Modularity-Enabled Partial Express Operations in Zone-Based Flexible Feeder Transit

Charalampos Sipetas*[1], Mónica Menéndez[2], and Konstantinos Gkiotsalitis[3]

[1]Post-Doctoral Associate, Division of Engineering, New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
[2]Professor, Division of Engineering, New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
[3]Assistant Professor, Department of Civil Engineering, National Technical University of Athens, Greece

Short summary

Flexible transit services are widely used as many-to-one feeders in rural and suburban areas with intermediate demand, yet their flexibility often induces substantial in-vehicle travel-time penalties due to cumulative deviations. This study investigates whether modular vehicles enabling in-vehicle transfers can support partial express operations that mitigate such penalties without external transfers. We develop an analytical model for a zone-based feeder system with checkpoints, capturing re-partitioning of service zones as express units depart. Performance is evaluated using an integrated generalized-cost framework capturing operator and user costs, including walking and riding. Results across a structured design space of demand densities and service-area geometries indicate that modular express operations can reduce total generalized cost in various configurations, primarily driven by peak riding-cost reductions of approximately 19–22%. The findings highlight the potential of modular coupling and in-vehicle transfers as an operational enhancement for flexible feeder systems under intermediate demand conditions.
Keywords: Flexible transit; Modular vehicles; Operations research applications; Partial express services; Mobility management

1 Introduction

Public transport provision in rural and suburban areas remains challenging due to dispersed land uses and typically low-to-intermediate demand levels, which often results in weak connectivity to major hubs (Wang et al., 2015). Selecting an appropriate service concept is non-trivial. Conventional fixed-route transit (CT) is operationally efficient at high demand but can be inefficient at low demand, whereas demand responsive transit (DRT) offers high spatial flexibility but becomes costly as demand increases (Quadrifoglio et al., 2006). Flexible transit (FT) services (or "semi-flexible") occupy the intermediate space between CT and DRT and are frequently deployed as many-to-one feeders to improve first/last-mile connectivity (Koffman, 2004). FT operations include multiple service types (e.g., route deviation, point deviation, demand-responsive connector), which differ in the degree of flexibility and operational constraints.

A substantial amount of FT literature focuses on system design and performance evaluation (Quadrifoglio et al., 2006). While FT can enhance accessibility, it may impose substantial in-vehicle time penalties on passengers already on board, because serving additional downstream requests requires detours and dwell time accumulation (Sipetas & Gonzales, 2021). Introducing express segments can mitigate these penalties, yet with conventional vehicles this typically requires external transfers, which introduce additional disutility and can reduce service attractiveness (García-Martínez et al., 2018).

In parallel, rapid technological advances have enabled modular vehicle concepts, in which multiple units can couple/decouple and passengers can move between connected units, allowing capacity adaptation and potentially new service patterns (NEXT Future Transportation Inc., 2022). However, studies on the use of modular vehicles in FT settings remain limited (Guo et al., 2018; Liu et al., 2021; Tang et al., 2024; Luo et al., 2025). Existing contributions address, for example, switching between CT and FT under demand uncertainty (Guo et al., 2018), terminal-based deployment with deviations beyond checkpoints (Liu et al., 2021), decouple-to-serve and rejoin operations along

a fixed route (Tang et al., 2024), and continuum-approximation design of modular feeder transit (Luo et al., 2025).
Motivated by in-vehicle travel-time inefficiencies in flexible many-to-one feeder services and the transfer disutility of conventional express implementations, this study proposes a modular multi-vehicle, multi-zone feeder system enabling partial express services through in-vehicle transfers. We develop an analytical model for a checkpoint-based FT system with zone re-partitioning as express units depart, and evaluate performance using a generalized-cost framework including operator, walking, and riding costs. The objective is to assess the extent to which in-vehicle transfers can reduce riding-time penalties and total system cost relative to a comparable non-express baseline. To our knowledge, the role of in-vehicle transfers as an enabler of express operations in multi-zone FT systems has not been previously examined, and this study provides a proof-of-concept assessment.

2 Methodology

We consider a multi-vehicle/multi-zone flexible feeder (FT) service operating within a rectangular service area of width W and length L. The system follows a many-to-one travel pattern, delivering passengers to a major hub located at $x = L$. Demand density is assumed to lie between values where FT services are justified. The proposed operation therefore combines (a) spatial reliability via fixed checkpoints (CT-like structure) and (b) spatial coverage via door-to-door deviations for pre-booked requests (DRT-like flexibility), consistent with point-deviation FT operations (Koffman, 2004).

Fleet sizing, zoning, and service logic

A fleet of homogeneous vehicles (or modular units) is deployed. With demand density Q (pax per unit area per hour), service headway H (hours per vehicle), and vehicle capacity K (pax per vehicle), the minimum number of vehicles required to sustain one direction per cycle is

$$N_{\min} = \left\lceil \frac{QHWL}{K} \right\rceil . \tag{1}$$

The service area is then partitioned into $N_{\min}$ longitudinal zones to avoid overlap and reduce redundant lateral movements. In the baseline configuration, each vehicle is assigned to a different zone. Along the centerline of each zone, checkpoints are placed every S distance units along the x-direction. Vehicles are required to visit checkpoints for synchronization and to serve walk-up passengers, and may deviate within their assigned zone between consecutive checkpoints to serve booked requests.
Demand is assumed uniformly distributed. In the boarding direction, passengers may board at booked locations or at checkpoints and alight only at the hub; in the alighting direction, the reverse applies. Passengers are classified by access mode as:

- **Booked requests** (γ): passengers served at a non-checkpoint location through in-advance booking, representing a proportion $\gamma \in [0, 1]$ of the total demand.
- **Walk-up requests** $(1 - \gamma)$: passengers served at checkpoints without prior booking, representing the remaining proportion $(1 - \gamma)$ of the demand.

Booked requests are assumed known sufficiently in advance for routing/scheduling. Expected walk-up demand at checkpoints is assumed predictable from historical patterns.
Figure 1 illustrates (a) baseline FT operation and (b) the modular extension described next.

Modular extension and partial express services

The baseline system can be extended by modular units that can physically merge and allow in-vehicle passenger transfers. At each checkpoint, the system evaluates whether cumulative demand collected by all units up to that checkpoint (including walk-up boardings at the checkpoint) can fill an integer number of units. If so, all units converge to the main corridor ($y = W/2$) to merge and enable in-vehicle transfers; a subset of units then departs as express (non-stop) to the hub, while the remaining units continue regular flexible service. The service area is re-partitioned into fewer, wider zones corresponding to the remaining regular units, and the procedure repeats at subsequent checkpoints. Under the deterministic setting considered here, demand is assumed known in advance, so the sequence of zone re-partitioning and corresponding checkpoint locations

is determined ex ante and known to users. If the cumulative demand is insufficient to fill an integer number of units, no express units depart and all units continue standard FT operation.

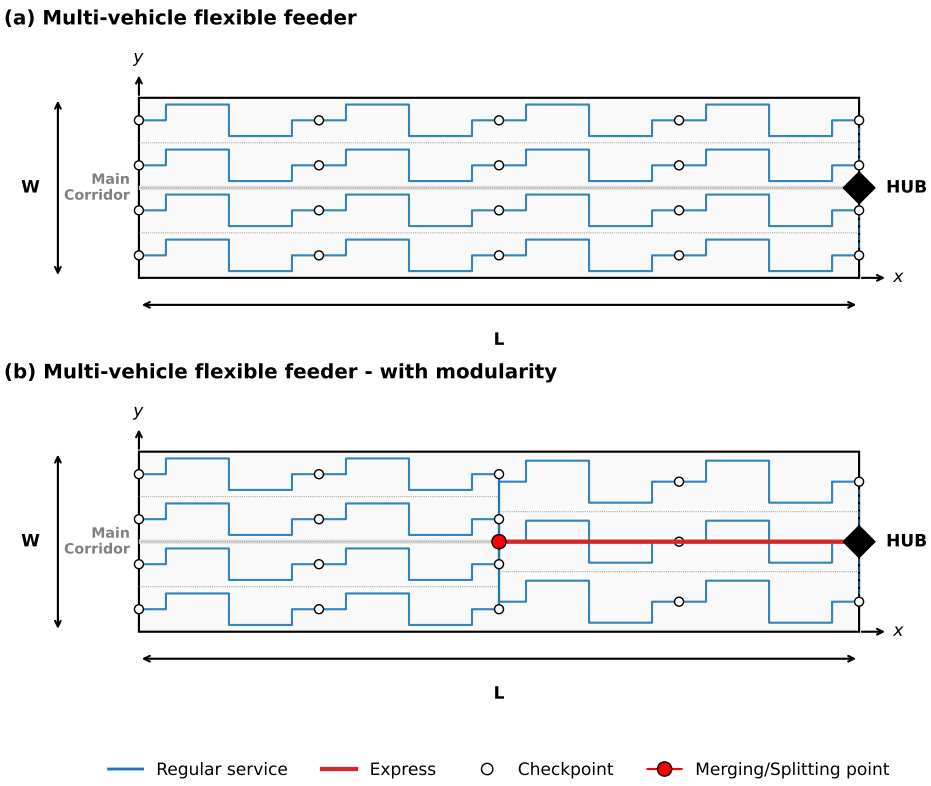


Figure 1: Multi-vehicle flexible feeder: (a) without modularity; (b) with modularity and partial express departures enabled by in-vehicle transfers.

Interval definition

Checkpoint spacing S partitions the corridor length L into $I = L/S$ intervals indexed by $i \in [1, I]$, considering values of L and S such that L/S is an integer. All zones share the same checkpoint x-coordinates ($x = 0, S, \ldots, L$). We define x_1^i and x_2^i as the starting and ending x-locations of each zone in interval i, respectively (with $x_2^i - x_1^i = S$). For interval i, the midpoint (and checkpoint y-location) of the zone served by regular unit $n \in [1, N_r^i]$ is

$$y^{n,i} = \frac{2n-1}{2N_r^i} W, \qquad \forall i \in [1, I],\ n \in [1, N_r^i], \tag{2}$$

where N_r^i is the number of regular-service units (one per zone) operating in interval i. For modeling, service of a zone in interval i begins when the unit departs x_1^i (for $i = 1$, after boarding walk-up passengers at $x = 0$) and ends when it departs x_2^i.
Since interval i is served by N_r^i regular units, zone width in interval i is

$$w^i = \frac{W}{N_r^i}, \qquad \forall i \in [1, I]. \tag{3}$$

Demand and fleet evolution per interval

The total booked (flexible) demand served upon request per zone in interval i is

$$\lambda_r^i = \gamma Q H S w^i, \qquad \forall i \in [1, I]. \tag{4}$$

Walk-up demand served at the first checkpoint ($x = 0$) of interval 1 per zone is

$$\lambda_c^0 = (1-\gamma) Q H \tfrac{S}{2} w^1. \tag{5}$$

At a checkpoint located at the end interval i (x_2^i), the served walk-up demand is

$$\lambda_c^i = \begin{cases} (1-\gamma)QHSw^i, & 1 \le i < I, \\ (1-\gamma)QH\frac{S}{2}\,w^I, & i = I,\ n \neq \text{central zone}, \\ 0, & i = I,\ n = \text{central zone}. \end{cases} \tag{6}$$

At the last interval, if the number of zones is odd, walk-up passengers in the central zone have already reached the hub and therefore do not require feeder service. Accordingly, total demand served in each zone of interval i is

$$\lambda^i = \begin{cases} \lambda_c^0 + \lambda_r^1 + \lambda_c^1, & i = 1, \\ \lambda_r^i + \lambda_c^i, & 1 < i \le I. \end{cases} \tag{7}$$

At each x_2^i location except $x_2^I = L$, the system checks whether cumulative demand can fill one or more express units. Let N_e^i be the number of express units departing at the end of interval i and λ_{lb}^i the passengers not accommodated by express capacity (left behind) at that checkpoint. Then

$$\lambda_{lb}^i = \begin{cases} N_r^1\lambda^1 - N_e^1 K, & i = 1, \\ N_r^i\lambda^i + \lambda_{lb}^{i-1} - N_e^i K, & 1 < i < I, \\ 0, & i = I, \end{cases} \tag{8}$$

and

$$N_e^i = \begin{cases} \left\lfloor \dfrac{N_r^1\lambda^1}{K} \right\rfloor, & i = 1, \\ \left\lfloor \dfrac{N_r^i\lambda^i + \lambda_{lb}^{i-1}}{K} \right\rfloor, & 1 < i < I, \\ 0, & i = I. \end{cases} \tag{9}$$

Denoting θ^i as an indicator of whether there are express services at the end of interval i or not (with $\theta^0 = 0$), we have:

$$\theta^i = \begin{cases} 1, & N_e^i > 0, \\ 0, & N_e^i = 0, \end{cases} \qquad \forall\, i \in [1, I]. \tag{10}$$

Finally, the number of regular units per interval evolves as

$$N_r^i = \begin{cases} N_{\min}, & i = 1, \\ N_r^{i-1} - N_e^{i-1}, & 1 < i \le I. \end{cases} \tag{11}$$

Travel distances per interval

We assume that regular units follow rectilinear travel consistent with grid-constrained networks and adopt a non-backtracking policy commonly used in FT/DRT performance models (e.g., Quadrifoglio et al. (2006)). For interval i, lateral distance from zone midpoint to the meeting corridor $y = W/2$ is

$$D_\ell^{n,i} = \left| y^{n,i} - \frac{W}{2} \right|, \qquad \forall i \in [1, I],\ n \in [1, N_r^i]. \tag{12}$$

The distance traveled by a regular-service unit in interval i to serve λ_r^i booked requests is

$$D_r^i = 2\frac{w^i}{4} + (\lambda_r^i - 1)\frac{w^i}{3} + S, \qquad \forall i \in [1, I]. \tag{13}$$

An express unit departing after interval i travels

$$D_e^i = L - iS, \qquad \forall i \in [1, I]. \tag{14}$$

Travel times per interval

Regular units travel at constant speed V. Deterministic in-interval travel time equals distance divided by V plus stop-related time, assuming one passenger per booked stop:

$$t_r^i = \frac{D_r^i}{V} + \lambda_r^i(\tau_1 + \tau_2), \qquad \forall i \in [1, I], \tag{15}$$

where τ_1 is total door opening and closing time and τ_2 is boarding time per passenger. Checkpoint boarding time at $x = 0$ is

$$t_b^0 = \tau_1 + \lambda_c^0 \tau_2, \tag{16}$$

and checkpoint boarding time at the end of interval i is

$$t_b^i = \begin{cases} \tau_1 + \lambda_c^i \tau_2, & 1 \le i < I \text{ or } i = I,\ n \neq \text{central zone}, \\ 0, & i = I,\ n = \text{central zone}. \end{cases} \tag{17}$$

When $\theta^i = 1$, all regular units in interval i meet at $y = W/2$ to enable transfers. Lateral travel time is

$$t_\ell^{n,i} = \frac{D_\ell^{n,i}}{V}, \qquad \forall i \in [1, I],\ n \in [1, N_r^i]. \tag{18}$$

The maximum lateral travel time in interval i is

$$t_{\ell,\max}^i = \frac{W}{2V}\left(1 - \frac{1}{N_r^i}\right), \qquad \forall i \in [1, I]. \tag{19}$$

Differences in lateral travel times across units in interval i require synchronization at the meeting point, resulting in a waiting time for units that arrive earlier. This waiting time is given by

$$t_{\mathrm{w},\ell}^{n,i} = t_{\ell,\max}^i - t_\ell^{n,i}, \qquad \forall i \in [1, I],\ n \in [1, N_r^i]. \tag{20}$$

For the first merge within a cycle, synchronization reflects a single lateral displacement; for subsequent merges, units also had to reposition laterally at the start of the current zone, effectively doubling the synchronization component. We capture this via $\kappa^i \in \{1, 2\}$:

$$\kappa^i = \begin{cases} 1, & \sum_{j=1}^{i} \theta^j \le 1, \\ 2, & \sum_{j=1}^{i} \theta^j > 1, \end{cases} \qquad \forall i \in [1, I]. \tag{21}$$

Merging must allocate sufficient time for in-vehicle transfers, denoted τ_m. A conservative feasibility condition is obtained by considering a passenger walking from the back of the last unit to the front of the first unit in a merged formation of N_r^i units:

$$\tau_m \ge \frac{l\, N_r^i}{V_K}, \qquad \forall i \in [1, I], \tag{22}$$

where l is unit length and V_K passenger walking speed. A buffer time τ_b is applied before resuming regular service.

Alighting times upon arrival at the hub, for regular and express arrivals, are

$$t_{a,r} = \tau_1 + \left(\lambda^I + \frac{\lambda_{lb}^{I-1}}{N_r^I}\right)\tau_2, \tag{23a}$$

$$t_{a,e} = \tau_1 + K\tau_2. \tag{23b}$$

where λ_{lb}^{I-1}/N_r^I follows from the uniform allocation of left-behind passengers among regular units in the last interval.

The total expected time of regular-service unit n in interval i is

$$T_r^{n,i} = \begin{cases} t_b^0 + \tau_b + t_r^1 + t_b^1 + \theta^1 t_\ell^{n,1} & \\ \quad + \theta^1 t_{\mathrm{w},\ell}^{n,1} + \theta^1 \tau_m + \tau_b, & \text{if } i = 1, \\ \theta^{i-1} t_\ell^{n,i} + t_r^i + t_b^i + \theta^i t_\ell^{n,i} & \\ \quad + \theta^i \kappa^i t_{\mathrm{w},\ell}^{n,i} + \theta^i \tau_m + \tau_b, & \text{if } 1 < i < I, \\ \theta^{I-1} t_\ell^{n,I} + t_r^I + \tau_b + t_\ell^{n,I} + t_{a,r}, & \text{if } i = I,\ n \neq \text{central zone}, \\ \theta^{I-1} t_\ell^{n,I} + t_r^I + t_{a,r}, & \text{if } i = I,\ n = \text{central zone}, \end{cases} \qquad \forall\, n \in [1, N_r^i]. \tag{24}$$

For an express unit departing after interval i, the expected time to the hub (including alighting) is

$$T_e^i = \frac{D_e^i}{V} + t_{a,e}, \qquad \forall i \in [1, I]. \tag{25}$$

Cycle time and total fleet

Let T^n be the total boarding-direction time for unit n (from $x = 0$ to the hub, including alighting). A unit may remain in regular service throughout, or depart as express after some interval $j^n < I$ (with $j^n = I$ if it never departs as express). Then

$$T^n = \begin{cases} \displaystyle\sum_{i=1}^{I} T_r^{n,i}, & \text{if } j^n = I, \\ \displaystyle\sum_{i=1}^{j^n} T_r^{n,i} \; + \; T_e^{j^n}, & \text{if } j^n < I, \end{cases} \qquad \forall\, n \in [1, N_{\min}]. \tag{26}$$

The boarding-direction completion time is governed by the last unit to reach the hub:

$$T_{\max} = \max_{n \in [1, N_{\min}]} T^n. \tag{27}$$

The (conservative) cycle time is

$$C = 2\, T_{\max} + \tau_t, \tag{28}$$

where τ_t is a fixed slack between directions. The number of cycles required to maintain headway H is

$$M = \left\lceil \frac{C}{H} \right\rceil, \tag{29}$$

and the total number of units is

$$N = M N_{\min}. \tag{30}$$

Operator costs

Let a_o be a fixed operator cost coefficient (monetary units per veh–time) and b_o a variable coefficient (monetary units per veh–time–capacity). The cost per veh–time of operating a capacity-K vehicle is $a_o + b_o K$. With O operational time units per day, total expected operator cost per day (both directions) is

$$F_O = 2(a_o + b_o K) \left[\sum_{i=1}^{I} \sum_{n=1}^{N_r^i} T_r^{n,i} \; + \; \sum_{i=1}^{I} N_e^i\, T_e^i \right] \frac{O}{H}, \tag{31}$$

where O/H is the number of vehicle dispatches per day under headway H.

Walking costs

Walk-up passengers walk to the nearest checkpoint. Under uniform demand, expected walking distance per passenger is $S/4 + w^i/4$. With walking speed V_K and walking cost coefficient a_K (monetary units per passenger per time), total daily walking cost (both directions) is

$$F_K = 2a_K \left[N_r^1 \lambda_c^0 \frac{S + w^1}{4V_K} \; + \; \sum_{i=1}^{I} N_r^i \lambda_c^i \frac{S + w^i}{4V_K} \right] \frac{O}{H}. \tag{32}$$

Riding costs

Riding costs depend on access mode. Assuming random boarding order at checkpoints, expected boarding time for a walk-up passenger equals $0.5\, t_b^i$. Random order is also assumed for alighting at the hub. For walk-up passengers boarding at $x = 0$ (interval 1) in zone/unit n, we have:

$$R_{walk}^{n,0} = \lambda_c^0 \Big(0.5\, t_b^0 + \tau_b + t_r^1 + \theta^1 t_\ell^{n,1} + \theta^1 \kappa^1 t_{\mathrm{w},\ell}^{n,1} + \theta^1 \tau_m + \tau_b \Big), \qquad \forall n \in [1, N_r^1]. \tag{33}$$

For walk-up passengers boarding at the end of interval i, we have:

$$R_{walk}^{n,i} = \begin{cases} \lambda_c^i \left(0.5\, t_b^i + \theta^i t_\ell^{n,i} + \theta^i \kappa^i t_{\mathrm{w},\ell}^{n,i} + \theta^i \tau_m + \tau_b\right), & 1 \le i < I, \\ \lambda_c^I \left(0.5\, t_b^I + \tau_b + t_\ell^{n,I} + 0.5 t_{a,r}\right), & i = I,\ n \neq \text{central zone}, \\ 0, & i = I,\ n = \text{central zone}, \end{cases} \qquad \forall n \in [1, N_r^i]. \tag{34}$$

The riding time for booked-request passengers served in interval i is:

$$R_{book}^{n,i} = \begin{cases} \lambda_r^i \Big(0.5\, t_r^i + t_b^i + \theta^i t_\ell^{n,i} + \theta^i \kappa^i t_{\mathrm{w},\ell}^{n,i} + \theta^i \tau_m + \tau_b\Big), & 1 \le i < I, \\ \lambda_r^I \Big(0.5\, t_r^I + t_b^I + \tau_b + t_\ell^{n,I} + 0.5 t_{a,r}\Big), & i = I,\ n \neq \text{central zone}, \\ \lambda_r^I \left(0.5\, t_r^I + 0.5 t_{a,r}\right), & i = I,\ n = \text{central zone}, \end{cases} \qquad \forall n \in [1, N_r^i]. \tag{35}$$

Left-behind passengers (not accommodated in express units at the previous checkpoint) accrue riding time as

$$R_{left}^{n,i} = \begin{cases} 0, & \text{if } i = 1, \\ \lambda_{lb}^{i-1} T_r^{n,i}, & \text{if } 1 < i < I, \\ \theta^I t_\ell^{n,I} + t_r^I + \tau_b + t_\ell^{n,I} + 0.5 t_{a,r}, & \text{if } i = I,\ n \neq \text{central zone}, \\ \theta^I t_\ell^{n,I} + t_r^I + 0.5 t_{a,r}, & \text{if } i = I,\ n = \text{central zone}, \end{cases} \qquad \forall\, n \in [1, N_r^i]. \tag{36}$$

For passengers riding on express units departing after interval i:

$$R_e^i = N_e^i K \left(\frac{D_e^i}{V} + 0.5 t_{a,e}\right), \qquad \forall i \in [1, I]. \tag{37}$$

With riding cost coefficient a_R (monetary units per passenger per time), total expected daily riding cost (both directions) is

$$F_R = 2 a_R \left(\sum_{n=1}^{N_r^1} R_{walk}^{n,0} + \sum_{i=1}^{I} \sum_{n=1}^{N_r^i} R_{walk}^{n,i} + \sum_{i=1}^{I} \sum_{n=1}^{N_r^i} R_{book}^{n,i} + \sum_{i=1}^{I} \sum_{n=1}^{N_r^i} R_{left}^{n,i} + \sum_{i=1}^{I} R_e^i \right) \frac{O}{H}. \tag{38}$$

3 Results and discussion

The numerical experiments utilize the input values of Table 1. The main outcome measure is the total generalized cost (i.e., sum of operator and user costs) savings when the proposed modular-based system with express services is implemented compared to the baseline system with no express services. Results are reported only for parameter combinations where both configurations require the same total fleet size under fixed headway H (Eq. 30); others are excluded as non-comparable. Performance is evaluated over a structured grid of (Q, W, L) values with $Q \in [2, 6]$ (pax/km^2/h), $W \in [1, 3]$ km, and $L \in [6, 12]$ km (step 0.25), consistent with magnitudes reported in the literature. All remaining inputs follow Table 1, unless stated otherwise. In particular, parameters S, H and γ are varied in dedicated sensitivity analyses.

Service area and demand

Figure 2 presents the relative generalized-cost savings across combinations of (Q, W, L). The modular configuration performs more favorably in narrower service areas, where lateral travel distances and merge-related synchronization delays are smaller. In contrast, shorter corridor lengths more frequently result in unequal fleet requirements under fixed headway H, reducing the number of comparable cases. Demand density does not exhibit a monotonic relationship with performance, with benefits depending on the interaction between geometry and demand.

Table 1: Input parameters

Parameter Name	Notation	Value	Units	Source / Justification
Operator cost (constant)	a_0	4.98	EUR/veh-h	(Tirachini & Antoniou, 2020) (adjusted for inflation)
Operator cost (variable)	b_0	0.39	EUR/veh-h-pax	(Tirachini & Antoniou, 2020) (adjusted for inflation)
Dwell time (fixed)	τ_1	20.00	sec/stop	(National Academies of Sciences et al., 2013)
Dwell time (per passenger)	τ_2	3.00	sec/pax	(National Academies of Sciences et al., 2013) (maximum value used)
Buffer time	τ_b	30.00	sec	—
Cruising speed	V	40.00	km/h	(Khan & Menéndez, 2024)
Service headway	H	1.00	h/veh	(Gonzales et al., 2021)
Vehicle capacity	K	16.00	pax/veh	(NEXT Future Transportation Inc., 2022)
Modular unit length	l	2.50	m	(NEXT Future Transportation Inc., 2022)
Riding cost coefficient	a_R	6.90	EUR/h	(Börjesson & Eliasson, 2014)
Walking speed	V_K	4.50	km/h	(Sipetas & Gonzales, 2021)
Walking cost	a_K	13.80	EUR/h	($= 2 \times a_R$, (Sipetas & Gonzales, 2021))
Hub slack time	τ_t	10	min	(Sipetas & Gonzales, 2021)
Booking ratio	γ	0.80	unitless	—
Stop spacing	S	2.00	km/stop	—

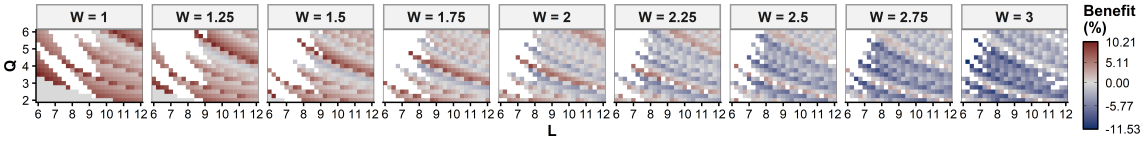


Figure 2: Generalized cost savings of the proposed system relative to the baseline across demand density (Q, pax/km^2/h), corridor length (L, km), and area width (W, km). Negative values indicate higher costs under the proposed system. White areas denote non-comparable cases.

Number of intervals

The impact of checkpoint spacing (S) is examined indirectly through the number of intervals $I = L/S$ into which the service area is divided to ensure an integer number of intervals across scenarios. Figure 3 reports relative benefits for configurations with $I = 3$, $I = 4$, and $I = 5$. Higher values of I (shorter stop spacing) are generally associated with greater benefits in narrower service areas, as more intervals create additional opportunities to release express units and reduce riding costs. As service area width increases, non-comparable cases become more frequent, particularly for longer corridors and higher demand densities.

Service headway

The effects of $H = 0.5$, $H = 1$, and $H = 1.5$ (h/veh) are examined in Figure 4. As headway departs from the intermediate case $H = 1$, non-comparable regions expand. For $H = 0.5$ (h/veh), non-comparable cases become more frequent at larger service area widths, although comparable cases exist across the full range of W. For $H = 1.5$ (h/veh), non-comparable cases dominate when $W > 2.5$ km, reflecting increased fleet sensitivity under longer cycle times. Additionally, under $H = 0.5$ (h/veh), low-width and low-demand areas exhibit near-zero benefits (grey areas), indicating approximate equivalence between the

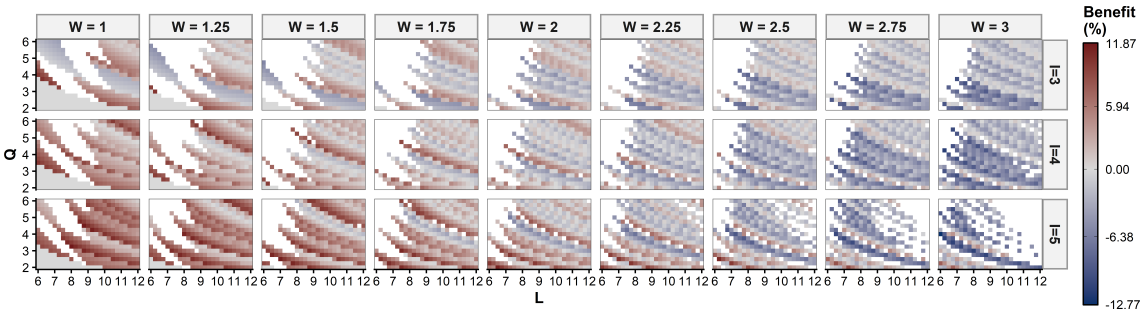


Figure 3: Generalized cost savings across demand density (Q, pax/km^2/h), corridor length (L, km), and area width (W, km), for (a) $I = 3$, (b) $I = 4$, and (c) $I = 5$. Negative values indicate higher costs under the proposed system. White areas denote non-comparable cases.

proposed and baseline systems under high-frequency operation.

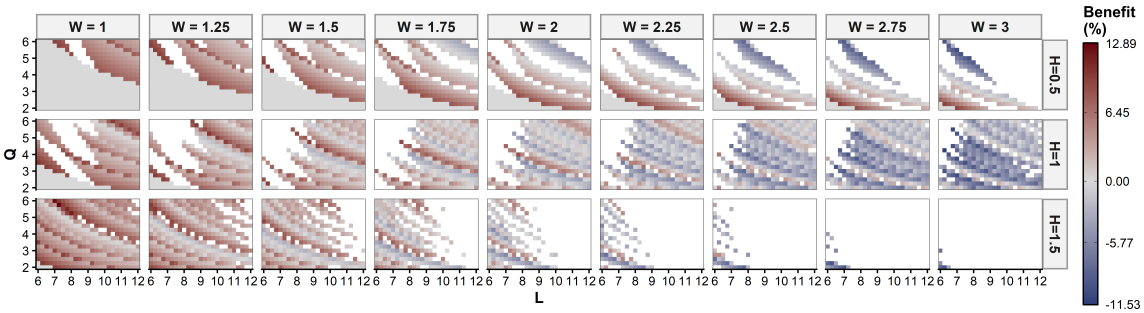


Figure 4: Generalized cost savings across demand density (Q, pax/km^2/h), corridor length (L, km), and area width (W, km), for headway H equal to (a) 0.50, (b) 1, and (c) 1.50 (h/veh). Negative values indicate higher costs under the proposed system. White areas denote non-comparable cases.

Percentage of booked requests

Values of $\gamma = 0.70$, 0.80, and 0.90 are examined in Figure 5, which shows similar spatial benefit patterns across (Q, W, L) for all three cases. Structurally, higher γ reduces walking costs but increases in-vehicle service time and operating costs due to more deviations. These opposing effects largely offset, resulting in relatively robust performance across the examined range of γ.

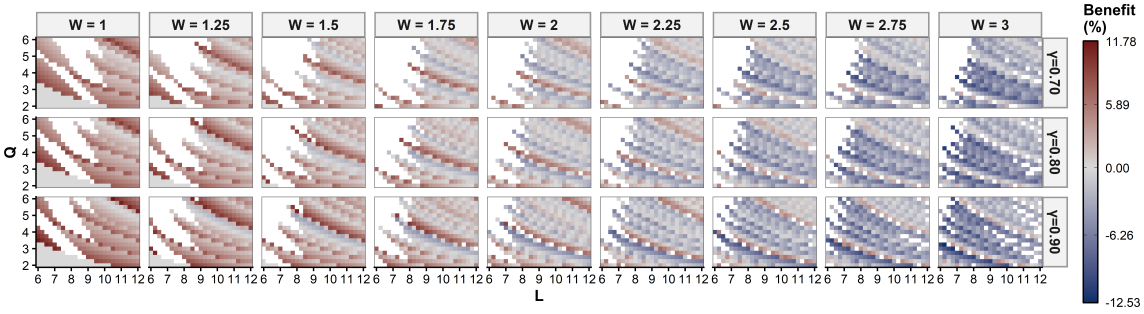


Figure 5: Generalized cost savings across demand density (Q, pax/km^2/h), corridor length (L, km), and area width (W, km), for booking share γ equal to (a) 0.70, (b) 0.80, and (c) 0.90. Negative values indicate higher costs under the proposed system. White areas denote non-comparable cases.

Summary of riding cost benefits

Since the primary objective of the modular configuration is to reduce excessive in-vehicle travel times in many-to-one systems, the maximum riding-cost reductions observed in each experiment are examined in Table 2. The largest reductions are generally associated with shorter corridor lengths, while no systematic pattern emerges with respect to demand density or service area width. These results underscore the potential of the proposed system to substantially reduce in-vehicle travel times under specific geometric configurations.

Table 2: Maximum riding-cost reductions observed across experiments (with Q in pax/km^2/h, H in h/veh and W, L in km)

Parameter varied	**Max benefit (%)**	Q	W	L	**Additional parameter**
Service area (Q, W, L)	19.0	4.75	1.75	7.50	–
Number of intervals (I)	22.1	2.50	2.50	6.25	$I = 5$
Service headway (H)	21.7	5.75	1.00	7.25	$H = 1.5$
Booking share (γ)	19.7	3.50	2.25	7.75	$\gamma = 0.70$

4 Conclusions

This paper developed an analytical modeling framework to examine a modularity-enabled multi-vehicle/multi-zone flexible feeder service with partial express operations through in-vehicle transfers at coupling events. System performance was evaluated using total generalized cost (sum of operator, walking, and riding costs) as the primary metric.

Across a broad design space, the proposed system yields the most consistent benefits in narrower service areas. Shorter stop spacing (more intervals) increases benefits by enabling more express departures and reducing riding-time penalties. Under short headways, gains diminish, with near-equivalence in low-width, low-demand cases. Longer headways can increase gains but expand non-comparable regions due to greater fleet sensitivity to cycle time. Varying γ yields similar spatial patterns, suggesting that reductions in walking costs and increases in deviation-related operating and riding costs largely offset. Peak riding-cost reductions of $\approx$19–22% occur, typically in shorter corridors where express departures mitigate cumulative delay.

These findings support modular coupling with in-vehicle transfers as a promising operational capability to reduce riding-time penalties in many-to-one FT feeders. Future work should relax deterministic assumptions by incorporating stochastic arrivals and travel times, evaluate operational control strategies that reduce the conservative cycle-time definition, and validate results using network-based simulation and/or empirical corridor geometries.

Acknowledgements

This work was supported by the NYUAD Center for Interacting Urban Networks (CITIES), funded by Tamkeen under the NYUAD Research Institute Award CG001.

References

Börjesson, M., & Eliasson, J. (2014). Experiences from the swedish value of time study. *Transportation Research Part A: Policy and Practice*, *59*, 144–158.

García-Martínez, A., Muñoz, J. C., & Giesen, R. (2018). Transfer penalties in multimodal public transport networks. *Transportation Research Part A: Policy and Practice*, *114*, 52–66.

Gonzales, E. J., Christofa, E., Sipetas, C., et al. (2021). *Flexible transit services* (Tech. Rep.). Massachusetts. Dept. of Transportation. Office of Transportation Planning.

Guo, Q.-W., Chow, J. Y., & Schonfeld, P. (2018). Stochastic dynamic switching in fixed and flexible transit services as market entry-exit real options. *Transportation Research Part C: Emerging Technologies*, *94*, 288–306.

Khan, Z. S., & Menéndez, M. (2024). A seamless bus network without external transfers using autonomous modular vehicles. *Transportation Research Part C: Emerging Technologies*, *168*, 104822.

Koffman, D. (2004). *Operational experiences with flexible transit services* (No. 53). Transportation Research Board.

Liu, X., Qu, X., & Ma, X. (2021). Improving flex-route transit services with modular autonomous vehicles. *Transportation Research Part E: Logistics and Transportation Review*, *149*, 102331.

Luo, X., Fan, W., Xu, M., & Yan, X. (2025). Optimal design of on-demand modular feeder transit services. *Transportation Research Part C: Emerging Technologies*, *178*, 105245.

National Academies of Sciences, E., Medicine, et al. (2013). Transit capacity and quality of service manual.

NEXT Future Transportation Inc. (2022). *NEXT is now.* Retrieved from `https://www.next-future-mobility.com/` (Accessed March 24, 2025)

Quadrifoglio, L., Hall, R. W., & Dessouky, M. M. (2006). Performance and design of mobility allowance shuttle transit services: bounds on the maximum longitudinal velocity. *Transportation science*, *40*(3), 351–363.

Sipetas, C., & Gonzales, E. J. (2021). Continuous approximation model for hybrid flexible transit systems with low demand density. *Transportation Research Record*, 0361198121997131.

Tang, C., Liu, J., Ceder, A., & Jiang, Y. (2024). Optimisation of a new hybrid transit service with modular autonomous vehicles. *Transportmetrica A: transport science*, *20*(2), 2165424.

Tirachini, A., & Antoniou, C. (2020). The economics of automated public transport: Effects on operator cost, travel time, fare and subsidy. *Economics of Transportation*, *21*, 100151.

Wang, C., Quddus, M., Enoch, M., Ryley, T., & Davison, L. (2015). Exploring the propensity to travel by demand responsive transport in the rural area of lincolnshire in england. *Case Studies on Transport Policy*, *3*(2), 129–136.