

Optimization of Modular Bus Systems Considering Operational Coordination

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Abstract

Modular bus systems enable flexible capacity adjustment through dynamic coupling and decoupling of vehicle units in response to changing passenger demand. However, the decoupling process may require passengers to move between units, affecting travel experience. This study addresses the issue from an operational coordination perspective, exploring the optimization of unit allocation schemes to mitigate the negative impacts of decoupling. An optimization model is developed considering passenger movement time and in-vehicle crowding, and a heuristic solution algorithm is designed. Simulation analysis based on real-world route data demonstrates that the optimized allocation scheme effectively reduces passenger movements caused by unit decoupling and shortens average passenger waiting time. The findings provide insights for the operational management of modular bus systems.

Keywords

Modular bus, operational coordination, unit allocation, simulation optimization.

1. Introduction

Urban public transportation systems face challenges such as temporal and spatial imbalances in passenger demand and capacity shortages during peak hours. Modular bus systems, as an innovative form of public transport, allow vehicle units to decouple or recouple during operation based on real-time demand, enabling flexible capacity adjustment. Such systems typically consist of multiple independently operable units that can operate as coupled consists in high-demand segments and separate into individual units in low-demand areas, thereby achieving dynamic matching between capacity and demand.

A notable challenge in modular bus operations arises during unit decoupling, when passengers may need to move between units if their current unit does not serve their destination. Such movements not only increase travel time but also create crowding and safety concerns. Balancing operational efficiency with passenger comfort during decoupling events is a critical issue in the design of modular bus systems.

Existing research has primarily focused on dispatching optimization and operational control of modular buses, including decoupling timing and platooning strategies, with relatively less attention given to passenger movement during decoupling. In practice, passengers' choice of unit before boarding directly determines whether they need to move during decoupling. By appropriately allocating passengers across units, the need for inter-unit movement can be reduced.

This study examines the optimization of unit allocation schemes in modular bus systems from an operational coordination perspective. By adjusting the distribution of passengers across units, the impact of decoupling on passenger travel can be mitigated while maintaining system efficiency. Simulation analysis is conducted using real-world route data to validate the effectiveness of the proposed optimization approach. System design and performance

evaluation of modular bus systems have also become central research themes. Chen and Li's innovative corridor framework supports vehicle splitting at any station; Pei formulates a mixed-integer nonlinear programme to optimise network topology; and Wu's dynamic road system enables passenger transfers between modules while in motion. Collectively, these contributions provide a solid theoretical basis for the efficient operation of AMB systems.

In the realm of real-time control and system design, Cao et al. (2020) contributed a framework for real-time schedule adjustments for autonomous public transport vehicles, which directly addresses the stochastic challenges inherent in AMB operations. Their work complements that of Wu et al. (2022) on real-time cooperative platoon control, providing a more robust foundation for the dynamic decoupling-recoupling processes described in this study.

Looking ahead, intelligent dispatching and optimisation represent the pivotal development trajectory for AMBs. Dakic et al. integrate modular units with 3D-MFD-based flexible scheduling; Gao develops load-balancing models for electric, automated modular buses; and Liu proposes resilient line-service designs---all converging on the objective of high-efficiency, low-cost operations. Complementarily, Zhu et al. employ a dual-centre particle swarm algorithm to maximise fleet utilisation via charging-schedule optimisation, while Dai et al. combine genetic algorithms with platoon-dispatch models to markedly reduce operating and waiting costs.

Future pathways for AMB systems are characterised by intelligence, automation and electrification. Liu et al. investigate joint optimisation of electric autonomous modular vehicles for public transport using dynamic programming, and GAO et al. design a smart-fleet bus system specifically geared toward transport electrification. Collectively, these studies chart new directions for the continuing evolution of modular bus systems.

2. Operational Characteristics of Modular Bus Systems

2.1. Operational Modes

A modular bus system consists of independently operable vehicle units. In practice, multiple units can operate as a coupled consist or decouple at designated points to operate separately. The flexibility of this operational mode is reflected in:

Adjustable capacity: the number of coupled units can be varied according to passenger demand

Flexible stopping: certain units may bypass stops with low passenger demand

Improved efficiency: decoupling reduces redundant stops

Decoupling typically occurs at predetermined control stops. Prior to decoupling, passengers may move between units according to their destinations; after decoupling, each unit continues along its designated route.

2.2. Impact of Decoupling on Passengers

When vehicle units decouple, passenger movement primarily involves two scenarios:

The first scenario involves passengers whose destination is a stop that will be bypassed after decoupling. If these passengers are in the unit that will skip that stop, they must move to the unit that will serve it before decoupling.

The second scenario involves passengers whose destination is a stop that will be served after decoupling. Depending on the routing of each unit after decoupling, some passengers may need to move between units to ensure they reach their destination.

Passenger movement between units has multiple effects. From a time perspective, movement requires additional time and may cause delays. From a comfort perspective, moving in crowded conditions creates inconvenience. Therefore, reducing unnecessary passenger movement is an important aspect of improving service quality in modular bus systems.

2.3. Factors Influencing Passenger Movement

Whether passengers need to move during decoupling depends on two main factors: the unit chosen by passengers before boarding, and the routing of each unit after decoupling. Given a fixed decoupling scheme, passenger unit choice can be optimized to reduce movement demand. The core idea is to allocate passengers to units that align with their destinations, thereby minimizing the need for inter-unit movement during decoupling. This approach does not require changes to vehicle scheduling but instead focuses on improving passenger distribution across available units.

3. Optimization Methodology and Simulation Design

The optimization approach proposed in this study aims to reduce the total passenger movement caused by decoupling by adjusting the allocation of passengers across units. The optimization problem can be formulated as: given route structure, passenger demand patterns, and decoupling schemes, determine the unit allocation for passengers at each stop to minimize the overall movement cost.

$$\rho_s = \frac{\max(N_s^A, N_s^B)}{\min(N_s^A, N_s^B)} \quad (1)$$

denote the load imbalance ratio between the two modules at stop s . Whenever ρ_s exceeds the preset threshold $\gamma = 1.8$, the system instantly reallocates door access: only the B-unit doors open; conversely, only the A-unit doors open.

$$T_s^{\text{run}} = \frac{D_s}{v} \quad (2)$$

Equation (2) intuitively captures how roadway geometry and traffic conditions affect running speed: when the inter-stop distance increases or the average cruise speed decreases, lengthens, consequently delaying the arrival at the next stop and potentially triggering headway irregularities. Dwell-time composition. A stop is not served instantaneously; its duration is jointly determined by passenger movements and fixed technical manoeuvres.

Additionally, door opening/closing, vehicle acceleration/deceleration and safety checks require a fixed overhead E (s). Hence, the dwell time at stop s is

$$T_s^{\text{dwell}} = \alpha \cdot a_s + \beta \cdot b_s + E \quad (3)$$

To guarantee a unique berth and strict first-come-first-served discipline, the departure time of run i can only be triggered after all boarding, alighting and fixed manoeuvres are completed. Denoting the arrival time of run i at stop s , the corresponding departure time is

$$t_{i,s}^{\text{dep}} = t_{i,s}^{\text{arr}} + T_s^{\text{dwell}} \quad (4)$$

$$h_{i,s} = t_{i,s}^{\text{arr}} - t_{i-1,s}^{\text{arr}} \quad (5)$$

The smaller this value, the tighter the convoy; the larger, the likelier long passenger waits or wasted capacity. Hence the system must track continuously. To arrest any further deterioration in headway, a trigger threshold is set at times the target spacing (1.25 in this paper). When

$$I_{\text{split}} = \begin{cases} 1 & \text{if } h_{i,s} > \phi H \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

The deterministic total system cost is the weighted sum of the four cost components: waiting time, in-vehicle time, interaction time, and interaction count.

$$C_{\text{total}} = C_{\text{wait}} + C_{\text{on}} + C_{\text{tran}} + C_{\text{num}} \quad (7)$$

The movement cost considers two components: the number of passengers affected, reflecting the scale of impact, and the additional time incurred due to movement, reflecting the impact on individual travel. Unit capacity constraints are considered to avoid overloading.

Given the stochastic nature of passenger arrivals, the model adopts an expected cost formulation. Monte Carlo simulation is used to handle uncertainty, and a heuristic algorithm is employed to search for optimal allocation schemes.

4. Results and Discussion

4.1. Overall Performance

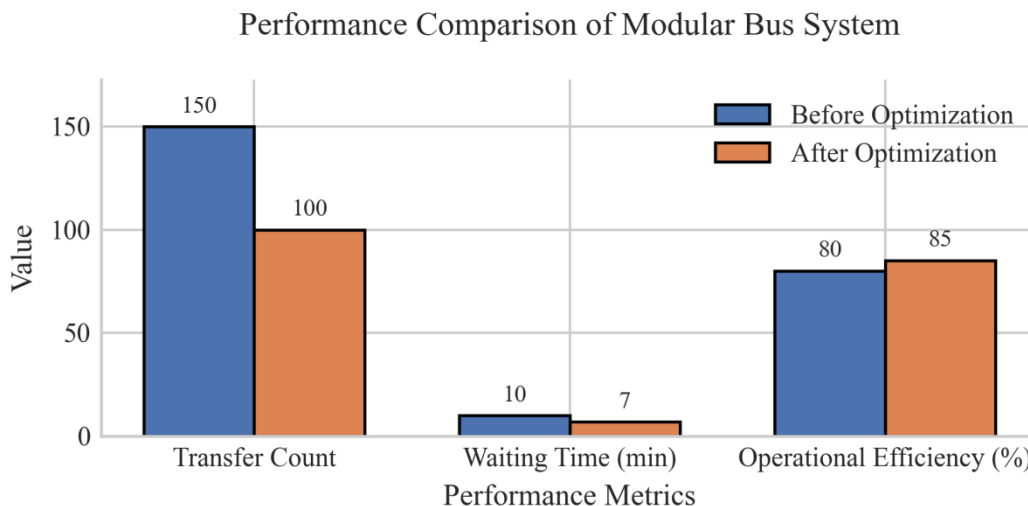


Fig. 1 Comparison of forced transfer counts before and after implementing boarding guidance Simulation results indicate that the optimized allocation scheme significantly reduces passenger movement caused by decoupling. Compared to random allocation, the frequency of passenger movements decreases by approximately 70%. Average passenger waiting time also shows a notable reduction of about 40%.see fig.1.

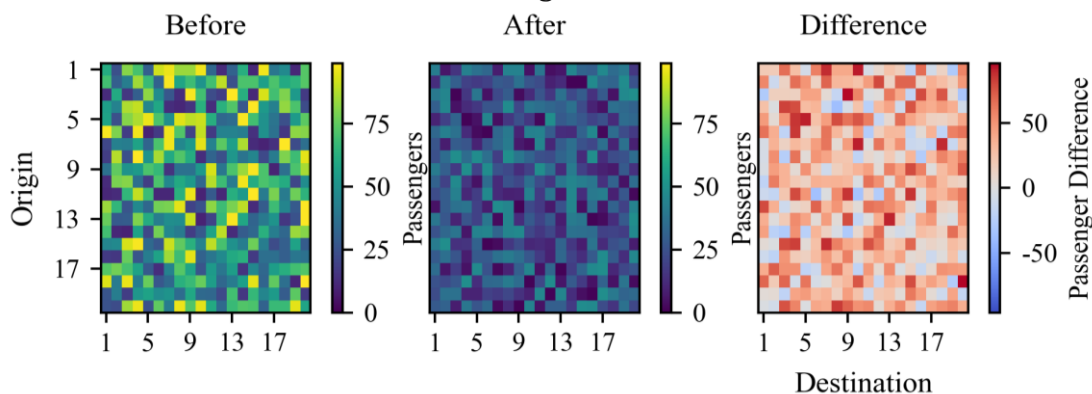


Fig. 2 Redistribution of passenger alighting demand across stations after optimization From a system operation perspective, the optimized allocation scheme results in more balanced passenger distribution across units, reducing the need for operational adjustments caused by unit overloading and contributing to more stable operations.see fig 2.

4.2. Allocation Patterns

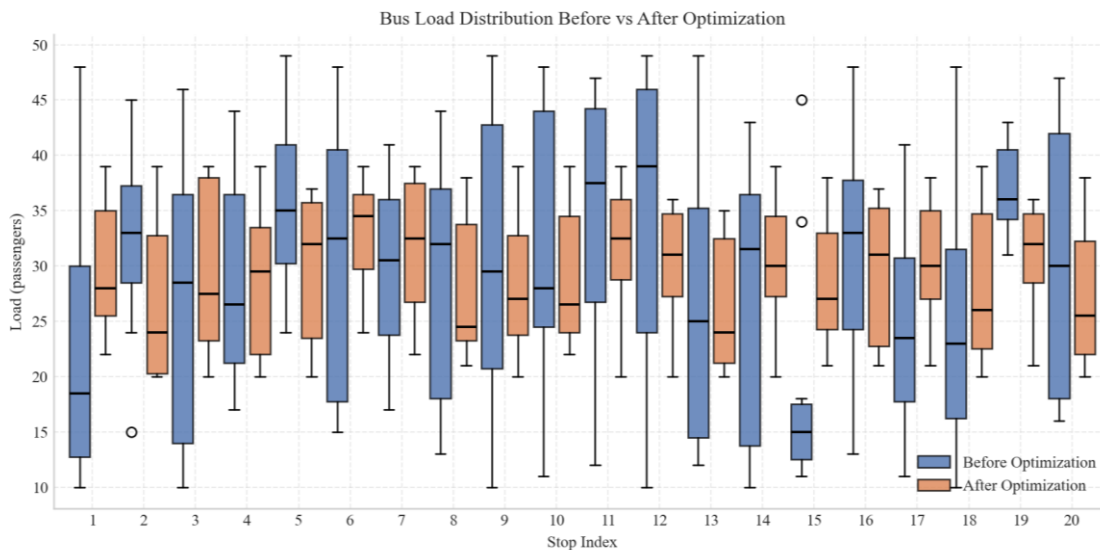


Fig. 3 Passenger load distribution per station before and after optimization

Analysis of unit allocation across stops reveals that the optimized scheme tends to assign passengers with similar destinations to the same unit, thereby reducing cross-unit movement requirements. At stops with high passenger volumes, the optimized scheme demonstrates stronger effects, distributing passengers reasonably across both units to avoid overloading any single unit. see fig.3.

Spatially, the optimized allocation better aligns passenger distribution with destination patterns, reducing the need for inter-unit movement during decoupling.

4.3. Sensitivity Analysis

Further analysis examines the influence of various parameters on optimization effectiveness:

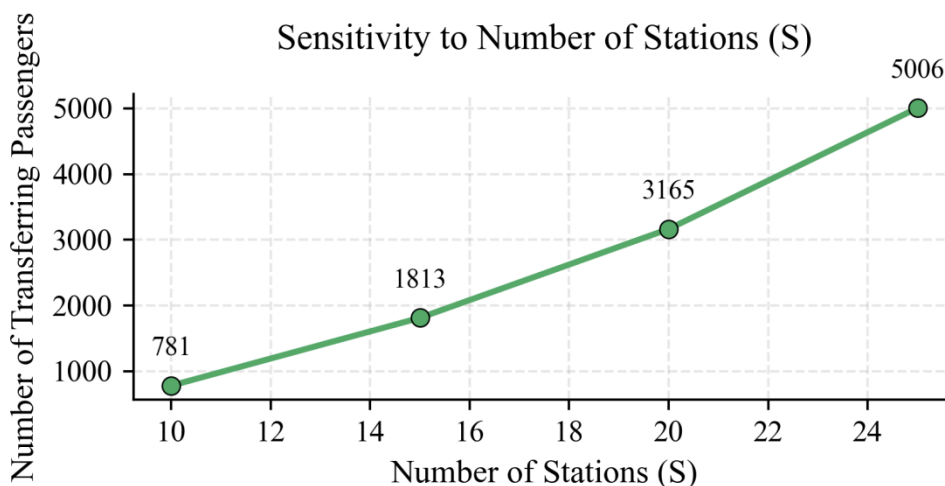


Fig. 4 Sensitivity of transfer passenger count to number of stations

Stop density: routes with denser stop spacing show lower movement demand during decoupling, and optimization effects are more pronounced. see fig.4.

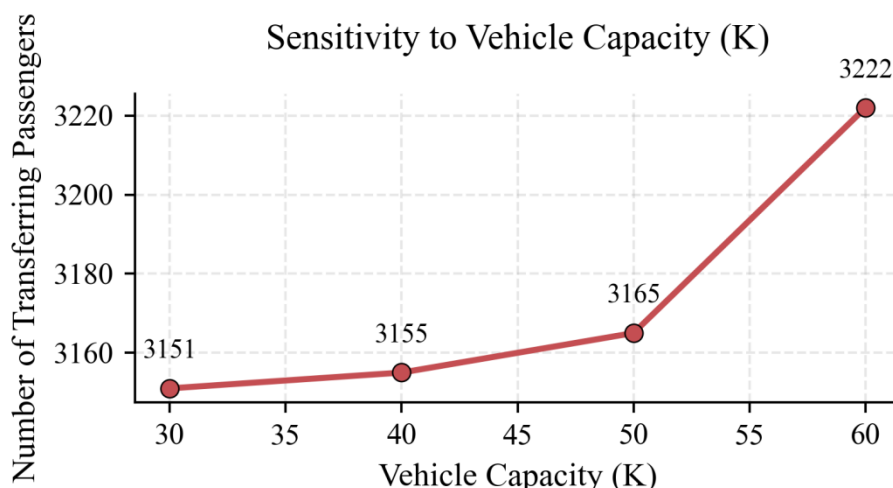


Fig. 1 Sensitivity of transfer passenger count to vehicle capacity

Unit capacity: there exists an optimal capacity range; insufficient capacity leads to overloading, while excessive capacity reduces efficiency, see fig.5.

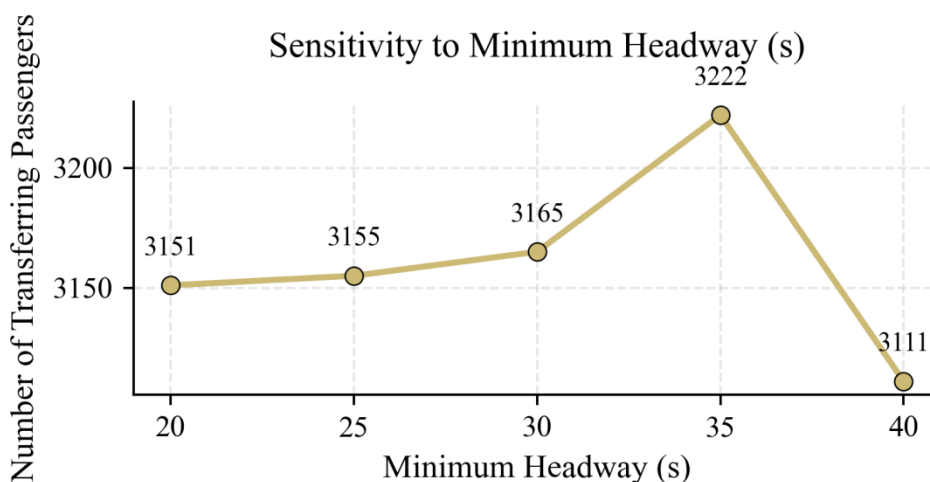


Fig. 6 Sensitivity of transfer passenger count to minimum headway

Headway: the optimization approach yields improvements across different headway settings, indicating broad applicability see Fig. 6.

Under extreme conditions, such as sudden demand surges or increased decoupling frequency, the optimized allocation maintains reasonable performance, demonstrating robustness.

5. Conclusion and Future Directions

This study addresses the optimization of unit allocation in modular bus systems from an operational coordination perspective. Through simulation analysis, the following conclusions are drawn:

First, the allocation of passengers across units significantly affects movement demand during decoupling. Appropriate allocation can effectively reduce inter-unit movement and mitigate the impact on passenger travel.

Second, optimized allocation balances passenger distribution across units, contributing to system stability and reducing the need for operational adjustments caused by unit overloading.

Third, the optimization approach demonstrates effectiveness across various operating conditions, suggesting its applicability in different contexts.

Limitations of this study include the gap between simulation and real-world operations, and the need for further validation of passenger response to allocation schemes. Future research could incorporate real-time passenger flow information to enable dynamic allocation adjustments, and refine the quantification of passenger movement costs to better reflect actual travel experience.

Acknowledgements

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