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CAPACITY EVALUATION OF MIXED PASSENGER–FREIGHT TRAFFIC ON HIGH-SPEED RAILWAY LINE

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Abstract. The research analyzes the compatibility of railway circulation between High Speed passenger trains and freight trains operating on the same infrastructure, with particular reference to the estimation of line capacity according to International Union of Railways (UIC) methodologies. This represents a case of complex compatibility, dictated by the different mechanical and dynamic characteristics of the rolling stock involved. These differences strongly influence the heterotachicity that must be taken into account both in the design and in the operational management of the line, as well as in addressing the problem of calculating and optimizing the capacity of the railway corridor. The analysis is carried out using the Terzo Valico dei Giovi as a case study, which represents the first Italian High Speed/Capacity line where a truly mixed use of the railway infrastructure for both passenger and freight services is envisaged. The study has been developed by examining different scenarios of mixed traffic circulation through the application of UIC capacity assessment approaches, based on the evaluation of headways, occupation times and timetable stability margins, in line with the principles defined in UIC Leaflet 406. This process leads to the definition of an operational timetable for the line and to the quantification of the impacts on the available line capacity, as well as on train travel times and overall operational performance. The results show that freight capacity is highly sensitive to train mass, dropping from 160 paths (800 t) to 48 paths in other cases. The UIC 406 compression analysis confirms that on high-speed lines, freight train performance and traffic heterogeneity are the main determinants of capacity saturation, as heavier trains significantly increase infrastructure occupation time and quickly consume bottleneck capacity despite temporal separation and advanced signaling systems.

Keywords: mixed train traffic, high speed railway line, line capacity.

1. Introduction

In recent decades, high-speed railway (HS) systems have experienced rapid expansion worldwide, becoming a key component of sustainable mobility strategies for medium- and long-distance passenger transport. At the same time, rail freight transport is increasingly recognised as an essential element for reducing greenhouse gas emissions and road congestion, especially along major logistic corridors connecting ports, industrial hubs, and inland terminals. These two strategic objectives often converge on the same railway infrastructure, raising the question of whether high-speed passenger and freight trains can effectively coexist on lines designed for high-speed operation.

The mixed operation of passenger and freight trains on high-speed or high-capacity (HS/HC) railway lines presents a complex technical and operational challenge (Myronenko & Hrushevska, 2018). Passenger high-speed trains and freight trains exhibit markedly different mechanical, dynamic, and operational characteristics, including axle loads, braking performance, acceleration capabilities, maximum speed, and resistance to motion. These differences lead to heterotachic traffic conditions, which strongly influence line design, timetable planning, capacity calculation, and maintenance strategies.

From a theoretical standpoint, railway capacity is maximised when traffic is homogeneous, both in terms of speed and performance. Conversely, heterogeneous traffic patterns introduce conflicts, increase headways, and reduce the effective utilisation of infrastructure. This issue is particularly critical on HS/HC lines, where high construction and maintenance costs require a very efficient use of available capacity in order to justify the investment.

Despite the fact that many HS/HC lines in Europe have been technically designed to allow freight traffic, actual mixed operation remains rare. Hawken (2014) says that coexistence is possible thanks to advanced signalling systems. In Italy, all high-speed/high-capacity lines have been built with geometric and structural characteristics suitable for both passenger and freight

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trains. However, the only freight service that operated on the Italian high-speed network to date was the Mercitalia Fast service, operated by Mercitalia Rail using an ETR500 trainset adapted for freight transport (Ruvio et al., 2022; Urbański et al., 2022).

The limited implementation of freight services on high-speed lines is mainly due to three interrelated factors. First, the availability of suitable rolling stock is still limited, particularly with regard to multisystem locomotives equipped with ERTMS (European Rail Traffic Management System) Level 2 and freight wagons designed for high-speed operation. Second, the strong demand for passenger mobility on HS lines requires high frequencies and maximum operating speeds, leaving little flexibility for inserting slower freight trains. Third, freight trains generate higher dynamic loads on the track, increasing wear and maintenance needs, which often conflict with the night-time maintenance windows traditionally used for freight operations.

International experiences further underline these difficulties. Studies carried out by the Sutrai Erakuntza Foundation (2016) have highlighted the challenges associated with introducing freight traffic on Spanish high-speed lines, which were originally conceived exclusively for passenger services. The conversion of such lines to mixed use entails significant technical constraints, construction costs up to 30% higher, and more demanding design parameters, including large curve radii, low gradients, stronger track structures, and stricter noise limitations. Maintenance costs are also considerably higher – between 10% and 20% – especially when heavy freight traffic is involved, which still represents the majority of long-distance rail freight flows.

From an operational perspective, inserting a slow freight train – typically operating at 90–120 km/h – into a timetable dominated by passenger trains running at speeds above 250 km/h leads to a reduction in line capacity and increases the complexity of conflict management and timetable construction. These aspects directly affect the commercial offer, as they limit the number and quality of train paths that can be marketed.

When the coexistence of passenger and freight services leads to unacceptable performance degradation, infrastructure managers may need to consider mitigation strategies such as temporal separation (e.g. freight curfews during peak passenger hours) or physical separation (e.g. grade-separated junctions, freight bypasses, or partial or full line segregation). Historical examples include the construction of freight bypasses around major urban nodes to free up capacity for passenger services.

Several international case studies illustrate the different approaches adopted to manage mixed traffic. The Basra–Al Faw railway project in Iraq is primarily designed for freight transport, with limited passenger services operating in the few available slots and overtaking taking place at dedicated stations (Strale, 2016). In Chicago, freight trains are subject to curfews during weekday peak hours on lines shared with the Metra suburban rail system, although such agreements were negotiated when freight volumes were lower than today. Similar curfew arrangements are in place in Sydney, where freight operators share tracks with the highly utilised Sydney Trains network (European Court of Auditors, 2018). In Canada, Canadian National has built a freight bypass north of Toronto to divert heavy freight traffic away from congested passenger corridors (International Union of Railways [UIC], 2012). In the United States, the Fox Chase Line (SEPTA) in Philadelphia has implemented partial line segregation to mitigate conflicts between slow freight and fast passenger services. In Spain, the Barcelona–French border corridor represents a well-known bottleneck where freight and high-speed passenger services converge on a line originally designed for high-speed passenger traffic.

These examples demonstrate that mixed passenger–freight operation on HS/HC lines generally represents a limiting factor for line capacity, mainly due to differences in speed profiles and vehicle characteristics (López-Pita & Robusté, 2001; Li et al., 2023; Myronenko & Matsiuk, 2018; Fumasoli et al., 2015).

Starting from these information, the present research analyses mixed-traffic operation through a real case study, focusing on its impact on line capacity and travel times.

2. Background and theoretical framework

Railway capacity can be defined as the maximum number of trains that can be operated over a given section of infrastructure within a specified time period, under defined operational conditions and with an acceptable level of quality. In practice, capacity is not a fixed value but depends on infrastructure characteristics, signalling systems, rolling stock performance, timetable structure, and operational rules.

In homogeneous traffic conditions, where trains have similar speed profiles and performance, capacity is mainly determined by minimum headways imposed by signalling and safety systems. In heterogeneous traffic conditions, additional constraints arise due to differences in acceleration, braking and cruising speeds. These differences increase the minimum spacing between trains and often require additional buffer times to maintain timetable stability.

On high-speed lines, these effects are amplified by the large speed differentials between passenger and freight trains. Even when freight trains are technically capable of operating at higher speeds, their acceleration and braking performance remains significantly inferior to that of multiple-unit passenger trains, leading to longer occupation times of critical infrastructure elements such as block sections, junctions, and stations.

Another key aspect of mixed traffic operation concerns infrastructure degradation. Freight trains typically have higher axle loads and different dynamic characteristics compared to passenger trains. When operated on infrastructure optimised for very high speeds, freight trains can generate increased rail wear, particularly in curves with large radii designed for high-speed passenger services.

Studies have shown that introducing low-speed freight trains into high-speed curves can significantly increase rail corrugation and rolling contact fatigue, leading to higher maintenance costs and more frequent interventions. These interventions often need to be scheduled during night-time hours, which traditionally represent the main operating window for freight services, thereby creating a structural conflict between operation and maintenance needs.

3. Methodology

The research methodology combines analytical capacity assessment with microscopic railway traffic simulation. The objective is to evaluate the impact of mixed high-speed passenger and freight traffic on line performance under different operational scenarios.

The analysis was carried out using:

- analytical formulations for the calculation of theoretical and practical line capacity;
- simulation-based tools, specifically OpenTrack, to model detailed operational scenarios.

The methodology adopted in this study is based on the capacity assessment principles defined in UIC Leaflet 406. In particular, line capacity is evaluated by compressing the train paths included in the timetable in accordance with the UIC 406 procedure, in order to identify the most critical line section from a capacity-consumption perspective.

For this purpose, the train paths of each traffic category are reconstructed using the OpenTrack simulation software, starting from the detailed characteristics of the infrastructure, the signalling system, and the rolling stock. Both high-speed passenger trains and freight trains are modelled, taking into account their respective performance parameters (maximum speed, acceleration and braking characteristics, train length and mass), as well as the operational constraints imposed by the signalling and train control system.

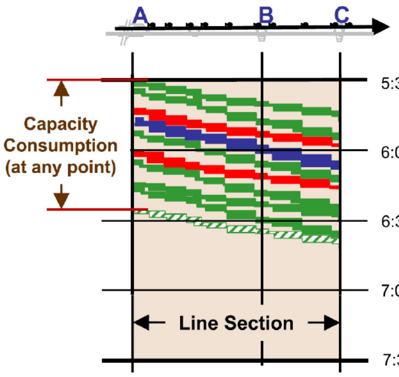

Figure 1. Timetable on a double-track line after compression (source: UIC Code 406, 2013)

Specifically, the methodology is based on the timetable compression method (see Figure 1), which makes it possible to overcome the limitations of purely analytical approaches and to accurately represent the actual operating conditions of the railway system. This approach allows the practical capacity of railway infrastructure to be assessed without resorting to data-intensive and time-consuming microscopic simulations.

For the analysis, homogeneous line sections are identified according to infrastructural and operational characteristics, such as the number of tracks, signalling system, junctions, and service pattern changes. In addition, node routes and the corresponding route blockings in the event of conflicts are defined and modelled.

For each section, within a representative time window (typically ≥ 2 hours), the infrastructure occupation time is calculated by applying the following assumptions:

- virtual compression of timetable train paths;
- elimination of buffer times;
- preservation of the original train sequence;
- consideration of minimum headways imposed by the signalling system and rolling stock characteristics.

Where necessary, additional buffer times related to crossings, maintenance activities, transitions between time periods, and route blockings within railway nodes are also taken into account.

Capacity consumption is expressed as the ratio between occupation time and available time, and is compared with the UIC quality-of-service thresholds. For line segments with capacity consumption below 100%, both the remaining capacity and the usable capacity are estimated. The segment exhibiting the highest capacity consumption is identified as the representative bottleneck of the analysed line or node.

The timetable compression procedure can also be applied at the level of individual nodes (stops or stations) or deviations along a given corridor. In this case, occupation time is associated with the node traversal routes and with the corresponding blocking times of all conflicting routes.

The analysis therefore requires a detailed reconstruction of train movements by route and time of passage, assuming that successive train movements are compacted by separating them by only the blocking time of the conflicting route, whenever a conflict exists.

Several performance indicators were evaluated for each scenario, including:

- line capacity and saturation levels;
- headways and minimum spacing;
- maximum and average operating speeds;
- travel times for passenger and freight services;
- occurrence of speed reductions;
- delays and delay propagation effects.

Different freight traffic insertion strategies were tested, such as isolated freight trains and grouped freight train packages, in order to analyse their interaction with passenger services and their effect on infrastructure utilisation.

4. Case study: The Terzo Valico dei Giovi

The Terzo Valico dei Giovi is a new high-capacity railway line connecting Genoa with the Po Valley and Northern Italy (see Figure 2). It represents a strategic link between the Port of Genoa and the European rail freight corridors. The line is designed for mixed passenger and freight traffic, with a maximum passenger speed of 250 km/h and the possibility to operate freight trains up to 750 m in length.

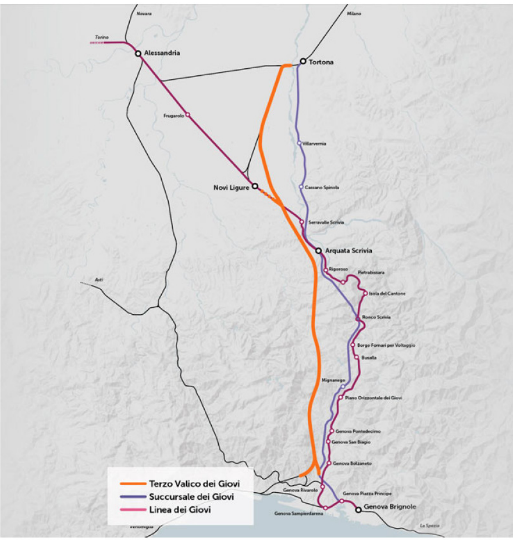

Figure 2. Terzo Valico dei Giovi railway line (Ministero delle Infrastrutture e dei Trasporti, n.d.)

Specifically, the analysed railway line has a total length of 53 km, of which approximately 37 km are developed in tunnels. The infrastructure is characterised by a maximum longitudinal gradient of 1.25%, which is compatible with high-speed passenger operations but represents a potentially constraining factor for freight traffic.

The line is designed for maximum operating speeds between 200 and 250 km/h and is equipped with double tracks and the ERTMS Level 2 signalling system, ensuring continuous train supervision and reduced headways (5 minutes) under homogeneous traffic conditions. The infrastructure is designed for an axle load corresponding to class D4, allowing the circulation of heavy freight trains, subject to compliance with operational constraints.

With regard to the loading gauge, the line complies with the P/C80 profile, making it suitable for the operation of standard freight rolling stock, including intermodal units. The block length (module) is equal to 750 m, which directly influences minimum headways and capacity consumption, particularly under mixed passenger–freight traffic conditions.

These infrastructural and signalling characteristics provide the technical framework within which the mixed operation of high-speed passenger trains and freight trains is analysed, forming the basis for the capacity assessment carried out according to the timetable compression methodology.

The baseline passenger service supply (Table 1) was derived from the RFI Commercial Plan and includes significant increases in frequency on key relations, particularly between Genoa and Milan and Genoa and Turin. This passenger train offer represents the reference scenario against which freight insertion strategies were evaluated.

Freight services were added to the baseline timetable following different operational logics, including:

- isolated freight paths inserted between passenger services;
- grouped freight paths forming dedicated freight “windows”;
- progressive saturation of available capacity.

Each configuration was simulated to assess its impact on both passenger and freight performance.

Table 1. Passenger service frequencies with the Terzo Valico

Relation	Current frequency	Future frequency
Genoa – Milan	1 train/h (via old line)	2 trains/h
Genoa – Turin	5 trains/day	8 trains/day
Ventimiglia – Milan	6 trains/day	8 trains/day

The train types considered are listed below:

- Freight trains (F) with a length of 750 m hauled by a 6,400 kW locomotive and maximum speed 80 km/h;
- Intercity trains (IC) with a capacity of 750 passengers, hauled by a Siemens ES64 U4 locomotive and maximum speed 160 km/h;
- High-speed trains (HS) with a capacity of 500 passengers, operated by ETR1000 trainsets and maximum speed 250 km/h.

The railway line capacity analysis is performed assuming a line utilisation of 16 hours of daytime mixed passenger service, 2 hours dedicated exclusively to freight operations, and 6 hours allocated to maintenance activities. Under these assumptions, Figure 3, Figure 4 and Figure 5, Table 2 and Table 3 summarise the results obtained for three scenarios characterised by different freight train hauled masses, namely 800 t, 1,000 t and 1,200 t.

The results, reported in Table 3, show that the number of high-speed (HS) and Intercity (IC) passenger train paths remains constant across all scenarios, with

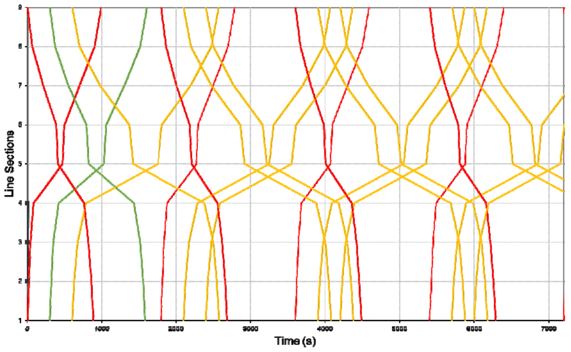

Figure 3. Train paths with freight train with hauled mass of 800 t (HS in red, IC in green and Freight in yellow)

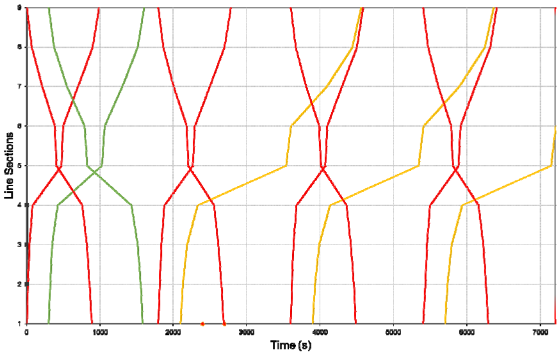

Figure 4. Train paths with freight train with hauled mass of 1,000 t (HS in red, IC in green and F in yellow)

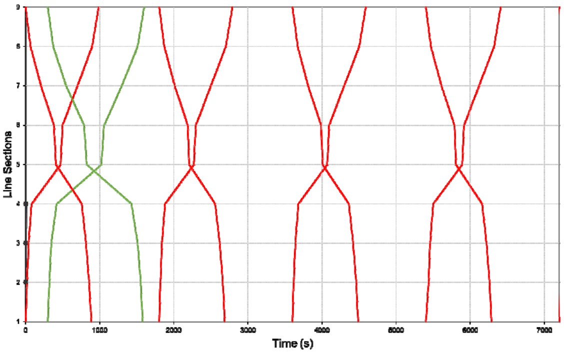

Figure 5. Train paths with freight train with hauled mass of 1,200 t (HS in red, IC in green and Freight in yellow)

Table 2. Travel time in the different scenario simulated

Scenario with Freight Train	HS / IC (minutes)	F (minutes)
800 t	15 / 22	33
1,000 t	15 / 22	41
1,200 t	15 / 22	48

64 high-speed and 16 Intercity trains operated during the daytime service window. This indicates that, within the analysed operating framework, passenger services are not directly affected by variations in freight train mass, as freight traffic is mainly accommodated in the dedicated time window.

Table 3. Line capacity in the different scenario simulated

Scenario with Freight Train	HS / IC (trains day)	F (trains/day)
800 t	64 / 16	160
1,000 t	64 / 16	48 (during night time)
1,200 t	64 / 16	48 (during night time)

However, significant differences are observed in terms of freight capacity. In the scenario with a hauled mass of 800 t, timetable compression according to UIC 406 allows up to 160 freight train paths to be accommodated. When the hauled mass increases to 1,000 t, freight capacity drops sharply to 48 trains, and no further reduction is observed for a hauled mass of 1,200 t. This result indicates that the critical section, as identified through the compression procedure, reaches full capacity once a certain performance threshold is exceeded.

In UIC 406 terms, the heavier freight trains lead to a substantial increase in infrastructure occupation time on the most constraining line sections, driven by longer running times, reduced acceleration performance and increased headway requirements. As a consequence, the capacity consumption approaches or exceeds the UIC reference thresholds for acceptable quality of service, resulting in a saturated timetable and limiting the number of feasible freight paths. In this specific case, an increase in occupation time of approximately 25% is sufficient to critically strain the line and push the infrastructure into a saturated operating condition. Beyond this saturation point, further increases in hauled mass do not significantly affect the number of compressed paths, as the capacity of the bottleneck section is already fully consumed.

Overall, the results confirm that, on infrastructure primarily designed for high-speed passenger services, the application of the UIC 406 timetable compression method provides a robust framework for highlighting how freight train performance parameters directly translate into capacity constraints. The analysis demonstrates that even under temporal separation, freight train mass and dynamic performance are key determinants of usable capacity, and should therefore be explicitly considered in strategic and operational planning of mixed passenger–freight high-speed lines.

The results confirm the theoretical expectation that heterogeneity is the main limiting factor for capacity on HS/HC lines. While advanced signalling systems such as ERTMS Level 2 can mitigate some effects, they cannot fully compensate for large performance differences between train types.

5. Conclusions

This study confirms that mixed operation of high-speed passenger and freight trains on HS/HC infrastructure significantly affects line capacity and operational performance. Differences in speed, dynamic behaviour, and operational requirements generate conflicts that must be carefully managed through appropriate timetable design and infrastructure planning.

The Terzo Valico case study demonstrates that, under specific conditions and with advanced signalling systems such as ERTMS Level 2, mixed traffic operation is technically feasible. However, the achievable capacity strongly depends on the adopted freight insertion strategy and on the level of passenger service demand.

Simulation results highlight the importance of integrated analytical and simulation-based approaches for evaluating mixed-traffic scenarios, supporting infrastructure managers and operators in defining robust and commercially viable service offers.

Future research may focus on optimising timetable robustness, evaluating long-term maintenance impacts, and comparing alternative infrastructure layouts or partial segregation solutions to further improve the coexistence of high-speed passenger and freight services.

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