A Simulation-Based Framework for Assessing Capacity, Service Quality, and Profitability Trade-off in Railway Corridors

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SHORT SUMMARY

As railway networks are requested to accommodate higher traffic volumes, infrastructure managers face a fundamental trade-off between throughput, timetable robustness, and economic performance. Adding trains can increase access-charge revenue, but it can also reduce recovery margins and amplify the propagation of delays, thereby increasing performance-related penalties. This paper presents a mesoscopic simulation-based framework for assessing that trade-off at corridor level by integrating traffic-density scenarios, conflict-resolution logic, and a simplified financial evaluation based on Track Access Charges (TAC) and Performance Regimes (PR). Using an assumed corridor and Swedish pricing parameters as an illustrative case, the analysis shows that net economic performance is non-linear with respect to traffic density: beyond a certain utilization range, secondary delays increase faster than revenue, reducing net profit. The contribution is therefore methodological: to demonstrate how operational simulation and financial assessment can be combined to identify traffic-density ranges that remain economically robust under stochastic disturbances.

Keywords: Railway capacity, Delay propagation, Economic optimization, Service Quality, Track Access Charge, Performance Regime

1. INTRODUCTION

Modern railway management is concerned not only with scheduling trains efficiently, but also with understanding how stochastic disturbances propagate through a timetable as traffic density increases. The trade-off between maximizing capacity, commonly expressed in trains per hour, and preserving service quality becomes especially critical once the system approaches saturation and secondary (knock-on) delays begin to rise more rapidly (Sogin et al., 2015). In such conditions, timetable performance cannot be assessed solely in terms of nominal capacity, because a schedule that appears efficient under ideal conditions may prove fragile when exposed to even small random disturbances.

Although the International Union of Railways (UIC) 406 methodology provides a standardized basis for assessing capacity consumption through timetable compression (Landex et al., 2008), established capacity assessment approaches often place greater emphasis on throughput than on the economic consequences of degraded operational stability and service quality (Xu et al., 2026). This creates a need for analytical frameworks able to connect operational performance with financial outcomes, particularly in corridors where modest primary disturbances can propagate quickly across tightly packed schedules.

To address this gap, the present study develops a customized Python-based mesoscopic simulation framework for corridor-level analysis. The model represents train movements through segment-based travel times, dynamic headway constraints, and priority-based conflict resolution, allowing the interaction between traffic density and delay propagation to be examined under controlled assumptions. In this respect, the simulation draws on the broader literature on train movement modeling and calibration, while remaining intentionally simplified for comparative scenario analysis rather than exact microscopic reproduction of dispatching operations (Cunillera et al., 2023).

The operational module is integrated with a financial assessment based on TAC and PR, which are used to represent, respectively, the revenue associated with additional train paths and the economic consequences of propagated delay. This focus is consistent with prior work on how TAC mechanisms and PRs influence the generation and propagation of train delays (Asmari and Ricci, 2025). Within this integrated framework, the study examines how economic performance evolves with traffic density and whether an intermediate utilization range can be identified in which additional throughput remains economically attractive without triggering disproportionate delay costs (Xu et al., 2026).

2. SIMULATION LOGIC

The simulation model represents train movements on a railway corridor as a sequence of arrivals and departures at ordered stations. Each train i is defined by a stopping pattern, direction, priority level, commercial speed (v_i), dwell time (τ_i^{dw}), and a scheduled headway ($H_{Timetable}$). Infrastructure is represented by a set of stations with cumulative distances, from which segment lengths and running times are derived. In addition, a minimum-spacing parameter S_{min} is used to determine the minimum dynamic headway between consecutive trains.

For each train, the nominal timetable is first constructed without disturbances or conflicts. Let station s and station $s+1$ be two consecutive stops of train i, and let x_s denote the cumulative distance of station s. The running time on segment $(s, s+1)$ is computed as:

$$\tau_{i,s}^{run} = \frac{x_{s+1} - x_s}{v_i} \times 60 \tag{1}$$

where distance is measured in kilometers, speed in km/h, and time in minutes.

The initial arrival time at the origin station is given by the base simulation time t_0 plus scheduled headways:

$$a_{i,1}^0 = t^0 + H_{Timetable} \tag{2}$$

At the origin, departure is initially equal to arrival, unless additional delay is later imposed. For subsequent stations, nominal arrival is computed recursively as:

$$a_{i,s+1}^0 = d_{i,s}^0 + \tau_{i,s}^{run} \tag{3}$$

and nominal departure as:

$$d_{i,s}^0 = a_{i,s}^0 + \tau_i^{dw} \tag{4}$$

In the next step, the model applies a speed-dependent minimum headway, where the required separation between trains depends on the minimum-spacing parameter S_{min} and the speed (v_i) of train i, ensuring a minimum feasible spacing in minutes. After generating the nominal timetable, exogenous primary delays are introduced: each train may receive a delay with probability p, and the delay magnitude is drawn from a predefined interval and applied from a selected station

onward, shifting all subsequent arrivals and departures. The model then checks for conflicts between trains using the same segment. For trains in the same direction, the required headway must be respected at both departure and arrival. Conflicts are resolved iteratively through a rule-based procedure in which the lower-priority train is delayed and its downstream timetable is updated accordingly. In this way, the simulation captures how primary disturbances propagate through train interactions under increasing traffic density.

3. ECONOMIC ANALYSIS METHODOLOGY

The financial assessment is based on two mechanisms commonly used in European railway systems to link infrastructure use and operational performance to monetary outcomes: TACs and PRs. TAC represents the revenue received by the infrastructure manager for accommodating train services on the network. In this framework, it serves as a proxy for the gross economic benefit of infrastructure use, since revenue increases as more train paths are scheduled and operated. For the corridor considered, TAC is modeled as proportional to the number of scheduled trains, using an access-charge revenue per train path:

$$TAC = Number\ of\ Trains \times Distance \times TAC\ Rate \tag{5}$$

On the other hand, PR captures the performance-related monetary consequences of delay and is treated here as part of the broader charging framework. To isolate the effect of congestion-induced unreliability, only propagated secondary delay is priced. Primary delay is introduced exogenously as a stochastic disturbance and treated as an external shock rather than an outcome of timetable design. The analysis therefore evaluates not the direct cost of the initial disturbance, but the extent to which timetable saturation amplifies it through train interactions. For each train, total final delay is measured at destination, and secondary delay is defined as the portion of that final delay exceeding the exogenous primary delay, bounded below by zero. The corridor-level PR is then obtained by multiplying the sum of secondary delays by a unit monetary penalty per minute of propagated delay.
Net profit is therefore evaluated as:

$$Net\ Profit = TAC - PR \tag{6}$$

Under this formulation, TAC reflects the gross benefit of adding trains, while PR reflects the incremental economic burden associated with delay propagation under increasingly dense traffic conditions. The economic sweet spot is the traffic density (N^*) that maximizes economic performance.

4. RESULTS AND DISCUSSION

The economic evaluation of the simulated rail corridor is based on a financial framework derived from the Swedish railway market, selected here as the case study context for the analysis. The relationship between operational frequency and net profitability is assessed by balancing infrastructure revenues and delay-related costs under Swedish conditions. In this case, the infrastructure manager receives EUR 115.84 per 100 train-kilometers, while delay impacts are valued at EUR 7.09 per minute of delay recorded at the final destination. These parameters provide the financial basis for evaluating how increasing traffic density affects the economic performance of the corridor.

Simulation Setup and Fleet Profiles

The simulation utilizes a heterogeneous fleet to represent a realistic mix of traffic. Each service type is defined by its speed, the duration of its stops (dwell time), and its hierarchical importance for conflict resolution:

Table 1. Fleet Profiles

Service Class	Speed (km/h)	Dwell Time (min)	Priority Level
High-Speed	130	2	1 (Highest)
Regional	100	3	2
Commuter	80	5	3

To test the robustness of the corridor, the simulation introduces random operational disruptions. In this analysis, there is a 10% probability that any given train will experience an initial disruption. When such an event occurs, the duration of the delay is randomly selected from a range between 5 and 15 minutes.

The shift from profitable to unprofitable operation arises from a non-linear delay-propagation mechanism. At low to moderate traffic densities, timetable slack and dispatching priorities are generally sufficient to absorb localized disturbances before they spread across the network. As service frequency increases and departures become more closely spaced, however, each conflict-resolution decision consumes a greater share of the residual time margin. Consequently, delays that would have remained contained under lower-density conditions begin to propagate to subsequent departures and arrivals, thereby exposing a larger number of trains to PR penalties. Within this framework, the economic module computes net profit across different traffic densities by iterating over service frequencies expressed in trains per hour. This makes it possible to identify the threshold at which the marginal revenue generated by an additional train is offset, and ultimately outweighed, by the cumulative financial penalties associated with the delays it induces in other services.

Identification of the "Economic Sweet Spot"

The results of the simulation indicate that maximizing the number of services on a corridor rarely translates to maximum profitability. Instead, there exists a specific "Economic Sweet Spot" where the relationship between track usage and service quality is optimized. As illustrated in Figure 1, the network's performance can be interpreted across three traffic-density regions based on the behavior of the TAC revenue, PR penalty cost, and total profit curves.

- Low-density region: at lower numbers of scheduled trains, TAC revenue increases steadily while PR penalty costs remain low, so total profit stays positive. In this region, the timetable has sufficient flexibility to absorb small disturbances, and delay propagation remains limited.
- Balanced region: around the marked "Sweet Spot," corresponding to 6 trains per hour, the corridor reaches its most favorable economic balance, with a total profit of EUR 806. At this point, additional train paths still generate revenue without triggering substantial growth in delay-related costs. The system therefore operates near its best trade-off between utilization and robustness, and minor primary delays can still be absorbed without causing severe secondary delay propagation.
- High-density region: as the number of scheduled trains increases further, PR penalty costs rise much more rapidly than TAC revenue, indicating that the timetable has become increasingly sensitive to disturbances. In this region, even small delays propagate through

the dense traffic pattern, causing the total profit curve to decline sharply and eventually become negative, as the economic impact of cumulative delays exceeds the marginal revenue gained from adding more services.

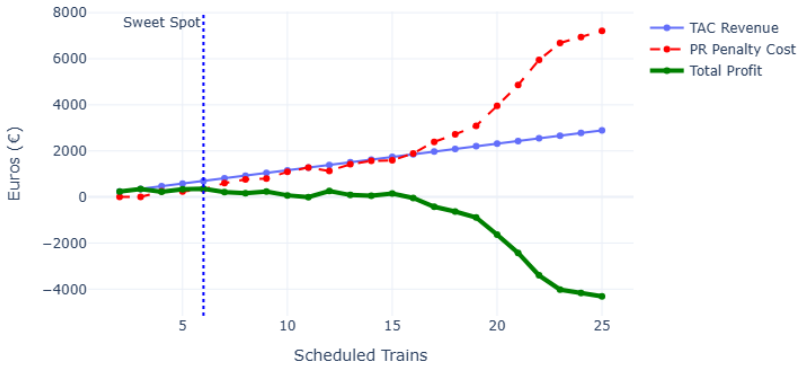


Figure 1. Infrastructure manager profit regarding different network utilization

5. CONCLUSION AND FUTURE DIRECTIONS

Since the identified economic optimum depends on the assumed corridor configuration, fleet composition, conflict-resolution rules, and the Swedish financial parameters adopted in the analysis, the findings should be interpreted as a proof of concept rather than as a basis for network-wide generalization. Alternative infrastructure layouts, dispatching strategies, or delay patterns may alter both the position and the magnitude of this optimum. The principal contribution of the study is therefore methodological, namely, to demonstrate how operational simulation can be integrated with financial assessment in order to identify traffic-density ranges that remain economically robust. The simulation and economic assessment further indicate that railway profitability is not a linear function of traffic volume, but instead emerges from the balance between capacity utilization and operational stability. Using an assumed corridor with Swedish financial parameters as an illustrative case, the analysis identifies an intermediate utilization range at which economic performance reaches its maximum. The results show that, although the introduction of additional services initially increases gross revenue, a distinct threshold is ultimately reached beyond which reduced timetable flexibility allows even minor stochastic disturbances, on the order of 5-15 minutes, to spread into broader system instability. Under such saturated conditions, punctuality-related penalties increase more rapidly than the marginal gains associated with additional train paths, eventually generating net losses for the infrastructure manager while also reducing service quality for operators. These findings indicate that the most effective timetable is not necessarily the one that maximizes track occupancy, but rather the one that preserves adequate recovery margins. Future research should therefore extend the model toward more adaptive and scalable decision support, including dynamic priority logic based on real-time economic consequences, expansion from a single corridor to an interconnected multi-line network, and the use of machine learning methods, such as reinforcement learning, to identify more robust high-density scheduling patterns.

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