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Infrastructure design for robust operations on railway corridors – Quantifying the combined effects of overtaking tracks and dispatching strategies

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Abstract

Railway infrastructure in densely utilized European networks is coming under increasing stress, especially on main traffic corridors shared by passenger and freight services with different speed profiles and stopping policies. Siding tracks allowing to change the train order are important design features to optimize capacity and to ensure robustness by allowing to schedule more trains with different characteristics and to adjust train order in operations. This work presents a comprehensive analysis of the relationship between infrastructure layout, dispatching policy, and operational stability for double-track railway lines, investigating the effect of additional overtaking tracks on the performance of rail corridors. A timetable-ensemble generating approach is used and the operational robustness is evaluated using mesoscopic discrete-event simulation of train operations on the corridor considering a set of typical dispatching heuristics observed in practice. The method is then applied in a case study for a railway corridor in Southern Germany and the robustness of the infrastructure design is evaluated as a function of the strength of perturbations. Overall, the study demonstrates the importance of well-designed dispatching strategies for simulation-based scenario evaluation and shows how the benefit of additional overtaking tracks depends on timetable heterogeneity, traffic load, and the level of primary delays.

Keywords: railway; railway corridor; infrastructure design; capacity; performance modeling, operational stability; timetabling; dispatching

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1. Introduction

In view of growing passenger numbers and freight volumes, railway networks in Central Europe are experiencing more and more stress on the infrastructure, leading to increased wear and delays. As a result, measures to maintain service quality and stability of operations need to be implemented. One example of such measures is given by Germany, where a general overhaul of the infrastructure on central transportation corridors is currently performed, including an upgrade of the existing infrastructure with additional crossovers and overtaking tracks to satisfy the requirements of a future national timetable concept (Deutschland-Takt) and to provide additional flexibility in managing operations.

Infrastructure projects are generally evaluated based on a cost-benefit analysis featuring the projected needs in terms of track capacity and timetable feasibility. However, system designs, which may nominally appear to satisfy the planning requirements, risk being insufficient in perturbed operations. While the robustness and stability of timetable concepts can be evaluated and the effectiveness of infrastructure adjustments can hence be quantified, limited decision support and understanding exist for quantifying the benefits of infrastructure adaptations for the flexibility and robustness of operations on railway lines shared by passenger and freight services. This is particularly true in the case of a significant deviation of services from their scheduled slots.

Given the differing speed profiles and uncertainty in the order of trains, sufficient provision of overtaking tracks allowing for the change of train order and to adjust traffic flow is vital to maintaining a good service quality and performance on these corridors. In the present study, we seek to understand and optimize the effect of overtaking options as a function of the traffic volume and general reliability of operations on the performance of rail corridors. The results can serve to provide decision support in strategic long-term planning in assessing the robustness of operations and the flexibility of the infrastructure, also allowing for the quantification of the benefit of additional resilience in infrastructure design.

The paper is structured as follows: After a review of related work in section 2, the methodology for timetable generation, simulation, and evaluation is introduced in section 3. Results are divided into two subsections, where subsection 4.1 deduces determining factors for the benefit of overtaking stations from the analysis of a wide variety of generic scenarios, while subsection 4.2 applies these insights to a real-world example.

2. Related work and own contribution

Providing decision support for railway infrastructure design is an important aspect of railway capacity analysis. Various approaches have been proposed to assess the quality of timetabling and operational robustness on a given infrastructure (Sameni and Moradi, 2022; Lusby et al., 2018). Implicitly, the infrastructure design of railway corridors and the number and position of overtaking stations are considered in many methods, e.g., as a function of minimum headway times (Deutsche Bahn AG, 2022), infrastructure segmentation depending on the location of scheduled overtakings (UIC, 2013), or timetable-ensemble-based approaches (Coviello et al., 2023; Weik et al., 2020). However, the role and effectiveness of line designs to mitigate delays, focusing specifically on infrastructure design, has received relatively little consideration. Jensen et al. (2017) propose a procedure for assessing the capacity of a given infrastructure, including robustness estimates for an ensemble of timetables. Lindfeldt (2010b) uses a more holistic approach and relates infrastructure, timetable and perturbations to the resulting operational quality using microscopic simulations. Due to the great detail of such microscopic simulation methods, computation time tends to limit the number of scenarios for which such evaluations can be performed. To circumvent this limitation, Zinser et al. (2019) present an alternative to time consuming microscopic simulations using a discrete event approach.

On railway lines, the impact of overtaking stations on operational stability has been studied in (Kogel, 2021; Lindfeldt, 2010a,b). Kogel (2021) focuses on the extension of analytical models by including overtakings, using a hybrid simulation-based approach to provide input data for analytic models. To the best of our knowledge, (Lindfeldt, 2010b) is the only work that systematically analyses the impact of the spacing of overtaking stations for different timetable and disturbance scenarios on operational stability.

In the present study, we extend the work performed by Lindfeldt (2010a). First, the focus is explicitly put on overtaking stations as operational points that allow for traffic flow control in the simulation approach. Second, different dispatching strategies used by infrastructure managers are taken into account as an additional factor influencing operational quality.

The main contributions of our work are:

1. An analysis framework integrating infrastructure design, timetable generation, and time-efficient operational simulation, including a variety of dispatching strategies, is introduced.
2. A timetable ensemble generation approach allowing to generate families of feasible timetables preserving important structural properties for different infrastructure layouts is presented.
3. The effects of additional overtaking stations on operational stability on railway corridors are evaluated.
4. The usability of the approach is demonstrated in an analysis of a railway line in Southern Germany.

3. Method

As systems under investigation, we consider double-track railway lines connecting two hub stations *A* and *B*, disposing of a fixed-block signaling infrastructure with parameterizable length of block sections and position of overtaking tracks. As the main question of this study is the usability and effect of overtaking stations, the central parameter defining infrastructure scenarios in the study is the number of overtaking stations between the two hubs.

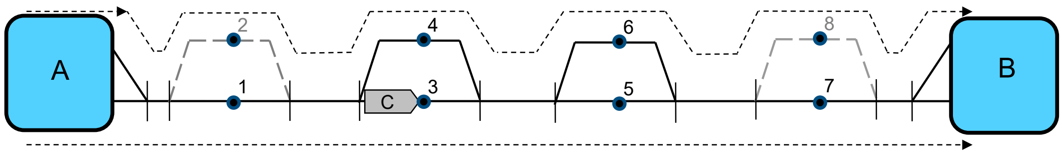

Fig. 1. Schematic depiction of the rail corridor considered. Infrastructure layouts differ by the number of overtaking stations (grey dashed lines).

For the analysis of the corridor, an ensemble of periodic timetables with multiple passenger and freight services is considered, reflecting typical operations on mixed-service rail corridors. To this end, timetables are generated for different train combinations and orders, and the feasibility of all timetables is verified microscopically based on blocking times denoting the infrastructure occupation of trains as determined by the signalling system.

Given the generally large uncertainty of the timing of freight trains, in particular, which requires massive dispatching and limits the applicability of timetable-based approaches, a mesoscopic discrete-event simulation of operations on rail corridors is performed to assess each scenario's operational stability. The simulation can be adjusted for different dispatching strategies such that specific events at overtaking stations trigger dispatching decisions that decide to either hold the respective train back or release it to the subsequent track segment.

3.1. Dynamic event-activity-graph construction

Event-Activity-Graphs are widely used for modeling railway operations and timetabling (Goverde, 2007). In this work, they are used to generate timetables and to perform operational simulations, where each event corresponds to either an arrival or departure event in a hub or overtaking station. The activities encoding the minimum durations between two connected events correspond to minimum running and dwell times for successive events belonging to the same train and minimum headway times for events belonging to successive trains occupying the same resource.

Each event's time is calculated according to the following equation:

$$t_j = \max(\max_{i \in P(j)} a_{i,j} + t_i, s_j), \tag{1}$$

with t_j the time of event j, $P(j)$ the set of predecessors of event j, $a_{i,j}$ the minimum duration of the activity connecting event i and j and s_j being the scheduled event time.

To model unscheduled overtakings, the dependencies relating different trains cannot be assumed fixed but need to be set dynamically for each overtaking station and single-track section. Therefore, a heuristic method is developed to dynamically reorder the sequence of departure events at each overtaking station throughout the corridor, depending on the current state of all trains. The procedure is presented in Algorithm 1. It is worth noting that deadlocks, which would correspond to cycles in the resulting event-activity graph, are avoided by iteratively selecting the next departure event for each overtaking station. The resulting temporal sequence of departures thereby determines the dependencies between departure events, which contradicts the formation of any cycles.

Timetables are parameterized by defining periodic departures at hub A and the maximum speed for each train type. From this, minimum running and headway times are calculated. Together with the predefined departure events, the entire activity graph can be constructed using Algorithm 1, resulting in a conflict-free timetable.

For the operational simulation of a given timetable, departure times are perturbed by adding a stochastic delay drawn from an exponential delay distribution, which is widely used in railway modeling (Deutsche Bahn AG, 2022; Weik et al., 2016; Yuan, 2006). Again, the activity graph can be dynamically constructed, thereby modeling the operation given the uncertainty in the departure times and dispatching in the form of performing unscheduled overtakings.

Algorithm 1 Dynamic event-activity-graph construction algorithm

```
Input: all scheduled event nodes
Output: all event times
Initialize track_segment_to_last_departure ← {}
Initialize root_nodes ← all event nodes with no predecessors
Initialize dispatching_events ← []
while root_nodes ≠ ∅ do
    changed ← False
    event ← root_nodes.pop()

    // This block calculates event times if possible. Otherwise, the events are added to the dispatching queue.
    if event.is_arrival_event or event.is_dispatched then
        set_time(event)                                                   ▷ Uses eq. 1
        Add successors of event to root_nodes
        changed = true
    else if event.is_departure_event then
        dispatching_events.add(event)
        root_nodes.insert(event, 0)
        changed = true
    else
        root_nodes.insert(event, 0)
    end if

    // This block processes the dispatching queue.
    if dispatching_events ≠ ∅ and not changed then
        dispatching_event ← dispatching_events.pop()
        alternative_trains ← alternative trains that could be dispatched next into next_track_segment
        // Decides, if the train should enter the segment next using one of the functions from 3.2.
        if dispatcher(dispatching_event, alternative_trains) then
            //Add the event corresponding to the last train entering the segment to the predecessors.
            last_event ← track_segment_to_last_departure[next_track_segment]
            dispatching_event.predecessors.add(last_event)
            //Add the current dispatching event to the segment.
            track_segment_to_departure[next_track_segment] ← dispatching_event
            dispatching_event.is_dispatched ← true
        else
            dispatching_events.add(dispatching_event)
        end if
    end if
end while
```

3.2. Dispatching heuristics

In our framework, dispatching heuristics are functions that are called at the moment a train is ready to depart from a hub or overtaking station, here referred to as dispatching time $t^d_{v,w}$, where v refers to the train and w to the station. A dispatching function can take the entire system state at the dispatching time into account (but typically only looks at a subset thereof) and returns a boolean value: *true* if the train is supposed to enter the next section as soon as possible and $false$ in case it is supposed to be held back.

The dispatching policies discussed and compared in this paper are:

- *FSFS:* This abbreviation stands for first scheduled, first served and describes a strategy where the scheduled train order is strictly maintained.
- *FIFO:* The first in, first out dispatching strategy dispatches trains as soon as they are ready, thereby ignoring alternative trains approaching the overtaking station.
- *Look-ahead:* The look ahead dispatching heuristic consists of three steps:

    1. Identify alternatives
    2. Model alternative decisions one step into the future
    3. Estimate delays
    4. Dispatch

While the first two heuristics are well-known in the context of rail dispatching, the look-ahead strategy requires a more detailed description. In the following, the train triggering a dispatching decision will be referred to as $train_{disp}$ and the station from which $train_{disp}$ needs to be dispatched is referred to as $station_{dispatch}$. Step 1 identifies a set of trains that, in principle, could be sent before $train_{disp}$, i.e., trains that could overtake $train_{disp}$. These trains either perform a dwell activity in $station_{dispatch}$ at the time of the decision or approach $station_{dispatch}$. Step 2 will then calculate two scenarios for each of the alternative trains. One scenario will assume $train_{disp}$ to be dispatched first. In contrast, the second will assume the alternative train to be dispatched first based on predicted dispatching times for the alternative train. Step 3 then predicts the delays for $train_{disp}$ and each alternative train in both scenarios. This gives a matrix of numbers $M_{k,l}$, where k runs over all alternative trains and l over both scenarios. An aggregating function will then take this matrix as input and return the decision as a boolean value.

The look-ahead strategy, given its perception of the effects of dispatching, is expected to be superior in most scenarios. However, the aggregating function significantly influences the propagation of delays, which is why two different weightings of delays will be considered here: The *linear* (subsequently abbreviated by *LAL* for 'Look-Ahead-Linear') function returns *true* if the sum of the predicted delay of $train_{disp}$ and the alternative train at the next station is lower, in the scenario where $train_{disp}$ is dispatched first for each alternative train. By contrast, the *quadratic* function (subsequently abbreviated by *LAQ* for 'Look-Ahead-Quadratic') compares the squared sum of predicted delays rather than the linear sum, thereby avoiding the buildup of large delays.

4. Results

4.1. Generic systems

We subsequently study the effects of the level of uncertainty, overtaking station spacing, timetable, and dispatching strategy on operational performance using the aforementioned approach. To this end, a generic railway line with a length of 100 km is considered. On this line, 960 scenarios are simulated using a Monte Carlo approach. Operational quality is quantified using the average arrival delay at the final station $\bar{d}_{arr,f}$. The primary delay level corresponds to the scale parameter of the exponential distribution from which primary delays are drawn. An overview of all quantities defining a scenario is provided in Table 1.

Each timetable consists of two service types defined by their maximum speed, both running with a frequency determined by the following equation:

$$f_{slow} = f_{fast} = \frac{\rho}{2}, \tag{2}$$

Table 1. Parameters and values for scenario generation.

Parameter	Values
Traffic Load ρ [Trains/h]	4, 6, 8, 10
Max speed of faster service v_{fast} [km/h]	200, 140, 110
Overtaking spacing ΔL [km]	6, 12, 24, 48
Primary delay level $\bar{d}_{arr,i}$ [s]	0, 120, 240, 360, 480
Dispatching strategy	FSFS, FIFO, LAL, LAQ

where f_{slow} and f_{fast} refer to the frequency of the respective service. Furthermore, all timetables are constructed for the infrastructure layout with the least overtaking stations in order to isolate the effect of additional overtaking stations on operational stability. While the maximum speed is constant at a value of 100 km/h for the slower service, the speed of the faster service is varied according to the parameter v_{fast} in Table 1.

Figure 2 shows the best-performing dispatching strategy for each combination of timetable, infrastructure, and primary delay, ordered by the level of primary delays. While there is a clear tendency towards higher output delays as a function of the level of the initial perturbation, there does not seem to be a clear indication towards an optimal dispatching strategy for all scenarios, demonstrating the necessity to integrate the dispatching strategy into strategic planning procedures in order to get a realistic estimate for operational performance.

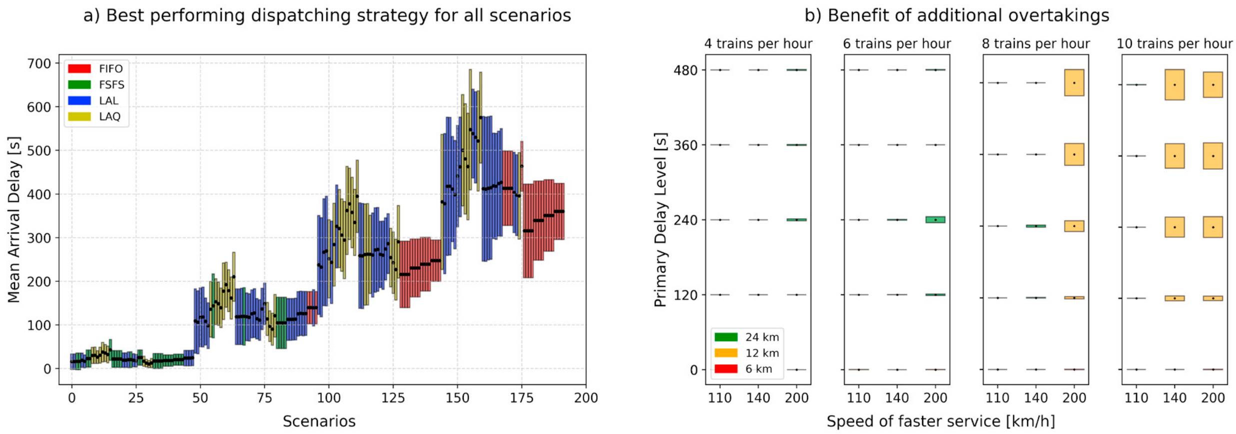

Fig. 2. (a) Best-performing dispatching strategy for each combination of timetable, infrastructure design, and primary delay level. Scenarios without primary delay are not considered, resulting in 192 (12 timetables, 4 infrastructure designs, and 4 primary delay levels). The best-performing dispatching strategy is indicated by color for each scenario defined by timetable, infrastructure, and primary delay level. The height of each bar indicates the standard deviation of the mean arrival delay across the various Monte Carlo realizations. Scenarios are ordered w.r.t. applied primary delay. (b) Operational quality in the case of additional overtaking stations as opposed to the base layout for each combination of timetable and primary delay level. The color of each box indicates the best-performing infrastructure layout, while the height indicates the benefit $\Delta\bar{d}^{I}_{arr,f}$ defined in Equation 3 and uses the same scale as the primary delay level.

This leads to the following key aspect of our framework: Each scenario, defined by infrastructure and timetable, is simulated for each dispatching strategy. Only the best-performing strategy is used to estimate the operational quality of this combination of timetable and infrastructure, while the rest is discarded. The reasoning for this approach is the assumption that experienced real-world dispatchers will perform at least as well as the best of our heuristic strategies.

This allows for evaluating the benefit of overtaking stations depending on the timetable and primary delay by separating operational details from the impact factors relevant to strategic planning. Figure 2 illustrates the benefit of the best performing infrastructure layout compared to the base layout with only two overtaking stations for each timetable and primary delay level. This benefit is quantified as the difference in mean arrival delay

$$\Delta\bar{d}^{I}_{arr,f} = \bar{d}^{I_B}_{arr,f} - \bar{d}^{I}_{arr,f}, \quad (3)$$

where $\bar{d}^{I_B}_{arr,f}$ refers to the mean arrival delay of the base infrastructure layout ($\Delta L = 48\ km$) and $\bar{d}^{I}_{arr,f}$ refers to the mean arrival delay of the scenario regarded. In Figure 2 corresponding results are visualized by the height of each box.

It can be seen from Figure 2 that the highest benefits are achieved for high traffic loads, speed differences and primary delay levels, i.e., in agreement with expectations, the results are most prominent in case of dense heterogeneous, and strongly perturbed operations. In all these cases, the layout with the 12 km spacing of overtaking stations performed best, consistently outperforming the infrastructure layout with a 6 km overtaking spacing. This exposes the limitation of widely used, locally-operated dispatching policies analyzed in this study: Ideally, the additional operational flexibility provided by more overtaking stations should never lead to a decrease in stability. However, the heuristic and local nature of the policies does not assure such behavior.

4.2. Case study

Finally, we apply our approach in a case study to the railway line between Regensburg and Nuremberg (see Figure 3), a heavily-used corridor served by passenger long-distance and regional services, as well as freight traffic. Infrastructure data is retrieved from (OpenStreetMap contributors, 2017), and the passenger timetable is retrieved from (Delfi, 2025).

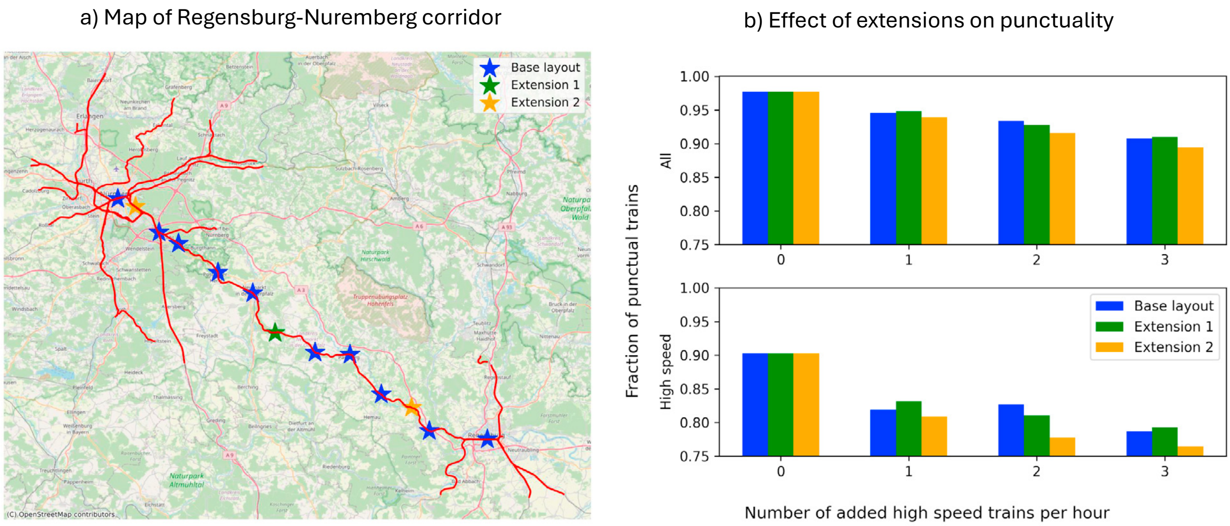

Fig. 3. Case Study overview: (a) A map of the corridor with the extensions considered in the case study. (b) Fraction of trains with a delay less than 6 min. for a primary delay level of 240 s. Only scenarios where high-speed trains are added to the existing passenger timetable are considered, while the color indicates the infrastructure layout illustrated in a).

Again, a variety of scenarios are considered by combining different extensions to the real-world infrastructure layout, different timetables and levels of primary delay. The two infrastructure extensions include one and three additional overtaking stations. Each additional overtaking station is placed in the middle of the two successive existing overtaking stations with maximum spatial separation. The timetables are generated by adding zero, one, two and three trains per hour to the passenger timetable. The additional trains either all have a maximum speed of 90 km/h or use the maximum speed allowed by the respective speed limit throughout the entire corridor.

When applying the benefit analysis based on Equation 3 on the case study, we surprisingly observed that neither of the extensions shown in Figure 3a) seems to yield any benefit compared to the existing base layout. This can probably be explained by the system's properties and the observations in Section 4.1: For the generic system, operational quality was significantly improved only by decreasing the overtaking spacing up to 12 km, and for timetables with a standard deviation in speed of at least 20 km/h. The Regensburg-Nuremberg corridor has one section where the two successive overtaking stations are 20.5 km apart. In contrast, for all remaining sections, the spacing is 14 km or less. The standard deviation in speed for the 20.5 km section, however, exhibits at most a value of 15 km/h. This suggests that this corridor is saturated with overtaking stations for the timetables considered. In general, unscheduled overtakings are a measure to sacrifice the travel time of a slower train for the benefit of a faster train. This motivates a more differentiated perspective provided by Figure 3b). Here, the fraction of trains arriving at their respective final stops with a delay smaller than 6 min (the punctuality threshold in Germany) is shown for a primary delay level of 240 s. Only scenarios where high-speed trains are added to the existing timetable are considered. While the top subplot shows the fraction of punctual trains across all train types, the bottom subplot shows the fraction of punctual high-speed trains. For one additional high-speed train, *Extension* 1 increases the share of punctual high-speed trains by 1.3 percentage points. This highlights several important aspects for infrastructure planning: First, it shows the ambiguity in quantifying the benefit of overtaking stations, as the additional operational flexibility does not affect all train types equally. Furthermore, we see no strong tendency for benefit to increase with the traffic load, highlighting the necessity to model each scenario (as well as the dispatching policies) explicitly, rather than relying on general rules.

5. Conclusion and outlook

This work introduces a framework for the evaluation of the benefit of additional overtaking stations on railway corridors. This framework allows for the efficient construction of large timetable ensembles and time-efficient operational simulation using a Monte Carlo approach. At the core of this framework lies a dynamic event-graph construction routine (Algorithm 1), thereby ordering departure sequences based on state-dependent heuristics. By performing operational simulations with a variety of dispatching strategies, a better estimation of the operational performance can be achieved for each combination of timetable and infrastructure layout. Due to the low computational cost, a large number of timetable-infrastructure scenarios can be evaluated. An analysis of a generic system revealed that traffic load, primary delay level, and heterogeneity, quantified by the differences in speeds of services, are determining factors for the benefit of additional overtaking stations. The framework was applied to evaluate the corridor connecting the two German cities, Regensburg and Nuremberg, for which the benefit of the additional overtaking stations is more ambiguous: while overall delay is not reduced, the punctuality of high-speed trains is increased for specific timetables. In the future, the systematic analysis of the influence of dispatching strategies should be extended by including reinforcement learning based methods and other heuristic methods that weigh the build-up of delays associated with overtaking decisions depending on the service type. This could help to fully explore the flexibility in tuning the trade-offs in operational quality between different service types.

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