Effect of energy efficient train driving methods on the railway infrastructure capacity in periodic timetable networks

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Effect of energy efficient train driving methods on the railway infrastructure capacity in periodic timetable networks

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Abstract

Railway operation according to the principles of periodic timetable is one of the most common methods for organizing rail traffic in Europe. This method is used or intended to be used for train operations in such areas or countries, where also the railway network is heavily used. These geographic areas correlate with the areas where also an increased pressure on energy saving is growing.

One of the options how to reduce train energy consumption represents also different planning of railway operation (timetabling) and the consecutive execution of such operation. This is done in particular by adjusting time reserves integrated in the timetable at design phase as well as by alternative using of such integrated reserves during the operation phase.

Depending on other components of railway operations, such as operational concept, heterogeneity of such concept or extend of available infrastructures, the energy efficient train driving methods can significantly and differently affect the capacity utilization of given infrastructures.

This paper discusses some different energy saving methods of train operation depending on available infrastructures and operation requirements and analyses and evaluates additional capacity requirements for particular railway infrastructures.

Keywords

railway operation ; infrastructure capacity ; capacity utilization ; energy efficient train driving; energy efficient driving ; buffer time

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1. Introduction

There are many different options, how to reduce train energy consumption in all three main subsector of railway system – infrastructure, rolling stock and timetabling. This paper is analysing the effects of energy efficient driving methods. Option how to reduce train energy consumption represents also different planning of railway operation (timetabling) and/or the consecutive execution of such operation. This is done in particular by adjusting time reserves integrated in the timetable at design phase as well as by alternative using of such integrated reserves during the operation phase.

Capacity of railway networks is limited and generally nowadays many lines are heavily used, especially in the agglomeration areas and on the connections between these regions. Also minor additional capacity requirement change could switch the situation for particular railway infrastructures. Therefore different energy saving methods of train operation depending on available infrastructures and operation requirements are analysed and additional capacity requirements for particular railway infrastructures will be evaluated if necessary to enable energy efficient train driving methods on such infrastructures.

2. No reserve = No saving?

The most energy-efficient way to move the train from A to B reduces the consumed amount of energy to the minimum. But it is difficult to determine the minimal energy consumption exactly. Since the dislocation effect could at least theoretically be realized completely without energy supply, only the various resistance factors have to be overcome, if both kinetic and potential energy stay unchanged. The most important ones are the rolling and wind / air resistance. The drag is usually estimated by series of experiments where the real resistance is measured as the train is moving with constant speed. As a result, usually a quadratic, speed dependant function of drag is produced. The drag function is then typically given by $F_{RESISTANCE}(v) = a + bv + cv^2$. By using these values can be shown that the minimal energy consumption is reached at a very low speed, defined as $0 + dv$ with the energy consumption approximately equals to the mechanical work $W = F_{RESISTANCE} * s$, where the $F_{RESISTANCE}(v) = a + bv + cv^2$ becomes arbitrarily close to $F_{RESISTANCE} \approx a$ and where a, b, c are constants.

The opposite case constitutes the minimal running time. This is the shortest running time that can be achieved for a given train run with the given train set and the given vehicles on the given infrastructure by maximal using of all available technical features and options and without any time or other reserves. In ideal case, the minimal running time under ideal circumstances could still be reduced, because for such calculation the boundary conditions are chosen to be always reachable in the usual situation. By neglecting these marginal effects, this is the minimal achievable running time.

There was no operational concept / timetable foreseen, so it was possible by defining of a timetable to choose also the final energy consumption for each train and/or for the whole timetable. Options for energy optimization strategies based on the state of the operational concept illustrate the following Table 1**.**

Table 1 Energy optimization methods depending on future operational concept and actual state

Operational concept state	Nr. of trains	Energy optimization method
DESIGN phase - without direct train path conflicts	1	Choosing of running time (and then by searching of ideal energy efficient solution)
	two and more	Choosing of running time and solving indirect train path conflict (typically by elimination of all non-commercial stops)
OPERATION phase - with possible train path conflicts	1	Using timetable reserves
	two and more	Using timetable reserves and solving train path conflict (rescheduling) (typically by elimination of all non-commercial stops)

If operational concept is existing and therefore timeslots for each train are known, searching for suitable energy efficient train driving method is generally possible by using existing running time reserves of the particular train, or in case of impending train path conflict by using rescheduling methods for one or more trains.

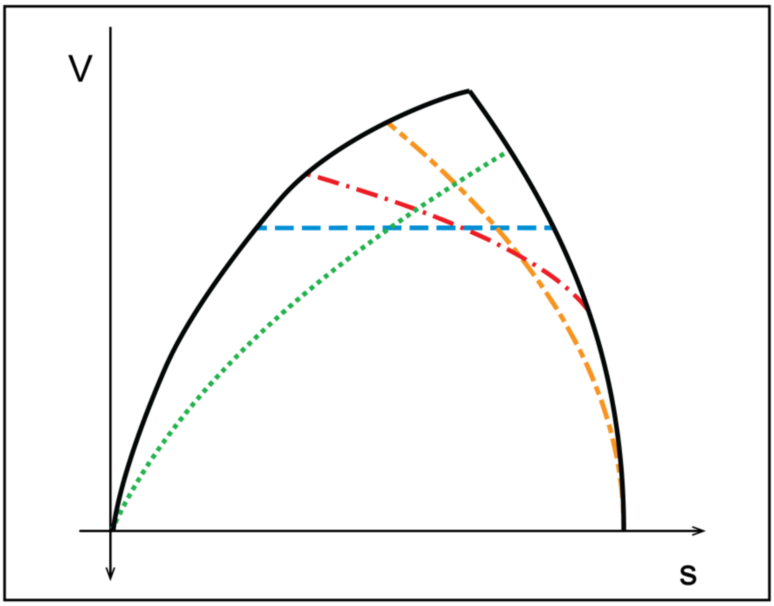
The running time can be freely chosen from the whole interval between minimal running time and the time which represents the absolute minimal energy consumption (and where the time becomes arbitrarily close to infinity). In the vast majority of cases over the different railway operators and railway companies, the values near the minimal running times are used with small reserves only. Depending on line, rolling stocks, train type and some other parameters, the additional reserves to 20 per cent as additional time add (reserve) as well as load supplement are usually applied.

2.1 Energy efficient train driving methods

By choosing a running time, the final running time for the whole path is set, but not the energy consumption at all. The sum of all running times over all blocks is defined too (Figure 2 illustrates similar case for single block), but the particular running times for the each block may differ. There is no already known and broad accepted strategy, which solution is (always) the best.

For given running time, which is longer than minimal running time and therefore it could be realise, some typical strategies are shown in the Figure 1.

Figure 1 Energy efficient train driving strategies



The black line represents the minimal running time for a given case. This strategy illustrates the maximum energy consumption[2]. The different colours represent different strategies, how to reduce the maximum energy consumption:

- blue means reducing the maximum allowed speed
- red line represents coasting effects
- green curve represents operating with reduced acceleration
- orange curve describes operating with reduced deceleration

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[2] ‘Maximal energy consumption’ in this case means for only one train operating in the network, without any non-commercial stops and other conflicts. Otherwise, the energy consumption could grow beyond the given limit.

Each of such strategies may be the optimal energy efficient train driving method for a given running time. Depending on the train type, especially on the ability to use regenerative braking for converting the kinetic energy back into electrical energy and related adhesive weight ratio are crucial for the decision, which strategy in the particular case is the best one.

Regenerative braking make possible the already for the train operation consumed energy, which is then stored in form of kinetic energy of the moving train, to convert back by braking to original form of the energy, typically to electrical energy. This ‘energy conversion’ is associated with partial energy loss because of necessary double transformation of energy supplied. With typical efficiency of vehicles with electric transmission about 85-90% (e.g. [1]) is possible to recover over 70% of residual kinetic energy in ideal case. For all other vehicles, like diesel powered vehicles or electric vehicles with an electrodynamic brake only, this energy is usually converted by braking to useless heat. In these situations, already transformed energy is irrecoverably consumed at the latest as the vehicle stops.

A very basic parameter, which affects the regenerative energy calculation, is the adhesive weight ratio of the train, which is not reducing the amount of the regenerate energy, but affecting the necessary time for this conversion. In general terms, fully regenerative braking process takes always as much time as acceleration phase of the train movements because of the wheel rail adhesion constrain and the limitation to brake by the powered axis of the train only.

To decelerate faster, if necessary, the regenerative braking is used on all equipped axis only and the not equipped ones are braked as usual. It is typical for the train with low adhesion ratio like freight trains or by frequently stopping trains, where fast stopping is elementary. In such cases, at least the same ratio of kinetic energy (according to adhesive weight ratio) will be regenerate.

3. Railway infrastructure capacity impacts

By the changing of overall running times and therefore also block section occupation times for both shifting the occupation window and alter the occupancy time of such windows, some capacity impacts are unavoidable. Three different capacity effects could be observed: negative (loosing capacity), positive (gaining capacity) and none (without capacity change). According Table 1 there are four different situations with different infrastructure capacity implications.

In almost all possible cases, the energy efficient train driving methods change the running times (at least the section’s running times) as well as reduce the railway infrastructure capacity. Compared to minimal running time, some additional time is always needed. That causes additional / longer occupations and reduction of available capacity at the same time.

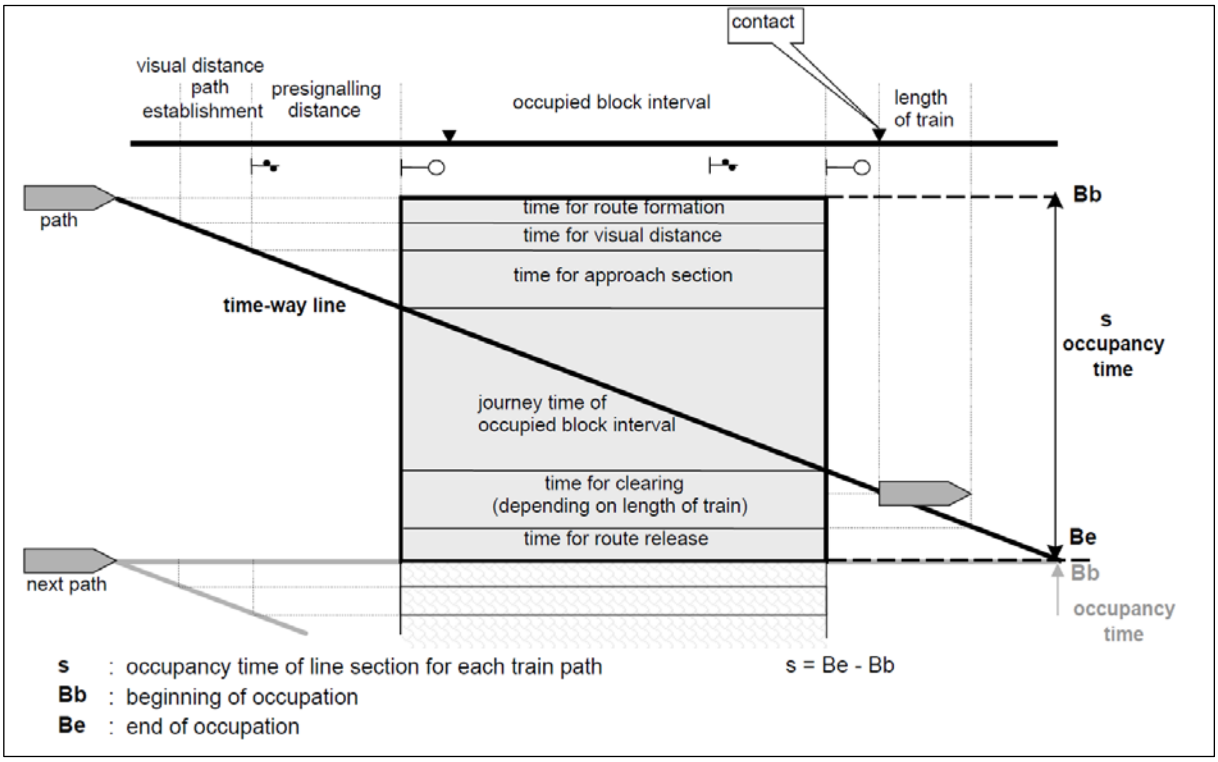
The difference between design and operation phase consists in dealing with timetable reserves. At design phase, each reserve represents an additional blocking time, in operation phase is assumed, that timetable is already designed and fixed. Reserves are then part of already allocated capacity and therefore not part of capacity evaluation anymore. If not so, situation from operation phase will be identical to the design phase.

3.1 Capacity impact of single train situations

For the situation, where only one running train is considered, the Figure 2 illustrates the initial situation. By increasing reserves, overall capacity impact is negative because the train operates slower and occupies the infrastructure for a longer time slots. But even there is no general way how to decide, if this situation will have positive or negative local capacity impact. The single block occupation is heavily depending on chosen method to save energy.

Just in one case, at the operation phase, when only one train operates in one single block only and where some optimization rules are applied, the new occupation time of the block will remain the same. In this case, also the section running time remains unchanged.

Figure 2 Physical attributes of the single block section



Source: [4]

3.2 Capacity impact of multiple train situations: Time reserves and the possible use in periodic timetable

In the case of multiple train situations, the capacity heavily depends on operational concept phase, number of block sections, where the optimization is applied and newly on heterogeneity of railway service. For periodic timetable, homogeneous timetable or heterogeneous timetable combined from a small number of periodic train paths is typical.

The situations for multiple train operation are generally similar to the situations for single train ones. In case of operating trains in one block sections only as well as for homogeneous train operating in homogeneous blocking time stairways, solutions are equivalent for both design- and operating phase with single train situations. In other cases, energy efficient train driving methods cause stabilizing or reducing of railway infrastructure capacity use.

3.2.1 Heterogeneous train operations

Heterogeneous train operations (or heterogeneous timetables) are operational concept combined from a small number of periodic train paths. For the cases of periodic timetable, the paths repeat regularly.

When considering each train alone, the capacity consumption (as presented in 3.1) grows in every case. If each train is considered as a part of the system and the originally isolated effects are assessed cumulatively, the impact of additional train running time reserve on capacity is then positive or negative depending on the reserves distributions.

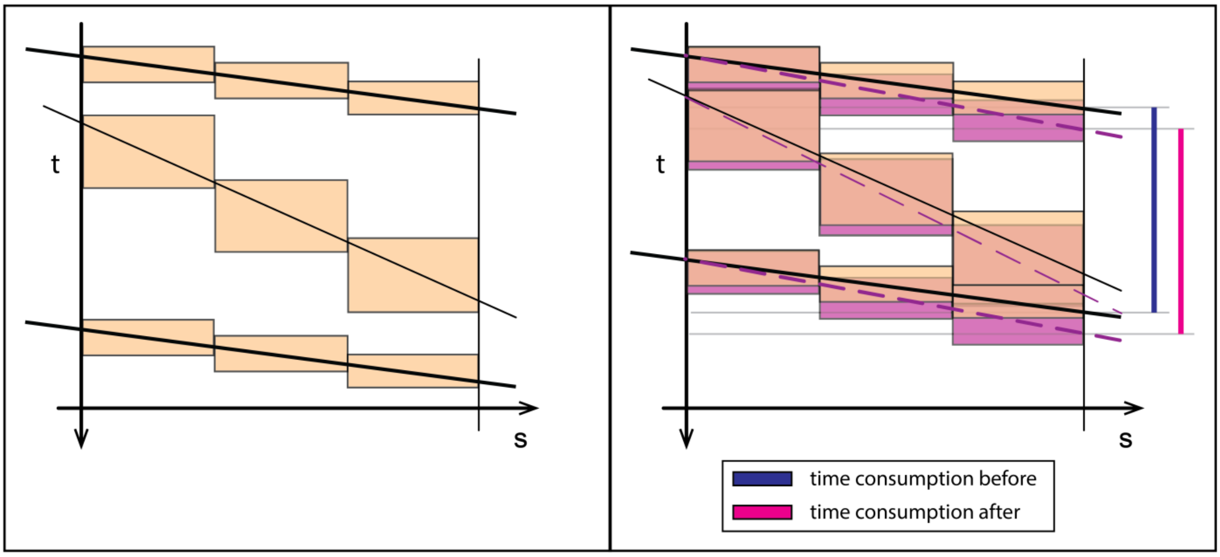
The situation can also be changed by change of timetable heterogeneity factor. Generally, the trains operate then according to the train paths from the graphical timetable more and less ‘parallel’. If heterogeneity of the traffic is reduced, capacity consumption is reduced too and vice versa. This rule is universal, well known and could also be partly used for energy optimization. The solution how to reduce the heterogeneity is either to add an additional time to the faster trains or to reduce the additional time by the slower trains (which is not optimal for energy efficient driving ability of such trains). Without changing the heterogeneity factor, the situation is identical to the reserve-distribution case.

The running time reserves are distributed along the train path in three main ways: on a linear basis, absolutely on the beginning or on the end of the path or in combination of such factors. The second main condition represents the absolute value of such reserves. In some cases, the reserves have fixed value; in other cases, the value is counted as percentage of the minimal running time.

The situation without the growth of the total infrastructure capacity use occurs when the reserve increases exclusively in non-critical block sections by any method. Without reduction of operational concept heterogeneity, which is equivalent to reduce of capacity utilization, the allocation of additional reserve is allowed only at non-critical block sections (always valid for the first train only) and their neighbouring combinations.

Initial heterogeneous situation illustrates the Figure 3 on the left side, where all the train are considered as a part of one system and therefore are going to be shifted together (so called ‘compression method’) by critical block sections to each other. On the right side of Figure 3, a case after shifting together (orange) and a linear reserve distribution (magenta) is shown.

Figure 3 Heterogeneous train in initial situation (left); ‚compressed‘ and ‚with linear reserve‘ (right)



For the case of a linear reserve distribution is important, if the reserve value for different train is set as a percentage or as an absolute value. Is the reserve defined as a percentage, the heterogeneity ratio increases and the available capacity decreases. Is the reserve set as a same absolute value for all trains (as Figure 3 right), then it is possible to distribute the reserve linearly in almost unlimited[3] way without changing of heterogeneity factor (according own calculation partly using the theory of “Sum of Shortest Headway Reciprocal (SSHR)” and “Sum od Arrival Headway Reciprocal (SAHR)” from [5]). The available reserve for each individual train in such scenario is higher, the consumed infrastructure capacity is identical and the applied method for energy efficient train driving does not affect the infrastructure capacity at all.

3.2.2 Homogeneous traffic on the line with heterogeneous sections

When homogeneous trains operate on the line with non-homogeneous sections (and therefore non-homogeneous blocking time stairways), the situation is different. In this case, the capacity consumption either grows as by one train scenarios or remains substantially unchanged, if the additional reserve is distributed within the non-critical block sections. The situation is entirely equivalent to the previous chapter in case of one train type only.

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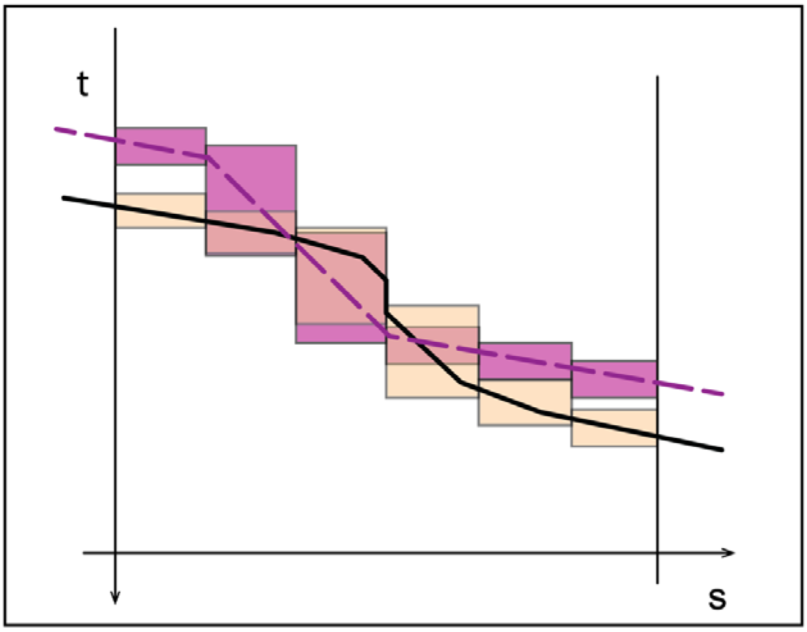
[3] According to the Figure 3 (right) this rule can be interpreted as “to each train in each block section with the exception of critical block section of the faster train in combination, if this train operates first”.

3.2.3 Avoiding conflict at operation phase

Rescheduling is a method for solving train path conflict, which is typically done by elimination of non-commercial stops. This strategy is based on the fact, that any unplanned stop and following acceleration always consume much more time and energy than the early deceleration, running with lower speed and acceleration back to the ideal entry speed into limiting section. In the overall evaluation the system capacity increases, whereas in case of line sector evaluation, the capacity decreases prior to the arrival at the potential conflict point. Situation from already existing application in Lötschberg base tunnel, Switzerland, illustrates Figure 4.

Figure 4 Avoiding conflict at operation phase



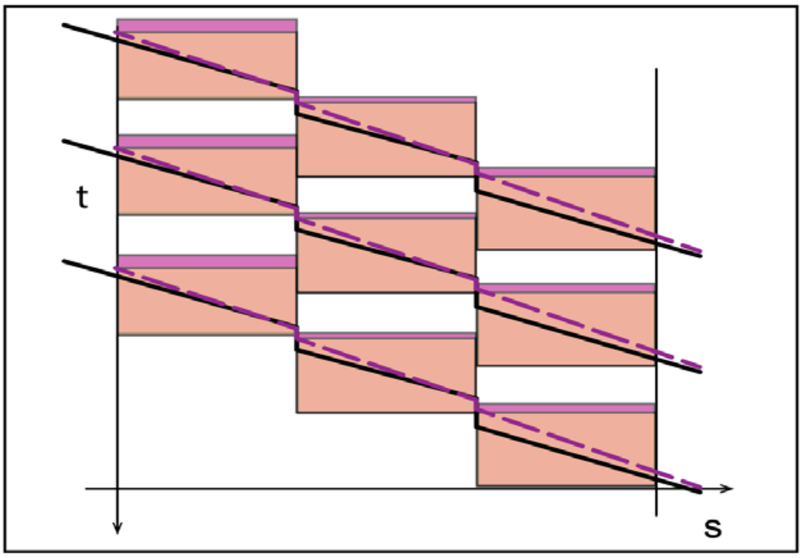
In case of additional junction situated on the arrival at the potential conflict point and existing traffic through, the capacity situation remains unclear with growth of capacity in one part and reduction in another part.

3.2.4 Special case: Suburban train's earlier departures

This case is a special form of proposal, which deals with time reserves that differ strongly during the different hours and/or days. This could include any parameters, related to different weights and train formations, different routes or different stop policy. The dependence between energy consumption of the required train operation, the possible energy saving by minimal extension of running time and combination with varying minimal station stopping times could be combined into partly another reserve use policy (simplified illustrates also in 2.1). The required stops times for boarding change in very short periods during the days. The periodic timetable characteristic, where the boarding process period is during the whole day same, but dimensioned for the peaks, enables alternative use of this time reserve during non-peaks hours.

During these periods, the trains could leave the stations earlier, like immediately after the boarding is completed. That is nowadays not possible because of the published timetable. The solution is to shift the departure time to the earlier position and add this time difference to the running time to the next stop. During the non-peak periods, this additional time could be newly used for energy saving (dashed line in Figure 5), while during the peak periods the situation remains same (solid line in Figure 5), because the train has enough time to reach the next stop punctually. The only difference is the slightly higher delay on the departure from these stations. The infrastructure capacity impact over longer segments tends to be nil, with possible minimal local negative effects.

Figure 5 Earlier departure case



4. Résumé

Different cases and strategies with different impacts on usage of railway capacity have been presented. There are no always applicable rules and also the effects of energy efficient train driving methods on the capacity consumption are not always the same. Typically, the capacity consumption grows for single train situation and it grows also when each train is considered separately. But in the multiple train situations, the total capacity consumption could also be stable or could decrease (summary in Table 2).

Table 2 Cases where the energy efficient train driving methods are not reducing the railway infrastructure capacity

Operational concept state	Dealing with reserves	Nr. of trains	Cases not reducing capacity
DESIGN phase	Changing / defining timetable reserves	1	–
	Changing / defining timetable reserves	2+	Heterogeneous train operations (3.2.1), Homogeneous traffic on the line with heterogeneous sections (3.2.2), Special case: Earlier departures (3.2.4)
OPERATION phase	Using / distributing timetable reserves	1	Single block section optimization (as generally described in 2.1)
	Using / distributing timetable reserves	2+	Avoiding conflict (3.2.3)

The asset is to plan and organize train operation, path and whole timetable to reduce the energy consumption of the trains according their impact on the railway capacity. In the cases, where additional capacity exists, every solution can be used. In other cases, solution for the same capacity consumption or capacity-gaining solution could be used to reduce the overall energy consumption of the railway system.

5. References

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