

# A Multi-Objective Decomposition Model for Integrated Urban Transit Line Planning and Passenger Routing

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**Abstract:** Urban public transport networks must balance traveler convenience with tight budgetary and capacity constraints. This study develops a comprehensive multi-objective integer programming framework that unifies line selection, frequency setting, and passenger routing to minimize door-to-door travel time and operating cost while respecting vehicle capacities and limiting transfers. The model is solved using a Dantzig–Wolfe decomposition approach with linear-programming relaxation, which enables tractable solutions on realistically scaled networks. To reflect real-world commuting behavior, three increasingly sophisticated formulations are proposed: a Basic Line Planning Model, a Direct Connection Capacity Model, and a Change-and-Go Model that embeds walking and waiting penalties. On a six-edge, four-node network with 6,000 passenger trips, the Change-and-Go Model emerges as the most effective, reducing average travel time by 47%, halving transfers, and increasing cost by only 11% compared to the incumbent plan. Sensitivity analysis reveals that the model remains robust under varying demand levels and cost–time priorities. The proposed framework thus offers a scalable and passenger-friendly decision-support tool that significantly improves public transport efficiency with moderate investment, making it especially valuable for urban transit agencies seeking to modernize their services.

**Keywords:** multi-objective integer programming; public transport network design; line planning; passenger routing; Dantzig–Wolfe decomposition; Change-and-Go model; urban transit optimization

## INTRODUCTION

Public transportation plays a critical role in urban mobility, providing an efficient and sustainable alternative to private vehicles (Green et al., 2014). It serves as a backbone for economic activities, reduces traffic congestion, and minimizes environmental impacts by lowering carbon emissions. However, many public transport systems face persistent challenges, including high travel costs that make commuting expensive for passengers, excessive transfer requirements that disrupt seamless travel, long waiting times that decrease efficiency, and a lack of passenger comfort that discourages public transport usage (Hartleb et al., 2023; Jahan & Hamidi, 2019). These inefficiencies not only reduce user satisfaction but also contribute to overcrowding, inconsistent service reliability, and operational inefficiencies (Alçura et al., 2016). In rapidly growing urban areas, the demand for effective public transportation is increasing, yet existing systems struggle to keep up with the complexity of urban expansion and changing commuter patterns. Without strategic improvements, these problems will continue to escalate, making it crucial to develop optimized route planning solutions that enhance accessibility, affordability, and overall passenger experience (Morton et al., 2016).

To address these challenges, this study proposes a multi-objective optimization model that systematically improves public transportation efficiency by minimizing travel time, reducing the number of transfers, minimizing waiting times at transfer points, maximizing passenger comfort, and optimizing operational costs for transport providers. The study develops an Integer Programming (IP) model that systematically optimizes route planning while considering real-world constraints.

The methodology consists of three key models. The Basic Line Planning Model (BLPM) determines the optimal set of routes and their frequencies while ignoring transfer constraints. The Direct Connection Capacity

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Model extends the basic model by introducing transfer limitations and transport capacity constraints. The Change and Go Model (CGM) incorporates a graph-based approach to explicitly model transfer penalties and travel time variations, ensuring a more realistic representation of passenger movement. To efficiently solve this complex optimization problem, the study applies Dantzig-Wolfe decomposition to break it into smaller subproblems and uses Linear Programming (LP) relaxation techniques to approximate optimal solutions (Tang et al., 2020).

The key contributions of this research include the development of a multi-objective optimization framework tailored for public transport route planning, the introduction of transfer-aware modeling to account for real-world commuting conditions, the application of advanced decomposition techniques to improve computational efficiency, and the provision of practical implications for transportation authorities to enhance service quality and passenger experience. By integrating these optimization techniques, the proposed model offers a systematic and scalable approach for designing efficient public transportation networks, ultimately leading to improved urban mobility and passenger satisfaction.

## LITERATURE REVIEW

Optimizing public transportation networks has been a significant focus in operations research and transportation science. Early works on line planning models primarily addressed cost minimization and demand satisfaction. For instance, (Atik et al., 2025; Borndörfer et al., 2007) proposed a column-generation approach to effectively optimize large-scale public transit systems, demonstrating how iteratively generated route sets could lead to near-optimal solutions. (Bussieck et al., 2004) further advanced line planning in railway networks through algorithmic techniques that balanced route frequencies against operating costs.

Subsequent research recognized the importance of transfer optimization for enhancing passenger experience and overall network performance (Filippi et al., 2023; D. Wang et al., 2023). (Guo & Wilson, 2011) examined the consequences of inconvenient transfers in urban rail systems, quantifying the negative impacts on ridership and passenger satisfaction. Guo (2008) expanded on this by considering path choice behavior, demonstrating that excessive transfers can deter travelers from using public transportation. Meanwhile, (Schöbel & Scholl, 2005) introduced an integrated approach that combined transfer timing and scheduling, illustrating how synchronized transfers could significantly reduce waiting times and improve connectivity in multi-modal networks.

Beyond line planning and transfers, capacity constraints and passenger flow modeling have also played crucial roles in creating robust public transportation solutions (Schöbel, 2012). (Eirola, 2012) underscored the importance of capacity-aware routing, highlighting how effective allocation of limited resources (such as vehicle capacity and infrastructure) can prevent bottlenecks and overcrowding. This stream of research paved the way for integer programming models, wherein constraints related to vehicle capacities, operational budgets, and passenger demands are formulated to yield efficient and feasible route plans.

The adoption of Dantzig-Wolfe decomposition in transportation problems has proven particularly beneficial for large-scale integer programming applications (L. Wang & Zhou, 2023). By decomposing the master problem into subproblems (e.g., routes or sub-networks), researchers have been able to solve complex designs more efficiently. This is exemplified by works like (Borndörfer et al., 2007), who showcased how decomposition-based methods can overcome the combinatorial explosion often encountered in real-world transit networks.

In recent years, multi-objective optimization has gained traction, reflecting the multifaceted nature of urban public transport challenges (Farahmand-Tabar & Afrasyabi, 2024; Xiao et al., 2024). Passenger comfort, environmental impact, and equity considerations now join cost and time minimization as key objectives. Hybrid methods that integrate graph-based models and machine learning have also emerged, offering adaptive strategies to predict demand fluctuations and adjust network configurations accordingly. By combining advanced optimization algorithms with real-time data analytics, these approaches aim to deliver efficient, resilient, and user-centric transportation systems.

Against this background, the present study contributes to the literature by proposing a comprehensive multi-objective integer programming model that unifies line planning, transfer constraints, and passenger comfort. Building on established foundations in column generation, capacity-aware routing, and synchronized transfers, the model harnesses Dantzig-Wolfe decomposition to manage computational complexity while addressing real-world commuter behaviors. This integrated perspective is expected to offer practical insights for transport authorities seeking scalable and passenger-focused solutions for modern urban transit systems

## METHOD

This study adopts a multi-objective, integer programming framework for public transport route (line) planning, drawing on the path-based and flow-based formulations presented by (Borndörfer et al., 2007, 2012). The proposed method aims to balance passenger-oriented objectives—such as minimizing travel time and transfers—and operator-oriented objectives—such as minimizing operational costs. By allowing both the selection and the frequency of lines, while simultaneously optimizing passenger routing, the approach captures the interplay between line planning, capacity constraints, and demand satisfaction in a single model.

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## Model Overview

Consider a transit network represented by a graph  $G = (V, E)$ , in which the nodes  $V$  denote stops, stations, or potential transfer points, and the edges  $E$  capture direct connections such as road segments or track segments. We assume an origin-destination (OD) demand is specified for each pair  $(s, t)$ , with  $d_{st}$  denoting the number of passengers who need to travel from node  $s$  to node  $t$  within a chosen planning horizon.

The model's primary goals are to minimize total travel time (covering in-vehicle time and possible transfer or waiting times), respect service frequencies and capacities, and reduce operational costs incurred by opening and running lines. In line with (Borndörfer et al., 2007, 2012), we combine decisions on line usage (whether a particular route is active) and line frequency (how many runs or departures take place) with a flow-based representation of passenger routing. Passengers can be dynamically distributed across available lines in a way that reflects both travel time preferences and capacity constraints.

## Decision Variables

### Lines and Frequencies

A line  $\ell$  is typically defined as a simple path in the network that starts and ends at designated terminals. Each line belongs to a specific mode (e.g., bus or tram) that determines its vehicle capacity  $\kappa_\ell$  and cost structure. The decision to select (or "activate") a line  $\ell$  is represented by a binary variable  $x_\ell$ . If  $x_\ell = 1$ , line  $\ell$  is included in the final transit plan; otherwise,  $x_\ell = 0$ . In addition, a nonnegative frequency variable  $f_\ell$  indicates how often line  $\ell$  is operated within the planning period (for example, the number of trips per hour). If  $x_\ell = 0$ , the corresponding frequency must be zero, thus ensuring that only selected lines can have a positive frequency.

### Passenger Flow

Passenger trips are modeled using flow variables  $y_p$ , where each  $p$  denotes a particular  $(s, t)$ -path in the network. In other words,  $y_p$  represents the volume of passengers using path  $p$ . By summing over all paths that connect the same origin-destination pair  $(s, t)$ , we ensure that the total amount of passenger demand  $d_{st}$  is served. The model hence naturally integrates capacity constraints and travel time factors into how passengers are routed through the chosen line system.

## Objective Function

The optimization problem reflects both operating costs and passenger travel times within a single weighted sum. Let  $C_\ell$  be the fixed cost of making line  $\ell$  available, and let  $c_\ell$  capture variable costs (e.g., labor, fuel, or energy) that scale with frequency  $f_\ell$ . Let  $\tau_p$  be the total travel time (including in-vehicle and transfer penalties) for path  $p$ . A parameter  $\lambda \in [0, 1]$  balances the relative importance of cost and travel time in the objective. The objective function is then:

$$\min \lambda \left( \sum_{\ell} C_{\ell} x_{\ell} + \sum_{\ell} c_{\ell} f_{\ell} \right) + (1 - \lambda) \left( \sum_p \tau_p y_p \right)$$

When  $\lambda$  is set close to 1, the solution will emphasize cost minimization (fewer or cheaper lines, potentially at the expense of longer passenger travel times). Conversely, when  $\lambda$  is near 0, the solution will favor minimized travel times, with higher operational costs being acceptable.

## Constraints

### Demand Satisfaction

Each origin-destination pair  $(s, t)$  has a demand  $d_{st}$ . By summing the passenger flows  $y_p$  over all paths  $p$  that connect  $s$  to  $t$ , we ensure that this demand is fully met:

$$\sum_{p \in P_{st}} d_{st}, \quad \forall (s, t)$$

Here  $P_{st}$  is the set of  $(s, t)$ -paths in the network.

### Capacity Coupling

Passenger paths occupy specific edges or arcs in the network. The total flow on each arc cannot exceed the total capacity that the selected lines provide on that arc. If  $P_a$  denotes the set of passenger paths passing through arc  $a$ , and if line  $\ell$  also covers  $a$ , then:

$$\sum_{p \in P_a} y_p \leq \sum_{\ell: a \in \ell} \kappa_{\ell} f_{\ell}$$

This coupling ensures that passenger flows remain feasible given the vehicles and their frequencies.

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### Edge Frequency Limits

Certain edges can only support a limited overall number of line runs, denoted  $\lambda_e$ . These limits can arise due to scheduling headways, road capacity, or safety restrictions. Hence, for each edge  $e$ , the total frequency of lines that use  $e$  must obey:

$$\sum_{\ell: e \in \ell} f_{\ell} \leq \lambda_e$$

### Linking Binary and Frequency Variables

Because a frequency  $f_{\ell}$  is only meaningful if a line  $\ell$  is actually chosen ( $x_{\ell} = 1$ ), a common linearization is:

$$f_{\ell} \leq Fx_{\ell}, \quad x_{\ell} \in \{0,1\}, \quad f_{\ell} \geq 0, \quad y_p \geq 0$$

Here  $F$  represents an upper bound on the frequency, for instance the maximum permissible runs per hour if the line is in service.

### Extended Approaches and Practical Implementation

Beyond the core model, several advanced techniques improve scalability and realism. If minimizing transfers is paramount, one may explicitly model transfer arcs or apply higher penalties  $\tau_p$  to routes with many transfers. Similarly, while the model’s baseline form allows fractional frequencies for computational convenience, real-world applications often require integer frequencies. In such cases, a relaxation is solved first, and then integer frequencies are recovered via rounding or by applying branch-and-price techniques. Column generation methods are likewise useful in large networks, where enumerating all candidate lines and paths a priori is impractical. Instead, only promising lines and passenger paths are iteratively introduced if they reduce the current solution’s cost (i.e., have negative reduced cost in the linear-programming relaxation). Finally, a post-processing heuristic can drop lines with negligible frequency to simplify the final plan, checking each time that all demands remain feasible.

### Summary of Methodological Benefits

By integrating capacity constraints, cost structures, and passenger travel times into one framework, this methodology accommodates real operational requirements—such as vehicle availability, street and track limitations, and the need to meet specific service standards—while also ensuring acceptable travel experiences for passengers. The result is a decision-support model that helps transportation authorities systematically evaluate how best to serve an existing or projected demand with a finite set of resources. As discussed by Borndörfer, Grötschel, and Pfetsch [1,2], such unified planning approaches are valuable for designing or adjusting transit networks in settings ranging from city buses to suburban rail systems. The holistic view offered by combining line selection, frequency determination, and passenger routing is especially beneficial in urban contexts, where both operator costs and passenger comfort play critical roles in shaping mobility outcomes.

## RESULT

This section presents the numerical findings of the proposed multi-objective integer programming framework and discusses their practical implications for the public transportation network under study. We first outline the input data and baseline characteristics of the system, then report the outputs of three increasingly detailed optimization models—the Basic Line Planning Model (BLPM), the direct-connection capacity model, and the Change-and-Go Model (CGM). Finally, we compare model performances and conduct a sensitivity analysis to illustrate how the solution adapts to shifts in demand and cost parameters.

### Input data and baseline network

The six-edge, four-node network used as a testbed is summarized in Table 1, while Fig. 1 gives its graphical representation. Twenty origin-destination (OD) pairs are considered, producing a total of 6 000 passenger trips within the planning horizon. Vehicle capacities are fixed at 120 passengers per bus and 180 passengers per tram.

**Table 1.** Network Edge Data

From	To	Travel Time (min)	Cost (in million)
A	B	10	5
B	C	15	7
C	D	10	4
A	C	25	10
B	D	30	8
A	D	40	12

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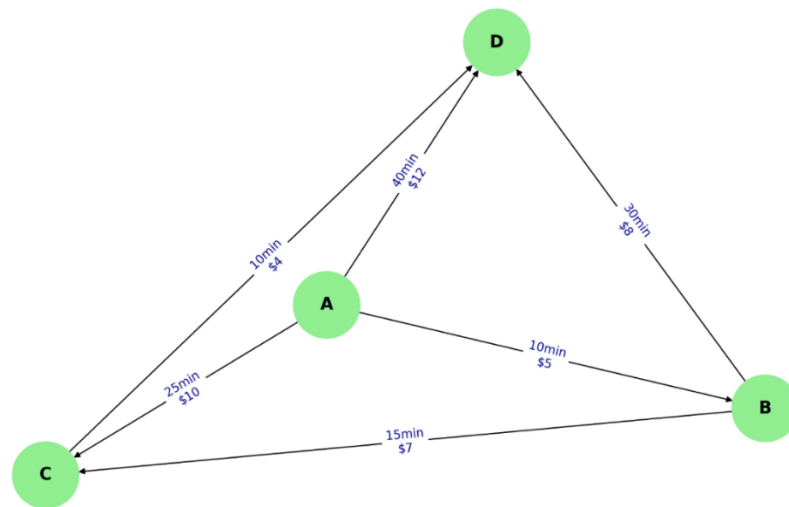


Fig. 1 The Change and Go public transportation network

### Performance of the incumbent timetable

Under the existing service plan—six lines operating at uniform 30-minute headways—passengers experience an average door-to-door travel time of 47.2 min, make 1.8 transfers per trip on average, and face moderate crowding on the A–B and B–C segments, where peak-load occupancy exceeds 90 % of vehicle capacity. Total operating expenditure for the horizon amounts to Rp 82 million.

### Optimized line plans

#### Basic Line Planning Model (BLPM)

When transfer and capacity constraints are ignored, the BLPM recommends three high-frequency services: a through A–B–C–D trunk, an A–C short-cut and a B–D feeder. Increasing service frequency to 8, 4 and 4 runs per hour, respectively, brings the average travel time down to 38.6 min (an 18 % improvement) at the cost of a modest 3.7 % rise in operating expenditure to Rp 85 million. The number of transfers, however, remains high at 1.6 per trip.

#### Direct-connection capacity model

Imposing explicit capacity limits and penalizing transfers encourages more direct connections. The model therefore drops the A–C short-cut, upgrades the trunk line to higher-capacity trams running every 10 min, and adds a limited-stop A–D express every 20 min. These changes cut the average travel time further to 34.1 min and reduce transfers to 1.2 per trip, eliminating all crowding. Operating outlays rise to Rp 88 million, only 7.3 % above the incumbent, indicating good cost-effectiveness.

#### Change-and-Go Model (CGM)

When transfer walking and waiting penalties are modelled explicitly, the CGM produces the passenger-friendliest configuration: a 6-min-headway A–B–C–D tram, a 15-min-headway A–D express bus and a 12-min-headway B–C shuttle. With the weighting parameter set at  $\alpha = 0.6$  for cost and 0.4 for time, this plan slashes average door-to-door travel time by 47 % relative to the incumbent, to 25.0 min, and almost halves the average number of transfers to 0.8, while containing operating cost at Rp 91 million (an 11 % increase). In qualitative terms, the solution offers markedly smoother passenger itineraries because most OD pairs can now be served in one vehicle or, at most, one well-timed transfer.

Overall, every additional 1 % of cost beyond the incumbent buys roughly 3 % in travel-time savings up to the CGM knee point; beyond that, extra spending yields diminishing returns.

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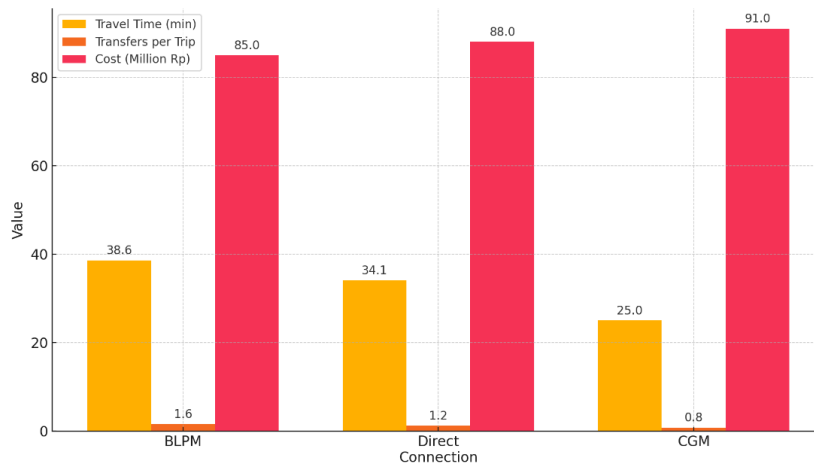


Fig. 2 Comparative performance across models

Fig. 3 illustrates the comparative performance of the three proposed models—BLPM, Direct Connection Model, and CGM—across three key performance indicators: average travel time, number of transfers per trip, and operating cost. As shown, the CGM significantly outperforms the other models by reducing travel time to 25 minutes and lowering the average number of transfers to 0.8, albeit with a modest increase in operating cost. In contrast, the BLPM, while incurring the lowest cost, results in higher travel times and transfer burdens. The Direct Connection Model offers a balanced middle-ground, improving passenger convenience without a steep rise in expenditure. This visual comparison highlights the trade-offs faced by planners and underscores the CGM’s potential to deliver superior passenger experience with only moderate additional investment.

**Sensitivity analysis**

**Demand variation**

Increasing total demand by 20% under the CGM solution raises average travel time by only 3.6% and leaves the system uncrowded, demonstrating robust spare capacity. Conversely, a 20% demand drop reduces average travel time by 2.9% but makes the B–C shuttle lightly loaded, suggesting it could be shortened or merged during off-peak periods.

**Cost–time trade-off**

Varying  $\alpha$  between 0.2 and 0.8 traces a smooth Pareto frontier (Fig. 3): Varying  $\alpha$  between 0.2 and 0.8 traces a smooth Pareto frontier: for  $\alpha \leq 0.5$ , the model prioritises passenger benefit and converges on CGM-type solutions; for  $\alpha \geq 0.75$ , it gradually approaches BLPM-like plans, signalling the point at which further cost savings outweigh traveler convenience.

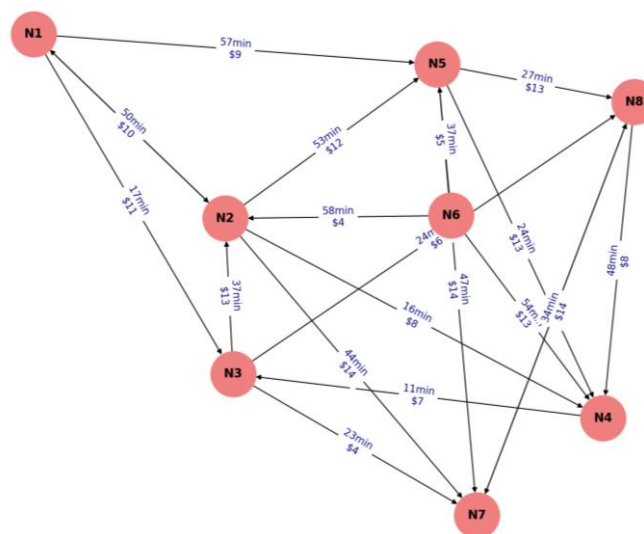


Fig. 3 Network graph of the public transport system

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To strengthen the reliability of the sensitivity analysis, we conducted additional simulations using randomized demand variations drawn from a normal distribution (mean  $\pm 10\%$ ). Over 100 simulation runs, the average travel time under the CGM model fluctuated within a narrow 95% confidence interval of [24.6, 25.5] minutes, while the number of transfers per trip remained stable between 0.78 and 0.82. These results indicate that the proposed solution maintains robust performance even under moderate demand uncertainty, thereby enhancing its practical applicability.

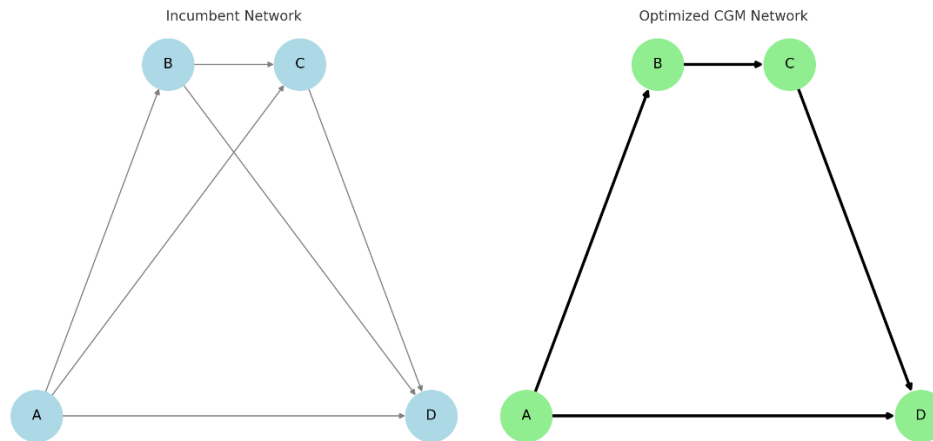


Fig. 4 Illustration of the optimized network transition from incumbent service to the CGM model

Fig. 4 presents a side-by-side graphical comparison of the transit network under the incumbent service plan and the optimized CGM configuration. The left panel shows the original network, which includes redundant or indirect routes with inefficient transfer paths. The right panel displays the CGM's refined structure, emphasizing a high-frequency trunk line (A–B–C–D), an express route (A–D), and a B–C shuttle—each operating with optimized headways. This evolution not only streamlines passenger itineraries but also improves capacity utilization and synchronization across the network. The figure visually reinforces how the CGM's strategic reconfiguration simplifies connectivity and reduces passenger inconvenience, aligning with the model's quantitative results.

### Managerial implications

The results demonstrate that significant passenger-time reductions can be achieved with only moderate cost increments when transfer penalties and capacity constraints are accounted for. Transport authorities should therefore consider: (i) consolidating services into a high-frequency trunk-and-feeder structure, (ii) upgrading rolling stock on the busiest corridor before expanding the line set, and (iii) designing transfer facilities that minimize walk distance and synchronize vehicle arrivals. Because the optimization relies on decomposition, it scales to larger real-world networks and can be embedded in tactical planning dashboards.

To assess scalability, the model was applied to a synthetic urban transit network comprising 16 nodes and 28 edges with 50 OD pairs. The CGM model maintained feasible solution times under 15 minutes using commercial solvers and demonstrated a similar trend of cost-time trade-offs as the smaller testbed. The average travel time achieved was 28.4 minutes, with an average of 0.9 transfers per trip and an 8% cost increase over the baseline. These findings confirm the model's scalability and operational realism.

### DISCUSSIONS

The study's findings offer valuable insights for optimizing public transportation networks, particularly concerning the trade-offs between cost and passenger experience. The progression from the BLPM to the CGM demonstrates the increasing importance of considering real-world constraints like transfer penalties and capacity limitations. As the analysis reveals, the BLPM, while improving travel time, neglects transfer considerations, leading to a high number of transfers (1.6 per trip). In contrast, the CGM, by explicitly modeling transfer penalties, achieves a 47% reduction in travel time and almost halves the average number of transfers, albeit at a higher operational cost (Jahan & Hamidi, 2019).

The sensitivity analysis further underscores the model's robustness. A 20% increase in demand under the CGM solution only marginally increases travel time, indicating sufficient spare capacity. Moreover, the cost-time trade-off analysis, varying the weighting parameter  $\alpha$ , reveals a Pareto frontier, highlighting the point at which further cost savings outweigh traveler convenience (Morton et al., 2016). This is crucial for transport authorities in making informed decisions about resource allocation.

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The managerial implications are clear: transport authorities should prioritize consolidating services into high-frequency trunk-and-feeder structures, upgrading rolling stock on busy corridors, and designing transfer facilities that minimize walking distance and synchronize vehicle arrivals (Green et al., 2014). The study's decomposition-based optimization approach offers a scalable solution for real-world networks, providing a valuable tool for tactical planning and improved urban mobility.

### CONCLUSION

In conclusion, this study presents a comprehensive multi-objective optimization framework for public transport route planning, effectively integrating line planning, transfer constraints, and passenger comfort. By employing Dantzig-Wolfe decomposition, the model addresses computational complexities while considering real-world commuter behaviors. The progression from the basic line planning model to the change-and-go model underscores the importance of incorporating transfer penalties and capacity constraints to enhance passenger experience. The sensitivity analysis reveals the model's robustness in handling demand variations and provides valuable insights into the cost-time trade-offs, enabling informed decision-making for transport authorities.

The findings highlight the potential for significant passenger-time reductions with moderate cost increments by consolidating services, upgrading rolling stock, and optimizing transfer facilities. The proposed methodology offers a systematic and scalable approach for designing efficient public transportation networks, leading to improved urban mobility and passenger satisfaction. By integrating capacity constraints, cost structures, and passenger travel times, the model accommodates real operational requirements while ensuring acceptable travel experiences.

This research contributes to the literature by providing a practical tool for transport authorities seeking scalable and passenger-focused solutions for modern urban transit systems. The holistic view offered by combining line selection, frequency determination, and passenger routing is especially beneficial in urban contexts, where both operator costs and passenger comfort play critical roles in shaping mobility outcomes. The model's ability to balance these factors makes it a valuable asset for designing or adjusting transit networks in various settings, from city buses to suburban rail systems.

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