



CANCEL-RUN FRONTIERS FOR DELAYED TRAINS UNDER RAILWAY PERFORMANCE REGIMES

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Abstract

This study examines how small schedule buffers and overtaking permissions affect cancel-or-run decisions for delayed trains under the Performance Regimes (PRs) applied in European countries. For a given primary delay (r_0) and a remaining run time r , secondary delays caused to following services are computed. Primary and secondary delays are then mapped into PR-minute equivalents through country-specific thresholds, caps, and rates, and compared with a cancellation yardstick derived from path-cancellation rules. Four operational scenarios are assessed on identical timetables: (S1) no overtaking, no buffer; (S2) station overtaking, no buffer, (S3) no overtaking with sub-threshold buffer(s), and (S4) station overtaking combined with sub-threshold buffer(s). For each scenario, a strategy-conditioned frontier (θ) is obtained, as the smallest primary delay at which cancellation becomes cost-preferred to continuing. Outputs include per-country frontiers, a comparative strategy analysis identifying regions in where buffering or overtaking widens or shrinks the safe-to-run region. The framework separates timetable-propagation mechanics from policy parameters, enabling reproducible cross-country comparisons and actionable guidance without assuming operating-cost inputs. The processes are simulated using an original Python-based simplified timetabling software.

Keywords: delay propagation, timetable buffering, performance regimes, dispatching decision, train cancellation

1 Introduction and research background

Extensive research has addressed railway delay propagation and timetable robustness using both microscopic and macroscopic simulation approaches [1]. Punctuality remains a central performance indicator, typically defined as the proportion of trains arriving within a specified delay threshold [11]. A key distinction in the literature separates primary delays from secondary (reactionary) delays, with studies showing that the latter often dominate overall system performance. Methods based on macroscopic tools, such as PROTON, have enabled systematic separation and analysis of these delay components [1], while diffusion-based approaches further model delay spreading across networks [2], reinforcing the importance of capturing propagation dynamics accurately. More recent work frames delay management as an integrated problem linking propagation mechanisms, timetable design, and institutional incentives [1, 3]. Primary disturbances propagate through networks via headway constraints, conflicts, and priority rules, while operational measures such as buffering and overtaking influence the extent of delay amplification. At the same time, PRs translate operational outcomes into financial or regulatory consequences. Empirical and simulation-based studies highlight the role of capacity utilization, operational variability, and dispatching rules in shaping propagation patterns, particularly in mixed-traffic systems [5, 6].

However, many rescheduling approaches remain deterministic, often assuming fixed disruption durations or demand conditions, and therefore may not fully capture the complexity of real-world delay evolution [12].

Despite this growing body of work, several gaps remain. First, there is a lack of reproducible cross-country methodologies that isolate policy effects by holding delay-propagation mechanics constant while varying national PR parameters. Second, limited attention has been given to sub-threshold buffering strategies, even though such margins may significantly affect outcomes without triggering PR penalties [8]. Third, overtaking is rarely analyzed as a policy-sensitive control, despite its role in redistributing delays across trains and market segments [9]. Finally, increasing regulatory focus on performance schemes within the European railway framework highlights the need for comparable and policy-consistent analytical tools, particularly in light of cross-border coordination and harmonization challenges [1, 2, 10].

2 Methodology

This study uses a Python-based simulation framework to analyze delay propagation under controlled timetable and dispatching conditions. A deterministic baseline timetable is generated parametrically and kept identical across all experiments, ensuring that differences arise only from operational strategies and PR parameters. Primary delays are introduced exogenously without altering the timetable structure, and propagation is computed using formula (1) based on headway and spacing constraints, producing a delayed timetable with potential conflicts. These conflicts are resolved via a priority-based mechanism that allows station overtaking or enforces first-come-first-served rules, generating secondary delays.

$$D_n = \max \left[0, \left(\delta_n^{pri} + (H_{min} - \sum_{k=1}^{n-1} H_k) \right) \right] \quad (1)$$

Where:

- D_n - Total delay applied at the origin of train n (secondary delays) in minutes
- δ_n^{pri} - Primary delay applied at the origin of train n in minutes
- H_{min} - Minimum required headway between any two trains in minutes
- H_k - Planned headway between origin departures k and $k+1$ in minutes.

Sub-threshold buffers can then be applied without triggering PR penalties. Delays are aggregated at the train level, and a cancellation reference time is computed based on total delay and PR-specific costs, yielding endogenous cancel-or-run decisions. All scenarios share identical mechanics, varying only operational controls and PR parameters for consistent comparison.

3 Case study

The framework is applied to Austria, Norway, and Sweden, enabling cancel-or-run decisions to be compared under identical timetable mechanics so that differences reflect PR parameters rather than operational conditions. Delay penalties and cancellation charges are modeled from both RU and IM perspectives and expressed in PR-consistent units. A strategy-conditioned cancellation frontier (θ) is derived, identifying the minimum delay at which cancellation becomes preferable as a function of remaining runtime and operational strategy. By holding timetable mechanics fixed, the frontiers isolate how PR design and operational controls shift the boundary between run and cancel outcomes.

3.1 Performance regimes across studied countries

In this section, for each case study, PR and cancellation fees are evaluated from RU and IM perspectives (table 1), θ is derived (tables 2 and 3), identifying the primary delay at which cancellation becomes cost-preferred.

Table 1 PR fees in studied countries [EUR/min]

Country	IM		RU	
	Passenger	Freight	Passenger	Freight
Austria	0.7755	0.7755	0.7755	0.7755
Norway	9.62	3.47	14.13	5.03
Sweden	7.09	7.09	7.09	7.09

Table 2 Calculated θ for the studied countries where responsible party is a RU

Fees and θ based on market segment	Austria	Norway	Sweden	Unit
Cancellation fee-Passenger	461.93	703.55	188.69	EUR
θ -Passenger	595.65	50.03	26.65	min
Cancellation fee-Freight	461.93	1055.32	188.69	EUR
θ -Freight	595.65	211.06	26.65	Min

Table 3 Calculated θ for the studied countries where responsible party is an IM

Fees and θ based on market segment	Austria	Norway	Sweden	Unit
Cancellation fee-Passenger	461.93	496.99	188.69	EUR
θ -Passenger	595.65	51.87	26.65	min
Cancellation fee-Freight	461.93	745.48	188.69	EUR
θ -Freight	595.65	216.081	26.65	Min

Under the Austrian PR, delay-related penalties are capped at 120 minutes. As a result, the simulated delay levels do not lead to cancellation decisions based solely on delay accumulation.

3.2 Base scenario and assumptions

To ensure consistency and comparability across all scenarios, a set of key assumptions is defined (table 4). These assumptions form the basis of the modelling framework, allowing results to reflect the operational and regulatory mechanisms under study. By standardizing selected parameters, the analysis isolates the effects of delay generation and propagation under different PRs. Based on these assumptions, a reference timetable, hereafter the Original Timetable, is constructed (figure 1).

Table 4 Assumed variables to create the timetable

Type of service	Train length [m]	Speed [km/h]	Dwelling time [Min]	Track length [km]	Number of trains	Spacing [km]	Minimum spacing [km]
Regional	150	130	5	100	5	5	5
Commuter	60	80				5	

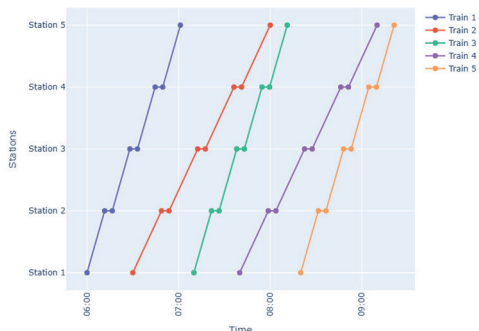


Figure 1 Baseline timetable space time diagram without delays

3.3 Scenario 1: no overtaking without buffer

This scenario represents a baseline dispatching policy in which station overtaking is not possible and no timetable buffers are applied. Conflicts arising from delay propagation are resolved strictly according to priority and minimum spacing constraints, resulting in maximum secondary delay transmission to the following trains. As shown in figure 2 and table 5, under the Swedish PR all three trains are subject to cancellation in both freight and passenger services, irrespective of whether responsibility lies with the RU or the IM. In contrast, under the Norwegian regime no passenger trains are cancelled when the IM is responsible, whereas responsibility attributed to the RU results in the cancellation of Train 1. No cancellations occur in Austria, nor in the Norwegian freight sector, across the analyzed cases.

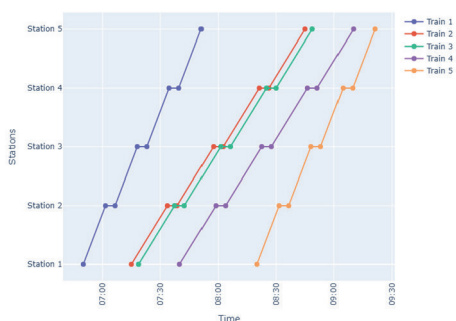


Figure 2 No overtaking without buffer times space time diagram

Table 5 Summary of delays for the first scenario

Train Number	Delay [min]	Primary/secondary
1	50	Primary
2	45	Primary
3	37.5	Secondary
4	0	-
5	0	-

3.4 Scenario 2: station overtaking without buffer

In this scenario, station overtaking is allowed according to train priority rules, while no time-table buffers are introduced. This configuration isolates the effect of overtaking, without modifying scheduled running or dwell times. As illustrated in figure 3 and table 6, the first and the second trains are cancelled under the Swedish PR irrespective of market segment or responsibility attribution. In Norway, the same two trains are cancelled in the passenger sector when responsibility is assigned to the RU, while no cancellations occur when responsibility lies with the IM. No trains are cancelled in the Norwegian freight sector or in either sector in Austria across the analyzed cases.

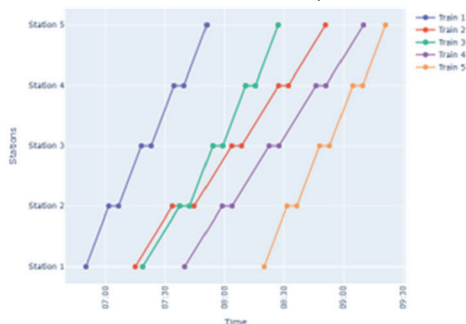


Figure 3 Overtaking without buffer times space time diagram

Table 6 Summary of delays for the second scenario

Train Number	Delay [min]	Primary/Secondary
1	50	Primary
2	51.05	Primary + Secondary
3	15.95	Secondary
4	0	-
5	0	-

3.5 Scenario 3: no overtaking with buffer

This scenario (figure 4 and table 7) examines the effect of introducing sub-threshold time-table buffers while maintaining a no-overtaking policy. To optimize the delay of train number 3, buffers are applied in a controlled manner, ensuring that they remain below PR delay thresholds.

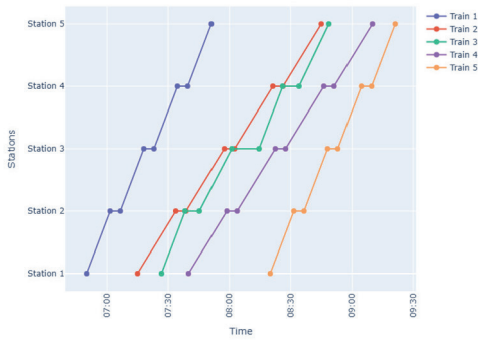


Figure 4 No overtaking with buffer times space time diagram

Table 7 Summary of delays for the third scenario

Train number	Delay [min]	Primary/Secondary
1	50	Primary
2	45	Primary + Secondary
3	24,5	Secondary
4	0	-
5	0	-

By introducing sub-threshold buffers, 2 minutes at station 2, 3 minutes at station 3, and 8 minutes at the origin, the applied margins do not independently trigger PR penalties but reduce the delay of Train 3 by 13 minutes. As a result, unlike in the other scenarios, Train 3 is not cancelled in any of the analyzed cases, irrespective of responsibility attribution or market segment.

3.6 Scenario 4: station overtaking with buffer

The final scenario (figure 5 and table 8) combines station overtaking with sub-threshold buffering, representing the most flexible dispatching strategy considered in this study. Both controls are applied simultaneously to mitigate delay propagation and reduce exposure to PR penalties.

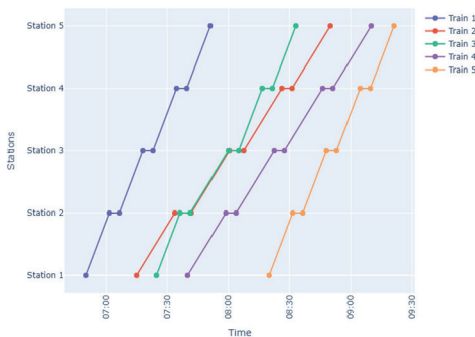


Figure 5 Overtaking with buffer times space time diagram

Table 8 Summary of delays for the fourth scenario

Train number	Delay [min]	Primary/Secondary
1	50	Primary
2	45	Primary + Secondary
3	15.95	Secondary
4	0	-
5	0	-

In figure 5, the combination of station overtaking and sub-threshold buffering allows Train 3 (a faster commuter service) to overtake Train 2 (a slower regional service) at Station 3. By adding 6 minutes to Train 3 at its origin and 3 minutes and 2 minutes of buffer to Train 2 at stations 2 and 3 respectively, the secondary delay previously transmitted to Train 2 is entirely eliminated. Consequently, Train 2 no longer crosses the cancellation frontier under the Norwegian PR, illustrating how flexible dispatching and strategic buffering work in tandem to mitigate regime-specific penalties

4 Conclusion

This paper introduced a regime-consistent framework to analyze cancel-or-run decisions under European PRs. While the results demonstrate that sub-threshold buffering can effectively prevent cancellations, the study has certain limitations. The simulation utilizes a deterministic baseline timetable and priority-based dispatching which may not capture the full stochastic variability of real-world operations, such as driver behavior or weather-related speed restrictions. Future research should incorporate stochastic delay distributions using Monte Carlo methods and investigate the impact of passenger-oriented metrics on cancellation decisions. For practical operations and timetable planning, it is recommended that IMs prioritize the placement of sub-threshold buffers at critical interaction points where overtaking is frequent. Furthermore, the findings suggest that the harmonization of PRs across international corridors is essential to ensure consistent operational decisions for cross-border services.

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