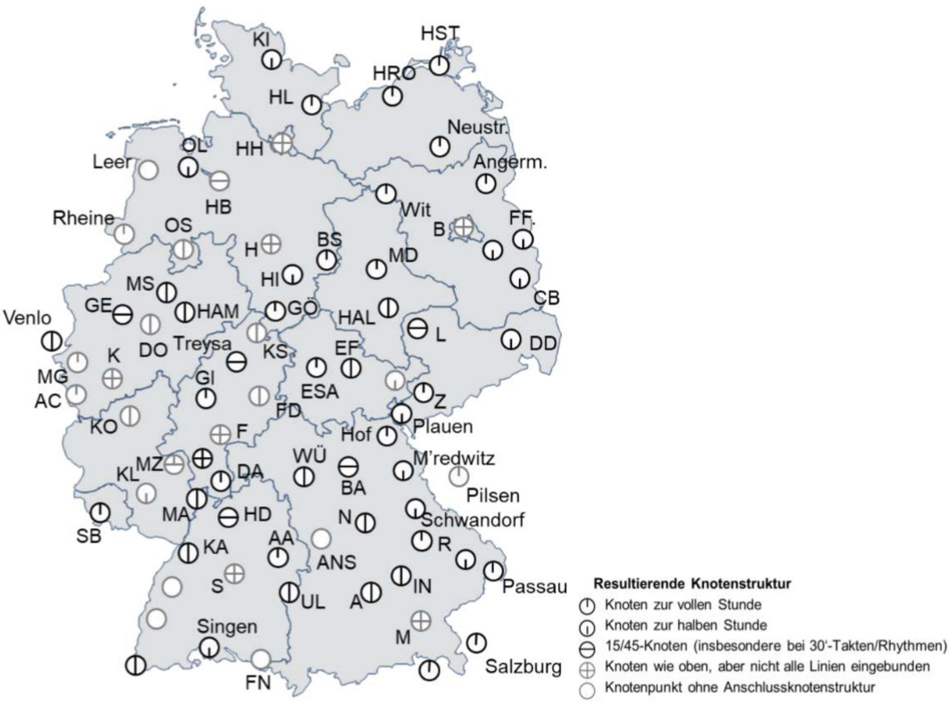

Fig. 4. Location of nodes in the target timetable (Source: [1])

4.5. Methodological conditions for the construction of the freight train timetable

The Deutschlandtakt intends to enable the further development of freight transport according to the traffic forecast for 2030. Freight transport is an equal part of the study and is planned at the same level of detail as passenger transport. However, the procedure for freight transport differs from that for passenger transport.

The study also included freight transport by defining system freight train lines. These lines were considered, assuming a frequency of one hour or two hours. The system lines are not assigned to a specific rail operator. They are just a representation of the traffic forecast. The limit for which a link was considered as a system line was 10 trains/day (5 trains/day/direction). It was assumed that the planned capacity reserves would be sufficient for traffic volumes below this value and that lower volumes were irrelevant for network dimensioning.

The following characteristics were assumed for freight trains: model freight train: Br 185, weight 2000 tonnes, maximum speed 100 km/h, length 740 meters. Deviations from these parameters were also assumed on a case-by-case basis (e.g., a 120 km/h speed was assumed on high-speed lines). The characteristics of the example trains reflect rather conservative assumptions. The selected parameters reflect a relatively heavy train, and the selected maximum speed applies to the most commonly used freight trainsets. This conservative approach is justified as it dimensions the rail network on the safe side.

In addition, the study also considers elements such as:

– the development of a freight network with 2-hourly intervals between selected railway stations with a maximum journey time of 3.5 – 4 hours,
– addition of short-distance freight trains to adequately cover large local freight traffic,
– the addition of "flexible train lines" that go beyond the forecast and allow further growth in freight traffic.

4.6. Identification of investment projects

The timetable is central to the medium- and long-term railway network expansion strategy. Bottlenecks and elements of the network requiring restructuring are defined based on planned services, passenger flows, and stakeholder expectations, considering the following factors:

– traffic conflicts (e.g., crossing train runs, insufficient train intervals, insufficient capacity on lines and in nodes),
– travel time deficits needed to connect nodes,
– remaining bottlenecks in the traffic organization.

To eliminate the identified bottlenecks, the necessary investment tasks have been defined to meet the transport goals defined in the target timetable. These include the following categories:

– directly related to regional and agglomeration traffic to implement the timetable or improve capacity,
– related to regional and agglomeration traffic to separate regional and long-distance traffic in railway nodes,
– directly related to long-distance and freight traffic to increase capacity or reduce travel times
– investment tasks related to freight traffic are necessary for traffic exceeding the forecast 2030 (for the so-called "flexible train line").

The list of investment tasks was not intended to be a complete list of all possible and sensible investments in the rail network in Germany. The analysis did not include Investment tasks concerning freight stations, intermodal terminals, technical stations, or changes to the infrastructure of railway stations and stops.

4.7. Principles of economic assessment for identifying economically inefficient lines

A preliminary economic assessment followed the second iteration. It aimed to identify non-economic elements of the transport offer and infrastructure tasks. It consisted of three stages:

1) Examination of whether the concept of the transport offer corresponds to the forecast traffic flows (comparison of demand with the offered number of seats in long-distance traffic, Fig. 5.).
2) Identifying sections with increased service offers that are not balanced by increased demand.
3) Identification of uneconomic infrastructure tasks for passenger and freight traffic.

The preliminary economic assessment results were used to optimize the transport offer further. However, no cost-benefit analysis was carried out, and the economic efficiency of individual investment tasks was not examined.

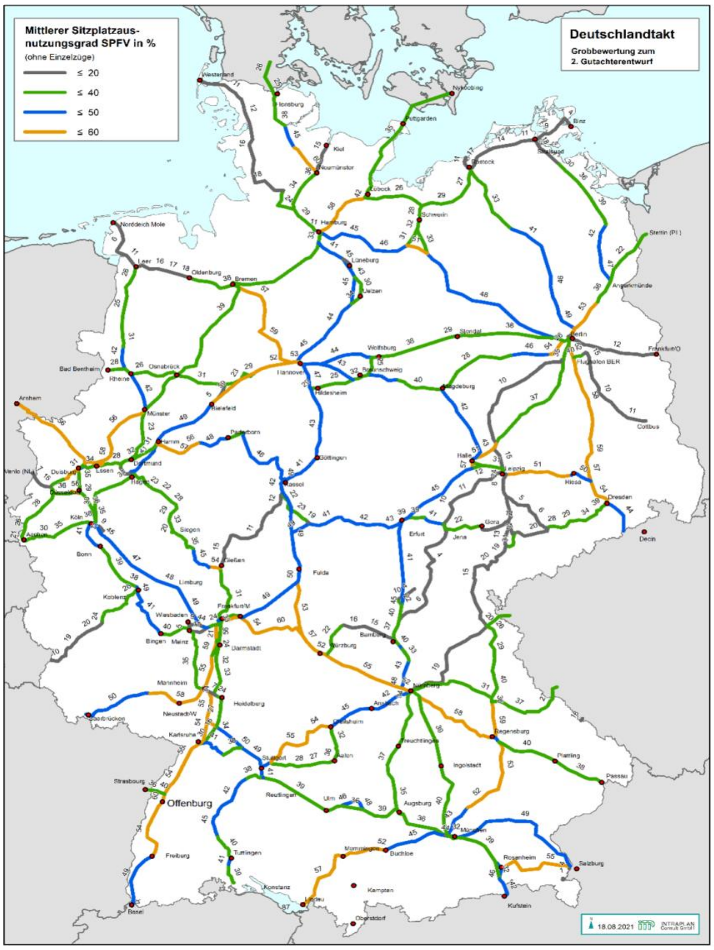

Fig. 5. Average seat occupancy rate in long-distance traffic in % (Source: [1])

The preliminary economic assessment results, following stakeholder consultation, were considered in the next iteration of the analysis. Where a line was identified as uneconomic or under-demanded, it was agreed that it was retained if it met at least one of the following:

- the line (or part of it) is currently in operation,
- line can be provided on existing or already built infrastructure and does not result in the need to build any new infrastructure,
- the line can be offered soon on a self-sufficient basis,
- line runs at the edge of the network for traffic reaching border areas,
- the line is cross-border,
- the line already operates in a combined model (both long-distance and regional trains).

5. Analysis of railway infrastructure development in Austria

5.1. General remarks

Austria has also defined a long-term strategy for developing the railway infrastructure. This study has been named "Target Network 2040" (German: "Zielnetz 2040") [32] and includes recommended investments for the further development of the railway network in a perspective of 15 – 20 years. The proposal was prepared by experts from the Federal Ministry for Climate Protection, ÖBB-Infrastruktur AG, the railway infrastructure manager, and the consultancy and advisory company SCHIG mbH. It is based on Austria's National Mobility Strategy 2030 [22]. Thanks to an extensive consultation process, it also considers the expectations of a wide range of stakeholders, such as the federal states and rail industry organizations. Also, in this strategic study, the basis for infrastructure development planning was the IPT. It should be noted that this study is a continuation and next phase of the existing strategy – with a horizon of 2025.

5.2. Basis for the study, background data and assumptions

The development of the Target Network 2040 is based on the Target Network 2025+, the relevant legal conditions and transport policy objectives, general network-related analyses, studies, and forecasts. The strategy is a supply-focused approach to developing the Austrian rail network in the 2040 perspective. The investment projects identified within this strategy are based on the concept of an assumed transport offer.

The design of the transport offer is based on a system of passenger and freight train lines and an assumed periodic timetable. Much of the data required for this strategy document is determined using a transport model. The passenger and freight transport models are based on the "Austrian Transport Mode". The transport offer and train services are defined based on transport targets and projected market development. This allows for determining the number of system train paths per hour and the direction for each market segment.

5.3. Organisational conditions for an integrated periodic timetable

As part of the "Target Network 204" development, a nodal network model for an IPT was defined with the most important nodes on the main national and international transport axes

(Fig. 6.). The model is an updated version developed for the 2025 perspective. It is an essential basis for further developing the service concept in passenger transport.

The basic layer of the Austrian IPT is long-distance rail transport, with regional and local transport coordinated at nodes. Particular attention is paid to optimizing nodes to achieve competitive total journey times for public transport. Since the priority is to combine the different modes of public transport in the best possible way and to reduce transfer times throughout the transport network, the main benefits are obtained at nodes in the transfer relationships. At the same time, the travel times of direct connections in domestic long-distance and international traffic are also reduced.

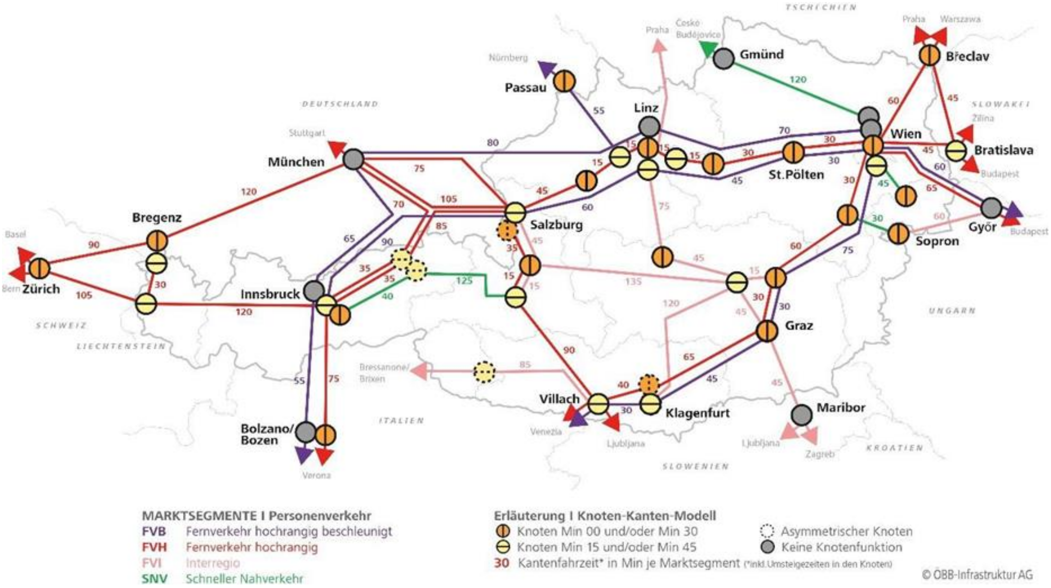

Fig. 6. Nodal network model for the integrated periodic timetable (Source: [32])

5.4. Service concept for passenger and freight transport

The target transport offer for passenger and freight transport was defined as system train lines. Their number per hour and direction for each market segment are presented as frequency maps assigned to individual railway lines. It forms the basis for determining the capacity requirements of the railway infrastructure.

The key assumption for long-distance passenger transport in the national IPT is expanding the transport offer and optimizing transfers at important transport nodes. At least one system train per hour and direction is planned between these nodes and regional centers as a basic service on national lines. On lines with high demand and competitive travel times compared to the car, a density of up to 2 system train routes per hour and direction is assumed for long-distance traffic. Along the European corridors, traffic is supplemented by international lines connecting important European rail nodes in neighboring countries. At least one system train route per hour and direction in international long-distance traffic is assumed, with appropriate densification depending on the relation.

Analogous to passenger traffic, system train paths for freight trains were defined and considered when dimensioning the railway infrastructure. According to the guidelines, at least two system lines per hour and direction for freight trains are planned for the TEN-T core network.

A significant development of agglomeration and regional traffic is also assumed. At least two system routes per hour and direction are planned as a basis for the transport offered in the direct vicinity of regional centers. Depending on the traffic forecasts, the offer is expanded - usually by supplementing it with connections from other market segments – e.g., high-speed regional trains – to offer up to 4 connections per hour. In some agglomerations, extending the offer further is necessary to meet demand.

5.5. The assessment methodology and procedure for selecting investment projects

Developing the assessment method consisting of three elements took approximately 1.5 years (2021-2022). Based on an analysis of the basic documents, together with selected stakeholders, particularly the federal states and transport associations, transport targets are defined for sections of the network, and possible investment tasks are identified to achieve them. On this basis, 25 'modules' have been created. These are packages of projects that share a common functional or spatial context and contribute to achieving the objective and transport corridor-specific effects. Four of these modules form a so-called country-wide core module due to their systemic relevance for an IPT in Austria.

A timetable concept and the necessary infrastructure requirements are defined for each module. The transport offer is based on system train lines for all passenger and freight transport market segments. The investment tasks and infrastructure projects required for this were then pre-designed from a technical point of view to the extent that technical feasibility could be assessed and approximate costs estimated. The effects of the investments were evaluated based on the transport model. The modules designed in this way are assessed using a standardized method. It includes three main elements: a macroeconomic cost-benefit analysis, an indicator assessment, and additional environmental indicators.

The investment costs of the individual modules and the projects within these modules are determined using a standardized cost estimation method to make the projects included in the analysis comparable. This method is based on the results of the preliminary technical concepts and the defined unit costs of the assumed typical technical and construction solutions. The project costs are included in the module assessment and form the basis for further analyses.

Project costs are given with pre-discounted values to interpret the costs better and assess possible future financing programs and a transparent comparison with future effects.

The macroeconomic cost-benefit analysis includes all significant and monetizable effects compared with investment costs. The evaluation criteria are from the analogous Swiss NIBA method [23]. Table 3 shows the defined indicators for each assessment area.

The cost-benefit analysis was complemented by an assessment of additional aspects that were not included in the economic analysis:

- noise pollution,
- passenger comfort,
- reliability/ punctuality of trains,
- wider economic benefits,
- the economic impact of employment during the construction phase,
- social justice.

Table. 3 Areas of assessment and indicators in cost-benefit analysis

Area		Indicator
Environment		1.1 Air pollutant emissions 1.2 Greenhouse gas emissions (during construction and operation)
Economy	Service offer	2.1 Passenger transport operating costs (excluding energy) 2.2 Operating costs of freight transport (excluding energy) 2.3 Infrastructure operational management (operating costs) 2.4 Infrastructure maintenance costs 2.5 Investment costs
	Energy	2.6 Energy costs in passenger and freight transport
	Demand	2.7 Benefits of regular passenger rail services (travel time gain, travel time, transfer time, frequency of transfers) 2.8 Benefits of rail freight traffic (gain in transport time) 2.9 Benefits of additional rail passenger transport (without energy) 2.10 Benefits of additional rail freight transport (without energy)
Society		3.1 Accidents 3.2 Road congestion/travel time savings 3.3 Road maintenance costs

Source: [32]

The second element of the assessment was an analysis of the following indicators:
- removal of bottlenecks,
- network resilience,
- resilience to natural hazards,
- improved trans-regional accessibility,
- improved accessibility beyond conurbations.

Comparative value indicators describe established transport policy objectives that are not fully analysed in macroeconomic analysis. This is due to the difficulty of determining the financial value of the mentioned criteria.

The third element of the project evaluation was the environmental analysis, in which the following indicators were assessed:
- noise (human health),
- natural resources (water, soil, land; animals, plants, habitats),
- human use requirements (landscape, material assets, cultural heritage).

Environmental indicators include legally standardized conservation objectives that are not included in the cost-benefit analysis and indicator assessment. By including environmental indicators, environmental impacts can be assessed.

The assessment of the modules also included a business case. The business assessment is carried out from a 'railway system' perspective. In the method used, all railway operators are considered as a whole, i.e., independent of individual companies, for long-distance passenger transport, regional passenger transport, and freight transport. The revenues and costs of the railway infrastructure companies are also presented together regardless of the formal division of the companies.

Vehicle, staff, energy costs, and market revenue are calculated for rail transport companies. For the infrastructure manager, maintenance costs resulting from the expansion of the network and increased traffic, operating expenses, and module investment expenditures are included.

The results of the individual module evaluation form the basis for selecting those modules to be included in the 2040 target network. Generally, these are the modules for which the overall economic benefits exceed the investment costs, confirming that the module's implementation is justified. Modules for which, from a macroeconomic perspective, a recommendation for implementation in the 2040 horizon cannot be made are documented for a new analysis with a post-2040 horizon.

5.6. Transport effects of the target network

"Target Network 2040" creates the infrastructure conditions for developing and improving the efficiency of the railway system. The aim is to increase passenger and freight traffic in rail transport. Induced traffic resulting from the development of the railway infrastructure is also taken into account. This also applies analogy to rail freight transport: in this case, increasing route capacity, reducing transport times, and improving the performance of the rail network play significant roles in increasing the attractiveness of rail freight transport and consequently increasing the demand for transport.

Implementing the investment tasks planned for the 2040 target network eliminates existing and projected bottlenecks that may form due to traffic growth on the railway network (Fig. 7, 8). It also provides the potential for further development of rail transport in the long term.

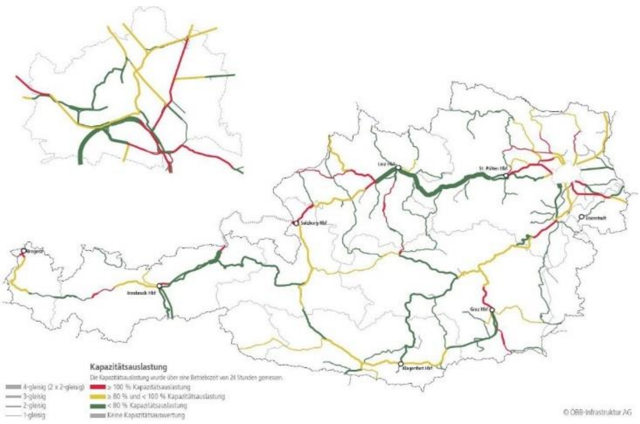

Fig. 7. Capacity utilisation in the reference scenario in 2040. (Source: [32])

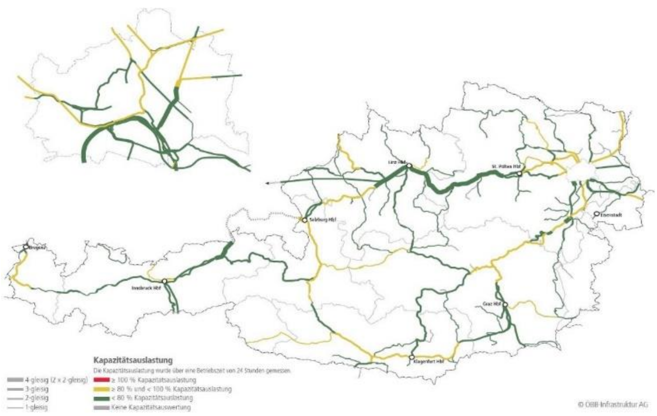

Fig. 8. Capacity utilization with the implementation of the Target Network 2040 (Source: [32])

The study's authors report that 2018 operational work on the Austrian rail network amounted to approximately 156 million train kilometers. Without the implementation of the target network, this is forecast to be 200-210 million train kilometers in 2040. On the other hand, implementing investment tasks will enable 255-265 million train-kilometers.

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Planowanie rozwoju infrastruktury kolejowej w powiązaniu z tworzeniem zintegrowanego cyklicznego rozkład jazdy pociągów

Streszczenie: Artykuł analizuje znaczenie powiązania planowania rozwoju infrastruktury kolejowej z wprowadzaniem zintegrowanych cyklicznych rozkładów jazdy. W kontekście rosnących kosztów inwestycji i eksploatacji infrastruktury transportowej, odpowiednie planowanie jest kluczowe dla optymalnego wykorzystania środków publicznych. Celem artykułu jest przedstawienie, jak planowanie rozwoju infrastruktury kolejowej może być skutecznie powiązane z wdrażaniem zintegrowanych cyklicznych rozkładów jazdy, co ilustrują przykłady z Niemiec i Austrii. Autor analizuje studialne opracowania z tych krajów, aby pokazać, w jaki sposób zintegrowany cykliczny rozkład jazdy może poprawić atrakcyjność transportu kolejowego, zapewniając regularność i łatwość przesiadek. W badaniach przedstawiono porównanie różnych rozkładów jazdy oraz ich wpływu na funkcjonowanie systemów kolejowych. Przeanalizowano też studia przypadków z Niemiec i Austrii, gdzie zastosowano teoretyczne założenia w praktyce. W obu przypadkach procesy konstrukcji rozkładu jazdy oraz planowania rozwoju infrastruktury były procesami iteracyjnymi, składającymi się z kilku etapów. Istotną rolę odgrywały procesy szerokich konsultacji z interesariuszami branżowymi, a także władzami centralnymi i lokalnymi. Wyniki wskazują, że wdrożenie zintegrowanego cyklicznego rozkładu jazdy skraca czas podróży oraz zwiększa liczbę pasażerów, co zaobserwowano zwłaszcza w Szwajcarii w projekcie „Bahn 2000”. Analizy strategiczne koncentrowały się na identyfikacji niezbędnych inwestycji infrastrukturalnych, a w szczególności likwidacji i zapobieganiu powstawania wąskich gardeł na sieci kolejowej. Wnioski z artykułu sugerują, że planowanie rozwoju infrastruktury w powiązaniu z konstrukcją strategicznego zintegrowanego cyklicznego rozkładu jazdy jest kluczowe dla optymalizacji systemów kolejowych, co zwiększa na ich atrakcyjność i konkurencyjność. Zastosowanie analogicznej metodyki powinno być rozważane w planowaniu rozwoju infrastruktury kolejowej.

Słowa kluczowe: infrastruktura kolejowa, zintegrowany cykliczny rozkład jazdy, planowanie transportu, rozwój kolei, przepustowość sieci kolejowej