

Article

Joint Line Planning for High-Speed Rail, Intercity Rail, Suburban Rail, and Metro Under Through Operation Mode

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Abstract

Multi-system integration (e.g., high-speed rail, intercity rail, suburban rail, and metro) in regional rail transit has become an important strategy for enhancing regional travel quality. Nevertheless, optimizing line plans for such integrated networks remains a challenging task. Existing approaches are typically limited to dual-system integration and rely on pre-specified line pools, while often overlooking rolling stock heterogeneity. These limitations inevitably constrain the flexibility of stopping patterns and hinder the achievement of global cost optimality for the entire system. To address these challenges, this study proposes a comprehensive optimization framework for multi-system line plans. First, a hierarchical decoupling of the multi-system physical network is performed to identify candidate train service routes. Second, a deeply coupled network consisting of train service and passenger travel is developed. Subsequently, a multi-commodity flow model is established, incorporating critical constraints such as flexible stopping rules, rolling stock-system compatibility, and connecting line capacities. This framework integrates decisions regarding flow distribution, frequency, route design, stop patterns, and rolling stock assignment. Validated via a real-world case study using Gurobi, the results indicate that the through operation mode reduces operator costs by 20.4% and passenger costs by 6.5% compared to independent operations. This research offers a quantitative tool for developing coordinated plans that improve operator efficiency and passenger experience.

Keywords: multi-modal transportation modeling; multi-standard rail transit; through operation; line planning; multi-commodity flow model

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1. Introduction

In recent years, as metropolitan areas and urban agglomerations have increasingly become the primary spatial carriers of economic activity and population growth, multi-modal transportation modeling has garnered widespread attention. In the context of regional rail transit, multi-system integration refers to the coordinated and seamless connection of heterogeneous rail networks—such as the metro, suburban rail, intercity rail, and mainline/high-speed rail—within a metropolitan area or urban agglomeration [1]. This integration can be conceptualized and modeled through physical interconnections, resource optimization, and coordinated operations. It holds significant potential for enhancing transport efficiency, reducing operational costs, and improving overall passenger experience.

Figure 1 illustrates a typical multi-system regional rail transit environment. As shown, the network is composed of heterogeneous layers—high-speed rail (HSR), intercity rail, suburban rail, and metro lines—serving different spatial scales from central urban cores to satellite cities. Key to this integration are the physical interconnection nodes (interchange hubs), which serves as the infrastructure basis for realizing passengers' cross-system travel.

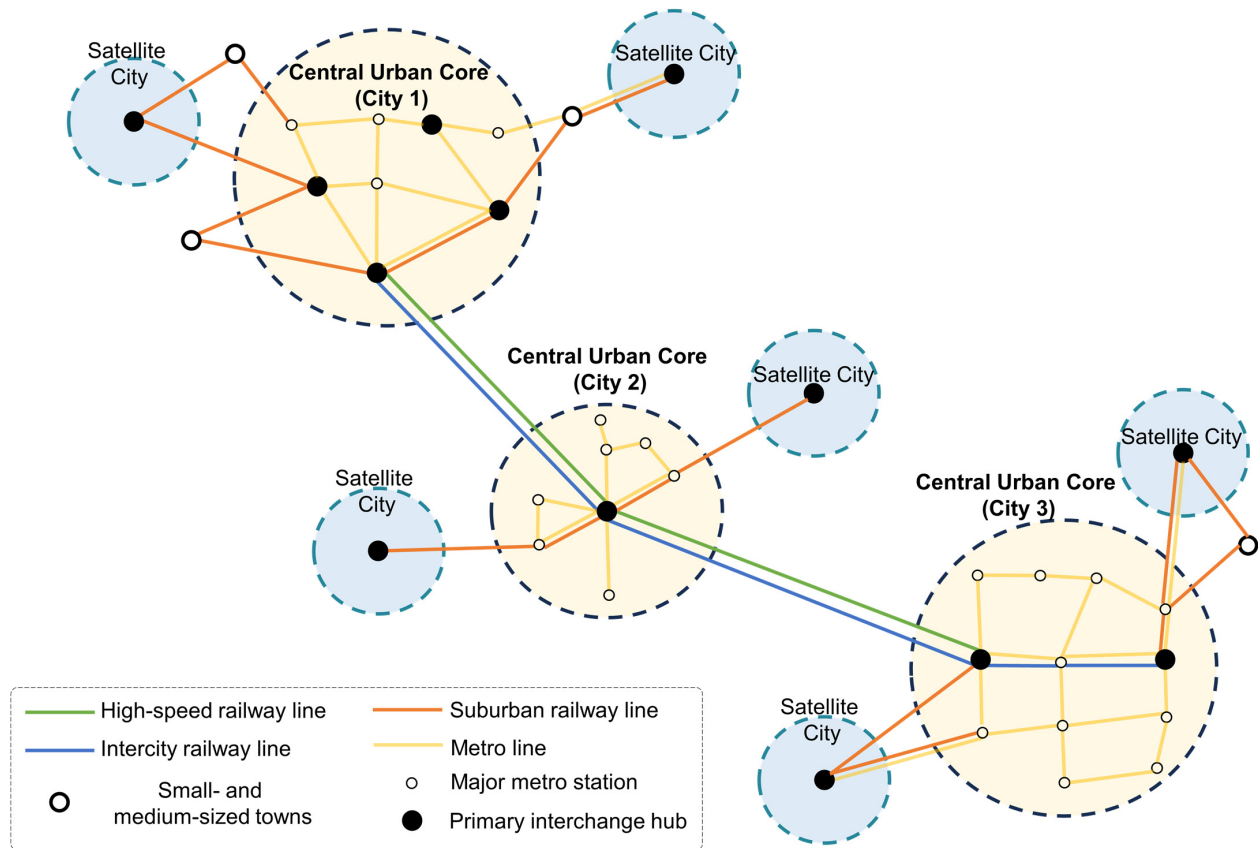


Figure 1. Schematic representation of multi-system regional rail transit integration and interconnection.

Under the multi-system integration framework, the through operation mode aims to achieve continuous train service across different networks and to provide direct passenger journeys by harmonizing technical standards, ensuring vehicle compatibility, and enhancing infrastructure interoperability [2]. Since the 1980s, countries such as Germany [3,4], Japan [5,6], Spain [7], France [8], and the United States [9] have conducted extensive theoretical research and practical exploration of through operation, predominantly between two rail systems. Accordingly, existing studies on line planning under through operation mode remain largely confined to two-system integration, while research on the joint optimization of four systems (HSR, intercity rail, suburban rail, and metro) remains limited. For instance, Li et al. [10] optimized metro and suburban rail scheduling based on cross-system passenger flows, ignoring the within-system demand. Huang [11] considered both cross-system and within-system passengers and developed a bi-level programming model for line-plan scheduling of an intercity rail line and a suburban rail line under through operation. Ren et al. [12] incorporated passenger path selection and studied flow-oriented scheduling for a suburban and metro express and local trains. Peng et al. [13] considered passenger flow, route design, train composition, and stop schedules in an integrated optimization of suburban rail and metro trains for through operation. Lin et al. [14] focused on the optimization of line planning for rail systems that share tracks between metro and sub-

urban railway networks and presented a complex multi-objective programming model that maximizes the net profit of the operating companies and the time savings for passengers.

And based on that, Lin's later research [15] includes all four systems, but the integration method remains limited to pairwise combinations, focusing on collaboration between similar systems. Zheng [16] expanded the research to the four-network scope and developed optimization models for upper-level stop scheduling and lower-level passenger flow games. However, some limitations remain in Zheng's study: (1) Metro-related through operation is excluded. Although this assumption reduces the feasible through service space and improves tractability, metro through operation with other systems is often feasible in practice and has been widely examined in prior studies (e.g., metro–suburban rail). As a result, the model may underrepresent realistic multi-network integration scenarios. (2) Rolling stock type is not treated as a decision variable, which hinders the full utilization and optimization of fleet resources, consequently preventing the achievement of global cost optimality for the integrated system. Table 1 summarizes the comparison of related studies on multi-system line planning.

Table 1. Comparison of related studies on multi-system line planning.

Study	Network Scope	Stopping Pattern Generation	Modeling Approach	Rolling Stock Type
Li et al. [10]	Suburban and Metro	Endogenous (Variable)	Multi-objective programming	X
Huang [11]	Intercity and Suburban	Endogenous (Variable)	Bi-level programming	X
Ren et al. [12]	Suburban and Metro	Pre-fixed for suburban line	Multi-objective programming	X
Lin et al. [14]	Suburban and Metro	Pre-fixed (All-stop)	Multi-objective programming	X
Zheng [16]	Four systems	Endogenous (Variable)	Bi-level programming	X
This study	Four systems	Endogenous (Variable)	Multi-commodity flow model	✓

To address the research gap, this study extends two-system optimization to four-system integration and proposes an integrated decision-making approach. By deeply coupling the train service network and passenger travel network, we aim to achieve collaborative optimization of passenger demand and train schedules under four-system through operation. Specifically, this is performed as follows: (1) We perform hierarchical decoupling of the regional rail transit physical network to clearly define route levels and identify candidate routes. (2) For each candidate route, we construct the train service network (capturing train operations, stops, and skip-stop behavior) and the passenger travel network (quantifying passenger boarding, alighting, transferring, and waiting processes). The two networks are coupled through shared nodes to represent the dynamic interaction between “trains” and “passengers”. (3) Based on this dual-network coupling, we develop a multi-commodity flow model for optimizing the multi-system line plans. The model incorporates flexible stop patterns, compatibility between rolling stock type and system specifications, and capacity constraints of cross-system connecting lines, thereby integrating decisions on passenger flow distribution, train frequency, route design, and stop patterns. (4) Finally, we solve the model using the commercial solver Gurobi and validate the method through numerical experiments based on case studies. This framework not only addresses the limitations of existing research in terms of multi-system expansion and dynamic coupling but also highlights the resource substitution effects and cost saving potential of through operation.

The main contributions to our work are highlighted as follows:

- (1) A holistic four-system line-planning framework under through operation: We develop an integrated optimization framework that explicitly allows through operation across

HSR, intercity rail, suburban rail, and the metro, rather than restricting integration to two systems or excluding metro-related through services. This provides a more realistic representation of multi-network regional rail integration and enables system-wide coordination in line planning.

- (2) Endogenous integration of rolling stock heterogeneity and compatibility: We integrate the selection and assignment of rolling stock types into the line-planning decision-making process, addressing the limitation where existing models often neglect rolling stock heterogeneity. By incorporating rolling stock type as a core decision variable and embedding system compatibility as a critical constraint within the multi-commodity flow model, our framework achieves precise matching between service demand and physical assets. This not only ensures the technical feasibility of each through service but also leads to an accurate estimation of associated operational costs and system-wide resource substitution effects.

2. Problem Statement

The core research problem is defined as follows: within a regional rail network comprising four systems (HSR, intercity railway, suburban railway, and metro) and given regional passenger demand, jointly optimize rolling stock types, service routes, operating frequencies, and stopping patterns within and across system tiers so as to design a multi-system line plan that balances operation costs and passenger travel costs. Concretely, the problem entails three challenges:

1. How to address the heterogeneity of a multi-system network via a structured analysis that accurately enumerates feasible service routes;
2. How to establish a dynamic coupling mechanism that quantifies the bidirectional interdependence between the train service network and the passenger travel network;
3. How to integrate rolling-stock technological attributes with the spatiotemporal distribution of demand and system compatibility to achieve system-wide optimization of the service plan.

In the existing literature on line planning, when stopping patterns are not decision variables, a single train service network combined with a network flow model is typically adopted [17]. When stopping patterns are to be decided, many studies rely on a pre-specified line pool approach [18–20]: a set of train services (each with an embedded stopping pattern) is generated *ex ante*, and the optimization then selects the number of services to operate from this set. However, such an approach tends to decouple stopping design from passenger demand and thus underrepresents their endogenous linkage. To address this gap, we formulate the train service planning problem as a multi-commodity flow model, constructing in parallel a train service network and a passenger travel network and tightly coupling the two, thereby overcoming the above limitations.

2.1. Topological Analysis of Multi-System Network and Identification of Candidate Service Routes

At the physical level, multi-system rail transit networks exhibit pronounced heterogeneity and hierarchy, manifested in (1) functional partitions across different system tiers, (2) inter-system interchange stations and their connecting facilities (e.g., connecting lines), and (3) transfer facilities and relations (e.g., same-platform transfer), as shown in Figure 2. To characterize the feasibility of cross-system train operations under through operation mode and to provide a structured basis for constructing the subsequent train service and passenger travel networks, it is necessary to first convert the complex physical network into a modeling topology: through hierarchical abstraction and functional decoupling, we clarify each system's spatial distribution, the logic of cross-system connections, and the service coverage for passenger demand.

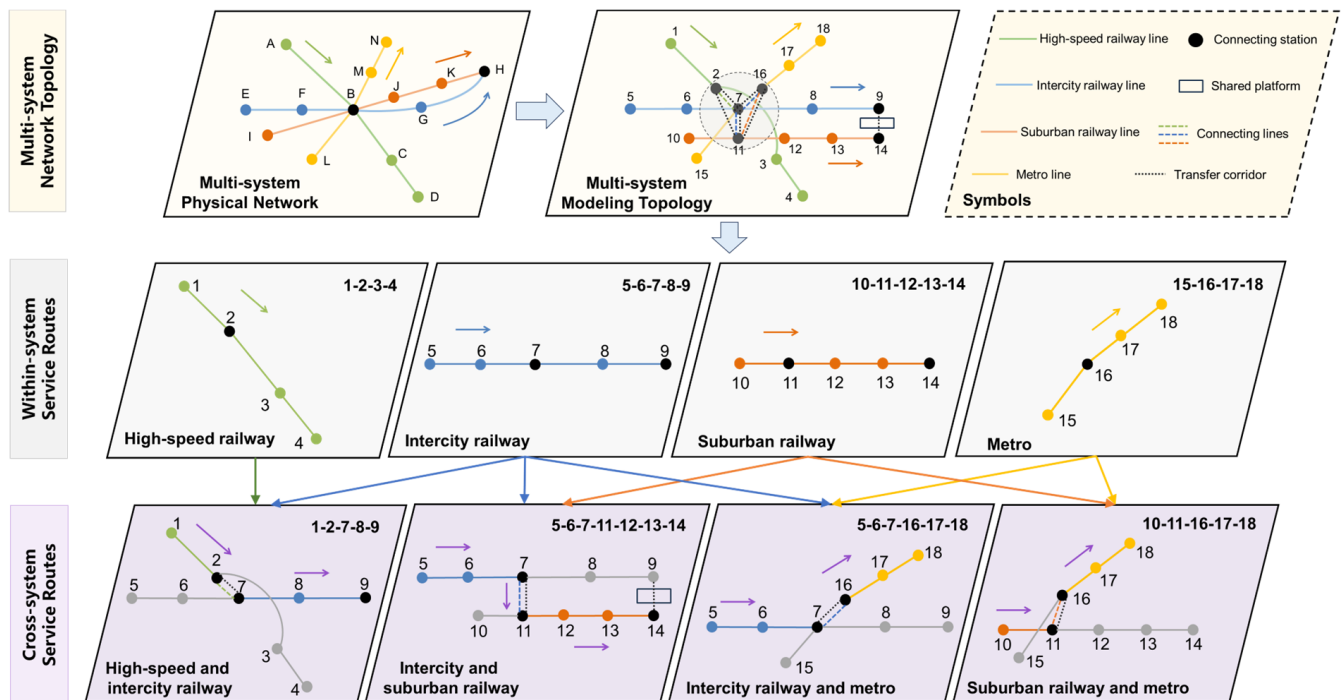


Figure 2. Hierarchical decoupling of multi-system regional rail transit network.

The physical network in Figure 2 comprises 14 stations (station A to station N). And in its corresponding modeling topology, nodes 2, 7, 11, and 16 form interchange hub B enabling trains to traverse systems via connecting lines, whereas nodes 9 and 14 are shared-platform transfer hubs that support same-platform passenger transfers only (no through running). Guided by these topological features, the hierarchical decoupling focuses on the following core elements:

- The functional boundaries of each system's mainline (e.g., high-speed line 1-2-3-4; intercity line 5-6-7-8-9);
- The physical channels for cross-system linkage (e.g., the connecting line from station 2 to station 7 provides the through path between high-speed and intercity systems).

The resulting layered decomposition is shown in Figure 2. It systematically identifies eight candidate service routes. Four are within-system routes that provide direct services within a single system. The other four are cross-system through routes. These routes enable continuous operations across systems by leveraging connecting lines and compatibility technologies. They can simultaneously serve within-system demand and cross-system direct demand. This set of candidate service routes provides a basis for constructing the coupled train service and passenger travel networks. They also support the subsequent optimization of the line plans.

2.2. Construction of the Coupled Train Service and Passenger Travel Networks

To capture the dynamic coupling between train operations and passenger movements under through operation mode, we develop a unified network framework based on the identified candidate service routes. The physical network is abstracted as a directed topology $G = \{V, A\}$. Here, the node set V represents key elements of the system (e.g., stations and train arrival/departure nodes), and the arc set A captures their relations (e.g., train movements and passenger transfers).

Using the intercity-suburban cross-system network in Figure 2 as an example, Figure 3 illustrates the multi-system train service network and the passenger travel network. The construction follows two complementary logics. The train service network describes the

movement of trains, including stopping, skip-stopping, and cross-system connection. The passenger travel network describes travelers' path choices, including boarding, alighting, transferring, and waiting. The two networks are coupled through shared nodes such as train arrival/departure nodes and dwell nodes.

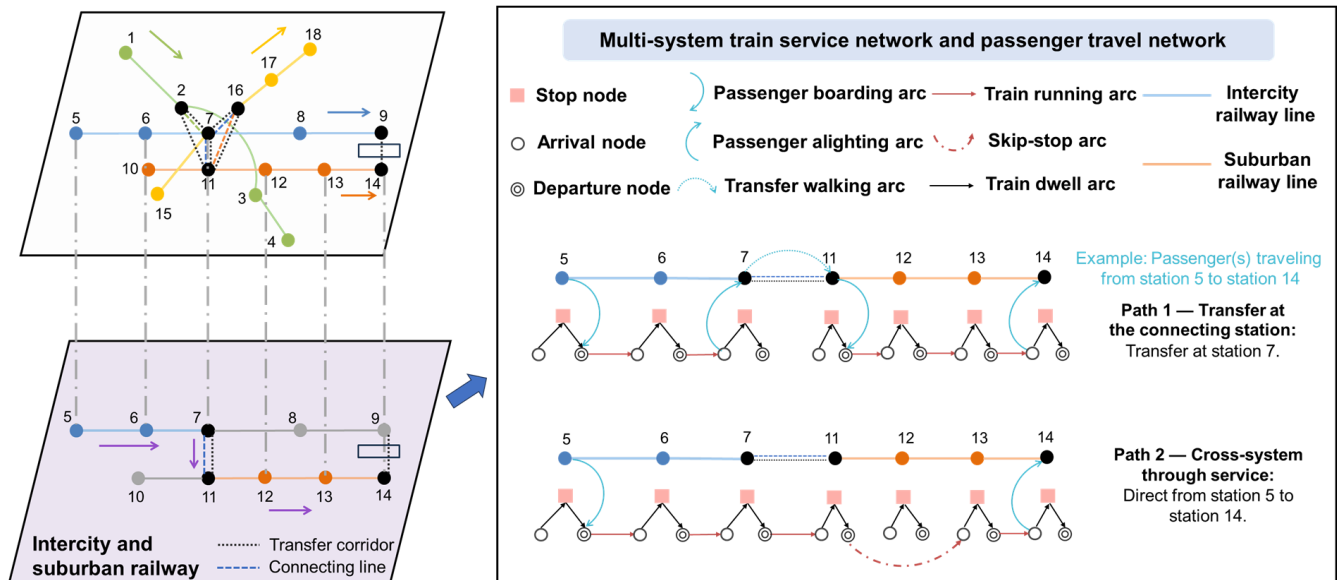


Figure 3. Schematic diagram of train service network and passenger travel network.

2.2.1. Node Set

The node set V consists of four subsets $V = \{N, V^{\text{arr}}, V^{\text{dep}}, V^{\text{dwe}}\}$, where the station nodes are $N = \{N^G, N^R, N^S, N^U\}$ (with N^G, N^R, N^S, N^U denoting the high-speed, intercity, suburban, and metro station sets; $n \in N$; and $|N|$ being the total number of station nodes). N belongs only to the passenger travel network and represents the physical spaces for boarding, alighting, and transfers.

Arrival, departure, and dwell nodes are $V^{\text{arr}} = \{v_n^{\text{arr}} \mid n \in N\}$, $V^{\text{dep}} = \{v_n^{\text{dep}} \mid n \in N\}$, and $V^{\text{dwe}} = \{v_n^{\text{dwe}} \mid n \in N\}$, which are shared by the train service and passenger travel networks and encode train arrivals, departures, and dwells, respectively.

Each of the above three virtual node sets has cardinality $|N|$. Hence, $|V| = 4 \cdot |N|$. This structured design separates the behavioral carriers of trains and passengers, while linking them through shared nodes. For example, a passenger moves from station node n to the corresponding train departure node v_n^{dep} via a boarding arc, reflecting the coupling logic that “passengers follow trains.”

2.2.2. Arc Set

The arc set A captures the dynamics of both trains and passengers through six subsets, $A = \{A^{\text{bo}}, A^{\text{al}}, A^{\text{wa}}, A^{\text{ru}}, A^{\text{dw}}, A^{\text{sk}}\}$, corresponding to boarding, alighting, transfer-walking, train-running, dwell, and skip-stop arcs.

The definitions of these arc types and the rules for computing their costs are given below; arc costs quantify passenger travel cost as the sum over arcs along a path.

1. Boarding arcs A^{bo} : directed arcs from station node n to its departure node v_n^{dep} . Cost: $b_{i,j}^{\text{bo}} = \text{VOT} \cdot t_{i,j}^{\text{bo}}$, where VOT is the value of the waiting time [CNY/min] and $t_{i,j}^{\text{bo}}$ is the expected waiting time, taken as one half of the relevant headway. For cross-system routes, we use the headway of the highest-tier system to reflect service differentiation.

2. Alighting arcs A^{al} : directed arcs from arrival node v_n^{arr} to station node n .
Cost: $b_{i,j}^{\text{al}} = 0$ if n is a destination station or a transfer hub. In other cases, $b_{i,j}^{\text{al}} = M$, where M is a large constant. This means that the non-planned alighting arc costs are set to a sufficiently large constant, to prevent passengers from alighting arbitrarily.
3. Transfer-walk arcs: directed arcs from a higher-tier interchange node to a lower-tier interchange node within the same station, representing in-station transfers.
Cost: $b_{i,j}^{\text{wa}} = \text{VOT} \cdot t_{i,j}^{\text{wa}}$, where $t_{i,j}^{\text{wa}}$ is the walking time [min].
4. Train-running arcs A^{ru} : directed arcs from v_n^{dep} , a departure node at station n to $v_{n'}^{\text{arr}}$, the arrival node at the next station, which represents pure inter-station running.
Cost: $b_{n,n'}^{\text{ru}} = \text{VOIT} \cdot t_{n,n'}^{\text{ru}}$, where VOIT is the value of in-vehicle time [CNY/min] and $t_{n,n'}^{\text{ru}}$ is the train running time from station n to n' [min].
5. Dwell arcs A^{dw} : directed arcs from arrival node v_n^{arr} to dwell node v_n^{dwe} and then to departure node v_n^{dep} , representing the full dwell process at station n .
Cost: $b_{i,j}^{\text{dw}} = \text{VOIT} \cdot (t_{i,j}^{\text{qt}} + 0.5 \cdot t_{i,j}^{\text{dw}})$, where $t_{i,j}^{\text{qt}}$ is the start/stop additional time [min] and $t_{i,j}^{\text{dw}}$ is the dwell time [min].
6. Skip-stop arcs A^{sk} : directed arcs from station departure node v_n^{dep} to $v_{n'}^{\text{arr}}$, the arrival node at the next station n' , representing the train bypassing intermediate station $\bar{n}$.
Cost: $b_{n,n'}^{\text{sk}} = \text{VOIT} \cdot (t_{n,\bar{n}}^{\text{ru}} + t_{\bar{n},n'}^{\text{ru}})$.

3. Mathematical Model

3.1. Basic Assumptions

The basic assumptions of this study are as follows:

- (1) The section running time of trains in each section and the dwell time at each station are fixed constants.
- (2) Train overtaking is not considered.
- (3) It is assumed that the passenger flow in the up and down directions is symmetric; that is, the total passenger flow in the up and down directions is basically equal during the study period. Therefore, only the one-way train operation scheme in each operation section is considered. Only the downward passenger flow is taken as input during modeling.
- (4) This study adopts a hierarchical downward compatibility principle: higher-tier rolling stock possesses the interoperability to operate on lower-tier infrastructures, whereas lower-tier rolling stock is restricted to its designated system. Specifically, high-speed trains could run on HSR, intercity, and suburban lines; intercity trains could run on intercity, suburban, and metro lines; suburban trains could run on suburban and metro lines; and metros could only run on metro lines.

3.2. Notation

The definitions of set symbols are shown in Table 2, and the definitions of parameter and variable symbols are shown in Table 3.

Table 2. Symbolic description of sets.

Symbol	Meaning
L_{cross}	Set of cross-line through routes; $L_{\text{cross}} = \{L^{\text{GR}}, L^{\text{GS}}, L^{\text{RS}}, L^{\text{RU}}, L^{\text{SU}}\}$ $L^{\text{GR}}, L^{\text{GS}}, L^{\text{RS}}, L^{\text{RU}}, L^{\text{SU}}$ refer to cross-line through route subsets of high-speed rail–intercity rail, high-speed rail–suburban rail, intercity rail–suburban rail, intercity rail–metro, and suburban rail–metro.

Table 2. Cont.

Symbol	Meaning
L	Set of routes; $L = \{L^G, L^R, L^S, L^U, L_{\text{cross}}\}$, L^G, L^R, L^S, L^U refer to cross-line through route subsets of the high-speed rail local route, intercity rail local route, suburban rail local route, and metro local route, $l \in L$. $L = \{1, 2, 3, \dots, L \}$: $ L $ denotes the total number of routes.
N_l	Set of stations passed by route l : $l \in L$ and $n \in N_l$.
N	Set of stations: $n \in N$ and $N = \{N_1, N_2, \dots, N_l, \dots, N_{ L }\}$.
E_{cross}	Set of sections on connecting lines; $E_{\text{cross}} = \{E^{\text{GR}}, E^{\text{GS}}, E^{\text{RS}}, E^{\text{RU}}, E^{\text{SU}}\}$, $E^{\text{GR}}, E^{\text{GS}}, E^{\text{RS}}, E^{\text{RU}}, E^{\text{SU}}$ refer to subsets for HSR–intercity, HSR–suburban rail, intercity–suburban, intercity–metro, and suburban–metro.
E	Set of sections; $E = \{E^G, E^R, E^S, E^U, E_{\text{cross}}\}$, E^G, E^R, E^S, E^U refer to subsets for the local HSR section, local intercity section, local suburban section, and local metro section. $e \in E$. $E = \{1, 2, 3, \dots, E \}$, $ E $ denotes the total number of sections.
K	Set of trains: $K = \{1, 2, 3, \dots, K \}$: $ K $ denotes the total number of trains and $k \in K$.
D	Set of rolling stock types: $d \in D = \{G, R, S, U\}$ where G (high-speed rail), R (intercity rail), S (suburban rail), and U (metro) represent different types.
P	Set of passenger groups: $p \in P$
A_i^+, A_i^-	Set of arcs entering and leaving node i , respectively.
$A_{l,n}^{\text{ab}}$	Set of boarding arcs and alighting arcs corresponding to station n for passengers using route l ; $l \in L, n \in N_l$
$A_{l,n}^{\text{ru}}$	Set of section running arcs of trains on route l from station n to the next station; $l \in L$ and $n \in N_l \setminus n_l^{\text{des}}$ where n_l^{des} is the terminal station on route l .
$A_{l,n}^{\text{sk}}$	Set of skip-stop arcs of trains on route l at station n ; $l \in L, n \in N_l$.
$A_{l,n}^{\text{dw}}$	Set of dwell arcs of trains on route l at station n ; $l \in L, n \in N_l$.
A	Total set of network arcs; $(i, j) \in A$, $A = A_{l,n}^{\text{ab}} \cup A_{l,n}^{\text{ru}} \cup A_{l,n}^{\text{dw}} \cup A_{l,n}^{\text{sk}} \cup A^w$.

Table 3. Symbolic description of parameters and variables.

Symbol	Meaning
a_d^{fix}	Fixed usage cost of type d rolling stock [CNY/km]
a_d^{run}	Unit distance cost of type d rolling stock [CNY/km]
m_l	Running distance of route l [km]
$b_{i,j}$	Cost of passengers passing through arc (i, j) [CNY]
h_d	Average departure headway of type d trains [min]
t_e^{ru}	Pure running time of trains between section e [min]
t_n^{dw}	Dwell time of trains at station n [min]
t_n^{qt}	Start/stop additional time of trains at station n [min]
f_{min}	Minimum frequency of routes during study period
θ_{min}	Minimum service frequency of station during study period
g_d	Maximum passenger capacity of type d rolling stock
c_e	Maximum passing capacity of section e during the study period
c^{GR}	Maximum carrying capacity of HSR–intercity connecting line
q_e	Passenger flow between section e
q_n	Boarding passenger flow at station n
η	Passenger comfort coefficient
$\rho_{l,e}$	Binary parameter, taking 1 if operation range of route l covers section e , otherwise 0
$\phi_{d,l}$	Binary parameter, taking 1 if type d rolling stock can operate on route l , otherwise 0
o_p	Origin station of passenger group p ; $p \in P$
d_p	Destination station of passenger group p ; $p \in P$
u_l	Binary variable, taking 1 if route l operates trains, otherwise 0
$v_{k,d}$	Binary variable, taking 1 if train k is operated by type d rolling stock, otherwise 0
$w_{l,n}$	Binary variable, taking 1 if trains on route l dwell at station n , otherwise 0
$x_{p,i,j}$	Binary variable, taking 1 if passenger p passes through arc (i, j) , otherwise 0
$y_{l,k,d}$	Binary variable, taking 1 if route l is served by train k using type d rolling stock, otherwise 0
$z_{l,n}$	Binary variable, taking 1 if trains operating on route l turn back at station n , otherwise 0
$\sigma_{l,k,d,n}$	Binary auxiliary variable, $\sigma_{l,k,d,n} = y_{l,k,d} \cdot w_{l,n}$, used for linearization processing

3.3. Objective Function

The first objective function Z_1 is to minimize the operation cost of rail transit enterprises. The cost components in Z_1 are classified into variable costs and fixed costs, which are defined and characterized as follows. Variable costs mainly include traction electricity consumption and track (infrastructure) usage charges. The total variable cost is positively correlated with the aggregate train kilometers over the study period; that is, it increases as the total train running distance rises. Fixed costs primarily cover expenses such as vehicle maintenance and inspection as well as carriage cleaning and servicing. These costs are not directly related to train running distance; instead, they are incurred on a per-train service basis, meaning that each operated train corresponds to one fixed-cost expenditure. The second objective function Z_2 is to minimize the total passenger travel cost, that is, the shortest total travel time. The total objective function is the weighted sum of these two objective functions, where α and β are the corresponding weights. On the basis of ensuring that these two items are basically of the same order of magnitude, decision-makers can adjust the weights of each item according to specific needs.

$$Z_1 = \sum_{k \in K} \sum_{d \in D} \sum_{l \in L} (a_d^{\text{run}} \cdot m_l \cdot y_{l,k,d} + a_d^{\text{fix}} \cdot y_{l,k,d}) \quad (1)$$

$$Z_2 = \sum_{p \in P} \sum_{(i,j) \in A} b_{i,j} \cdot x_{p,i,j} \quad (2)$$

$$Z = \alpha \cdot Z_1 + \beta \cdot Z_2 \quad (3)$$

3.4. Constraints

3.4.1. Passenger Flow Balance

Equation (4) indicates that passenger group p chooses a unique path from their origin station to the destination station; that is, the flow balance is maintained at all intermediate nodes. Equation (5) indicates that passenger group p must board at their origin station; that is, at the origin station of passenger group p , a boarding arc must be selected. Equation (6) indicates that passenger group p must alight at their destination station.

$$\sum_{(i,j) \in A_i^-} x_{p,i,j} = \sum_{(j,i) \in A_i^+} x_{p,j,i}, \forall p \in P, i \in V / \{o_p, d_p, v_{o_p}^{\text{arr}}, v_{d_p}^{\text{dep}}, v_{o_p}^{\text{dwe}}, v_{d_p}^{\text{dwe}}\} \quad (4)$$

$$\sum_{(i,j) \in A_j^- \cap A^{bo}} x_{p,i,j} = 1, \forall p \in P, i = o_p \quad (5)$$

$$\sum_{(i,j) \in A_j^- \cap A^{bo}} x_{p,i,j} = 1, \forall p \in P, i = o_p \quad (6)$$

3.4.2. Connections Among Passenger Flow, Trains, and Routes

(1) Connection between passenger flow and trains: There is an association between “whether passenger flow can take a certain route” and “whether the route operates trains”. If route l does not operate trains, the passenger flow on all its arcs is forced to be 0. This constraint can be expressed as

$$x_{p,i,j} \leq \sum_{k \in K} \sum_{d \in D} y_{l,k,d}, \forall l \in L, n \in N_l, (i,j) \in A_{l,n}^{ru} \cup A_{l,n}^{sk} \cup A_{l,n}^{dw} \cup A_{l,n}^{ab}, p \in P \quad (7)$$

(2) Connection between passenger flow and routes: As long as at least one route dwells at station n , passengers are allowed to choose the boarding and alighting arcs

corresponding to station n , as shown in Equation (8). Equation (9) indicates that when a train dwells at station n ($w_{l,n} = 1$), passengers cannot use the corresponding skip-stop arc.

$$x_{p,i,j} \leq \sum_{l \in L, n \in N_l} w_{l,n}, \forall p \in P, (i, j) \in A_{l,n}^{ab} \quad (8)$$

$$x_{p,i,j} \leq 1 - w_{l,n}, \forall l \in L, n \in N_l, (i, j) \in A_{l,n}^{sk}, p \in P \quad (9)$$

(3) Coupling of trains and routes: There is an association between “whether a train can take a certain route” and “whether the route actually operates”. If a train operates on route l , the route actually needs to be operated; that is, for any $y_{l,k,d} = 1$, the corresponding u_l must be 1, as shown in Equation (10). If no train operates on route l , the route does not need to be operated, as shown in Equation (11).

$$y_{l,k,d} \leq u_l, \forall l \in L, k \in K, d \in D \quad (10)$$

$$\sum_{k \in K} \sum_{d \in D} y_{l,k,d} \geq u_l, \forall l \in L \quad (11)$$

3.4.3. Train Operation Mode

Equation (12) indicates that only when a route operates trains ($u_l = 1$) can the corresponding route's trains dwell ($w_{l,n} = 1$). Equation (13) indicates that trains must dwell at the origin station n_l^{ori} and destination station n_l^{des} of their operating route. Equation (14) indicates that metro trains adopt the “stop at every station” operation mode.

$$w_{l,n} \leq u_l, \forall l \in L, n \in N_l \quad (12)$$

$$w_{l,n} = u_l, \forall l \in L, n \in \{n_l^{\text{ori}}, n_l^{\text{des}}\} \quad (13)$$

$$w_{l,n} = u_l, \forall l \in L^U, n \in N_l \quad (14)$$

The operating route must meet the minimum train departure frequency $f^{\min}$. When $f^{\min} = 1$, this constraint is equivalent to constraint (11); when $f^{\min} > 1$, constraint (11) is ineffective, and only this constraint needs to be considered. This constraint can be expressed as

$$\sum_{k \in K} \sum_{d \in D} y_{l,k,d} \geq f^{\min} \cdot u_l, \forall l \in L \quad (15)$$

3.4.4. Passenger Service Quality

Equation (16) indicates that the service section of operating trains needs to cover the entire line. Equation (17) indicates that the number of services received by each station during the study period is not less than the minimum value $\theta^{\min}$. Equation (17) is a nonlinear constraint; a binary auxiliary variable $\sigma_{l,k,d,n} = y_{l,k,d} \cdot w_{l,n}$ is introduced, and linearization processing is performed using Equations (18)–(21).

$$\sum_{l \in L} u_l \cdot \rho_{l,e} \geq 1, \forall e \in E \quad (16)$$

$$\sum_{l \in L} \sum_{k \in K} \sum_{d \in D} y_{l,k,d} \cdot w_{l,n} \geq \theta^{\min}, \forall n \in N \quad (17)$$

$$\sum_{l \in L} \sum_{k \in K} \sum_{d \in D} \sigma_{l,k,d,n} \geq \theta^{\min}, \forall n \in N \quad (18)$$

$$\sigma_{l,k,d,n} \leq y_{l,k,d}, \forall l \in L, k \in K, n \in N, d \in D \quad (19)$$

$$\sigma_{l,k,d,n} \leq w_{l,n}, \forall l \in L, k \in K, n \in N, d \in D \quad (20)$$

$$\sigma_{l,k,d,n} \geq y_{l,k,d} + w_{l,n} - 1, \forall l \in L, k \in K, n \in N, d \in D \quad (21)$$

3.4.5. Matching of Rolling Stock and Route

Equation (22) indicates that each train can choose at most one type of rolling stock. After assigning rolling stock types to trains, each train can undertake at most one route during the study period, as shown in Equation (23). Trains equipped with different types of rolling stock can only operate on routes with appropriate standards; that is, when $\phi_{d,l} = 0$, type d rolling stock cannot operate on route l and $y_{l,k,d}$ must also be 0, as shown in Equation (24).

$$\sum_{d \in D} v_{k,d} \leq 1, \forall k \in K \quad (22)$$

$$\sum_{l \in L} y_{l,k,d} \leq v_{k,d}, \forall l \in L, k \in K, d \in D \quad (23)$$

$$y_{l,k,d} \leq \phi_{d,l}, \forall l \in L, k \in K, d \in D \quad (24)$$

3.4.6. Line and Station Capacity

For any section, the total number of trains passing through cannot exceed the passing capacity c_e of the section, as shown in Equation (25). Cross-line through trains need to pass through connecting lines to achieve cross-line operation, so they must also meet the connecting line passing capacity constraint. Taking high-speed rail–intercity rail cross-line through trains as an example, this constraint can be expressed as Equation (26). Other cross-standard through trains can be inferred similarly.

$$\sum_{l \in L} \sum_{k \in K} \sum_{d \in D} y_{l,k,d} \cdot \rho_{l,e} \leq c_e, \forall e \in E \quad (25)$$

$$\sum_{l \in L^{\text{GR}}} \sum_{d \in D} \sum_{k \in K} y_{l,k,d} \leq c^{\text{GR}} \quad (26)$$

3.4.7. Passenger Capacity and Passenger Flow Demand

Equation (27) indicates that the section transport demand q_e needs to be met, and Equation (28) indicates that the boarding passenger flow demand q_n needs to be met.

$$\sum_{l \in L} \sum_{k \in K} \sum_{d \in D} y_{l,k,d} \cdot g_d \cdot \rho_{l,e} \cdot \eta \geq q_e, \forall e \in E \quad (27)$$

$$\sum_{l \in L} \sum_{k \in K} \sum_{d \in D} g_d \cdot \sigma_{l,k,d,n} \cdot (1 - z_{l,n}) \geq q_n, \forall n \in N \quad (28)$$

3.5. Model Complexity

The proposed joint line planning model is formulated as a binary integer linear programming (BILP) problem. The scale of the solution space is determined by the total number of decision variables. Let $|A|$, $|L|$, $|K|$, $|D|$, $|N|$, and $|P|$ denote the total number of arcs in the coupled network, candidate routes, available trains, rolling stock types, stations, and passenger groups, respectively. The number of variables in the model is summarized in Table 4. The total number of variables is $O(|L| + |K| \cdot |D| + 2 \cdot |L| \cdot |N| + |P| \cdot |A| + |L| \cdot |K| \cdot (|D| + 1))$.

Table 4. Number of variables.

Variable	Number
u_l	$ L $
$v_{k,d}$	$ K \cdot D $

Table 4. Cont.

Variable	Number
$w_{l,n}$	$ L \cdot N $
$x_{p,i,j}$	$ P \cdot A $
$y_{l,k,d}$	$ L \cdot K \cdot D $
$z_{l,n}$	$ L \cdot N $
$\sigma_{l,k,d,n}$	$ L \cdot K \cdot D \cdot N $

4. Case Study

To evaluate the effectiveness of the proposed model, this section presents a case study based on an abstraction of an actual regional rail network. We conduct numerical experiments to compare the optimized train service plans under two modes, (1) cross-system operation with through services and (2) independent operation without through services, and quantify the incremental system-wide benefits of through operation relative to independent operation. The model is implemented in Python 3.13 and solved using GUROBI 11.0.0 on a personal computer equipped with an Intel(R) Core(TM) Ultra 7 265K @ 3.90 GHz processor (manufacturer: Intel Corporation; city, state, country: Santa Clara, CA, USA).

Figure 4 (left) depicts the physical network of the case study. For modeling convenience, we construct a topology-based network with virtual nodes as illustrated in Figure 4 (right). In particular, virtual nodes 3, 8, 14, and 22 constitute interchange station C, while virtual nodes 10, 17, and 27 constitute interchange station I. Such interchange stations act as key interfaces for the physical interconnection of multiple rail systems and, within the “four-network integration” framework (i.e., high-speed, intercity, suburban, and metro systems), enable cross-system through operation and support network-level coordinated operations. According to the candidate service-route generation procedure described in Section 2.1, the whole network identifies ten service routes in total: five within-system routes and five cross-system routes.

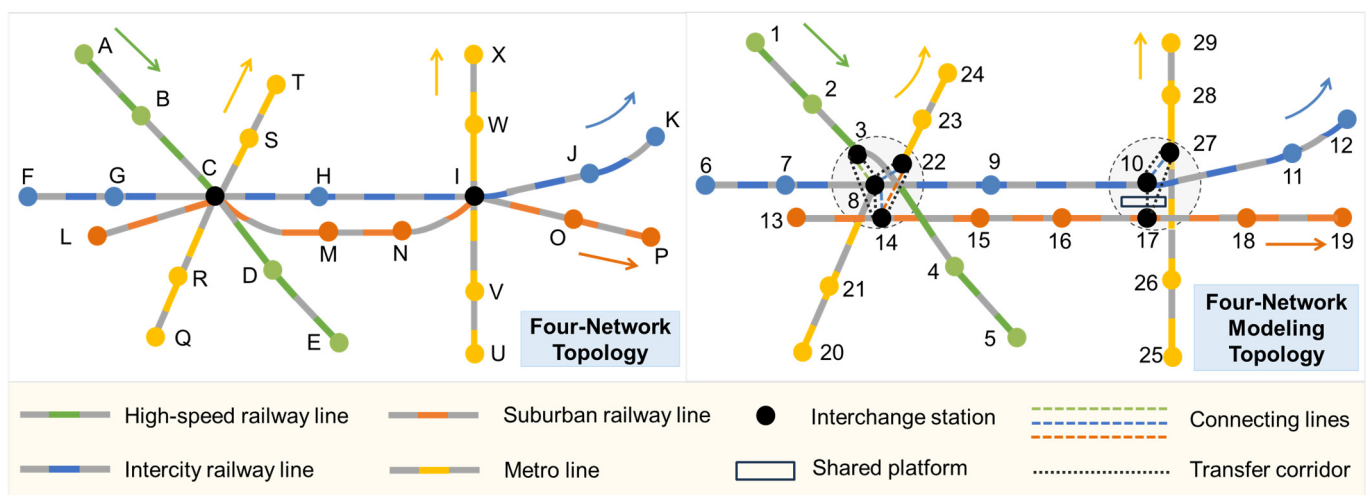


Figure 4. Case-study physical network and modeling topology.

4.1. Parameter Settings

The case study is prototyped on the regional rail network of a representative Chinese metropolitan area. The planning horizon is set to two hours, with a total passenger demand of 40,000. To reflect the agglomeration of rail transit demand, passengers are grouped into cohorts of 100 sharing the same origin–destination (OD) pair, yielding 400 passenger

groups in total; each group's OD is randomly assigned. The principal parameter settings are given in Table 5. Where system-level technical standards differ, key parameters take system-specific values, which are detailed in Table 6.

Table 5. Values of main parameters.

Parameter	Description	Value
m_l	Service distance of route l [km]	$m_1 = 200, m_2 = 120, m_3 = 60, m_4 = 8,$ $m_5 = 8, m_6 = 180.5, m_7 = 90.5$ $m_8 = 44.5, m_9 = 84.5, m_{10} = 14.5$
$b_{i,j}$	Cost for a passenger traversing arc (i, j) [CNY]	Computed from Section 2.2.2
$f^{\min}$	Minimum dispatch frequency of each route within the horizon	1
$\theta^{\min}$	Minimum service frequency at stations within the horizon	1
g_d	Max passenger capacity per train of type d [persons/train]	$g_G = 600, g_R = 600, g_S = 600, g_U = 800$
c_e	Max carrying capacity of section e within the horizon [trains/2h]	24
c^{GR}	Max capacity of the HSR–intercity connecting line [trains/2h]	10
η	Passenger comfort coefficient	0.9

Table 6. Values of key parameters based on different systems.

	HSR System	Intercity Rail System	Suburban Rail System	Metro System
Variable cost a_d^{un} [CNY/km]	320	260	180	120
Fixed cost a_d^{fx} [CNY]	500	400	300	200
Average headways h_d [min]	30	20	15	4
Section running time t_e^u [min]	20	12	10	3
Dwell time t_d^{dw} [min]	4	3	2	1
Start/stop additional time t_d^{qt} [min]	2	1	1	0.5

4.2. Passenger OD Statistics

Over the two-hour horizon, cross-system passenger demand totals 8600, accounting for 21.5% of the overall demand. Table 7 details the composition of cross-system demand: intercity–suburban is the largest segment (2600), followed by high-speed–suburban (2000), indicating strong connectivity between the metropolitan periphery and the central urban area. Station-level boarding and alighting values are shown in Figure 5a.

Table 7. Cross-system passenger flows by type over the study period (persons/2h).

	HSR–Intercity	HSR–Suburban	HSR–Metro	Intercity–Suburban	Intercity–Metro A	Intercity–Metro B	Suburban–Metro A	Suburban–Metro B	Total
Volume	1000	2000	200	2600	1000	600	800	400	8600

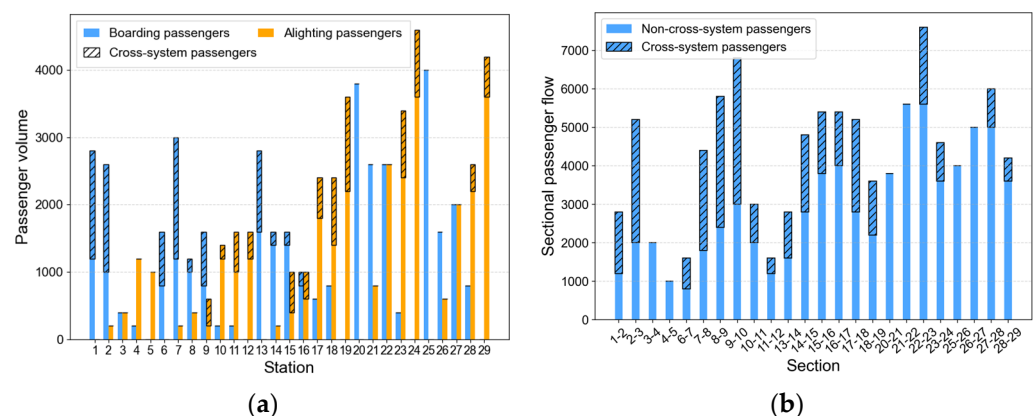


Figure 5. Number of passengers at each station and between stations. (a) Station-level boarding and alighting values. (b) Section-level passenger flow.

To compute sectional passenger flows, the cross-system OD records are pre-processed as follows. Whenever an OD involves cross-system travel, it is partitioned at the interchange station into two segments: origin $\rightarrow$ first interchange and first interchange $\rightarrow$ destination, and at subsequent interchanges if more than two systems are traversed [16]. After this pre-processing, the resulting sectional flows are obtained and visualized in Figure 5b.

4.3. Optimization Results

Building on the multi-commodity flow formulation and the demand of 400 passenger groups, we optimize the four-network train service plans under cross-system through operation mode and independent operation mode. Service frequencies by route/system type are reported in Table 8, with a visual summary in Figure 6. Detailed service plans and representative passenger paths are illustrated in Figures 7–10. The overall results are summarized in Table 9, which quantifies how the service design choices in Table 8 translate into aggregate differences in system performance and costs.

Table 8. Comparison of frequencies of different train types under two modes.

Route Type	Cross-System Through Operation		Independent Operation	
	Frequency (Trains/2h)		Frequency (Trains/2h)	
HSR	4	G	9	G
Intercity	1	R	12	R
Suburban	8	S	9	S
Metro A	8	U	10	U
Metro B	7	U	8	U
HSR–Intercity	5	G	--	--
Intercity–Suburban	1	R	--	--
Intercity–Metro A	1	R	--	--
Intercity–Metro B	6	R	--	--
Suburban–Metro A	1	S	--	--

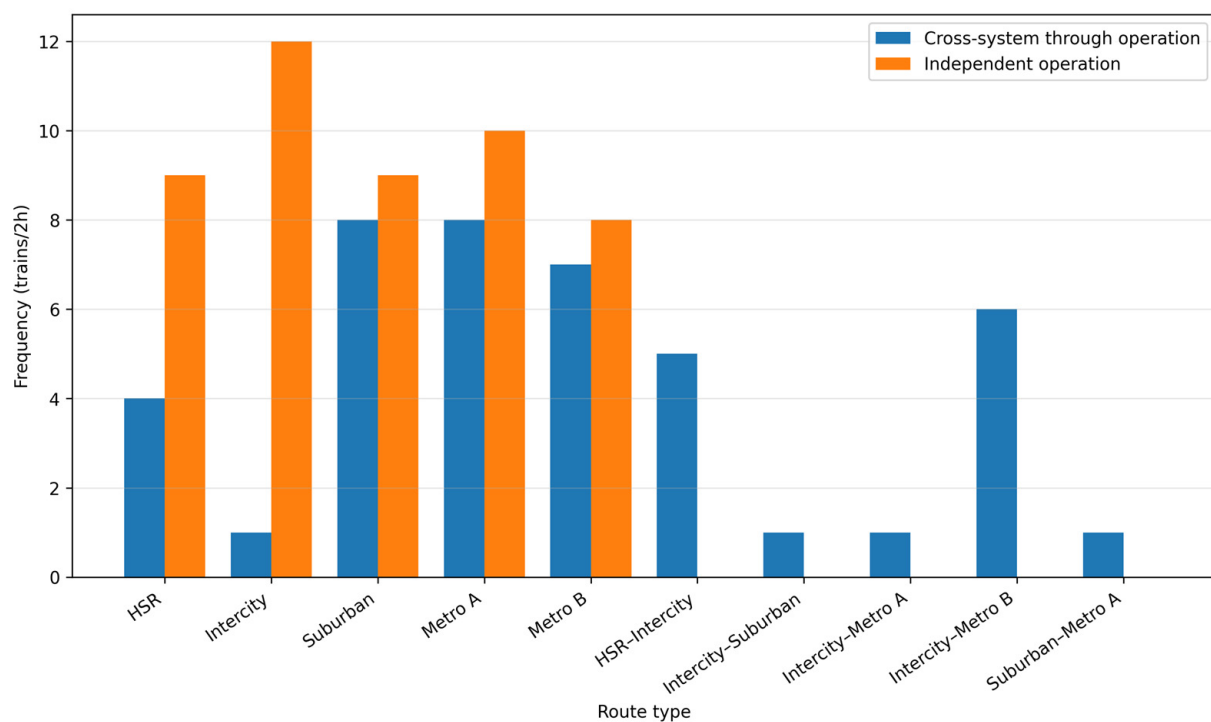


Figure 6. Visualization of frequency comparison of different train types under two modes.

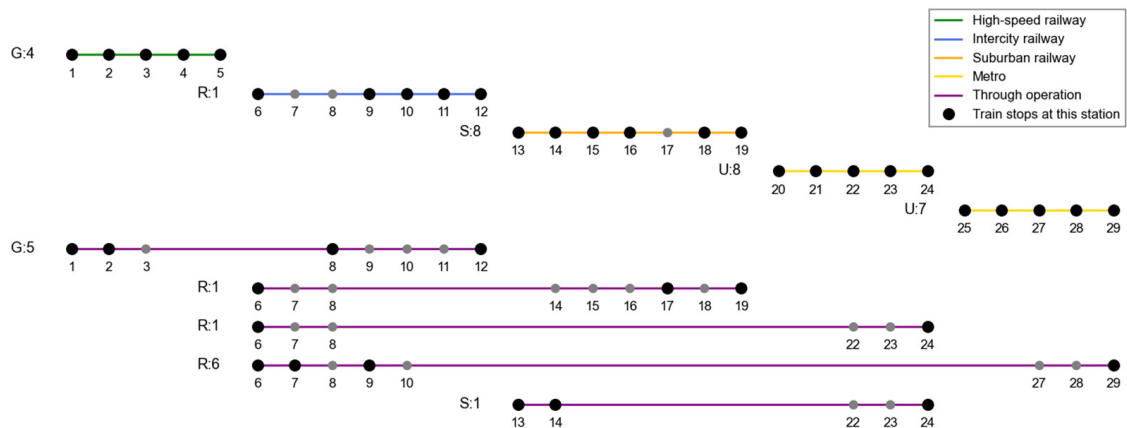


Figure 7. Multi-system line plans under through operation mode: rolling-stock-based representation.

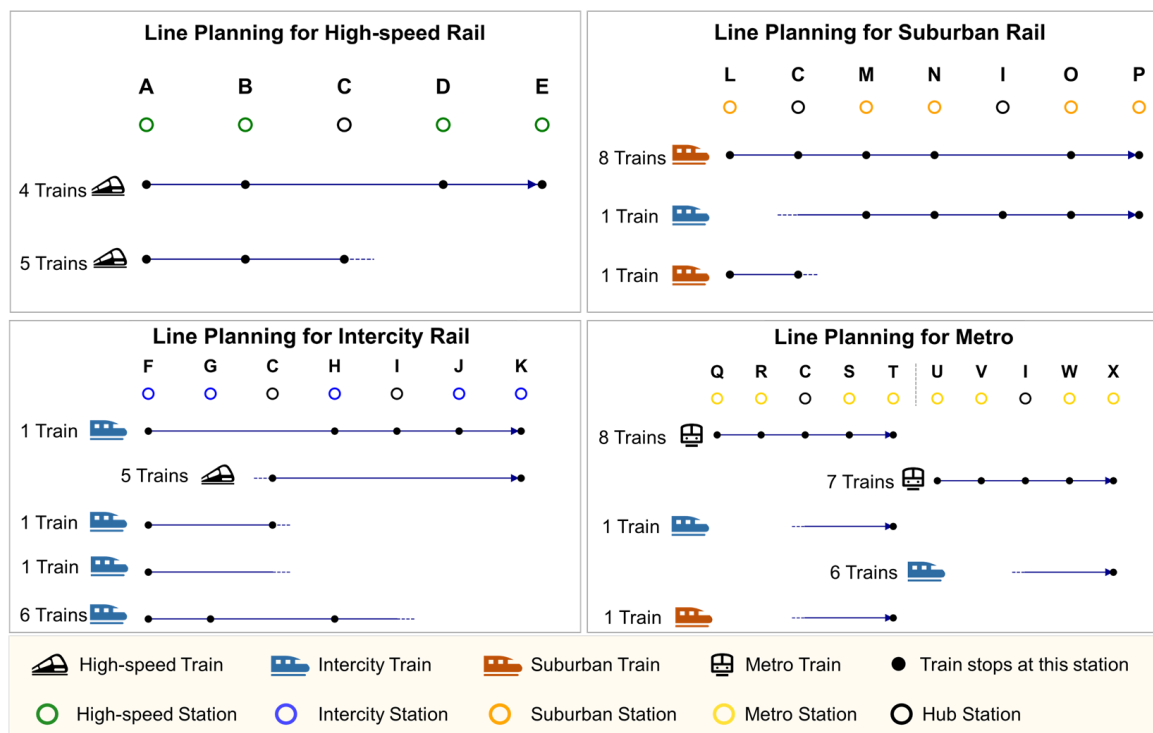


Figure 8. Multi-system line plans under through operation mode: line- and station-based representation.

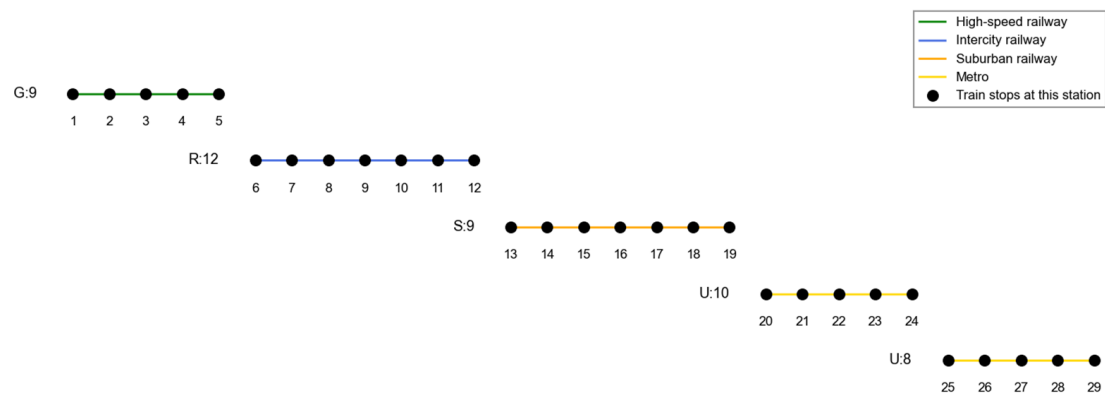


Figure 9. Multi-system line plans under independent operation mode: rolling-stock-based representation.

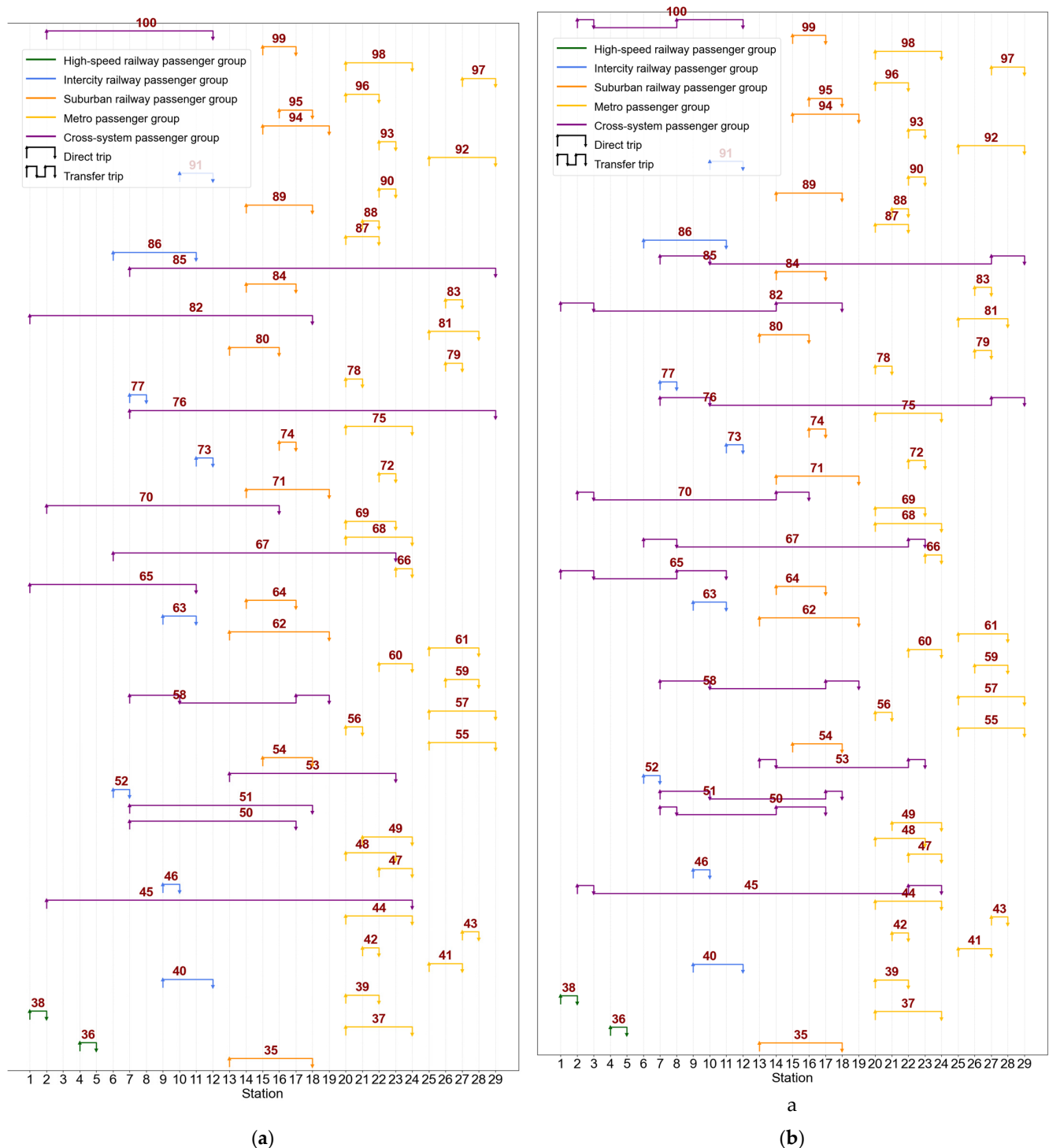


Figure 10. Passenger travel paths under two operation modes (example: passenger groups 35–100). (a) Passenger travel paths under through operation mode. (b) Passenger travel paths under independent operation mode.

We assign equal weights (0.5/0.5) to the two objectives (operator cost and passenger cost). From Table 9, relative to independent operation, cross-system through operation reduces operation cost by 20.4% and total passenger travel cost by 6.5%. These results indicate that through operation achieves bilateral cost improvements. The mechanisms are as follows.

Table 9. Overall comparison of solution results.

Operation Mode	Operation Cost [CNY]	Passenger Total Cost [CNY]	Number of Trains Deployed	Number of Passenger Transfers
Cross-system through operation	860,130	404,884	42	2600
Independent operation	1,080,480	432,896	48	8800

1. Drivers of operator cost reduction.

The reductions in the total number of trains used and in total train kilometers provide an intuitive explanation for the decrease in total operating cost. The through operation mode uses a total of 42 trains, which is 6 fewer than the independent operation mode (48 trains). Based on the values of m_l in Table 5, the total train kilometers under the through operation mode are 3079, representing a 21.5% reduction compared with the independent operation mode (3924 train km). In addition, through operation strengthens demand–supply matching and resource substitution: by aggregating within-system and cross-system demand onto through trains, the same rolling stock delivers multiple functions (“one train, multiple roles”). As shown in Table 8, over the study horizon the number of high-speed trains running on their own line drops from 9 to 4, intercity from 12 to 1, suburban from 9 to 8, Metro A from 10 to 8, and Metro B from 8 to 7, while cross-system services (e.g., five HSR ↔ intercity through trains) effectively substitute part of the within-system supply.

2. Drivers of passenger cost reduction.

The core mechanism is the reduction in transfer cost: passengers can choose direct cross-system through trains and thus avoid walking and queuing time at interchange stations. As shown in Table 9, under the through operation mode, the total number of passenger transfers (26) decreases by 70.5% compared with the independent operation mode (88). In addition, the model’s skip-stop arcs further shorten in-vehicle time on through trains by reducing unnecessary dwell. For example, an intercity ↔ suburban through service skips stations 7, 8, 14, 15, 16, and 18, saving 14 min of dwell time; this offsets the additional running time on the connecting line and ultimately lowers total travel cost.

In summary, the case study validates the advantage of cross-system through operation within a four-network integration context: coordinated scheduling and resource pooling across systems simultaneously lower operator costs and improve passenger efficiency, offering a practical organizing principle for operations under multi-system integration.

Figures 7 and 8 visualize, for the cross-system through operation mode, the spatial distribution of services and the associated resource allocation. By coordinating through circulations across systems, this regime enables more intensive use of network resources.

1. Functional integration of through trains.

Cross-system services such as HSR ↔ intercity and intercity ↔ Metro B (highlighted as “through operation” in purple in Figure 7) span multiple rail systems. Their paths chain together the interchange stations (e.g., nodes 3, 8, 14, and 22), simultaneously accommodating within-system demand on segments (e.g., HSR 1–2–3; intercity 6–7–8) and directly serving cross-system OD pairs (e.g., a direct trip from HSR station 1 to intercity station 12), thereby realizing a “one train, multiple roles” substitution effect.

2. Streamlining of within-system services.

Relative to the independent mode (see Table 8), the number of within-system trains is markedly reduced—HSR from 9 to 4, Intercity from 12 to 1, and Suburban from 9 to

8—while the added through services backfill capacity so that service frequencies on each system continue to satisfy passenger demand.

Figure 9 illustrates the independent operation in which each system runs independently with no through services. Compared to the through operation mode, the key differences are as follows:

1. Dense within-system operations.

Within-system trains are deployed at higher frequencies—HSR (G: 9 trains) and intercity (R: 12 trains)—with each fleet confined to its own line (e.g., HSR limited to segments 1–2–3–4–5 and intercity to 6–7–8–9–10–11–12). Passenger demand is met mainly by high within-system frequency, which leads to redundant resource deployment relative to the through operation regime.

2. Transfer dependence of cross-system passengers.

In the absence of through trains, cross-system ODs (e.g., HSR station 1 → intercity station 12) must transfer at interchange hubs (e.g., within hub C, between nodes 3 and 8), which significantly increases the transfer and circulation load at these hubs.

Figure 10 visualizes the paths of passenger groups 35–100 to show the main contrasts between the two modes.

1. Directness advantage under through running.

For cross-system passenger groups (e.g., Group 100: HSR station 2 → intercity station 12), paths are predominantly board–ride–alight with no transfer, completing cross-system travel on a single through service. The skip-stop design at selected stations reduces unnecessary dwell and shortens in-vehicle time, yielding lower total travel time than in the independent regime.

2. Transfer penalty under segregation.

Without through trains, cross-system groups (e.g., Group 100) must alight → walk/queue to transfer → board at interchange stations (e.g., alight at node 3 and transfer to intercity at node 8). The transfer walking/queuing time becomes a salient component of generalized passenger cost.

3. Path stability for within-system demand.

For HSR, intercity, suburban, and metro within-system passenger groups, paths in both modes remain the standard board–ride–alight pattern with minor differences. Notably, the streamlined within-system service in the through operation mode does not degrade service quality for these passengers, confirming the complementary capacity provided by through trains.

4.4. Sensitivity Analysis of Cross-System Flow Ratio

To investigate the adaptability and economic boundary of the proposed through operation mode under different passenger demand structures, this subsection designs a sensitivity analysis experiment with respect to the cross-system passenger flow ratio. While keeping the total demand of the test instance fixed at 40,000 passengers, a cross-system passenger flow ratio coefficient is introduced to adjust the composition of passenger flows. Let π denote the proportion of cross-system passenger volume in the total demand. In the base case in Section 4.2, $\pi \approx 21.5\%$. In this experiment, π is varied within the interval [5%, 40%] with a step size of 5%. By resampling the base OD matrix and adjusting the associated weights, eight sets of passenger demand data with different structures are generated. As π increases, within-system passenger flows decrease accordingly, while cross-system flows (e.g., HSR–intercity and intercity–suburban) increase, so as to mimic the dynamic evolution

from a regime dominated by independent operation to a highly integrated multi-system network. For each of the eight scenarios, the line planning model is solved under both the through operation mode and the independent operation mode, and the resulting operator operation costs, passenger travel costs, and cost saving rates are plotted in Figure 11.

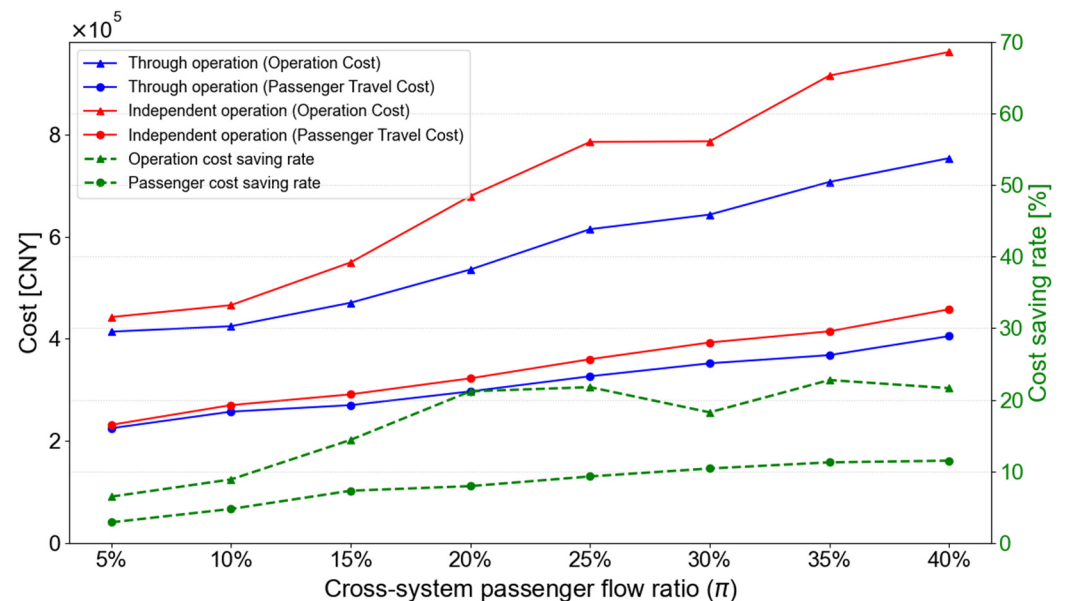


Figure 11. Comparison of costs and cost saving rates between through and independent operation modes under varying cross-system passenger flow ratios.

The experimental results reveal several key patterns. First, in terms of absolute cost levels, the through operation mode consistently outperforms the independent operation mode in both the operator's operation cost and passenger travel cost over the entire range of π . As the cross-system passenger flow ratio increases from 5% to 40%, both operation costs and passenger costs rise monotonically in the two modes. However, the cost curves under independent operation always lie above those under through operation and exhibit a steeper growth. This indicates that, in the presence of cross-system travel demand, separating different rail systems and forcing passengers to transfer at interchange stations simultaneously escalates system costs by increasing both the required train service volume and passengers' generalized travel time.

Second, from the perspective of cost saving rates, the relative advantage of through operation is more pronounced for operation costs. The operation cost saving rate (with the independent operation mode as the benchmark) generally increases with π : at $\pi = 5\%$, the saving is still limited and remains at a single-digit level; when π rises to the range of 15–25%, the saving rate grows rapidly and stabilizes at around 20% under high cross-system demand scenarios. This suggests that, as the volume of cross-system passenger flows expands, through operation enables the sharing of rolling stock and capacity across different systems via cross-system through trains, substantially reducing duplicated services and redundant train kilometers and thereby fully exploiting the coordination effects of integrated operations.

By contrast, the cost saving effect of through operation on passenger travel cost is more moderate but still robust. The passenger cost saving rate remains within approximately 5–15% over the entire range of π , increasing slowly with π and gradually approaching a plateau. This reflects that, on the one hand, through operation brings sustained time benefits to cross-system passengers by reducing the number of transfers and shortening waiting and within-station walking times; on the other hand, in this test instance passenger

travel cost accounts for a relatively limited share of the total system cost, so its marginal room for improvement is smaller, and hence the saving rate does not exhibit the sharp increase observed for operation costs.

Overall, under the given network and demand conditions, the through operation mode can substantially reduce the operator's operation cost while steadily improving passengers' travel experience. Its relative advantage over the independent operation mode becomes increasingly significant as the cross-system passenger flow ratio increases.

4.5. Robustness Checks Under Demand Surges and Capacity Reductions

To investigate the robustness of the optimized plans to parameter variations associated with demand surges and maintenance-induced capacity reductions, we conduct experiments under four different scenarios: +10% demand, +20% demand, −60% capacity, and −80% capacity. Specifically, all OD demands are proportionally increased to ensure comparability between the new experiments and the baseline case. And the capacity here refers to c^{GR} , the max capacity of the HSR–intercity connecting line [trains/2h]. We consider −60% and −80% capacity cases because, in the base scenario, the value of c^{GR} is set to 10, which is adequate according to the optimized result in Section 4.3. To ensure that capacity becomes restrictive and can meaningfully affect the optimal plans, we apply relatively large reductions (−60% and −80%) in the robustness checks.

The overall comparison of solution results under different scenarios is shown in Table 9. As summarized in Table 10, through operation mode consistently outperforms independent operation mode across the base case and all four stress-test scenarios. In every setting, through operation yields a lower operation cost (OC) and a lower passenger total cost (PC), while requiring fewer trains deployed (NTD) and inducing substantially fewer passenger transfers (NPT). This indicates that the cost advantage of the optimized through services is robust to both demand growth and maintenance-related capacity tightening.

Table 10. Overall comparison of solution results under different scenarios.

Scenario	Operation Mode	OC [CNY]	PC [CNY]	NTD	NPT
Base	Through operation	860,130	404,884	42	2600
	Independent operation	1,080,480	432,896	48	8800
+10% demand	Through operation	954,180	442,153	47	2800
	Independent operation	1,221,600	473,548	54	9700
+20% demand	Through operation	1,030,940	486,145	50	3000
	Independent operation	1,298,360	519,582	57	10,400
−60% capacity	Through operation	888,740	404,884	43	2600
	Independent operation	1,080,480	432,896	48	8800
−80% capacity	Through operation	964,420	404,884	45	2600
	Independent operation	1,080,480	432,896	48	8800

Base scenario is in Sections 4.1–4.3. OC: operation cost, PC: passenger total cost, NTD: number of trains deployed, NPT: number of passenger transfers. −60%/−80% capacity: max capacity of the HSR–intercity connecting line [trains/2h] is reduced by 60%/80% relative to the base case.

In demand-surge scenarios (+10%/+20% demand), when demand increases, both operation modes require additional supply and incur higher costs compared to the base scenario. Under through operation, OC rises from 860,130 (base) to 954,180 (+10.9%) and 1,030,940 (+19.9%), while PC increases from 404,884 to 442,153 (+9.2%) and 486,145 (+20.1%). The required NTD increases moderately from 42 to 47 and 50, and NPT increases slightly from 2600 to 2800 and 3000. In contrast, independent operation shows larger absolute levels and a persistently higher transfer burden (NPT 9700 and 10,400), together with higher OC (1,221,600 and 1,298,360) and PC (473,548 and 519,582). Overall, the results

suggest that through operation accommodates demand surges mainly by scaling direct services with limited additional transfers, thereby maintaining a clear advantage over independent operation.

Capacity-reduction scenarios (−60%/−80% capacity): Reducing the capacity of the HSR–intercity connecting line primarily affects the through operation plan, which relies on cross-line movements. Compared with the base case, through operation increases OC to 888,740 (+3.3%) under −60% capacity and to 964,420 (+12.1%) under −80% capacity, and NTD increases from 42 to 43 and 45, respectively. Notably, PC and NPT remain unchanged (PC = 404,884 and NPT = 2600), indicating that the optimized through operation plan can preserve passenger-side performance under tighter connecting-line capacity, at the expense of deploying slightly more trains and higher operating effort. Meanwhile, the independent operation results remain the same as the base case (since it does not exploit the connecting line) but still exhibit a higher OC/PC and much larger NPT. Even under the most restrictive capacity setting (−80%), through operation continues to deliver lower costs and markedly fewer transfers than independent operation, demonstrating strong robustness under infrastructure capacity degradation.

All of the experiments were implemented in Python 3.13 and executed on a personal computer with Intel(R) Core(TM) Ultra 7 265K @ 3.90 GHz processor (manufacturer: Intel Corporation; city, state, country: Santa Clara, CA, USA), with the commercial solver Gurobi 11.0.0. In terms of computational complexity, the most demanding scenario (a 20% surge in passenger demand) contained 167,910 binary variables and 754,465 constraints. After Gurobi presolve, the reduced model contained 30,234 binary variables and 92,576 constraints. The global optimum was reached within 20 s.

5. Conclusions and Future Research

This study investigates joint line planning for a four-system regional rail network (HSR, intercity rail, suburban rail, and metro) under the through operation mode. A unified optimization framework is developed to support integrated decision-making on service routes, frequencies, stopping patterns, passenger flow assignment, and rolling-stock type allocation. The framework consists of (1) a hierarchical decoupling of the multi-system physical network to identify candidate within-system and cross-system through routes and (2) a coupled train service and passenger travel network representation that captures the endogenous interaction between train operations (including skip-stop patterns) and passenger movements (boarding, alighting, waiting, and transfers). Building on this dual-network coupling, a multi-commodity flow model is formulated and solved using Gurobi to generate coordinated line plans under multi-system through operation.

A real-world-inspired case study demonstrates that, compared with the independent operation mode, the through operation mode can reduce operator operating cost by 20.4% and reduce total passenger travel cost by 6.5% under the tested setting. The cost reductions are mainly driven by the following: (1) resource substitution and demand aggregation (“one train, multiple roles”), where cross-system through trains partially substitute redundant within-system services; (2) transfer avoidance, as cross-system passengers can complete trips using direct through services; and (3) skip-stop designs that reduce unnecessary dwell time and thereby lower generalized travel cost. Sensitivity results further confirm that these advantages are robust across demand structures: as the cross-system flow ratio increases from 5% to 40%, through operation consistently outperforms independent operation in both operator and passenger costs; moreover, operator cost savings become more pronounced and stabilize at a relatively high level under medium-to-high cross-system demand, while passenger cost savings remain moderate yet persistent, providing quantitative

evidence for the adaptability and economic boundary of through operation-based multi-network integration.

Several extensions can further improve realism and robustness: (1) In this study, all trains are assumed to have fixed formations. Future work can allow multiple formation options per service to better accommodate demand fluctuations. (2) Capacities are treated as constants in the current model. In practice, capacity varies over time and can be constrained by cross-system interactions due to priority rules and headway coupling. These effects can be represented using time-dependent effective capacities, system-specific capacity shares, or explicit capacity-coupling constraints. (3) Future research can integrate timetable feasibility and rolling-stock circulation, while accounting for overtaking, time-varying demand, and disturbances.

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References

1. Chai, S.; Yin, J.; Tang, T.; Yang, L.; Liu, R.; Luo, Q. Integrated capacity allocation and timetable coordination for multimodal railway networks. *Transp. Res. Part C Emerg. Technol.* **2024**, *165*, 104681. [\[CrossRef\]](#)
2. Wang, Y.H.; Ju, M.Y.; Huang, W.Z.; Ren, A.; Zhou, D.T.; Meng, L.Y. Integrated cyclic train timetabling and rolling stock circulation for through operation of suburban railway and subway. *J. Railw. Sci. Eng.* **2025**, *22*, 2013–2026. (In Chinese)
3. Drechsler, G. Light railway on conventional railway tracks in Karlsruhe, Germany. *Proc. Inst. Civ. Eng. Transp.* **1996**, *117*, 81–87. [\[CrossRef\]](#)
4. Naegeli, L.; Weidmann, U.; Nash, A. Checklist for successful application of tram–train systems in Europe. *Transp. Res. Rec. J. Transp. Res. Board* **2012**, *2275*, 39–48. [\[CrossRef\]](#)
5. Ito, M. Through between railway operators in greater Tokyo. *J. Railw. Transp. Rev.* **2014**, *63*, 14–21.
6. Kurosaki, F. Through-train services: A comparison between Japan and Europe. *J. Railw. Transp. Rev.* **2014**, *63*, 22–25.
7. Novales, M.; Orro, A.; Bugarin, M.R. Madrid tram-train feasibility study conclusions. *Proc. Inst. Mech. Eng. Part F* **2003**, *217*, 1–10.
8. Sato, L.; Essig, P. How Tokyo’s subways inspired the Paris RER. *J. Railw. Transp. Rev.* **2000**, *23*, 36–42.
9. Phraner, S.D.; Roberts, R.T.; Stangas, P.K.; Karach, K.A.; Shortreed, J.H.; Thompson, G.J. *Joint Operation of Light Rail Transit or Diesel Multiple Unit Vehicles with Railroads*; National Academies Press: Washington, DC, USA, 1999.
10. Li, M.G.; Liu, J.F.; Liu, X.H.; Wang, J.; Li, J.H. Train planning for through operation between subway and suburban railway. *J. Transp. Syst. Eng. Inf. Technol.* **2017**, *17*, 178–184.
11. Huang, X.Y. Study on Train Operation Plan of Cross-Line Operation of Intercity Railway and Suburban Railway. Doctoral Dissertation, Beijing Jiaotong University, Beijing, China, 2022.
12. Ren, A.; Meng, L.Y.; Wang, Y.H.; Huang, W.Z.; Ren, R. Optimization of express/slow train operations in integrated suburban and urban rail systems based on passenger demand. *J. Beijing Jiaotong Univ.* **2024**, *48*, 153–163.
13. Peng, Q.Y.; Liu, S.Y.; Jiang, S.; Feng, T.; Chen, Y.; Zhang, Y.X. Collaborative optimization of suburban railway and metro train operation plans under the interconnection operational mode. *J. Transp. Syst. Eng. Inf. Technol.* **2025**, *25*, 36–47.
14. Lin, L.; Meng, X.L.; Cheng, X.Q.; Ma, Y.Y.; Xu, S.C.; Han, Z. Line planning under the operation mode of line sharing between metro and suburban railway. *J. Adv. Transp.* **2023**, *2023*, 8847456. [\[CrossRef\]](#)
15. Lin, L. Train Service Plan Preparation Under Through Operation Between Different Rail Transit Lines. Doctoral Dissertation, Lanzhou Jiaotong University, Lanzhou, China, 2024. (In Chinese)

16. Zheng, Y.H. Study on Regional Rail Transit Operation Plan Under the Background of Multi-Network Integration. Doctoral Dissertation, Lanzhou Jiaotong University, Lanzhou, China, 2022. (In Chinese)
17. Yan, F.; Yao, X.M.; Zhao, P.; Han, M.; Qiao, K. Modelling train operation plan for urban rail transit under interconnection operational mode. *J. China Railw. Soc.* **2023**, *45*, 13–21. (In Chinese)
18. Gattermann, P.; Harbering, J.; Schöbel, A. Line pool generation. *Public Transp.* **2017**, *9*, 7–32. [[CrossRef](#)]
19. Yao, Z.Y.; Nie, L.; Fu, H.L. Railway line planning with passenger routing: Direct-service network representations and a two-phase solution approach. *Transp. Res. Part B Methodol.* **2024**, *186*, 102989. [[CrossRef](#)]
20. Zhou, W.L.; Huang, Y.J.; Chai, N.J.; Li, B.; Li, X. A line planning optimization model for high-speed railway network merging newly-built railway lines. *Mathematics* **2022**, *10*, 3174. [[CrossRef](#)]

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