ShuttleSLAM: An Integrated Feeder and Arterial Bus Service Without Transfers

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SHORT SUMMARY

We leverage the in-motion transfer (IMT) capability of autonomous modular vehicles (AMVs) to propose a novel integrated feeder-and-arterial bus service with stop-less operations on the arterial route and seamless on-board passenger transfers between the arterial and feeder routes. This builds upon our recently developed SLAM (Stop-Less Autonomous Modular) bus paradigm, which eliminates the need for passengers to stop at each bus stop while traveling along a route. In the proposed "ShuttleSLAM" service, a shuttle detaches in-motion from the main bus at each feeder route to serve that route's demand, while the main bus continues along the arterial without stopping. The shuttle cycles the feeder route before returning to the arterial to attach in-motion to the next main bus. Simulation results show that, compared to an equivalent conventional feeder-and-arterial bus service, ShuttleSLAM can reduce passengers' average travel cost by $10-20\%$ while simultaneously increasing the system capacity by 50% or more.

Keywords: Autonomous modular buses; In-motion transfer; Integrated feeder bus; Modular bus units; Stop-less bus

1 LITERATURE REVIEW

In recent years, autonomous modular vehicles (AMVs) capable of in-motion transfer (IMT) have garnered significant attention from transportation researchers and practitioners. Viable prototypes have been developed by NEXT Future Mobility (NextFutureTransportation, 2018), which have been pilot tested in Padua and Dubai. Numerous research papers have explored the possible applications of IMTs in public transport, such as ride-sharing (Tian et al., 2022), route assignment (Gong et al., 2021; Wu et al., 2021), and addressing bus bunching (Khan et al., 2023; Khan & Menéndez, 2023). In particular, our previous work (Khan & Menendez, 2022) introduced the concept of a Stop-Less Autonomous Modular (SLAM) Bus service, which uses IMTs to perform stop-less operations, allowing passengers to bypass their non-destination bus stops while traveling along a bus line. In this paper, we extend this concept to a feeder-and-arterial network layout (Ibarra-Rojas et al., 2015). Previous research has shown that, in such networks, synchronization between the feeder and arterial services is important in reducing passengers' travel costs (Shrivastava & O'Mahony, 2006; Sivakumaran et al., 2012). Our proposed "ShuttleSLAM" framework takes this synergy a step further by facilitating seamless on-board transfers between the feeder and arterial services, which, coupled with stop-less operations on the arterial route, offers passengers a fast, efficient, and convenient end-to-end bus service.

2 CONCEPT

For the purposes of this proof-of-concept paper, we consider the simple feeder-and-arterial (or trunk-and-branch) bus service layout shown in Figure 1. The main arterial route has S equidistant stops, each of which is located in the center of a rectangular catchment zone. Each zone has a feeder service that has S_Z uniformly distributed stops. The zones are contiguous and measure X-by-Y meters in the directions parallel and perpendicular to the arterial route respectively.

Each physical ShuttleSLAM bus operating on the network consists of two modules: a main module composed of N_M pods that traverses the arterial route without stopping at any arterial

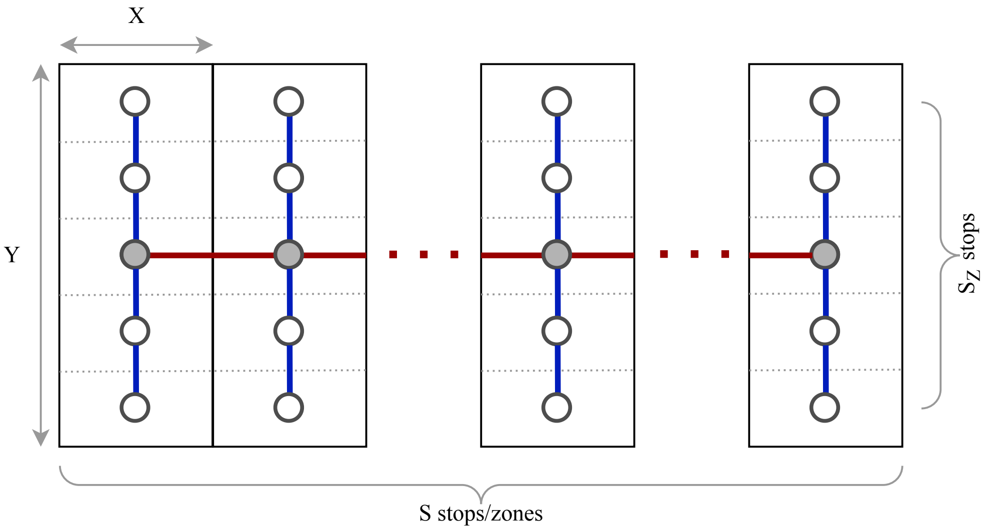

Figure 1: Illustrative network layout showing the arterial route (in red) and the feeder routes (in blue) in each zone. The grey circles represent arterial stops while the white circles represent feeder stops.

stop, and a shuttle module composed of N_S pods that serves the feeder routes. When the bus approaches an arterial stop s, the passengers whose destination is in zone s move internally to the shuttle module, while all other passengers move to the main module.[1] As shown in Figure 2, the shuttle module detaches and stops at the arterial stop to serve the passengers in that zone while the main module continues moving along the arterial route without slowing down. Meanwhile, another shuttle module, which had detached from the previous main module at arterial stop s and had thereafter completed a cycle along the feeder route to serve boarding and alighting passengers, now speeds up as the main module passes, and attaches to it. Thus, the main module bypasses the bus stop via a stop-less operation, swapping one shuttle module for another to serve passengers in that zone. The shuttle modules therefore cycle among the main modules, moving "back" by one bus at each stop.

If $N_S = 1$, then the shuttle module traverses the whole feeder route, stopping at each feeder stop to serve boarding and alighting passengers before returning to the arterial stop in time to attach to the next bus. However, if $N_S = 2$, then the shuttle module splits into its two constituent pods, with each pod serving one half/side of the zone before returning to the arterial stop.[2] This is the case shown in Figure 2.

The overall outcome of this operating framework is that the main module travels along the

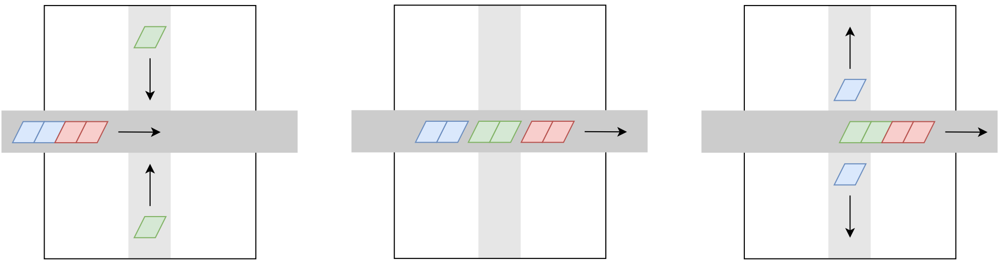

Figure 2: Steps of the stop-less operation at an arterial bus stop showing how one shuttle module (blue) is swapped out for another (green), allowing the main module (red) to bypass the stop. The module configuration shown is $N_M, N_S = 2$. Other configurations are possible.

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[1] This can be facilitated via an announcement and display in the bus.

[2] Larger values of N_S are also possible, but are not considered here.

arterial route uninterrupted, while the stopping at arterial bus stops is delegated to separate shuttle modules. This reduces passengers' arterial travel time, as each passenger stops only at the arterial stop of their desired alighting zone, thereby skipping intermediate arterial stops. The main modules' arterial cycle time is also reduced, as traveling and stopping occur in parallel during the stop-less operation rather than in series, as is the case in a conventional bus service. Furthermore, the transfers between the arterial and feeder routes occur seamlessly in-motion instead of requiring passengers to disembark from the shuttle, wait at a stop, and then board the main bus, as is the case in a conventional feeder-and-arterial bus service. This greatly reduces the transfer disutility, making the feeder-and-arterial layout much more convenient and acceptable for passengers.

3 Model Formulation

For the purposes of this proof-of-concept paper, we consider the following simple demand setting. Firstly, we assume that there is no intra-zone demand. Secondly, we assume that the demand M_{OD} from each origin zone to each destination (i.e. downstream) zone is the same. Given a total uni-directional demand of M passengers per hour, this gives

$$M_{OD} = \frac{2M}{S(S-1)}. \tag{1}$$

Within a zone, we assume that passengers' origin and destination points are uniformly distributed, and that they board and alight at the stop nearest to them, whether that is the arterial stop or a feeder stop. Under this setting, the average Manhattan distance between a passenger's origin/destination point and the closest stop is given by

$$d_Z = \frac{1}{4}\left(X + \frac{Y}{S_Z}\right). \tag{2}$$

At a walking speed of V_{walk}, the average *walking time* is then

$$T_{walk} = \frac{d_Z}{V_{walk}}. \tag{3}$$

The headway H of the feeder and arterial services is chosen to be the same to facilitate effective synchronization between the main and shuttle modules. Then, assuming that passengers arrive uniformly over time, the average *waiting time* for the next shuttle module is given by

$$T_{wait} = \frac{H}{2}. \tag{4}$$

We assume that boarding and alighting of passengers takes place concurrently, taking α time per passenger, and that a fixed extra time of E is lost at each stop (due to acceleration, deceleration, opening and closing doors, etc). When a shuttle module cycles its feeder route, it starts and ends at the arterial stop, visiting all other stops once. This cycle time is given by

$$\tau_Z = \frac{1}{N_S}\left(\frac{S_Z - 1}{S_Z}\frac{2Y}{V_{bus}} + K\alpha + S_Z E\right). \tag{5}$$

Note that this is a conservative estimation, since the maximum possible boarding/alighting delay is considered. This calculation takes into account whether the shuttle module is a single pod making a complete cycle of the feeder route ($N_S = 1$) or two pods making half-cycles in parallel ($N_S = 2$).

The average travel time faced by a passenger along the feeder route on the shuttle module (i.e. the *intra-zone time*) is given by

$$T_{zone} = \frac{\tau_Z}{2}. \tag{6}$$

Once again, this is a conservative estimation.

Once the shuttle module arrives at the arterial stop, it waits for the main module. The amount of *coordination time* spent waiting is

$$T_{coord} = H - \tau_Z. \tag{7}$$

Once the main module arrives, the shuttle module attaches to it as part of the stop-less operation, allowing passengers to start their journey on the arterial route. Passengers internally transfer to the main module, where they remain until the main module approaches their destination zone. Under the uniform OD demand assumption, the average number of zones traveled by a passenger on the arterial route is given by

$$A_Z = \frac{S+1}{3}. \tag{8}$$

Therefore, the average time spent traveling on the arterial route in the main module (i.e. the *arterial time*) is

$$T_{art} = A_Z \frac{X}{V_{bus}}. \tag{9}$$

When the main module approaches a passenger's destination zone, the passenger moves to the shuttle module, which detaches and stops at that zone's arterial stop. The next phase of the journey is another average time of T_{zone} spent in the shuttle module to reach the destination stop, finally followed by walking to the destination with an average time of T_{walk}.

The average travel cost of a passenger can then be calculated by taking the weighted sum

$$Q = T_{walk}w_{walk} + T_{wait}w_{wait} + T_{zone} + T_{coord}w_{wait} + T_{art} + T_{zone} + T_{walk}w_{walk}, \tag{10}$$

where the weights w_{walk} and w_{wait} represent the degree to which each component is perceived to inconvenience passengers compared to a unit of in-vehicle time.

The process for determining the headway H and the shuttle module size N_S is as follows. First, H is provisionally calculated as

$$H' = \max\{H_{min}, \tau_Z + \gamma\}, \tag{11}$$

where H_{min} is the minimum allowable headway and γ is a buffer time added to the cycle time to allow for stochasticity (e.g. intersection and traffic delays), ensuring that the shuttle module reaches the arterial stop in time to attach to the next main module.

The number of buses required to operate the service with headway H' is

$$B' = \left\lceil \frac{\tau + \gamma}{H'} \right\rceil, \tag{12}$$

where τ is the cycle time of the main module on the arterial route, given by

$$\tau = (S-1)\frac{X}{V_{bus}}, \tag{13}$$

since it traverses the whole route without stopping.

The expected load on the bus is at its maximum in the middle of the arterial route, and is given by

$$L' = M_{OD}\frac{H'}{3600}\left(\frac{S}{2}\right)^2. \tag{14}$$

The expected load on the shuttle module is constant throughout, and is given by

$$L'_S = M_{OD}(S-1). \tag{15}$$

The number of pods required for the shuttle module is then

$$N'_S = \left\lceil \frac{L'_S}{K} \right\rceil. \tag{16}$$

The number of pods required for the main module is then

$$N'_M = \left\lceil \frac{L' - L'_S}{K} \right\rceil. \tag{17}$$

The fleet size F required is then

$$F' = SN'_S + B'(N'_M + N'_S), \tag{18}$$

which accounts for both the buses traversing the arterial route and the shuttle modules traversing the feeder routes.

If this required fleet size is greater than the available fleet size F, then the provisional headway is increased such that the number of buses is reduced by 1, i.e. $H' = (\tau + \gamma)/(B' - 1)$. This process (Equations (14)-(18)) is then repeated until either the fleet size condition $F' \leq F$ is met, or B' hits 0, which means that the service is not feasible with the given fleet size.

Benchmark Conventional Bus Service

As a benchmark to compare with the proposed ShuttleSLAM service, we consider a conventional feeder-and arterial bus service which also uses autonomous pods, but without any attaching, detaching, or in-motion transfers. Instead, the conventional service has separately allocated vehicles of pre-determined sizes (i.e. fixed number of pods per vehicle) serving the arterial route and feeder routes in the traditional dwell-and-cruise manner, i.e. with the whole vehicle stopping at each bus stop. The conventional service uses the same network layout and demand distribution described above. We use a tilde accent ($\sim$) to indicate variables relating to the conventional service. Many of the equations describing the conventional service dynamics are equivalent to Equations (1)-(18); those that are different are given below.

Firstly, the headway $\tilde{H'}$ has an additional component compared to Equation (11), i.e.

$$\tilde{H'} = \max\{H_{min}, \tau_Z + \alpha K + E + \gamma\}. \tag{19}$$

The extra component $\alpha K + E$ is (a conservative estimate of) the dwell time of the arterial bus at the arterial stop, since there is no stop-less operation in the conventional service.

The loads $\tilde{L'}$ and $\tilde{L'_S}$ and shuttle bus size $\tilde{N'_S}$ are then calculated as before (Equations (14)-(16)), but the main bus size $\tilde{N'_M}$ accounts for the whole load $\tilde{L'}$ instead of $\tilde{L'} - \tilde{L'_S}$, so it differs from Equation (17), i.e.

$$\tilde{N'_M} = \left\lceil \frac{\tilde{L'}}{K} \right\rceil. \tag{20}$$

The arterial route cycle time $\tilde{\tau}$ includes the dwell times in addition to the cruising time from Equation (13), i.e.

$$\tilde{\tau} = (S - 1)\frac{X}{V_{bus}} + S\big(\alpha\tilde{L'_S} + E\big). \tag{21}$$

The number of buses $\tilde{B}$ required is then calculated as before (Equation (12)), but the required fleet size $\tilde{F'}$ is given by

$$\tilde{F'} = S\tilde{N'_S} + \tilde{B'}\tilde{N'_M}, \tag{22}$$

instead of Equation (18).

The calculations for $\tilde{T_{walk}}$, $\tilde{T_{wait}}$, $\tilde{T_{zone}}$ and $\tilde{T_{coord}}$ are analogous to Equations (3), (4), (6) and (7) respectively, but $\tilde{T_{art}}$ has an additional dwell time component compared to Equation (9), i.e.

$$\tilde{T_{art}} = A_Z\left(\frac{X}{V_{bus}} + \alpha\tilde{L'_S} + E\right). \tag{23}$$

Finally, the average travel cost $\tilde{Q}$ is calculated analogously to Equation (10).

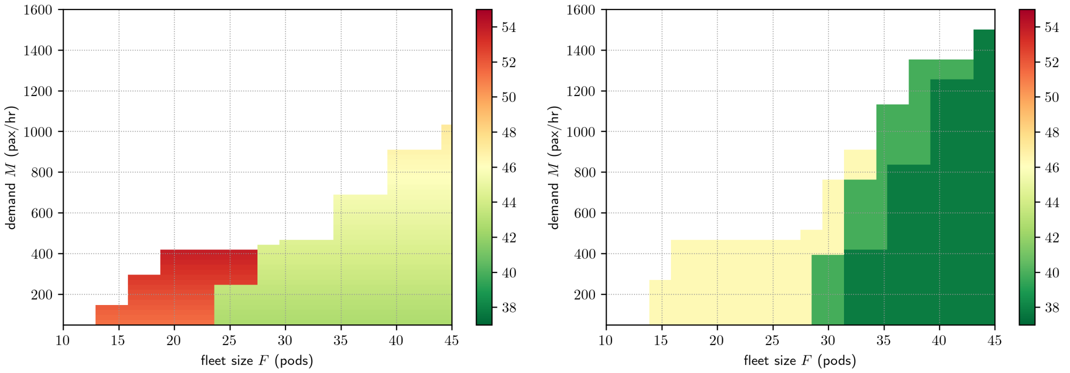
4 RESULTS

A list of the independent parameters used in the paper is provided in Table 1. We present results for a wide range of values of the hourly demand M and fleet size F in order to evaluate the performance of the ShuttleSLAM and conventional services under different conditions.

Table 1: Independent Parameters

Parameter	Notation	Units	Value
Number of zones	S	-	10
Number of stops in feeder route	S_Z	-	5
Zone width (= arterial stop spacing)	X	m	750
Zone height	Y	m	1500
Pod capacity	K	pax	16
Bus cruising speed	V_{bus}	km/h	20
Passenger walking speed	V_{walk}	km/h	4
Boarding/Alighting time per passenger	α	s	3
Fixed time lost per stop	E	s	20
Buffer time for cycle	γ	s	60
Minimum headway	H_{min}	s	180
Waiting time weight factor	w_{wait}	-	2
Walking time weight factor	w_{walk}	-	2

Figure 3(a) and (b) show the average travel costs Q for the conventional and ShuttleSLAM services respectively, across the region of parameter values where each service is feasible. There are several interesting observations to be made from these figures. The first is that the ShuttleSLAM service has a markedly wider feasibility region than the conventional service, i.e. it can serve a larger range of demands M with a given fleet size F. The next is that the ShuttleSLAM service has a considerably lower Q than the conventional service for most pairs of values of M and F. The third is that for both services, there is a significant and discrete drop in the cost at certain threshold as F increases. This threshold, which also depends on M, represents the point when there are enough pods available to shift from $N_S = 1$ to $N_S = 2$, thereby halving the average intra-zone travel time T_{zone} and allowing shorter headways H. This shift occurs later (i.e. at higher values of F) for the ShuttleSLAM service.



(a) Conventional bus service

(b) ShuttleSLAM service

Figure 3: Average travel cost Q for the bus services under a range of values of the demand M and fleet size F.

Figure 4 shows ϕ, the percentage savings in travel cost offered by the ShuttleSLAM service compared to the conventional service for a given pair of parameter values M and F. This is given by

$$\phi = 100\frac{\tilde{Q} - Q}{\tilde{Q}}, \tag{24}$$

and is defined only for pairs of values of M and F where both services are feasible. The main observation from this figure is that, for the vast majority of such parameter values, the ShuttleSLAM service offers sizeable cost savings ϕ of $10 - 20\%$ compared to the conventional service. ϕ generally increases with both M and F, indicating that the ShuttleSLAM service provides increasingly greater advantages for busier systems. There is also a small region where the conventional service

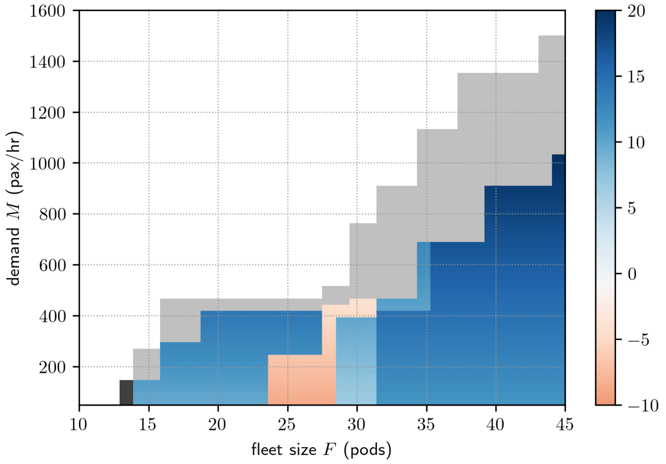
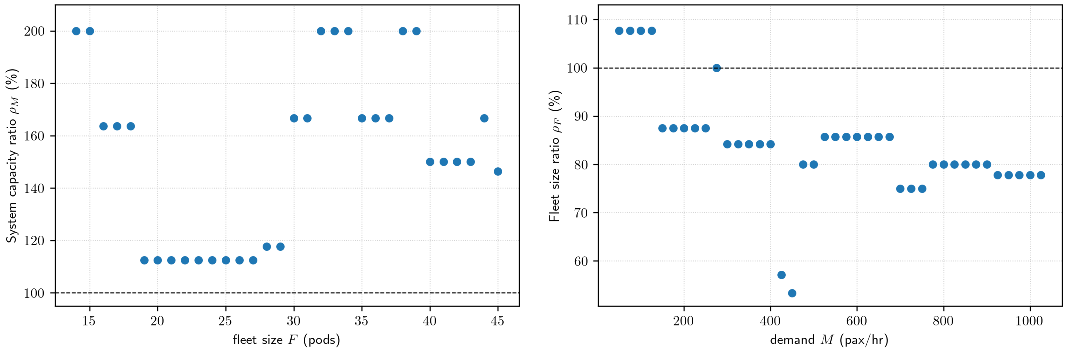


Figure 4: Percentage savings ϕ offered by the ShuttleSLAM service compared to the conventional service under a range of values of the demand M and fleet size F. The gray region is where only the ShuttleSLAM service is feasible, and the small black region is where only the conventional service is feasible.

outperforms the ShuttleSLAM service by $5-10\%$. This is where the conventional service has already crossed the threshold mentioned in the discussion of Figure 3 and is operating with two shuttles buses per zone ($N_S = 2$), while the ShuttleSLAM service has yet to cross the threshold and is still operating with one pod per shuttle module ($N_S = 1$). Even for the fleet sizes in this region, the ShuttleSLAM service has a larger system capacity than the conventional service. Overall, Figures 3 and 4 show that ShuttleSLAM provides much more preferable trips for commuters on average.



(a) System capacity ratio ρ_M

(b) Fleet size ratio ρ_F

Figure 5: Feasibility ratios between the ShuttleSLAM and conventional services.

Figure 5 shows two feasibility ratios between the ShuttleSLAM and conventional services. Figure 5(a) shows the system capacity ratio ρ_M, the maximum demand that the ShuttleSLAM service can serve with a given fleet size F expressed as a percentage of the maximum demand that the conventional service can serve with the same fleet size F. ρ_M often falls in the range $150-170\%$ (and sometimes even reaches 200%), which means that the ShuttleSLAM service typically has a system capacity at least 50% greater than the conventional service. Figure 5(b) shows the fleet size ratio ρ_F, the minimum fleet size that the ShuttleSLAM service requires to serve a given demand M expressed as a percentage of the minimum fleet size that the conventional service requires to serve the same demand M. ρ_F often falls in the range $75-90\%$, which means that the ShuttleSLAM service typically needs around $10-25\%$ fewer pods than an equivalent conventional service serving the same demand.

We also conducted a sensitivity analysis of the results shown here by varying the values of the parameters in Table 1 within reasonable ranges, including the number of stops S and S_Z and the zone dimensions X and Y, among others. While parameter changes do affect the results quantitatively, the key findings discussed here remain consistent throughout. These are: (1) the

ShuttleSLAM service has a much broader feasibility region than the conventional service, i.e. it can serve higher demands with a given fleet size (or, conversely, requires a smaller fleet size to serve a given demand), (2) when both services are feasible, the ShuttleSLAM service has a significantly lower travel cost in most cases, and (3) the benefits of the ShuttleSLAM service increase with the scale of the system.

5 Conclusion

In this paper, we leverage in-motion transfer (IMT) technology enabled by autonomous modular vehicles (AMVs) to provide the proof-of-concept of a novel feeder-and-arterial bus service framework called ShuttleSLAM that offers passengers a stop-less travel experience on the arterial route and seamless on-board transfers between the feeder and arterial routes. We build on the concept of a Stop-Less Autonomous Modular (SLAM) bus service, in which the boarding and alighting of passengers at bus stops is delegated to shuttle modules that attach and detach from a main module that traverses the route without stopping. We extend this paradigm by designing a feeder-and-arterial layout where the modules transfer passengers to and from the feeder routes by exchanging pods among each other to replace external transfers with IMTs. We provide a detailed model formulation of the proposed ShuttleSLAM service and evaluate its feasibility and benefits against a comparable conventional service under a wide range of network settings. We find that ShuttleSLAM has several advantages for passengers, such as shortening in-vehicle time due to the stop-less operations and greatly reducing transfer inconvenience by replacing external transfers with IMTs, leading to a $10-20\%$ reduction in their overall travel cost. Simultaneously, it also offers benefits for operators by significantly increasing the maximum capacity of the system, often by more than 50%, or reducing the required fleet size to address a given demand, usually by $10-25\%$. Overall, our results demonstrate that the ShuttleSLAM service is more efficient, scalable, and cost-effective compared to the conventional service.

In future work, we hope to relax our assumptions about the homogeneity of the route layout and demand, and model the stochasticity of passenger arrivals, alightings, and bus cruising times. The overall idea is to evaluate the proposed ShuttleSLAM service under a broader range of realistic operational settings. We will also conduct a more thorough sensitivity analysis of the effects of changing various system parameters, in order to better understand the conditions under which ShuttleSLAM is most beneficial. Finally, we want to study the possibility of making the feeder service on-demand instead of a fixed route, thereby modeling a hybrid customized ShuttleSLAM-like service which offers greater flexibility and reducing walking time for passengers.

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