Optimization of shared passenger-freight transport services for urban–rural buses

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SHORT SUMMARY

The shared passenger-freight transport services for urban–rural buses have been advocated to make full use of idle bus capacities during off-peak hours. Given the unstable characteristics of urban–rural passenger flow under the shared passenger-freight transport mode, how to allocate bus compartment space and ensure the service quality of both passenger and freight transport has become the critical issue. This paper proposes a flexible bus compartment space allocation method, based on which a mixed-integer programming (MIP) model aiming to minimize the total social cost is proposed to optimize the urban–rural bus timetable, compartment partitioning scheme, and freight allocation plan. An adaptive large neighborhood search (ALNS) algorithm is developed to solve the proposed model. This study is expected to prioritize passenger transport services while improving the quality of freight transport services, and demonstrate the application of the proposed urban–rural bus service optimization model through case studies.

Keywords: Adaptive large neighborhood search; Capacity allocation; Shared passenger-freight transport; Urban freight transport and city logistics; Urban-rural bus.

1. INTRODUCTION

In the operation of urban–rural public transport across many regions, passenger demand is unevenly distributed over the day, resulting in low passenger volumes during off-peak periods and substantial underutilization of transport capacity. Meanwhile, the scattered nature of logistics demand in rural areas raises the difficulty and cost of rural logistics distribution. Driven by the development of the e-commerce economy and continuous growth in total logistics volume, transport demand for rural logistics has been gradually increasing. For boosting operational revenue and alleviating financial subsidy pressure on local governments (He and Guan, 2023), also, helping address the bottlenecks in urban–rural logistics distribution, shared passenger-freight transport service for urban–rural buses is receiving a rising attention. It has been implemented in several cities and towns in China during off-peak periods, such as in Hubei and Zhejiang Provinces, to utilize surplus capacity in urban–rural bus systems.

In the implementation of shared passenger-freight transport on urban–rural bus services, the compartment space of urban–rural buses is divided into two parts: one for passenger transport and the other for freight transport (Bing et al., 2025). Freight transport not only occupies a portion of the bus compartment space but also extends the dwell time of urban–rural buses at stops due to in-transit parcel loading and unloading, which in turn exerts a negative impact on passenger transport services. The number of parcels loaded on each bus exerts varying degrees of influence on passenger travel for the current trip. On the demand side, passengers are concerned with wait time

and travel time, while shippers focus on the punctuality of delivery times (Cheng et al., 2023). To promote the implementation of integrated passenger–freight operation on urban–rural buses, it is essential to mitigate the adverse impacts of parcel transportation on passenger travel experience while ensuring the punctuality of freight delivery. For this reason, the allocation of compartment space has a significant influence on the quality of the shared bus services.

Current research has increasingly focused on operational challenges of urban–rural public transport within shared passenger–freight service systems. For example, Zeng and Qu (2023) constructed a spatiotemporal state network diagram for electric buses operating. Cavallaro and Nocera (2023) proposed an integrated demand-responsive passenger-freight transport model to address the high distribution costs of freight services in rural areas. Wang et al. (2024) examined the coordination of freight transport in urban–rural passenger-freight synergy. Bing et al. (2025) investigated the problems of compartment space allocation and bus type selection for passenger and freight transport. However, most existing studies regard the freight space of buses of the same type as fixed. Given the volatility of passenger flows in urban–rural public transport, the actual passenger load per trip often varies significantly during off-peak periods. If every bus is allocated the same freight space rather than allocating the compartment space based on the actual passenger load of the urban-rural bus, such a fixed allocation strategy will not only result in a waste of spare transport capacity but also lead to a decline in the service quality of the shared passenger-freight transport model.

To deal with the conflicts between passenger and freight services, this paper proposes a flexible compartment space allocation method for urban–rural buses under the shared passenger–freight transport mode. Based on the proposed method, a service optimization model will be established for optimizing the timetable, allocating passenger and parcel space flexibly for each bus departure, and formulating a freight allocation scheme, with the aim of minimizing the total social cost of urban-rural bus services. A case study of Chibi City in Hubei Province, China, is conducted under multiple scenarios.

2. METHODOLOGY

Problem description

As shown in Fig 1, consider a single-line urban-rural bus service system during off-peak periods, where each bus has the same compartment area Q and maximum parcel stacking height τ. All buses depart from the county town's starting point (numbered 1) and travel to the intermediate village and town stops, operating with non-uniform headways h_s and a fixed speed v. During the journey, all buses accommodate passenger and freight transport demands, finally arriving at the terminal station (numbered I) in the township. Prior to each departure, the rural-urban bus determines the freight space allocation proportion φ_s, based on the number of passengers G_{s1} at the starting stop, with the remaining compartment space allocated for passenger transport. The entire operational horizon is discretized into H equal time slots with a duration of λ. At time t, P_{ijt} passengers arrive at departure station i to wait for the bus, intending to travel to destination station j. The time required for per passenger to board is t^a, and the time required for per passenger to alight is t^b. Parcel demand u is available for pickup at stop o_u, with a latest arrival time requirement LT_u at the destination stop d_u. The volume of parcel demand u is denoted by q_u, where each standard parcel unit has a fixed volume V, and the average loading and unloading time required per standardized parcel unit is t^c. The greater the volume of parcel demand u, the longer the corresponding loading and unloading time at the stop.

In this service system, we make the following assumptions: (1) the volume of parcel demand can be quantified using a standard parcel unit; (2) Each parcel demand is indivisible and cannot be

split into multiple shipments; (3) The fleet size of urban-rural bus is sufficiently large to satisfy passenger demand during off-peak periods.

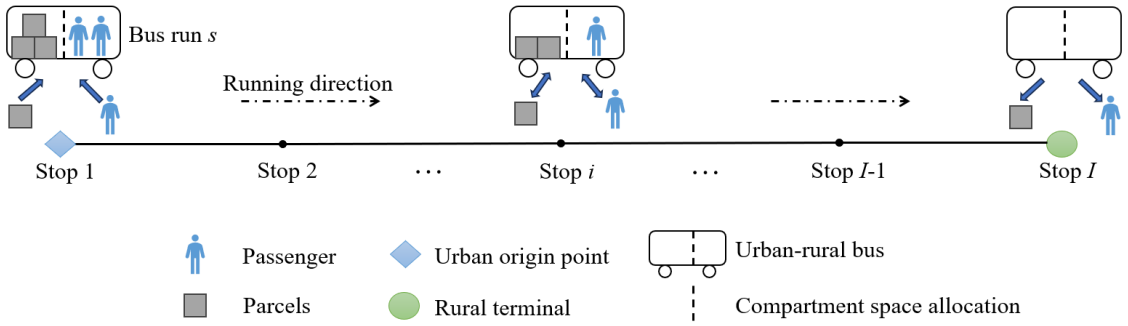


Fig 1: Urban-rural bus service with shared passenger-freight transport

The model

The mathematical notations are shown in Table 1. The model is constructed as follows. Equation (1) is the objective function for minimizing the total social cost of urban-rural bus services under the shared passenger-freight transport model. Equation (1.1) defines the passenger cost. Equation (1.2) defines the freight penalty cost. Equation (1.3) defines the bus operator cost.

$$minf = f_1 + f_2 + f_3 \tag{1}$$

$$\begin{aligned} f_1(x,h) \quad &= \sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{H} \alpha\,(r_{si} - \lambda t) P_{ijt} x_{sit} \\ &+ \sum_{s=1}^{S}\sum_{i=2}^{I} \alpha\left(t^a G_{si} + t^b L_{si} + t^c F G_{si} + t^c F L_{si}\right) B_{si} \end{aligned} \tag{1.1}$$

$$f_2(y,h) = \sum_{s=1}^{S}\sum_{u=1}^{U} max\left(r_{sd_u} - LT_u, 0\right)\rho q_u\, y_{su} + \sum_{u=1}^{U} \mu\left(1 - \sum_{s=1}^{S} y_{su}\right) q_u \tag{1.2}$$

$$f_3(n) = \sum_{s=1}^{S} \gamma l_{1,I} n_s \tag{1.3}$$

Constraint (2) denotes the arrival time constraint for urban-rural bus services.

$$\lambda \times t \times x_{sit} \le r_{si} \quad \forall t \in \Upsilon, \forall i \in N, \forall s \in K \tag{2}$$

Constraints (3) and (4) represent the service frequency constraints for urban-rural bus.

$$\sum_{s=1}^{S} x_{sit} = 1 \quad \forall t \in \Upsilon, \forall i \in N \tag{3}$$

$$\sum_{s=1}^{S} y_{su} \le 1 \quad \forall u \in \Omega \tag{4}$$

Table 1: Mathematical notations

Type	Notation	Definition
Sets	N	Set of bus stops, $N = \{1,2,\ldots,I\}$
	A	Set of arcs on bus line, $A = \{(i,j)\|i,j \in N, i \neq j\}$
	K	Set of bus runs, $K = \{1,2,\ldots,S\}$
	Ω	Set of parcels demand，$\Omega = \{1,2,\ldots,U\}$
	Υ	Set of discretized time intervals, $\Upsilon = \{1,2,\ldots,H\}$
Parameters	S	A sufficient number of departures to satisfy all passenger transport requirements
	λ	Length of discretized time intervals
	P_{ijt}	Number of passengers arriving at stop $i \in N$ during time $t \in \Upsilon$ for destination stop $j \in N$.
	q_u	Volume of parcel demand $u \in \Omega$
	o_u	Departure station for parcel demand $u \in \Omega$
	d_u	Arrival station for parcel demand $u \in \Omega$
	LT_u	Required latest arrival time for parcel demand $u \in \Omega$
	I	Number of stations on the bus line
	Q	Total area of a bus compartment
	τ	Maximum height of stacked parcels
	m	Average compartment area per passenger
	V	Volume of a standard parcel unit
	$l_{i,j}$	Bus travel distance between stop $i \in N$ to stop $j \in N$
	v	Average travel speed of buses
	t^a	Average time for boarding bus per passenger
	t^b	Average time for alighting from bus per passenger
	t^c	Average time for per parcel unit loading/unloading at each stop
	ρ	Unit time penalty cost coefficient for parcel delivery times
	μ	Penalty cost coefficient for failure to receive parcel dispatch request
	α	Unit cost of passenger waiting time for a bus
	β	Unit cost of passenger in-vehicle time
	γ	Travel cost of shared bus per kilometer
	h_{min}	Minimum bus headway
	h_{max}	Maximum bus headway
Variables	x_{sit}	0–1 variable, equal to 1 if passengers arriving at stop $i \in N$ during time $t \in \Upsilon$ can get on bus run $s \in K$, and 0 otherwise
	y_{su}	0–1 variable, equal to 1 if parcel demand $u \in \Omega$ can be loaded onto bus run $s \in K$, and 0 otherwise
	φ_s	Allocation proportion for freight transport for bus run $s \in K$
	n_s	0–1 variable, equal to 1 if bus run $s \in K$ is required, and 0 otherwise
	h_s	Headway between bus run $s-1 \in K/\{1\}$ and $s \in K$ from bus depot
	r_{si}	Arrival time of bus run $s \in K$ at stop $i \in N$
	G_{si}	Number of passengers getting on bus run $s \in K$ at stop $i \in N$
	L_{si}	Number of passengers getting off bus run $s \in K$ at stop $i \in N$
	B_{si}	Number of in-vehicle passengers for bus run $s \in K$ at stop $i \in N$
	FG_{si}	Number of parcels loaded onto bus run $s \in K$ at stop $i \in N$
	FL_{si}	Number of parcels unloaded from bus run $s \in K$ at stop $i \in N$

Constraint (5) is the formula for calculating the number of passengers boarding at a stop. Constraint (6) is the formula for calculating the number of passengers alighting at a stop. Constraint (7) is the formula for calculating the actual number of passengers on the bus at each stop.

$$G_{si} = \sum_{t=1}^{H} \sum_{j=i+1}^{I} P_{ijt} x_{sit} \quad \forall s \in K, \forall i \in N \tag{5}$$

$$L_{sj} = \sum_{t=1}^{H} \sum_{i=1}^{j} P_{ijt} x_{sit} \quad \forall s \in K, \forall j \in N \tag{6}$$

$$B_{sj} = \sum_{i=1}^{j} G_{si} - \sum_{i=1}^{j} L_{si} \quad \forall s \in K, \forall j \in N \tag{7}$$

Constraint (8) calculates the volume of parcels loaded at each stop, and Constraint (9) computes the volume of parcels unloaded.

$$FG_{si} = \sum_{u \in \Omega, o_u = i} q_u y_{su} \quad \forall s \in K, \forall i \in N \tag{8}$$

$$FL_{si} = \sum_{u \in \Omega, d_u = i} q_u y_{su} \quad \forall s \in K, \forall i \in N \tag{9}$$

Constraint (10) represents the passenger capacity constraint, and constraint (11) represents the freight capacity constraint.

$$\sum_{i=1}^{j} G_{si} - \sum_{i=1}^{j} L_{si} \leq \frac{Q}{m}(1 - \varphi_s) \quad \forall s \in K, \forall j \in N \tag{10}$$

$$\sum_{i=1}^{j} FG_{si} - \sum_{i=1}^{j} FL_{si} \leq \frac{Q\tau}{V} \varphi_s \quad \forall s \in K, \forall j \in N \tag{11}$$

Constraint (12) represents the constraint on the proportion of compartment space allocated for parcels.

$$0 \leq \varphi_s \leq 1 - \frac{mG_{s1}}{Q} \quad \forall s \in K \tag{12}$$

Constraints (13) and (14) respectively define the headway constraints for urban–rural buses.

$$h_{\min} - M(2 - n_s - n_{s+1}) \leq r_{s+1i} - r_{si} \quad \forall s \in K/\{S-1\}, \forall i \in N \tag{13}$$

$$h_{\max} + M(2 - n_s - n_{s+1}) \geq r_{s+1i} - r_{si} \quad \forall s \in K/\{S-1\}, \forall i \in N \tag{14}$$

Constraints (15) and (16) state that a bus must depart if it is assigned either passenger or parcel transport tasks.

$$n_s \geq x_{sit} \quad \forall s \in K, \forall t \in \Upsilon, \forall i \in N \tag{15}$$

$$n_s \geq y_{su} \quad \forall s \in K, \forall u \in \Omega \tag{16}$$

Constraint (17) specifies that rural-urban buses depart in sequence.

$$n_s \geq n_{s+1} \quad \forall s \in K/\{S-1\} \tag{17}$$

Constraints (18) and (19) calculate the arrival times of urban–rural buses at each stop.

$$r_{si} = \sum_{k=1}^{s} h_k + \frac{l_{1,i}}{v} \quad \forall s \in K, \forall i \in \{1,2\} \tag{18}$$

$$r_{sj} = \sum_{k=1}^{s} h_k + \frac{l_{1,j}}{v} + \sum_{i=2}^{j-1} \left(t^a G_{si} + t^b L_{si} + t^c F G_{si} + t^c F L_{si}\right) \quad \forall s \in K, \forall j \in N/\{1,2\} \tag{19}$$

Solution Algorithm

To solve the proposed model more efficiently, this study develops an adaptive large neighborhood search (ALNS) algorithm. The three decision layers, including departure timetable optimization, compartment space partitioning, and freight allocation, are decoupled according to their priority levels. Within the ALNS framework, dedicated removal and repair operators are designed for each layer. An adaptive mechanism coordinates the decisions across all layers during iterations to achieve overall optimization of the total system cost.

3. RESULTS AND DISCUSSION

The urban–rural bus network of Chibi City in Hubei Province, central China comprises three lines, all of which share a common bus depot situated in the Chengnan area, denoted by Stop 1 (Bing et al., 2025). This study selects one urban–rural bus line to apply the proposed model and solution algorithm. Table 2 presents the composition of the total social cost. The model and method proposed in this paper can basically meet the parcel delivery time requirements of urban-rural bus transport under the shared passenger-freight transport mode, which is conducive to the integration of freight transport services into the bus system. In the urban–rural bus service system under the integrated transport mode, if only passenger travel service quality is prioritised, what impacts will be imposed on freight service provision; conversely, if greater emphasis is placed on freight service quality, how passenger services will change remains unclear. Whether there exists a mutual promotional effect between passenger services and freight services will be further examined through numerical experiments and result discussions.

Table 2: Analysis of social cost composition

Total passenger cost	Total freight penalty cost	Total bus operator cost	Total social cost
258.14	2.08	279.01	539.23

To verify the feasibility of the proposed model, a comparison of two schemes of numerical experiments was conducted, with the cost unit as RMB and the time unit as minutes. The results are shown in Table 3. Scheme 1 yields the optimal solution derived from the proposed design model. Scheme 2 is carried out under a fixed departure headway of 10 minutes, excluding the impacts of freight transport and passenger boarding/alighting time, and Scheme 2 has two additional departures compared with the bus timetable of Scheme 1. A comparison between Scheme 1 and Scheme 2 shows that the average passenger waiting time experiences only a slight increase, and the in-vehicle time rises marginally as well. This proves that freight transport under the shared passenger-freight transport mode does not exert excessive impacts on passengers' travel time. To identify the upper limit of the optimization capability of the proposed model, further experiments will be conducted to determine the scale of parcel volumes and the duration of loading and unloading

times at which passenger travel quality cannot be guaranteed, and will provide references for the practical implementation of passenger–freight integrated operation on urban–rural bus routes.

Table 3: Comparison of the two schemes

Scheme	Total passenger waiting cost	Total passenger traveling cost	Total passenger cost	Average passenger waiting time	Average passenger traveling time
1	200.51	57.63	258.14	5.33	1.53
2	188.34	0	188.34	5.01	0

The optimal bus compartment space allocation scheme obtained from the numerical experiment is shown in Fig 2. To ensure sufficient riding space for passengers, the proportion of compartment space allocated for freight transport shall not exceed 60%. Therefore, the shared passenger-freight transport mode for the current bus run should be cancelled when the compartment space occupied by boarding passengers at the origin stop exceeds 75%. When the occupancy rate is below 75%, the freight volume should be reasonably allocated based on the number of parcel transport requests and the number of boarding passengers at the stop, with a certain amount of compartment space reserved exclusively for passengers. Compared with fixed compartment space partitioning schemes, the specific performance of the method proposed in terms of passenger service quality, freight service efficiency and bus operational costs will be verified by setting several typical passenger flow and parcel flow scenarios.

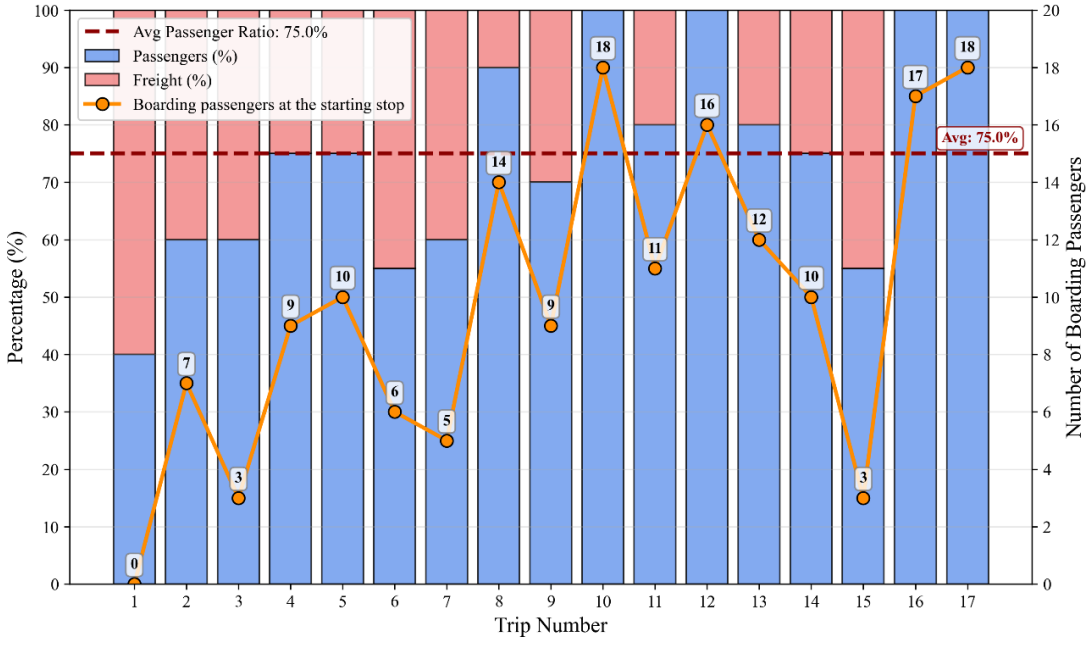


Fig 2: Flexible bus compartment space allocation scheme

4. CONCLUSIONS

Urban-rural bus service optimization problem plays a key role for sustainable transportation development. An urban-rural bus service optimization model under the shared passenger-freight transport mode is proposed in this study, which is target for providing a flexible bus compartment space allocation method and passengers' riding space is expected to be effectively guaranteed. Also, the proposed model is expected to effectively meet the freight delivery time requirements with a slightly increase in passengers' total travel time. Case studies will be focused to demonstrate the application of the proposed urban-rural bus service optimization. Compared with fixed compartment partitioning methods, the proposed method is expected to effectively mitigate the adverse impacts of parcel-occupied compartment space and handling time on passenger travel experience, and enhance the resilience of urban–rural bus services. This study is expected to propose service optimization recommendations to help urban–rural bus operators deal with the conflicting competition between passenger services and freight services, and provide decision support for the operation of urban–rural bus systems under the shared passenger-freight transport mode, so as to promote the implementation of the shared passenger-freight transport mode in urban–rural bus systems.

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