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# Railway Infrastructure Capacity in the Open Access Condition: Case Studies on SŽDC and ŽSR Networks

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## Abstract

The railway sector in the European Union is changing. The goal of EU transport policy is to liberalize the market for rail transport services, dismantle national transport monopolies, and open competitive public tenders to other train operators. For the optimal utilization of the railway infrastructure capacity, it is necessary to calculate it properly in terms of open access to the infrastructure. At present, many important corridors are at full capacity. Therefore, in order to increase the number of freight trains, it is necessary to implement certain measures to increase the track line capacity. Infrastructure capacity research is part of the complexity of the capacity management processes. A progressive approach to define it means to describe the estimating process of railway infrastructure capacity including progressive capacity allocation approaches as a key part of capacity management. The aim is to define the processes of the infrastructure capacity management on which depends the quality level of operational traffic management as well the efficiency of the traffic flow on the infrastructure. The partial objective is to investigate the impact of systematic train paths in periodic timetables on rail infrastructure capacity. The proposals fully respect the EU transport policy.

**Keywords:** transport policy, rail transport market, infrastructure capacity, train path, open access, capacity measurement

## 1. Introduction

The restructuring of the rail market has created new relationships between the players in this market. The examination of the relationship between the entities, the infrastructure manager, and the railway undertaking (herewith referred to as the RU) focuses on the assessment of the allocation of railway infrastructure capacity, with a view to knowing traffic technology and track-side technologies including the economic aspects. This complex issue is closely related to the determination of the capacity of the railway infrastructure, which represents the maximum possible offer of train paths for the infrastructure manager to construct the timetable [1–3].

The timetable is the operating plan and also offers train paths to potential customers. Loss of stability and timetable quality may result in the absence of spare capacity, that is, its exhaustion after allocation and after the completion of the timetable for the scheduled period [4].

The main objective of this chapter is to define the processes of managing the capacity of railway infrastructure with the aim of achieving high-quality operative management of traffic due to the efficiency of transport flow on the infrastructure. These objectives fully respect EU transport policy, which provides a framework for creating transparent conditions and minimizing risks in accessing transport infrastructure and ensuring the growing transport needs of the company at the required time and quality. The scientific contribution is proven in the application of theoretical knowledge in the field of railway transport technology in terms of a case study on the corridor's lines.

## **2. Requirements of carriers for railway infrastructure capacity**

The allocation of railway infrastructure capacity is a complex product of the infrastructure manager, which consists of a number of sub-services. The infrastructure manager is obliged to publish the conditions of access to the infrastructure (the so-called Network Statement [5]) and to determine the free capacity of each line section. Consequently, it is intended to allow nondiscriminatory access for railway undertakings.

The Network Statement contains mainly the technical characteristics of the railways, conditions for the allocation of rail capacity to applicants, including procedures for the lack of rail capacity, conditions for access to the network, information on the price for the allocation of rail capacity and pricing for the use of the infrastructure, requirements for the application for the allocation of rail capacity, etc.

The allocation of capacity is the sale of a particular train path(s) on specific line sections in a specific time window. From a technological point of view, it is important to correctly determine the technical capacity of the track section, that is, to determine the extent of train traffic for a given track section, to show sufficient stability of train traffic even during operational irregularities. The charging of capacity is one of the tools for number of train path regulation [6–8]. The economic aspect of capacity takes into account also the risk of paying sanctions to railway undertakings for failure to comply with the RU due to poor organization of train transport (see the introduction of the European Performance Regime (EPR) [9]). The process demands the reconciliation of the requirements of all RU with regard to the technological nature of rail transport, requiring railway undertakings to anticipate traffic flows and commodity flows in the medium term.

The line capacity, that is, the ability to insert the required train paths for a given part of the infrastructure in a certain time period, is expressed by the number of train paths that can be determined over a certain time window with given technical, operational, and personnel equipment and with the necessary transport quality achieved [1, 10, 11].

Capacity definition in UIC 406 Capacity [12] represents some consensus among individual infrastructure managers on this specific issue and suggests that a clear definition of capacity cannot be established. The International Railway Union (UIC) defines railway infrastructure capacity as "the total number of possible paths in a defined time window, considering the actual path mix or known developments, respectively, and the IM's own assumptions; in node individual lines or part of the network, with market-oriented quality" [1].

In principle, capacity (throughput permeability) can be determined by the following approaches [12, 10]:

- graphically;

- graphically-analytically;
- analytically; or
- simulation modeling.

An overview of the most preferred methodologies for capacity estimation is elaborated in the work [13]. The most comprehensive approach is to use simulation tools to evaluate the capacity of a railway infrastructure based on a real-world traffic model. Capacity assessment using simulation modeling methods provides a comprehensive assessment of the capacity characteristics of the transport infrastructure being solved. The result provided is only suboptimal in terms of the general approach depending on the course of the simulation. A problem here is the range of input data required for a simulation model (a detailed description of the infrastructure and dynamic properties of the vehicles), as well as the time data required for the simulation assessment. On the other hand, the new possibilities offered by simulation modeling are a prerequisite for its successful implementation in cases where it is justified. The criterion used here is primarily the stability of the timetable (the ability not to increase or decrease the input delay).

## **2.1 Relevant data for capacity allocation in the case study**

The capacity assessment is based on the evaluation of the existing timetable. Infrastructure dimensioning, operational performance, and quality of service are interdependent. If two variables are known, the third can be derived. Security requirements, general economic framework conditions, and environmental constraints are given by the external environment.

The following factors influence the capacity of a given infrastructure [11, 14]:

- number of train paths over a specified time interval;
- average speed;
- stability of train traffic (ability to dispose of the initial delay and its nontransfer to other trains); and
- heterogeneity, that is, with the number of different driving times and their large differences, capacity utilization increases.

The overview of the preferred methodologies among European Infrastructure managers is elaborated in the work of Kontaxi and Ricci [13]. The resulting average value of the stability coefficient (ratio of the output and input delays of the train on the monitored infrastructure in the simulation run) is the basis for assessing whether the infrastructure under investigation corresponds to the expected traffic range.

The train path is defined for the purposes of EP and ER 2012/34/EU directive establishing a single European railway area for the allocation of railway infrastructure capacity [15] as “the infrastructure capacity needed to run a train between two places over a given period.” The train path is defined by important parameters, such as train type, days of operation, routing, scheduled speed, arrival times, departures times, and transfer times at stations and stops.

The timetable shows the paths of all regular trains, trains as needed (on days of deployment), and canceled trains (they travel on specified days and their paths

cancel other train paths where the regular train must be waiting in the event of the jamming train being introduced). The insertion of train paths to the graphical timetable must be in accordance with the technological procedures of the station operation processes and traffic safety. The insertion of train paths to the timetable under SŽDC and ŽSR Railway infrastructure manager is performed gradually according to the following basic types [5, 11]:

- international and national expresses and fast trains;
- long-distance passenger trains;
- freight express trains;
- passenger trains to and from employment;
- feeder freight service trains on line sections before determining the final position of the running freight trains; and
- interfering train paths (regular train paths with special path construction, these trains are operated in dedicated days during the week or daily during a specific time period).

The RU submits timetable capacity requirements along with mandatory data summarized in **Table 1**. Only three of the twelve required data affect the calculation of train running times and thus the line capacity. At the same time, the RU communicates other specific data whose operational nature allows the train to assign the particular type and traffic calendar in particular. Although this is not data directly affecting infrastructure utilization, it is data that allow the capacity allocator to decide on the allocation or nonallocation of railway capacity from a legislative perspective.

Required data under the Network Statement	Influence on driving time
1. Identification data of the RU	N
2. Position route guidance	N
3. Timing of train path	N
4. Train type	N
5. Train set data specifications	Y
6. Technical data on traction vehicles including their number and function in the train	Y
7. Train driving calendar	N
8. Type of railway transport operated	N
9. Required tariff and nontariff conditions	N
10. Type and extent of services provided in the train	N
11. RU requirements for technological operations in stations	Y
12. Known extraordinary of the train	N

Source: authors on the ground of [4].

**Table 1.**  
Required data in rail capacity allocation request.

Three requirements summarize the kit's technical data, that is, the transport weight and the length of the train, tractive vehicle order in the train, and the requirements for technological procedures at the stations. The transport mass and train length shall be determined in tonnes and meters. The set values must comply with the instructions of SŽDC and ŽSR [11]. If a useful track length is less than the train length norm at the station, this shall be taken into account in the timetable. The transport weight of the train in relation to the regular driving times and consequently the technical norms of weight differ according to the types of driving resistance of individual types of trains. The established driving resistance types (marked as M, R, S, T, and U, for example) are indicated with the train weight normative value. If a freight train path is to be constructed in which the transport weight of the train vehicles is higher than the technical weight standard, then the number, type, and method of deployment of other active traction vehicles (locomotives) must be agreed.

It is important to precisely determine the binding travel time of the train concerned for the construction of the train path.

The methodology for determining the theoretical driving time assumes graphical and numerical solutions to the train equation. It is necessary to construct the tachogram of the train, that is, the algorithm or simulation of the ride, which is tasked with compiling the track and time waveforms by means of the train's differential equations, which result in a graphical dependency of the driving speed on the trajectory  $v = f(l)$  as well as dependency of the driving time on the trajectory  $f(l)$  [16].

At each stage of the train movement, the traction resistances that are overcome by the tractive force exerted by the driving axles of the tractive vehicle must be taken into account.

## 2.2 Driving time calculation presumptions

This section discusses overcoming the traction resistances that occur when starting, running at inertial speed, running, and braking as described in these physical equations [10]:

$$F_t = F_a + F_{0L} + F_{0V} + F_S + F_b \text{ [N]} \quad (1)$$

where  $F_t$  is the locomotive pulling force, its graphical representation in relation to speed is traction characteristic  $F_t = f(V)$ ;  $F_a$  is the resistance of mass inertia [N];  $F_{0L}$  is the driving resistance of the traction vehicle [N];  $F_{0V}$  is the driving resistance of trailers (loads or wagon set) [N];  $F_b$  is the braking resistance [N]; and  $F_S$  is the slope resistance [N].

For the driving resistance coefficient, which is specified for each tractive vehicle and load separately, the empirical relationship applies, where  $a$ ,  $b$ , and  $c$  are the infrastructure manager's table values:

$$p_0 = \frac{F_0}{G} = \frac{A}{G} + \frac{B}{G} \cdot V + \frac{C}{G} \cdot V^2 = a + b \cdot V + c \cdot V^2 \text{ [-]} \quad (2)$$

These are the quadratic dependencies and formulas applicable to approved vehicles, as measured by actual measurements on vehicles.

The calculations use the so-called inertial slope, which is defined as the slope that is numerically equal to the slope of the line on which a particular train moves at a constant speed. In determining the inertia slope, we proceed from the basic equation of train movement, assuming that the velocity is constant when the

acceleration resistance is zero. The graphical dependence of inertia on speed is the so-called  $s_0/V$  diagram. It is unique to the type of traction vehicle, the type of vehicle resistance, and the weight of the wagon set. Traction characteristics for each traction vehicle (locomotive and motor car) are constructed to obtain a traction force-speed dependence. The vertical y-axis shows the tractive force, and the x-axis shows the speed. The tractive effort curve in the traction diagram indicates a lot about the locomotive's operating characteristics.

The construction of graphical methods to determine the technical normative weight of a train set is based on the theory of nomograms. In practice, SŽDC and ŽSR most often use the Koreff intersection nomogram, constructed under the condition  $V = const$ . The tractive force values of the coupler for a given traction vehicle are given by the traction characteristic, and the coefficient of vehicle resistance can be determined from empirical relationships. The slope of the track is given by the parameters of the track. It follows from the equation of motion (3) that the left side corresponds to the linear dependence on the resistance of the tractive vehicles, and the right side of the linear dependence on the slope. Relations after adjustment for the weight determination of the transported vehicles are represented by two equations of lines whose relationship can be solved graphically.

$$F_{ts} - G_D \cdot f_{0V} = (G_L + G_D) \cdot f_S \quad (3)$$

where  $F_{ts}$  is the tractive effort of the locomotive on coupler [kN];  $G_D$  is the weight of wagon set [kN];  $G_L$  is the tractive vehicle weight [kN];  $f_{0V}$  is the driving resistance coefficient of transported vehicles [—]; and  $f_S$  is the slope resistance coefficient [—].

The practical expression of Koreff nomograms for transport practice is tables of the technical normative mass. Tables are compiled for each type of traction vehicle; at the intersection of a certain slope (track class) and the mass of the train set, there is the value of inertial speed that the traction vehicle of the given series is able to haul on a given inertia slope and with a given weight of trailer vehicles. Calculated driving time values are called theoretical driving times, rounded off to at least 0.1 min. Regular driving times rounded to 0.5 min are used for the timetable construction [1, 2, 10].

### 3. Identification of problems in railway infrastructure capacity management

For capacity management, the default requirements are:

- organization of the rail market (transport policy and transport market operators);
- technical aspects (infrastructure and interoperability); and
- technological aspects (traffic planning and management).

On the SŽDC and ŽSR networks, “open access” in freight and passenger transport is also possible. This has a major impact on capacity utilization. In the area of railway infrastructure capacity management, major problems in capacity utilization and path allocation have been identified. Under the conditions of the SŽDC and ŽSR railway network, new approaches in capacity analysis are defined and

methodological postulates for new approaches in capacity management in the following areas are defined:

- lack of efficient train paths for freight trains on transit corridors;
- application of the integrated tactic timetable for passenger trains; and
- an increase in the demand for “ad hoc” freight paths.

### 3.1 Lack of efficient train paths for freight trains on rail corridors and nodes

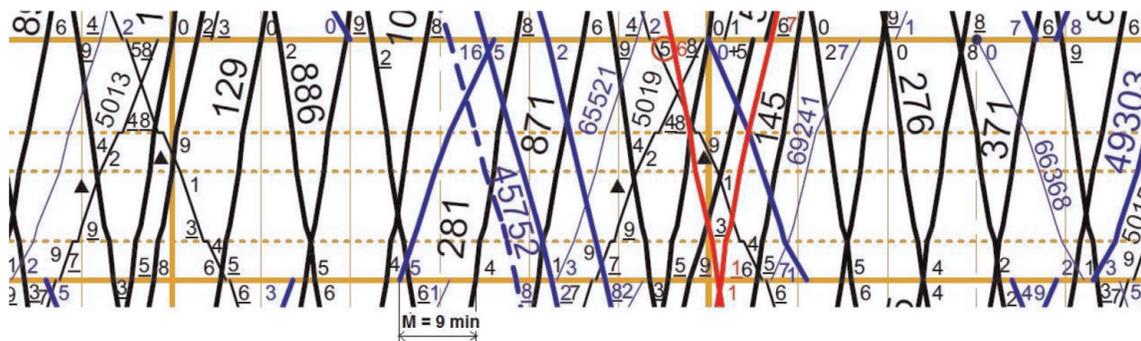
The capacity of the lines as a line construction is closely related to the capacity of the individual railway stations, where insufficient capacity of railway tracks at stations can cause a train to be rejected and wait at intermediate stations, which will further reduce line capacity (and in addition, unproductivity).

For a short case study on the 4th transit corridor, a section of the double-track line between railway stations A and B was chosen, which is characterized by:

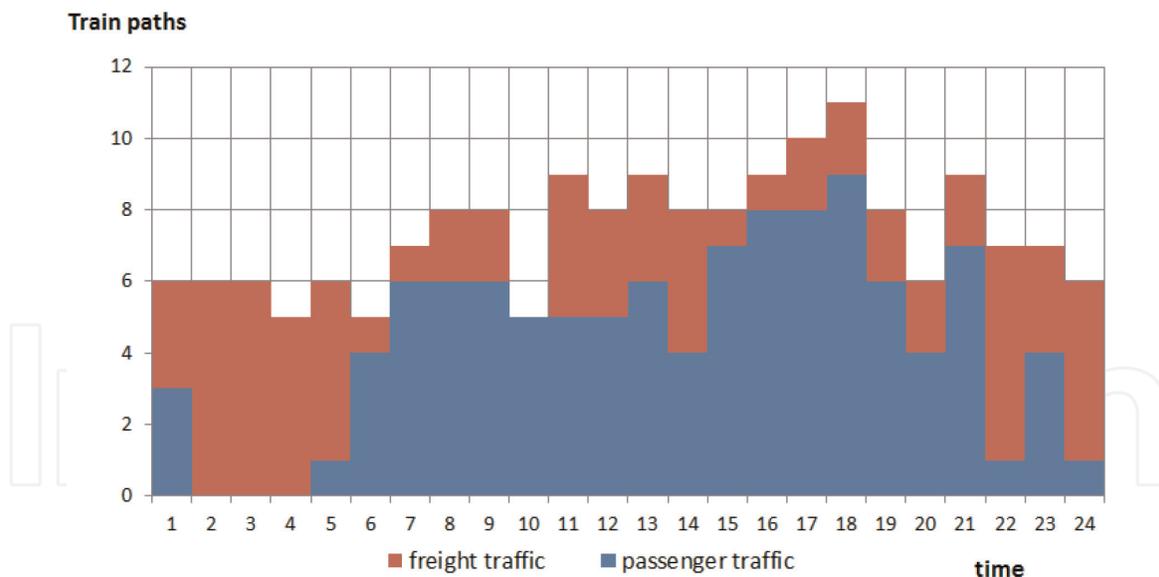
- track equipped with a fully automatic track and station security devices, with a short station and track operational intervals as well headways;
- both regional passenger transport and long-distance express and interregional transport are implemented on the line;
- international freight trains and relational freight trains are established on the line; and
- most trains pass through both stations bounding the interstation section under examination without stopping.

The typical timetable for that line is shown in the segment in **Figure 1**. Due to the preference of passenger transport in the allocation of timetable routes, the assumption can be made that any freight train can only be traced when it does not restrict the movement of passenger trains. The problem is the time taken by a freight train in a timetable, which is significantly longer compared to passenger trains.

In the timetable, the driving times for this section are of the order of Ex 4.5–5.0 min, regional passenger trains 11.0 min, freight expresses 7.5 min, and relational freight trains 9.5 min. To do this, there is need to add a start and stop



**Figure 1.** Headway for train sequence in odd direction (line with odd numbers) stopping freight express-passing express for the station (source: elaborated on ground of [11]).



**Figure 2.**  
*Histogram of timetable train paths in section A–B.*

surcharge of 2.0 min in case of overtaking. From the analysis of time elements, these values of the headway are determined for these train sequences:

- express—express 2.5 min;
- express—freight express 2.0 min; and
- freight express—express 9.0 min.

From these values, it can be seen that the minimum time gap between fast driving trains must be 11.0 min in order to drive the freight express train to the front station where it will be overtaken by the express train. If the freight express train is pathed to the next station, a buffer time of 11.5 min is needed.

The analysis of the constructed timetable in the surveyed section shows that the number of buffer times of at least 11.0 min in this section is on average 1–2 per hour in peak hours. At the same time, the Express-Express trains are most often traced at 8–10 min, which could be reduced to a subsequent interval of 3–5 min (more thorough train bundling).

Regular freight trains are traced a total of 66 trains/24 h, trains as needed five trains/24 h. From the graph in **Figure 2**, which is the histogram of the frequency of passenger and freight trains embedded in individual hours during the day, it is clear that the largest volume of passenger traffic is realized on corridor lines between 6.00 and 21.00 h. Freight traffic is generated at regular intervals throughout the day, and it can be seen that their journey during peak hours of passenger traffic cannot be smooth.

We will assume that freight trains enter the section under investigation at fixed intervals. It is therefore necessary to examine the time model, reflecting the sequence of freight trains and their ability to travel through the section under investigation, including by using the paths as needed. With 66 trains per 24 h, 2.75 trains are generated every hour and need to be transported. Due to the accuracy of the overall result, the situation is modeled using the distribution of trains processed in **Tables 2 and 3**.

Generalization of the case study conclusions for the capacity and mix of train paths in the timetable of the SŽDC transit corridors:

- the accumulation of passenger traffic between 6:00 am and 9:00 pm practically stops freight traffic;
- at this time, only freight express trains may overrun between express, fast trains, and passenger trains but not slower relational freight trains hauling individual wagon loads or empty wagons;
- time distance between passenger trains in the 9–15 min sequence does not create a sufficient buffer time for the insertion of freight train paths;
- freight trains that cannot pass through the section are waiting at the intersection stations, which mean that on average, four trains must wait 4 h from 4:00 to 8:00 pm;
- rush hour may shift slightly depending on which direction of the passenger traffic is stronger in the morning and afternoon and also depending on the distance of the relevant line from large agglomerations;

Time	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00
Entered freight trains	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
Stopped freight trains	0	0	0	0	0	0	1.75	3.5	4.25	5	7.75	6.5
Number of freight trains in timetable	3	6	6	5	5	1	1	2	2	0	4	3
Overhang of train path requirements over demand	0.25	3.25	3.25	2.25	2.25	-1.75	-3.50	-4.25	-5.00	-7.75	-6.50	-6.25
Number of stopped trains	0	0	0	0	0	1.75	3.50	4.25	5	7.75	6.5	6.25

**Table 2.**  
 Average number of delayed freight trains (0.00–12.00 h).

Time	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Entered freight trains	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
Stopped freight trains	6.25	6	4.75	6.5	8.25	9	9.75	3.5	4.25	5	1.75	1.5
Number of freight trains in timetable	3	4	1	1	2	2	2	2	2	6	3	5
Overhang of train path requirements over demand	-6.00	-4.75	-6.50	-8.25	-9.00	-9.75	-10.50	-4.25	-5.00	-1.75	-1.50	0.75
Number of stopped trains	6	4.75	6.5	8.25	9	9.75	10.50	4.25	5	1.75	1.5	0.75

**Table 3.**  
 Average number of delayed freight trains (12.00–24.00).

- the dense sequence of passenger trains during the day does not create any room for freight traffic extraordinary balancing. If freight trains are delayed on other sections, for example due to infrastructure, then delayed trains can only be transported after the peak rush hour, usually only at night time with an average stoppage of 10 h;
- exhausting the line capacity with passenger traffic causes measurable economic losses for freight RUs; and
- the free capacity of the track between 11.00 pm and 4.00 am is not used.

These findings lead to the need to define a powerful train path that can be systematized. The performance of the allocated paths is determined by the RU's data in the capacity allocation request that affects capacity. The analyzed data in Section 2 is mainly about the planned series of the traction vehicle for which regular driving times are computed. It is important to examine the momentum of the train, that is, its mass and acceleration, traction force, and vehicle resistance. These are key parameters that have a major impact on capacity, and the RU can influence these factors. In addition to train dynamics data, the use of infrastructure parameters also affects the level of technical and safety equipment of the traction vehicle. In particular, it concerns the equipment of the traction vehicle with train safety devices and telecommunications equipment, which affect the maximum possible train speed, the use of the transport infrastructure, and the length of its occupation by the train.

To optimize the use of capacity, we have identified operational and technological factors affecting the duration of infrastructure use by a train in the process of capacity allocation:

- train speed;
- train performance; and
- equipped with communication and security equipment.

The speed of the train can be distinguished as maximum speed, determined speed, technical speed, sectional speed, etc. As a criterion for assessing the train paths demanded by the RU with the help of the train speed, it is possible to use the relative speed [4]:

$$V_{rel} = \frac{60 \cdot L}{t_{us} \cdot V_{tr}} [-] \quad (4)$$

where  $V_{rel}$  is the relative speed;  $L$  is length of the examined track section [km];  $t_{us}$  is the travel time of the train on the examined track section including the dwell time; and  $V_{tr}$  is the prevailing line speed in the corresponding speed profile in the track section being tracked [ $\text{km h}^{-1}$ ].

Depending on the train's equation of motion (3), the power of the traction vehicle per unit of mass must be evaluated to compare the different train paths. This evaluation can be performed according to the criterion of relative power [4]:

$$P_{rel} = \frac{\sum_{x=1}^i P_{con}^x}{M_{train}} [\text{kW t}^{-1}] \quad (5)$$

where  $P_{rel}$  is the relative power [ $\text{kW t}^{-1}$ ];  $P_{con}$  is the continuous power of the traction unit [ $\text{kW}$ ] and  $i$  is the number of tractive vehicles; and  $M_{train}$  is the train weight [ $\text{t}$ ].

This criterion evaluates the actual performance of each examined train path, that is, the momentum of the train (its acceleration) and thus the occupation time of the infrastructure. The above criteria, in particular the criterion of relative speed, are also directly related to the technical equipment of the leading locomotive (tractive unit) by the communication and signaling equipment.

The use of infrastructure capacity, and hence its allocation, must be based on the train's equation of motion and thus on speed and power ratings, using criteria such as relative speed  $V_{rel}$  and relative power  $P_{rel}$ .

### **3.2 Application of the integrated timetable for passenger trains**

Research on the impact of a systematic timetable on infrastructure capacity shows that it reduces track capacity. In the case of the requirements for the fixed distribution of paths in time, the relevant period is ensured in such a way that at each clock node, it is necessary to reserve a certain part of the capacity before the train runs. Such reserved capacity affects the overall capacity of station heads and track sections. For example, works [17–20], which confirm this, are involved in research in this area. Even the analytical methodologies used to determine the capacity of SŽDC do not affect the construction of systematic interval paths in order to relate the calculation to the average train and to determine the average required buffer time. This capacity loss can only be compensated to a certain extent in the case of upgrading of track-side signaling equipment using the ETCS system of application level 3, where only the minimum “moving” track section is reserved for the train departing from the clock node.

Displacement of freight train paths on transit corridors seems problematic. This is due to the lack of a sufficient time window to insert the freight train path.

Certain theoretical solutions are offered by the works [21–23]. Freight trains, according to Lindner and von Reder [21], should have periodic time windows between passenger paths, adequate according to the required number of freight routes over the cycle time, into which individual freight train paths can then be constructed. These time windows should, as far as possible, be interconnected between successive line sections (if there is a demand for a freight path from one route to the next one, then the connection of the relevant time window with more follow-up should be sought). In case of insufficient capacity of the time windows or the necessity to overtake freight trains too often, they propose to review the structure of the passenger transportation offer (e.g., the individual time positions of individual lines or the number of service segments on the given track section). Of course, freight transport requirements must not lead to the breakage of important elements of the network supply, for example (in terms of passenger traffic flows) significant connection links.

Drábek [22] in his work presents systematic paths as a network capacity offer, which to some extent is similar to integrated periodic timetable in passenger transport, but takes into account rail freight needs.

These studies demonstrate the difficulty of addressing this issue. Methodologically, a distinction should be made between the procedures for timetable construction with the rail infrastructure adaptation procedures.

In the case of persistent trouble inserting train paths in the required sequence and required dwell times in the timetabling process, there may be a need to change the configuration of the railway infrastructure. The methodological

recommendation for rail infrastructure adaptation procedures only for strategic considerations and objectives can be summarized as follows:

- construction of timetable with a perspective mix of passenger and freight train routes;
- the subsequent definition of the necessary infrastructure measures to ensure the implementation of the required scope of transport at the required quality level:
  - to build other station tracks
  - about rebuilding station heads
  - about building rail crossovers
  - about building the next line track
  - about building new safety equipment
- adjusting and synchronizing driving times;
- assessment of the construction of infrastructure (lines and stations) with segregated freight traffic; and
- assessment of the construction of high-speed infrastructure with segregated passenger traffic according to the high speed TSI.

Lack of capacity is also due to the lack of useful lengths of station tracks on rail freight corridors (RFCs) [24] as completely unsatisfactory (the study considered sufficient rails with a length of at least 752 m).

The methodological recommendation for the timetabling is intended for intentions in current conditions and the search for technological solutions in the current state of infrastructure, which can be summarized as follows:

- achieving systematization and synchronization of freight train times; this is achieved by correctly determining the driving time, calculated for the selected level of the specified speed and the corresponding weight and type of the traction vehicle; to obtain a constructed synchronized path, RUs must meet the performance requirements of this path by providing a train assembly from vehicles that achieve a design speed of at least the specified speed and the tractive vehicles have the required performance to ensure the system driving time; and
- achieving systematization and synchronization of passenger train travel times by unifying speed levels for these paths; this means, similarly to freight trains, to create systemized paths with synchronized driving times.

The aim of systemization and synchronization of driving times is to achieve less heterogeneity in train path performance and bundling with minimized buffer time between occupancy times (headways).

A typical example of the distribution of train paths in the timetable on SŽDC resp. ZSR transit corridors was analyzed in a case study on a corridor line with five

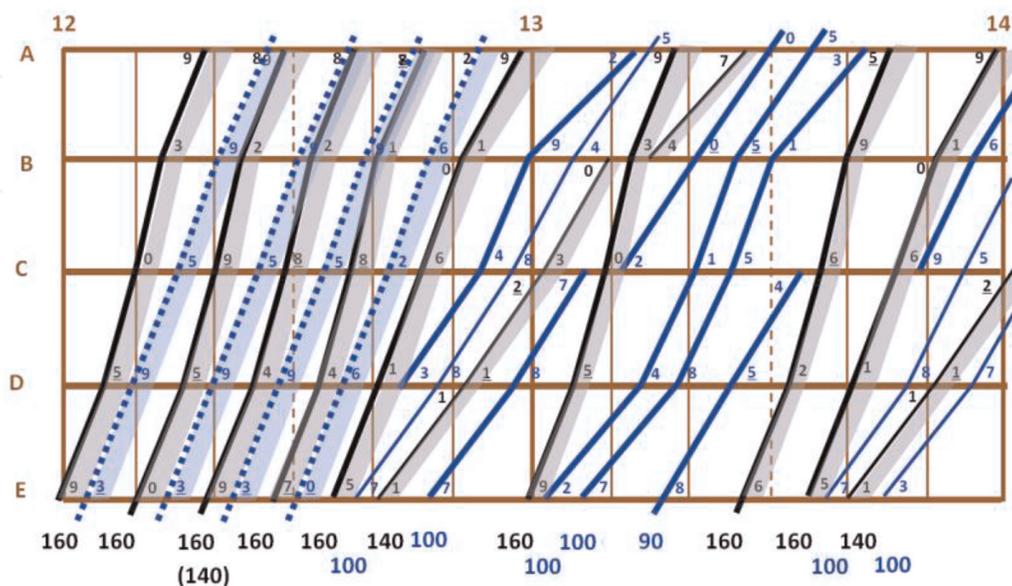
A–E stations on a double track line equipped with an automatic block [10, 16, 25, 26]. The analyzed section can be compared, for example, with the real section Kolín-Pardubice. Passenger trains (Ex category) are run at different times and with different stops. **Figure 3** shows the time spacing between Ex trains approximately 7.5–10.5 min at a headway of 2.5 min. This means a request for a buffer time for the path insertion of 5.0–8.0 min. However, the express freight train path needs more time to insert it, namely 12.0 min, which is indicated by the shading of the depicted occupancy time of passenger trains. This gray area must not be affected by the occupation time of another train. In this path configuration, eight freight train paths (freight express and relation freight trains) are inserted in a two-hour time window. The specified train speeds in  $\text{km h}^{-1}$  are listed below the graphical timetable. Ex trains are pathed to  $160 \text{ km h}^{-1}$ , passenger trains to  $140 \text{ km h}^{-1}$ , and Nex and relation freight trains up to 100 and  $90 \text{ km h}^{-1}$ .

**Figure 4** shows a study of the distribution of train paths after the systematization and synchronization of passenger train and freight train times. Following the adoption of the methodological recommendation, the Ex train paths are more closely bundled within 5 min to allow for the introduction of freight train paths with a standardized speed of  $100 \text{ km h}^{-1}$ . In this option, 14 freight train paths were successfully inserted in the 120 min time window. The start-up and stopping time charges for freight trains are problematic and considerably prolong the driving time and affect the possibility of inserting the train path into the buffer time. It would be ideal to achieve the condition that freight trains pass through all stations.

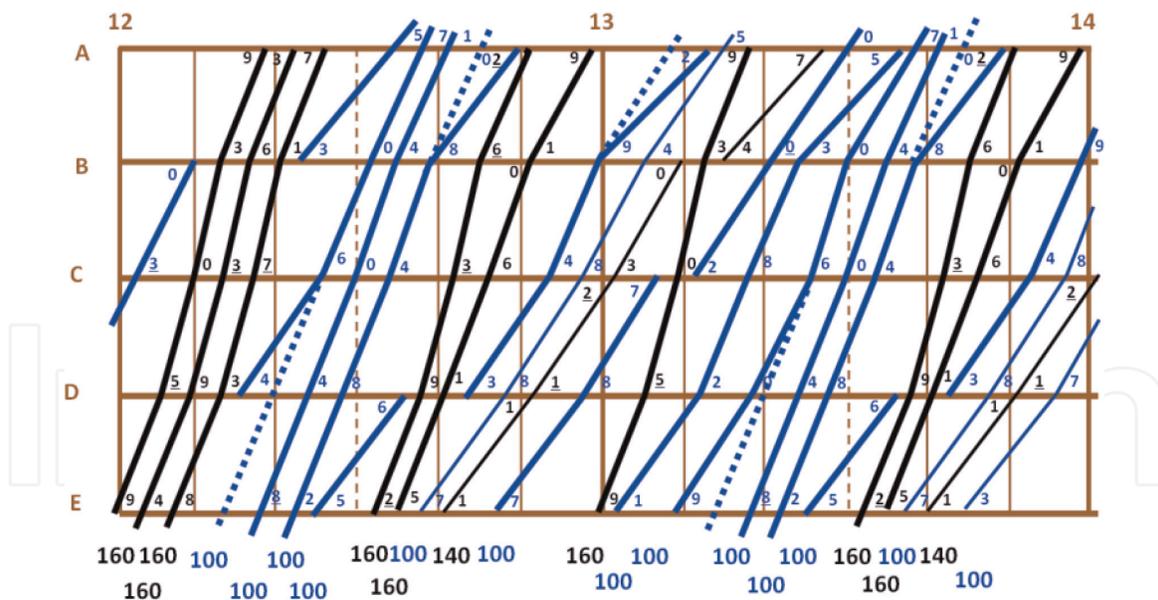
### 3.3 Increase in “ad hoc” train path requirements

From the perspective of the railway infrastructure manager, the growth of requests for “ad hoc” paths, that is, the operationally introduced paths not included in the timetable at the expense of planning regular train paths incorporated in the timetable, is a negative phenomenon.

In the context of individual ad hoc capacity allocation, we divide the capacity requests for “over 3 days,” “ad hoc” requests for “under 3 days” capacity, and “ad hoc” allocation for rail capacity for technical-safety tests of railway vehicles and



**Figure 3.** Inability to insert fast freight train paths (Nex) into gaps between express passenger trains (Ex) indicating the occupation time by those paths in a typical mix of train paths on the transit corridor section (numbers below the paths indicate the specified speed for that path).



**Figure 4.**

Example of arrangement of systemized and synchronized train paths for passenger and freight trains (numbers below the paths indicate the specified speed for that path).

other reasons. For “under 3 days” applications, it is up to the infrastructure manager to decide whether to allocate “ad hoc” paths to resolve conflicts (for example, allocate pre-constructed bidding paths) or allocate paths in residual track capacity without conflict resolution. Conflicts in these paths are handled operatively by the operating staff of the rail system operator.

Another administrative constraint is the fundamental difference between the approach of national infrastructure managers to the issue of reservation, allocation, and use of paths. By comparing the conditions on the SŽDC network, the Austrian ÖBB Infrastruktur, and the Polish PKP PLK, it is possible to find out that there is no uniform approach in the implementation of partial timetable changes. As a result, there is a situation where the train is already regularly on a single rail network, while on the neighboring rail network it is still in an “ad hoc” mode.

For mutual co-operation between applicants and capacity allocators in the process of allocation of railway capacity, national information systems are used for the setting of the annual timetable, as well as the information system for coordinating the allocated train paths (Path Coordination System) from RailNet Europe.

In the train path request process, it is also necessary to implement the TAF/TAP TSI (Technical Specification for Interoperability relating to Telematics Applications for Freight/Passenger Services) [27] for all rail freight operators in EU Member States. All participants in the transport process will have to be able to exchange precisely defined information and reports among themselves electronically. The TAF/TAP TSI will allow coordinating the development of information systems for request acceptance processes, capacity allocation, path design reconciliation, and path activation. However, in the interest of developing rail transport business, infrastructure managers seek to develop these technologies with the least possible financial impact on railway undertakings.

#### 4. New approaches to capacity management

The basic task of capacity management is to construct a basic timetable for a certain time period (all-year) based on infrastructure capacity planning and specific train path orders. The condition for the allocation of train paths is sufficient

capacity, that is, adherence to defined conditions for ensuring the timetable quality, in particular the transportation time, with which the required buffer time (backup time) is closely related. The remaining capacity (free paths) is offered as bidding catalog paths in “ad hoc” mode to RU [1, 6, 11].

The output of the capacity management process is the allocation of train paths and the determination of quantitative and qualitative indicators of the constructed timetable (as a result of the stability proof process), in particular occupancy time, waiting time, buffer time, or optimal traffic flow [10, 28].

New approaches to comprehensive management of infrastructure capacity can be broken down into the following headings:

- supporting the implementation of simulation procedures and UIC methodology for capacity utilization;
- marketing measures, in particular capacity management and capacity allocation activities; and
- organizational measures in technology, aimed at systematizing path allocation and operational traffic management.

The disadvantage for infrastructure managers who use analytical methodologies for capacity determination is that they no longer reflect the progressive requirements. This is mainly due to the development of computer technology and the related possibilities for modification of analytical methods, development of structure, and the heterogeneity of transport (loss of freight transport, development of suburban, and long-distance transport), or the shift from quantitative capacity to qualitative. The use of simulation methods is used to model railway traffic including the inclusion of operational irregularities, that is, delays, to the extent corresponding to reality. An important task is to fulfill the relevant model data, which corresponds as accurately as possible to the reality of infrastructure and vehicle parameters. The modeling of train delays and the feasibility of solving traffic situations have a significant impact on the accuracy of simulation outputs. The outcome of the simulation procedure is to determine the stability of the timetable. Different simulation programs (e.g., RailSys, OpenTrack, and SimuT) provide different results (using different ways of calculating driving times, solving conflicts between trains, etc.) [14]. Investigating the reduction of the initial delay means determining the average delay increase per train. An increase in delay of up to 0.5 min/train may still be acceptable, but this increase should be able to absorb adjacent infrastructure elements. It is recommended to increase the occupancy degree limit in the following cases [16]:

- in a peak computing period;
- average occupancy time is greater than 10 min; and
- it is a track with a specific traffic (e.g., only one type of trains prevails on a track that achieves low delays).

These indicators can be fully explored in simulation procedures supported by UIC Regulation 406 “Capacity.” Principal differences in analytical and simulation approaches in capacity exploration are shown in **Table 4**. There is no exact dependency between the degree of occupation and the quality of traffic, so analytical methods are less accurate [14, 16].

Methodology	Analytical methods (SŽDC, ŽSR)	Simulation methods (UIC)
Quality of operation	Based on the degree of occupancy of individual devices	Using quantities directly describing the quality of operation (delays)
Capacity relationship	Capacity related to infrastructure capacity	Related to specific timetable
Deterministic	Based on even track occupancy; unequal track occupancy can be used for tracks used only by freight transport	Uneven track occupancy

Source: [10].

**Table 4.**  
Basic differences in capacity research approaches.

*Marketing measures* are aimed at achieving optimum use of infrastructure (more evenly burdened) by using pricing and other tools in the capacity allocation process, in particular:

- allocation of train path depending on its time position;
- taking into account the acceptance of powerful train paths;
- deviations from the time position, that is, penalty for delay caused by the carrier, as well as delay bonuses caused by the infrastructure manager (EPR system);
- sanctions for nonuse of allocated capacity;
- stricter conditions for “ad hoc” capacity allocation; and
- the scope of use of ancillary services.

The essence of organizational measures is the systematization and synchronization of driving times, where the aim is to achieve less heterogeneity of train paths and to bundle it with minimizing buffer times. There is a need for a change in the configuration of the railway infrastructure in the event of persistent problems with the insertion of train paths in the required sequence and the required timetable stays. In the operative operation, the fixed specification and order of the train paths will be followed. In the case of delay, the right to the train path will not be guaranteed.

Capacity management processes include the train path ordering processes, strategic dialog and advisory phases, conflict coordination and resolution, and capacity allocation. The aim is to create a comprehensive, effective, and motivating model, which will be composed of both technological procedures and pricing policies leading to the provision of efficient train paths.

A prerequisite for creating a capacity management concept is capacity planning for its further development and use. The essence of capacity management is based on a plan to create a basic timetable, which is usually 1 year and thus represents a medium-term plan. The output of the capacity management process is the allocation of train paths and the determination of the quantitative and qualitative indicators of the constructed timetable (as a result of the stability proof process), in particular the occupancy time, waiting time, standby time, and optimum traffic flow. Achieving optimum traffic flow over time requires infrastructure managers to

use capacity management and marketing tools to allocate train paths to reflect traffic flow over time so as to get as close as possible to the defined optimal value. The first priority is the technical conditions for access to infrastructure and the second is the infrastructure access clearing system [2, 10, 16, 25, 28–31].

The aim is to create a comprehensive, effective, and motivating model consisting of both technological procedures and pricing policies, leading to the provision of efficient train paths:

- allocation of the train path depending on its time position, that is, providing more favorable conditions for the allocation of the path in the transport saddle;
- taking into account the acceptance by the carrier of efficient train paths;
- deviations from the time path, that is, the penalty for delays caused by railway undertakings, as well as delay bonuses caused by the Infrastructure Manager (European Performance Regime);
- when using capacity utilization, to reconcile the use of standby time and occupancy with the UIC methodology, in particular to define the upper occupancy level on lines with specific traffic (homogeneous timetable), which can be as high as 0.90;
- sanctions for nonuse of allocated capacity; and
- stricter conditions for ad-hoc capacity allocation.

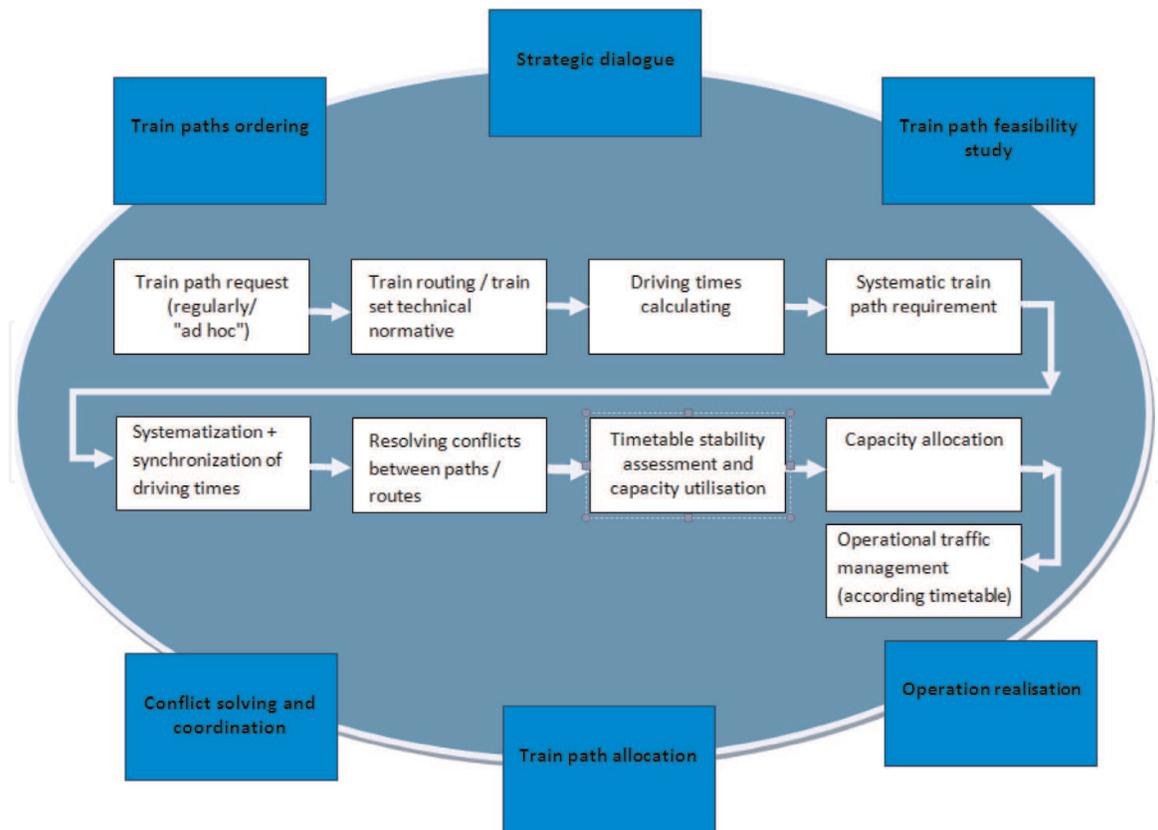
**Figure 5** shows the identified cycle of capacity allocation of the railway infrastructure using the proposed progressive methodological approaches. It is a set of methodological postulates in the following defined areas:

- setting a higher level of optimal capacity utilization in a specific timetable;
- determining the prioritization of train paths in the construction of the timetable, as well as in the operative management of traffic with the help of defining system times; and
- connecting the required heterogeneity and sequence of train paths, to provide the required performance paths, and to propose infrastructure measures if the conflicts cannot be resolved by technological measures.

These methodological proposals are only a simplified procedure for timetable creators. If they are to be the basis for further processing, especially by means of IT techniques, it is necessary to create a mathematical model that will be revised to a computer model after appropriate verification. After validation, it is the basis for the creation of an applied computer program. The proposed methodologies can then be imported into software products supporting the construction of the order and capacity indicators.

In the liberalized railway market, further development of infrastructure capacity utilization in:

- searching for optimum traffic flow in order to achieve the desired quality of transport;



**Figure 5.** Capacity allocation cycle using proposed progressive methodological approaches with regard to the railway infrastructure capacity.

- establishing a timetable for each day (planning period of 6 or 12 h), where operational planning and the interconnection of tools for timetabling and capacity planning with operational planning systems will be supported;
- expressing capacity as the ability to meet the requirements of specific train paths while guaranteeing the stability of the timetable operational model; and
- planning infrastructure configuration based on required capacity through infrastructure measures.

## 5. Conclusion

Sizing the railway infrastructure, operational performance and quality of operation are interrelated. If two variables are known, the third can be derived. For example, on the Prague-Ostrava route, the current trend of shortening the length of long-distance passenger trains but increasing their frequency as a result of the liberalization of the rail market (“open access”) significantly affects the capacity. From this situation, there is a clear need to plan a transport infrastructure for the future scope and concept of transport. Emergency events are a problematic point in the framework of the liberalization of rail transport, which is related to maintaining the number of traction units to the minimum possible. As a rule, RU does not have suitable tractive vehicles for diversion routes. The former unitary state railways had tractive vehicles for independent traction (multi-system locomotives), which could be used for such haulages (not only for freight).

In order to create harmonized conditions for access to infrastructure, it is important to correctly determine the optimum capacity of the railway

infrastructure, that is, the number of train paths that will be advantageous both for the infrastructure manager and operating and economical. The prerequisite for this is a clear definition of the capacity of railway infrastructure and train paths, determination of the basic principles of capacity detection by means of simulation tools, determination of optimum throughput, plus even ensuring the utilization of railway infrastructure capacity. The proposal outlined the process of determining the capacity of the railway infrastructure, including progressive capacity allocation approaches as key components of capacity management. The scientific and research contribution is proven in the focus, deepening the application of theoretical knowledge in the field of railway transport technology. The proposed procedures for determining the timetable stability and optimizing the process of inserting train paths into the timetable, with an emphasis on optimizing and systematizing them, can be applied as a manual for the needs of specific simulation procedures, as well as for the support software product developers. These benefits can be used in the practical tasks of allocating railway infrastructure capacity and identifying optimal traffic flow. At the same time, the proposed procedures for determining graphical stability can be applied as a manual for the needs of specific simulation procedures, as well as for creators of supporting software products.

The issue being solved by its impact on traffic and transport operations and on the railway market is so complex that a number of related aspects are subject to further research. When establishing capacity, focus should be on the required amount of buffer time and examining the waiting time in terms of overall capacity management and in the context of streamlining and shortening the entire process of allocating railway infrastructure capacity. These tasks have a significant impact on the main objective of European rail transport policy in order to strengthen its competitiveness in sustainable development.

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