Optimizing passenger and freight co-transportation on reservation-based bus routes

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1 Introduction

Public transport passenger and freight co-transportation is a system designed to enhance the overall efficiency and effectiveness of transportation networks (Li et al., 2021; Di et al., 2022; Hatzenbühler et al., 2023). In this system, public transport modes, such as subways and buses, are employed not only for passenger services but also for freight transportation, thereby integrating passenger and freight transport within the same journey (Bruzzone et al., 2021; Li et al., 2024).

However, existing studies focus mainly on rail transit for passenger and freight co-transportation in urban public transportation (Behiri et al., 2018; Di et al., 2022). Reservation-based bus (RB) services, which allow demand-driven route planning, have been underexplored in this context. RB systems are efficient and cost-effective in low-density or off-peak areas but face challenges when passenger demand is insufficient to cover operating costs, potentially leading to service cuts and declining ridership. Integrating freight transport into RB systems can address this issue by leveraging surplus capacity to sustain service viability and enhance operational flexibility. This not only stabilizes passenger services but also offers efficient freight solutions. Therefore, this study aims to optimize route design for RB passenger-freight co-transportation through a routing optimization model, unlocking the potential of this integrated framework.

2 Problem statement

This study focuses on the joint transportation of passengers and freight on reservation-based buses (RBs). Specifically, the problem can be approached through three different strategies. Strategy I treats passenger and freight transportation at the same stop as a single demand, where each vehicle visits each stop only once. This implies that, when both passenger and freight demands exist at a same stop, they must be served by the same vehicle. In contrast, Strategy II considers passenger and freight demands at the same stop as independent entities, allowing the stop to be visited by different vehicles. In this case, when there are both passenger boarding and freight loading, they can be handled by separate vehicles. Based on the idea of the second strategy, Strategy III is a complete separation of passengers and freight, i.e., passengers and freight need to be transported by different vehicles, at which point the objective is to use the bus company's idle vehicles to accomplish the transportation of freight, rather than sharing carriages as in the first two strategies.

3 Mathematical formulation

3.1 Definition of parameters and variables

To facilitate the modeling, some necessary assumptions of the problem need to be defined. First, the analysis focuses on off-peak hours when RB have surplus capacity available for freight transportation, and vehicles operate at a constant speed. Second, RB transports secure, standardized freight parcels, with each large parcel occupying the same space as a passenger. Third, passenger or freight demand at the same location must be completed in a single shipment without splitting. Finally, the study examines pairwise pickup/delivery and loading/unloading operations, where passengers or freight are transported between two stops in matched pairs. Moreover, Table 1 lists the notation used to build the mathematical model.

3.2 Optimization model

According to Table 1, the problem can be formulated as the following MILP model:

$$min\ \omega_1 * f_1(x) + \omega_2 * f_2(x) + \omega_3 * f_3(x) + \omega_4 * f_4(x) \tag{1}$$

Table 1: Parameters and variables.

Type	Symbol	Definition
Sets	K	Set of vehicles
	P	Set of pick-up/loading points, $P = \{1, 2, 3, \cdots, n_1\}$, where n_1 is the number of boarding/loading points
	D	Set of drop-off/delivery points, $D = \{n_1 + 1, n_1 + 2, n_1 + 3, \cdots, n_1 + n_2\}$, where n_2 is the number of alighting/unloading points
	T	Set of passenger pick-up/drop-off point pairs, T^+ represents pick-up point, T^- represents drop-off point
	N	Set of freight loading/unloading point pairs, N^+ represents loading point, N^- represents unloading point
	V	Set of points, $V = P \cup D \cup \{0\}$, where 0 represents transportation yard
	A	Set of arcs between different points, $(i, j) \in A$
Parameters	c_{ij}	Distance between point i and j
	v	Vehicle speed
	d_i^1	Passenger demand (i.e., number of boarding/alighting passengers) at the customer point i, if i is a boarding point, $d_i^1 > 0$; if i is a alighting point, $d_i^1 < 0$; else $d_i^1 = 0$
	d_i^2	Freight demand (i.e., number of loading/unloading freight) at the customer point i, if i is a loading point, $d_i^2 > 0$; if i is a unloading point, $d_i^2 < 0$; else $d_i^2 = 0$
	q	Vehicle capacity (set at 50 in this study, i.e., it can accommodate 50 passengers or 50 standardized packages individually, or a total of 50)
	t_{ij}	Travel time between point i and j, $t_{ij} = c_{ij}/v$
	$serv_i$	Service time at customer point i
	$[a_i, b_i]$	Time window in which vehicles are expected to arrive at customer point i
	$\omega_1, \omega_2, \omega_3, \omega_4$	Weighted factors of four sub-objectives in the generalised objective, denoting the average cost per unit distance of RB, the estimated value of passengers' time, the invested cost of using a RB, and the penalty for underutilization of vehicle capacity
	M	A sufficiently large positive number
Variables	x_{ijk}	If vehicle k passes through path $i \to j$, then $x_{ijk} = 1$, otherwise 0
	Q_{ik}^1	Number of passengers loaded when vehicle k leaves customer point i
	Q_{ik}^2	Number of freight loaded when vehicle k leaves customer point i
	s_{ik}	The moment vehicle k begins to serve the customer point i

where:

$$f_1(x) = \sum_{k \in K} \sum_{j \in V} \sum_{i \in V} c_{ij} x_{ijk} \tag{2}$$

$$f_2(x) = \sum_{k \in K} \sum_{(i,j) \in T} d_i^1 (s_{jk} - s_{ik}) \;/\; \sum_{i \in T^+} d_i^1 \tag{3}$$

$$f_3(x) = \sum_{k \in K} \sum_{j \in P} x_{0jk} \tag{4}$$

$$f_4(x) = \sum_{k \in K} \sum_{j \in V} \sum_{i \in V} \frac{(1 - (Q_{ik}^1 + d_j^1 + Q_{ik}^2 + d_j^2)/q) * x_{ijk}}{|V| - 1} \tag{5}$$

subject to:

$$\sum_{k \in K} \sum_{j:(i,j) \in A} x_{ijk} = 1 \qquad \forall i \in P \cup D \tag{6}$$

$$\sum_{j:(0,j) \in A} x_{0jk} = 1 \qquad \forall k \in K \tag{7}$$

$$\sum_{i:(i,0) \in A} x_{i0k} = 1 \qquad \forall k \in K \tag{8}$$

$$\sum_{i:(i,j) \in A} x_{ijk} - \sum_{i:(j,i) \in A} x_{jik} = 0 \qquad \forall j \in P \cup D, k \in K \tag{9}$$

$$\sum_{j:(i,j) \in A} x_{ijk} - \sum_{j:(n+i,j) \in A} x_{n+i,j,k} = 0 \qquad \forall i \in P, k \in K \tag{10}$$

$$x_{ijk} = 1 \Rightarrow s_{ik} + serv_i + t_{ij} \leq s_{jk} \qquad \forall (i,j) \in A, k \in K \tag{11}$$

$$s_{ik} \leq s_{n+i,k} \qquad \forall i \in P, k \in K \tag{12}$$

$$a_i \leq s_{ik} \leq b_i \qquad \forall i \in V, k \in K \tag{13}$$

$$Q_{0k}^1 = 0 \qquad Q_{0k}^2 = 0 \qquad \forall k \in K \tag{14}$$

$$x_{ijk} = 1 \Rightarrow Q_{ik}^1 + d_j^1 = Q_{jk}^1 \qquad \forall (i,j) \in A, k \in K \tag{15}$$

$$x_{ijk} = 1 \Rightarrow Q_{ik}^2 + d_j^2 = Q_{jk}^2 \qquad \forall (i,j) \in A, k \in K \tag{16}$$

$$max\{0, d_i^1 + d_i^2\} \leq Q_{ik}^1 + Q_{ik}^2 \leq min\{q, q + d_i^1 + d_i^2\} \qquad \forall i \in V, k \in K \tag{17}$$

$$x_{ijk} \in \{0, 1\} \qquad \forall (i,j) \in A, k \in K \tag{18}$$

$$Q_{ik}^1, Q_{ik}^2 \in N \qquad \forall i \in V, k \in K \tag{19}$$

$$s_{ik} \geq 0 \qquad \forall i \in V, k \in K \tag{20}$$

Eq.(1) represents the objective function of the model, aiming to minimize the combined costs for the bus company and passengers through a linear combination of four sub-objectives: (i) minimizing the distance traveled by RBs (Eq.(2)); (ii) minimizing passenger in-vehicle time minimizes the distance traveled by the RBs (Eq.(3)); (iii) minimizing the number of RBs (Eq.(4)); and (iv) minimizing vehicle capacity underutilization (Eq.(5)). Constraint (6) states that each customer point is served exactly once and by a single RB. Constraints (7) and (8) ensure that RBs' origin and destination are vehicle depot. Constraint (9) is the flow conservation constraint for each RB at each point. Constraint (10) ensure that the same passenger or freight requests are transported by the same RB. Constraint (11) demonstrates when the path x_{ij} has been selected, it represents that the vehicle k's service start time at point j is not less than the sum of its service start time at point i and its service time at point i and its travel time between points i and j. And Constraint (12) indicates that the drop-off or unloading of the same demand must follow the pick-up or loading of the same demand. Meanwhile, Constraint (13) ensures that vehicles must arrive designated demand point within the time window. Constraint (14) indicates that the total loading of the vehicle at the starting point is 0. Constraint (15) represents the fact that when path x_{ij} is chosen, the number of passengers in vehicle k departing from point j is equal to the sum of the number of passengers in vehicle k departing from point i and the number of passengers boarding and alighting at point i. Similarly, Constraint (16) shows the conservation of the quantity of freight between points i and j. Constraint (17) guarantees that the total passenger and freight load of a vehicle at any point must not be greater than the vehicle's capacity. Finally, Constraints (18) – (20) limit the range of values for the decision variables.

4 Solution approach

When the number of demand points is relatively low, both the number of variables and constraints in the model remain manageable, allowing a commercial solver to efficiently obtain a solution. However, as the number of demand points grows, the model's scale increases, leading to a reduction in the solver's efficiency. Therefore, we examine the application of the Adaptive Large Neighborhood Search (ALNS) algorithm to the problem. Starting from an initial set of solutions, ALNS iteratively improves them through a series of destroy and repair operations. Specifically, the destroy operation disrupts the current solution by removing part of it, while the repair operation rebuilds and improves the solution on the basis of the removed portion (He et al., 2023; Mo et al., 2023). Through this iterative destroy-repair cycle, ALNS progressively approximates an optimal or near-optimal solution to the problem.

5 Numerical experiments

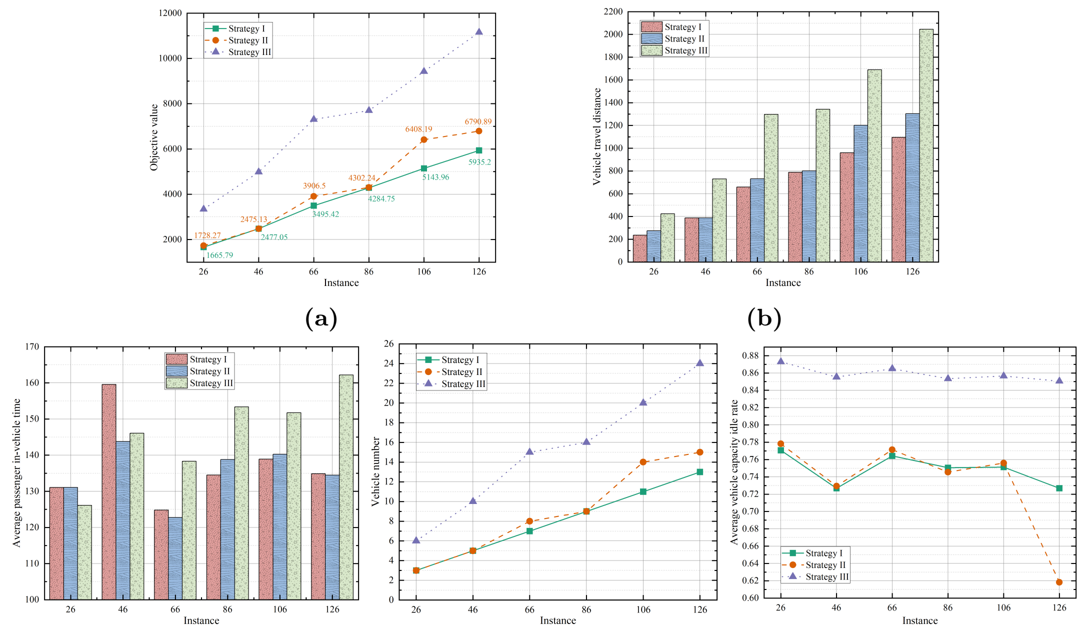
To evaluate the solution efficiency, we compare the performance of Gurobi and ALNS by conducting experiments with instances of varying scales. As shown in Table 2, for small-scale instances (with 46 or fewer demand points), the solutions generated by ALNS are identical to those obtained by Gurobi. However, for medium-scale instances, the Gurobi solver fails to find an optimal solution within the given time limit and can only provide an upper bound (UB) and a lower bound (LB). In contrast, ALNS is capable of identifying a suboptimal solution within the bounds established by Gurobi. For large-scale instances (with more than 106 demand points), Gurobi is unable to provide any solution range within the specified time frame. Moreover, as the number of demand points increases, the time efficiency advantage of ALNS becomes increasingly obvious.

Table 2: Comparison of results between the Gurobi and ALNS for different sized instances.

Instances	Gurobi				ALNS		
	UB	LB	Gap(%)	Time(s)	Best value	Average value	Time(s)
26	1,665.79	1,665.79	0.00	10.71	1,665.79	1,665.79	8.55
46	2,477.05	2,477.05	0.00	616.03	2,477.05	2,477.05	8.89
66	3,512.83	3,217.58	8.40	5,000.00	3,495.42	3,497.33	9.76
86	4,305.87	3,642.96	15.40	5,000.00	4,284.75	4,287.85	14.63
106	-	4,261.95	-	5,000.00	5,143.96	5,171.85	24.67
126	-	4,648.07	-	5,000.00	5,935.20	6,034.38	31.35

Moreover, we explore the changes in the total cost and the corresponding individual metrics under different strategies. It is obvious from Fig.1(a) that Strategy I consistently exhibits the lowest total cost across most instances, demonstrating its effectiveness in reducing passenger and freight co-transportation costs. Strategy II shows similar performance but is generally slightly higher in cost. Notably, the cost difference between Strategy II and Strategy I is minimal for instance sizes of 26, 46, and 86, with Strategy II even outperforming Strategy I at the instance size of 46. This suggests that separating passenger and freight demand at the same point may be advantageous in certain scenarios. In contrast, Strategy III is consistently the most costly, indicating that using idle dedicated buses for freight is not economically efficient.

Fig.1(b) shows that Strategy I minimizes vehicle travel distance, followed by Strategy II. Strategy III, which completely separates passenger and freight transport, requires more vehicles and results in higher total distance due to repeated paths. Figs.1(c) and 1(d) reveal that the number of vehicles aligns with total cost trends. At an instance scale of 46, both Strategy I and II use the same number of vehicles, but Strategy II has significantly lower passenger in-vehicle time, indicating high spatio-temporal heterogeneity in demand origins and destinations. Thus, separating passenger and freight demand improves overall performance. Finally, Fig.1(e) shows that Strategy II achieves higher vehicle capacity utilization at an instance scale of 126, due to greater spatio-temporal similarity between passenger and freight demands.



(a) (b) (c) (d) (e)

Fig. 1. Comparison of results under different strategies.

6 Conclusions

This study addresses the passenger-freight transportation problem in reservation-based bus systems by developing a MILP-based vehicle routing optimization model. Meanwhile, an ALNS algorithm is developed to solve the model, showing higher efficiency than Gurobi. Finally, analysis of passenger-freight co-transportation strategies shows that Strategy I is most cost-effective by aligning both types of demands at the same stop, making it suitable for coexistence scenarios. However, Strategy II offers greater flexibility, especially when there is high spatio-temporal heterogeneity of demands. In contrast, Strategy III is less ideal for small-scale demands due to underutilized vehicle capacity from dedicated freight vehicles. Future research should explore optimizing vehicle capacity combinations to enhance system efficiency and utilization under varying demands. Additionally, the current model assumes non-splittable demand, which necessitates further optimization when a single vehicle cannot meet all transportation needs.

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