A Modular, Adaptive, and Autonomous Transit System (MAATS): A In-motion Transfer Strategy and Performance Evaluation in Urban Grid

Citation for the original published paper (version of record):

Wu, J., Kulcsár, B., Selpi, S. et al (2021). A Modular, Adaptive, and Autonomous Transit System (MAATS): A In-motion Transfer Strategy and
Performance Evaluation in Urban Grid Transit Networks. Transportation Research Part A: General, 151: 81-98. http://dx.doi.org/10.1016/j.tra.2021.07.005

Transportation Research Part A 151 (2021) 81–98

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

A modular, adaptive, and autonomous transit system (MAATS): A in-motion transfer strategy and performance evaluation in urban grid transit networks

Jiaming Wu [a,b], Balázs Kulcsár [b], Selpi [c,d], Xiaobo Qu [a,*]

[a] Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg SE-41296, Sweden
[b] Department of Electrical Engineering, Chalmers University of Technology, Gothenburg SE-41296, Sweden
[c] Department of Computer Science and Engineering, Chalmers University of Technology, Gothenburg SE-41296, Sweden
[d] Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg SE-41296, Sweden

ARTICLE INFO

Keywords:
Autonomous modular bus
Public transit system
Nonlinear programming

ABSTRACT

Dynamic traffic demand has been a longstanding challenge for the conventional transit system design and operation. The recent development of autonomous vehicles (AVs) makes it increasingly realistic to develop the next generation of transportation systems with the potential to improve operational performance and flexibility. In this study, we propose an innovative transit system with autonomous modular buses (AMBs) that is adaptive to dynamic traffic demands and not restricted to fixed routes and timetables. A unique transfer operation, termed as "in-motion transfer", is introduced in this paper to transfer passengers between coupled modular buses in motion. A two-stage model is developed to facilitate in-motion transfer operations in optimally designing passenger transfer plans and AMB trajectories at intersections. In the proposed AMB system, all passengers can travel in the shortest path smoothly without having to actually alight and transfer between different bus lines. Numerical experiments demonstrate that the proposed transit system results in shorter travel time and a significantly reduced average number of transfers. While enjoying the above-mentioned benefits, the modular, adaptive, and autonomous transit system (MAATS) does not impose substantially higher energy consumption in comparison to the conventional bus system.

1. Introduction

Public transit has been long considered as the key component to develop sustainable transport systems due to competitive advantages in energy consumption, emissions, and congestion mitigation. Most public transit systems (e.g., buses, trams, light rails, metros) are operated with fixed routes and timetables, which are tractable for traffic agencies to design, maintain, and optimize. However, existing studies have identified that conventional transits have inherent limitations in meeting real-time and highly dynamic demands (Bie et al., 2020; Guo et al., 2017; Li et al., 2020; Ma et al., 2021; Varga et al., 2020; Qu and Wang, 2021), unpleasant travel experience related to transfers (Tyrinopoulos and Antoniou, 2008), and the vulnerability to bad weather (Tao et al., 2018). To improve the level of service, continuous efforts have been made to better design transit networks (Cats et al., 2016; Ceder and Wilson, 1986; Chen et al., 2018; Guihaire and Hao, 2008; Huang et al., 2018; Yan et al., 2013; Bagloee et al., 2011), timetables (Ceder, 1987; Niu and

* Corresponding author.
E-mail addresses: drxiaoboqu@gmail.com, xiaobo@chalmers.se (X. Qu).

https://doi.org/10.1016/j.tra.2021.07.005
Received 3 October 2020; Received in revised form 18 May 2021; Accepted 3 July 2021
Available online 21 July 2021
0965-8564/

Zhou, 2013; Chen et al., 2015; Huang et al., 2016; Sun et al., 2019), bus priority strategies (Wu and Hounsell, 1998; Ma et al.,2013; Guler and Menendez, 2014), etc. Along with these conventional treatments, several new ideas are proposed to take advantage of the cutting-edge technology in communication, autonomous vehicle, and control, such as the flexible bus system (Kim and Schonfeld, 2013; Zheng et al., 2019), personal rapid transit (Anderson, 2010), customized bus (Chen et al., 2021; Liu et al., 2015), and autonomous modular buses (Chen et al., 2019a). Among these new concepts, the autonomous modular bus (AMB) has recently received significant attention with the potential to improve flexibility in scheduling and operations, as well as reducing substantial driver labor costs and alleviating congestions (Hyland and Mahmassani, 2020). Promising progress in related technologies has also made the implementation of autonomous modular buses increasingly realistic (Qu and Wang, 2021). Many countries have started or scheduled field tests, such as the United Arab Emirates (Spera, 2016), Sweden (Susilo et al., 2018), China (Shepherd, 2019), Germany (Stein and Goebel, 2019), and the list goes on. More details can be found in a worldwide survey of recent pilot AMB projects in Ainsalu et al. (2018).

In the literature, it has been identified that AMB-like flexible transit systems can be very beneficial as a complement to the conventional transit system to provide last-mile or first-mile services but will lose merits when operating in a large scale because of increased costs and decreased service efficiency (Kim and Schonfeld, 2013; Chen and Wang, 2018). Therefore, it is well recognized that implementations of flexible transit systems should be limited to small areas with low demand (Nourbakhsh and Ouyang, 2012). In this paper, we demonstrate that, with the new AMB technologies, this deficiency can be overcome. Specifically, we propose an innovative transit system comprising AMBs that can adapt to dynamic demands on a large scale with competitive efficiency as an option for future transit systems.

The very basic idea of any modular transport system is that modular vehicles can be flexibly coupled and decoupled as desired. Extensive research has demonstrated the benefits of modular vehicles in improving capacity utilization rate, energy consumption, and providing door-to-door services (Kreutzberger, 2003; Chen et al., 2019a; Zhang et al., 2020). However, in the conventional concept of modular buses, the coupling or decoupling has to be accomplished at terminus or garages, and no adjustment can be made in operation. With the promising development of autonomous vehicles, we believe that this constraint can be relaxed by allowing vehicles to couple/decouple in motion, and further allowing passengers to transfer between coupled modular buses simultaneously (Xu et al., 2020). Based on this unique in-motion-transfer operation, the proposed transit system can operate with no virtual transfer stops, no fixed routes, and no pre-determined timetables.

We illustrate the operation of the proposed transit system from a passenger's perspective in Fig. 1. As shown in the figure, the passenger is on the black modular bus when departing from the origin point, and the desired path for this trip is to pass intersection **A** and **B**, and then go straight to the destination point. Note that the exemplified path is randomly selected only to illustrate how a trip is completed in the MAATS system, and it is not necessarily the shortest path. At intersection **A**, assuming that most other passengers on the black bus desire to go straight, the passenger thus needs to transfer in motion to the red modular bus, which has decided to turn left by the wishes of passengers in it. Similarly, at intersection **B**, the passenger needs to transfer again to the blue modular bus because the red modular bus is determined to go straight. Afterward, the blue bus will directly deliver the passenger to the desired destination.

The illustrative example in Fig. 1 indicates that the routing of AMBs only depends on the collective decision of passengers, rather than any pre-determined operating plans. Thus, we can expect that (a) modular buses can pick up any passenger regardless of the

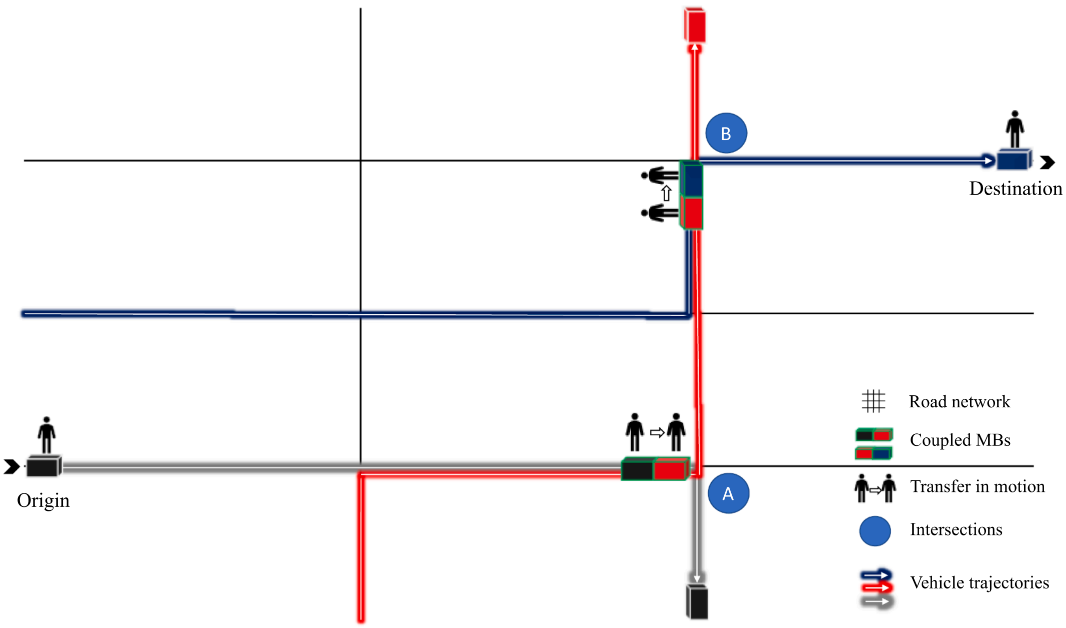


Fig. 1. An illustrative example of a passenger's trip in proposed modular bus system.

destination consistency between the boarding passenger and passengers on board, as long as there are enough spaces; (b) passengers can get on any random modular bus and will always be delivered through the shortest path. In other words, the proposed system is designed to inherit both advantages of private cars in terms of door-to-door service and conventional buses regarding shared mobility and efficient energy use. The transfer strategy is evidently a crucial decision process that largely determines system performance. From a passenger's perspective, mandatory transfers even though accomplished inside vehicles are very disrupting and thus should be reduced to a reasonable number, especially for older and vulnerable passengers. Frequent and complex driving maneuvers, such as changing lanes back and forth, will also lead to uncomfortable travel experiences and thus should be minimized. To this end, we develop an algorithm to jointly optimize modular vehicle trajectories and passenger transfer strategies, with the purpose of achieving a minimum number of passenger transfers and vehicle maneuvers. Based on the developed transfer strategy, we examine the operational performance from a passenger's standpoint with comparison to the conventional bus system. More detailed descriptions of the proposed system will be introduced later in Section 3.

The remainder of this paper is organized as follows: Section 2 introduces related studies and identifies research gaps to clarify the contribution of this study. Section 3 provides comprehensive descriptions of the proposed autonomous modular bus system. The optimal transfer algorithm is developed in Section 4 followed by a comparative study in Section 5. Section 6 concludes the paper with discussions.

2. Literature review

The idea of autonomous modular buses falls into the general category of flexible transit systems, which usually feature flexible routes and/or flexible timetables. Conventionally, such systems are adopted to low demand areas or to as first/last mile services where operational costs for mass transit systems are excessively high (Shen et al., 2018). In this area, a major research interest is the joint design of conventional and flexible transits (Narayan et al., 2020). Kim and Schonfeld (2013) proposed a mixed bus system with both conventional and flexible buses in a scenario with a traffic terminal and several local destinations. Case studies demonstrated that, by optimally integrating different kinds of bus services, the total operational costs could be significantly reduced compared with several other conventional bus systems. In the same context, they further investigated the merits of such integrated systems with various objectives and techniques, including timetable synchronization (Kim and Schonfeld, 2014), system welfare optimization (Kim and Schonfeld, 2015), and optimal service zone design (Kim et al., 2019). Guo et al. (2018) proposed a market entry-exit real options model to dynamically switch between a fixed and a flexible mode for last-mile services in a many-to-one region.

Other studies focus more on the system development of flexible transits as an exclusive service. Nourbakhsh and Ouyang (2012) developed a structured flexible transit system in which each bus operates in a predetermined area, while service zones of different buses form hub-and-spoke and grid networks. Comparative studies to conventional systems, such as fixed-route transits and taxi service, found that flexible bus systems are more likely to be beneficial under low-to-medium traffic demand. Frei et al. (2017) implemented a stated-preference survey to identify potential users of flexible transits and help better design future public transport systems. The survey revealed that pick-up at home services are highly desirable for flexible transit, and passengers who are currently using public transit or bikeshare members are more inclined to shift to the innovative flexible transits. Among these emerging flexible transit services, the costumed bus (CB), personal rapid transit (PRT), and the autonomous bus system are quite notable.

Different from the above-mentioned flexible transit systems that are implemented in low-demand areas, the costumed bus is subscription-based and mostly aiming at excessive demand areas. The general form of CB has been implemented in many countries, such as UK, Italy, US, and China (Brake et al., 2007; Liu and Ceder, 2015; Lyu et al., 2019; Chen et al., 2020; Liu et al., 2020). The CB systems aim at a group of passengers that have similar demand in time and space but do not have direct and fast access to conventional transits (Tong et al., 2017; Qiu et al., 2019; Lyu et al., 2019; Huang et al., 2020). Typical customers of the CB service could be commuters that work in the same community and live in the same neighborhood. To order a CB service, a passenger needs to subscribe first by providing the desired pick-up location, destination, and departing time. A CB line will then be assigned which the passenger can choose to deny or accept. If accepting, the passenger will be picked up at the agreed departing location and transported directly to the desired destination with many other passengers sharing the ride, during which there will be very few or no stops. Due to the subscription feature, the demand for CB systems is largely known which enables optimization on vehicle routing and passenger assignment. In this regard, Tong et al. (2017) developed a multi-commodity network flow-based model to optimize the utilization of customed buses to reach long-term profitability. To address the demand data availability problem which may be encountered when the CB service is in the planning stage or has just been initiated, Lyu et al. (2019) proposed a bus-line planning framework that is applicable to travel data sources. The framework consists of a demand prediction module, a bus stop planning module, and a bus scheduling module. Case studies demonstrated that the proposed framework could help attract more potential passengers. Comprehensive reviews on the field implementations of CB can be found in Mageean and Nelson (2003) and Brake et al., (2007).

Personal rapid transit (PRT) is another public transport system that provides on-demand and nonstop services in an exclusive guideway network (Anderson, 2010). Similar to the recently emerging autonomous modular buses, PRTs are also operated with small and automated vehicles, but its popularity could date back to the 1970 s (Irving et al., 1978). Since then, multiple PRT systems have been implemented in the United States (Sproule and Neumann, 1991), Korea (Suh, 2001), Sweden (Tegner et al., 2007), England (Lees-Miller and Wilson, 2012), and the United Arab Emirates (Mueller and Sgouridis, 2011). Mueller and Sgouridis (2011) conducted a simulation-based analysis on the service and energy performance of a PRT system to be operated throughout the Masdar City in Abu Dhabi. Based on the simulation results, the planned PRT system should be able to support normal demands but needs a reserved fleet to handle demand spikes caused by special events. The study also reveals the importance of guideway network design. To this end, Zheng and Peeta (2015) develop an optimal network design algorithm to minimize guideway construction and passenger waiting time. The designed network could also favor transit-oriented development to further reduce residents' dependence on private vehicles. Another possible issue with the PRT system that has been identified is related to the occupancy rate. A PRT vehicle designed for six passengers may only load 1.1 to 1.3 people (Carnegie and Hoffman, 2007), leading to a considerable waste of capacity. Chebbi and Chaouachi (2016) addressed this problem by developing an integrated redistribution model to jointly minimize empty movements and the number of occupied vehicles. The developed PRT system is also compared with other traffic modes through numerical experiments, which demonstrate the benefits of PRT in terms of travel speed and energy consumption.

Despite the pioneering use of automated vehicles and successful operations in several cities, the PRT system did not get widespread in the world. One major concern of initiating a PRT project is the cost of building guideways and the subsequent influences on other traffic participants. Existing studies estimate that guideways account for a large portion of the total construction cost (Yoder et al., 2000; Zhen and Peeta, 2015). In addition, the guideways will prune an isolated part out of the city land, which inevitably destroys the completeness of traffic networks, leading to decreased network capacity, longer travel time, and congestions. Therefore, existing implementations of PRTs are usually limited to close environments such as airports and school campuses.

There was a need for the guideway for safe operations of automated vehicles in the 1970 s, but it is not necessarily true in the near future since guideway-free automated vehicles are increasingly ready for open environments. The removal of guideways could also substantially expand the region of service and reduce operational costs. In this regard, the proposed autonomous modular bus system can be considered as an evolved version of the PRT in the modern era. Even though the concept of autonomous modular buses is new, several existing studies have already investigated key problems of designing and implementing such public transit systems (Cao and Ceder, 2019; Chen et al., 2019a; Chen et al., 2019b; Shi et al., 2020). One notable benefit of modular buses has been identified in addressing oversaturated or highly fluctuated demands (Chen et al., 2019a; Chen et al., 2019b; Dai et al., 2020*)*. It can be concluded that substantial operational benefits can be achieved even simply by adopting the "modular" feature (i.e., multiple bus units can be coupled and decoupled flexibly). Very recently, Hyland and Mahmassani (2020) conducted a comprehensive operational analysis of shared-ride automated mobility-on-demand services, one possible form of which could be the autonomous modular bus system investigated in this paper. Their study points out that allowing shared-rides significantly improves operational efficiency, but extra attention should be paid to curbside pickup time as it is a significant influencing factor to the system performance.

For an innovative type of bus with above mentioned benefits, related studies are still scarce. Most existing studies are conducted in a line-based scenario, i.e., addressing dispatching and flexible capacity design problems in a single bus line (Chen et al., 2019a; Chen et al., 2019b; Shi et al., 2020; Dai et al., 2020*)*. Very few studies, such as Hyland and Mahmassani (2020), investigate the problem as a complete transport system at the network level. However, in Hyland and Mahmassani (2020), the shared-rides is performed in a sense of car-sharing (e.g., the services Uber and Lyft provided in Pratt et al. (2019)) rather than in a public transport fashion.

Despite existing flexible transit systems can be very beneficial, they share a common limitation, that is they are complements to the conventional transit system rather than a complete system. In other words, those flexible transits are only applicable to very specific scenarios limited by demand *(*Nourbakhsh and Ouyang, 2012*)*, space/time (Shen et al., 2018; Kim and Schonfeld, 2015), or patterns of passengers (Huang et al., 2020). The current practice of a mixed system is an intuitive solution to take both advantages of conventional and flexible transits but inherently has to be a centralized and elaborately designed system to work efficiently, which is hardly scalable and adaptive to highly dynamic traffic demands. Thus, there is a need for an innovative transit system that is scalable and adaptive to most traffic scenarios, and the autonomous modular bus system seems like a promising solution.

Although we have witnessed promising developments of autonomous modular buses in recent years, several research gaps are notable. First, the coupling and decoupling of modular buses have to be accomplished at terminus or garages in most existing studies. This means that no adjustments to capacity or passenger reassignments can be made during service, losing the opportunity to better match dynamic demands. In-motion transfers enabled by AMBs show the possibility of minimizing stops/off-vehicles transfers, which could significantly shorten travel time. In view of this, the benefits of allowing passenger to transfer in-motion need to be explored. Second, most existing studies explore the merits of AMBs merely as an innovative type of vehicle that could enable flexible bus capacity in scheduling problems. Transit systems with AMBs are still operated in the same way as conventional bus systems and thus inherit the limitations related to fixed routes and timetables. It is thus imperative to develop a more flexible transit system with no fixed routes and timetables, taking the best advantage of autonomous modular vehicles. Last but not the least, existing studies indicated that flexible transit systems are only suitable for limited scenarios, such as small service zones or low demand areas, and therefore mostly serve as a complement to conventional transits. Whether a complete public transit system with only autonomous modular buses is beneficial remains unknown. How passengers should transfer efficiently in such a complete public transport system is vital yet unaddressed.

To bridge those aforementioned research gaps, we propose a modular, adaptive, and autonomous transit system (MAATS) operated exclusively with AMBs that is designed to provide door-to-door service on a large scale with comparable efficiency to the conventional bus system. The contributions of the present paper are as follows:

1. For the first time, the MAATS is developed as a complete system that is adaptive to traffic demands in a real-time manner with neither fixed routes nor off-vehicle transfers.
2. We propose an optimal in-motion transfer strategy to minimize passenger transfers and AMB movements and also guarantee that all passengers travel in their shortest paths, respectively.
3. We evaluate the performance of the proposed system from the passengers' perspective through numerical experiments. Some unique features of the AMB system are revealed and influencing factors on the operational efficiency are examined. A comparative study is also conducted against a conventional bus system in an urban grid transit network to demonstrate the efficiency of the proposed system.

3. Problem statement

3.1. Assumptions of the system

In this study, the proposed AMB-based transit system is assumed to have the following operational assumptions:

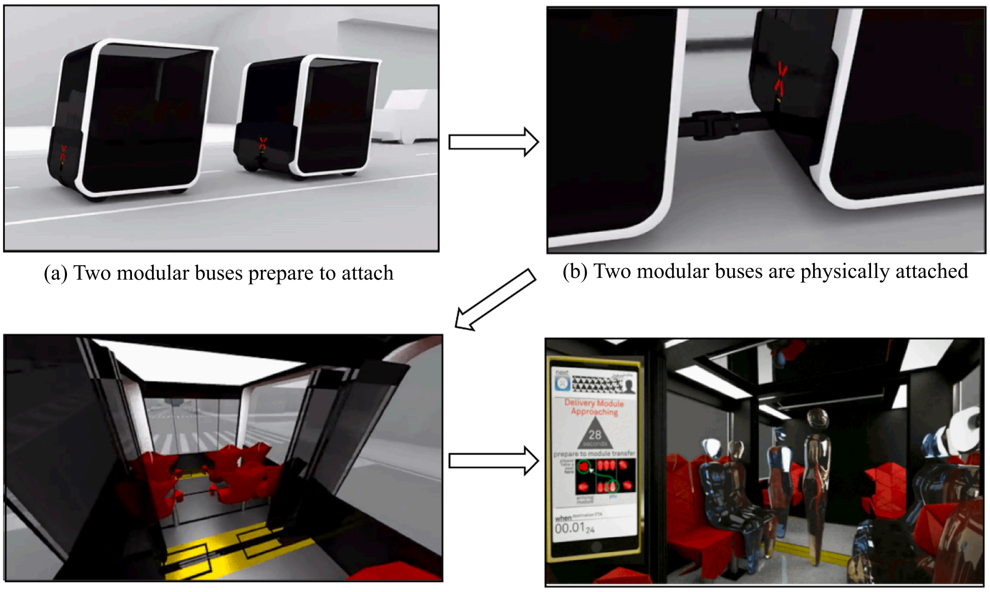
- Passengers need to specify their destinations through a mobile application, after which the shortest path for each passenger will be generated and executed by one or multiple AMBs.
- Passengers can get on any modular bus regardless of destinations of on-board passengers.
- If multiple AMBs are needed, the passenger will be directed through the mobile application to transfer in-motion between AMBs during the journey, and they follow all recommendations.
- In-motion transfers only occur between vehicles on the same lane before intersections where vehicles may then separate from each other to different destinations, such as signalized intersections and highway ramps.
- All modular buses are homogeneous with openable front and back doors to facilitate in-motion transfers.
- The number of AMBs are assumed to be sufficient in each road link to perform in-motion transfer and serve all passengers.

Based on the above assumptions, we introduce key operations of the proposed system. Note that in this paper, the purpose is to introduce the concept and basic operations of an innovative transit system, with no intention to elaborate on the details which need extensive future studies. Therefore, those intuitive assumptions are made only to complete the illustrative MAATS, while different approaches can certainly be adopted in practice.

3.1.1. In-motion-transfer

It is apparent that the in-motion transfer feature is a vital component of the proposed system. The operation of an in-motion transfer between two autonomous modular buses is illustrated in Fig. 2. Two AMBs driving on the same lane will attempt to adjust their speed to an identical speed, and then physically couple to each other. After a stable connection is established, interior doors will open and allow passengers to transfer from one modular bus to another. It is notable that such kinds of modular vehicles are already technically available and have been tested in practice (Spera, 2016).

The benefits of modular buses are threefold. First, in-motion transfer can balance the ridership between coupled buses by allowing passengers to move between modular buses. This leads to a better use of the available capacity, avoiding the commonly seen phenomenon in conventional systems that one bus is overloaded while the following bus is almost empty. Second, modular buses enable passengers to travel along the shortest path without off-vehicle transfers, as illustrated in Fig. 1. Third, the in-motion transfer feature is vital to provide service in a public transit form, without which each passenger will only be served by one AMB in the entire trip, and this AMB can only pick up passengers with similar destinations. In such conditions, the system will actually be downgraded to the customized bus or the ride-sharing system.



(a) Two modular buses prepare to attach

(b) Two modular buses are physically attached

(c) Interior doors open

(d) Passengers transfer between modular buses

Fig. 2. Passengers transfer between coupled modular buses in motion (Sources: https://www.next-future-mobility.com/home.

3.1.2. Passenger and AMB movements at intersections

Consider a platoon of AMBs approaching an intersection, as illustrated in Fig. 3. Even though each autonomous modular bus may carry passengers heading to significantly different destinations, there are only three local destinations at the current intersection, i.e., turning left, going straight, and turning right. Since AMBs are not operated with pre-determined fixed routes, the movement of each autonomous modular bus is not pre-determined at any intersection. This feature brings flexibility in assigning passengers and routes to modules, but also a very challenging problem of how to jointly assign AMB movements and make transfer plans to re-assign passengers with same turning needs to the same buses. Notably, the turning needs of passengers at each intersection are known basing on their origin and destination (OD) information.

In this paper, we develop an optimal transfer algorithm (see Section 4) to minimize the total number of passenger transfers and AMB movements. With the developed model, taking Fig. 3 as an example, each autonomous modular bus will be assigned with a turning direction and driving trajectories for the current intersection, and passengers will get instructions on the transfer plan, e.g., which AMB they should transfer to and when to start the transfer. The local trajectories of different AMBs are designed to jointly facilitate in-motion transfers so that passengers can be well separated and transfer to the target AMBs at the current intersection.

Theoretically, the in-motion transfers can be completed on any size of roads. However, in extreme conditions when the road link between intersections is exceptionally short, there is a possibility that the in-motion transfer cannot be completed in time. In such scenarios, some passengers will have to take a temporary detour at this intersection, similar to the capacity shortage phenomenon introduced in **Appendix A**. We believe that such scenarios are rare in practice and thus did not address them in this paper

3.2. The In-motion transfer problem

With the setup described in Section 3.1, the proposed transit system shows the possibility of providing comparable door-to-door services to taxies in a public transport form. Although we only present a conceptual description of the system, it is evident that the MAATS is operated on the basis of in-motion transfer operations, which essentially enable flexible routes of AMBs and passengers to travel smoothly. The in-motion transfer operations determine AMB trajectories and passenger movements at intersections, interchanges, etc., and thus highly impact the operational performance of the system. An efficient strategy to consolidate AMB and passenger movements is necessary to improve system performance.

To this end, the present paper promotes the development of the MAATS by addressing the key in-motion transfer problem. Specifically, we aim at proposing an optimal in-motion transfer strategy to minimize the totally number of AMB movements and passenger transfers, due to concerns about overcomplicated AMB maneuvers and too many transfers for passengers. It is notable that a global optimization of the total number of transfers for entire trips of all passengers entails complete information of highly dynamic and stochastic demands, which is generally intractable in practice. Therefore, we only perform local optimal operations at each intersection and then examine the network-level performance with numerical experiments.

4. Methodology

In this section, we develop a two-stage model to optimally design AMB trajectories and passenger transfer plans at a signalized intersection, as illustrated in Fig. 3. The developed method can also be applied in other infrastructures such as interchanges and ramps. The objectives are minimizing the total number of passenger transfers and the number of AMB movements, i.e., the number of bus maneuvers to perform in-motion transfers, respectively.

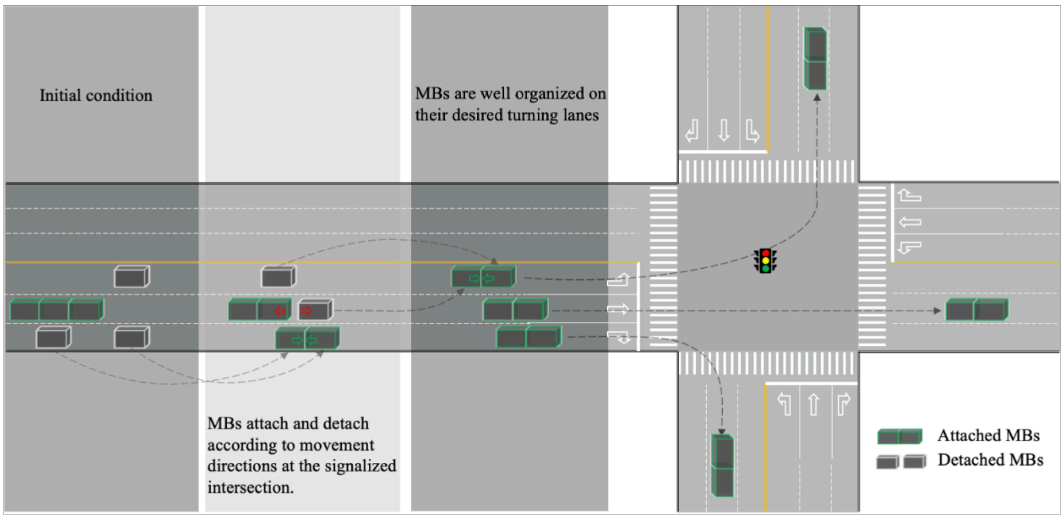


Fig. 3. The joint problem of passenger transfer and AMB movements at intersections.

The difficulty of this problem lies in the complexity of the in-motion transfer operations, especially when the routes of AMBs are not predetermined. On one hand, the turning direction of AMBs largely determines the transfer targets of passengers and thus the number of transfers that we seek to optimize. On the other hand, passengers' destinations put hard constraints on the movements of AMBs, as the in-motion transfers have to be performed to separate passengers at intersections. To this end, we develop a two-stage model in which the first stage problem seeks to minimize the total number of passenger transfers as introduced in Section 4.1. In the second stage, the optimal bus trajectory design problem is addressed which will be introduced later in Section 4.2. Solving the passenger transfer problem first indicates that we grant higher priority to passengers since the focus of this study is to evaluate the new system from the passenger's perspective.

Without loss of generality, we presume that a platoon of AMBs is approaching a D-leg signalized intersection on a multi-lane city road. There are passengers that desire to go to all the legs of the intersection, corresponding to D turning directions. The following assumptions are also made: (1) at the intersection, each passenger needs to transfer in-motion for at most one time to achieve comfort travel experience, especially for elder and vulnerable people; (2) all AMBs drive in the same speed during in-motion transfers. For convenience, we define the sets of AMBs as $\mathscr{I} := [1, 2, \cdots I]$, the turning direction indexed by $\mathscr{D} := [1, 2, \cdots D]$, and the number of time steps as $\mathscr{K} := [0, 1, \cdots K]$.

4.1. Stage one: Optimization of the number of passenger transfers

With the assumptions and setups mentioned above, in this stage, we seek to minimize the total number of passenger transfers. The objective function is formulated as

$$\min_{m_{i,d}} \sum_{i=1}^{I} \sum_{d=1}^{D} (1 - m_{i,d}) n_{i,d}^{0} \tag{1}$$

Where $n_{i,d}^{0}$ means the number of passengers that desire to turn to direction d in the initial condition, and $m_{i,d} \in \{0, 1\}$ indicating whether the AMB i will turn to direction d. Specifically, $m_{i,d} = 1$ indicates that AMB i will turn to direction d, while $m_{i,d} = 0$ means that the AMB i will not turn to direction d. The objective function in Eq. (1) represents the total number of passenger transfers.

To constrain that each autonomous modular bus can only be assigned with one turning direction, the following formula is used

$$\sum_{d=1}^{D} m_{i,d} = 1, \forall i \in \mathscr{I} \tag{2}$$

Furthermore, we deploy the following constraint to guarantee that there is enough capacity for all groups of passengers, where c is the capacity of AMBs.

$$\sum_{i=1}^{I} c \bullet m_{i,d} \geq \sum_{i=1}^{I} n_{i,d}^{0}, \forall d \in \mathscr{D} \tag{3}$$

Remark 1:. *In practice, there may be extreme conditions when the platoon capacity is insufficient for separating passengers and violate this constraint. Since we have assumed in Section 3 that the number of AMBs are sufficient for in-motion transfers, such extreme conditions are not considered in the present paper. Instead, we provide a complete solution to minimize the number of detour-passengers and also the number of transfers in the Appendix A to address this problem.*

The optimization problem formulated in Eq. (1) to Eq. (3) is an integer linear programming problem that can be easily solved by most commercial solvers. In this paper, we applied the lpSolve package in R (the programming language for statistical computing) to solve the above integer linear programming problem.

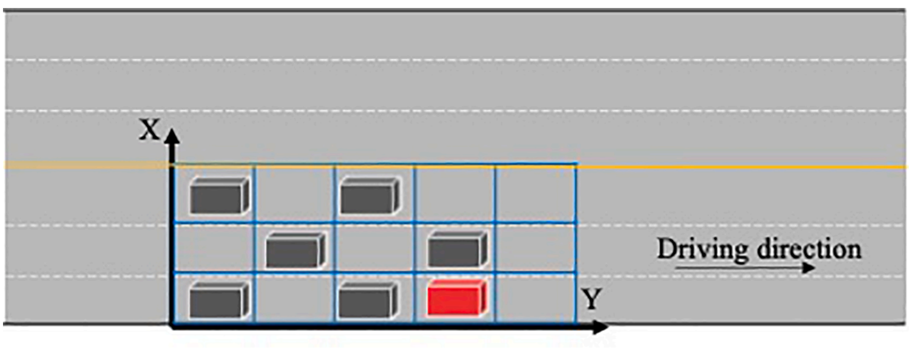


Fig. 4. Discretization of the autonomous modular bus platoon.

4.2. Stage two: AMB trajectory optimization

Based on the results from stage one, each AMB will be assigned explicitly with a turning direction at the current intersection. The subsequent question is how to optimally match passengers with AMBs and make transfer plans accordingly. Therefore, in this stage, the objective is to minimize the total number of movements of AMB that are required to complete the in-motion transfers. For the convenience of modeling, we investigate the problem in a discrete grid system relative to the identical speed, as shown in Fig. 4. Specifically, we discretize the road space into several homogeneous cells and assign AMBs to cells according to their midpoint. The purpose of this discretization is to facilitate the optimization of AMB trajectories, which will be introduced later in this section. With the discretized grid system, the objective function can be formulated as Eq. (4).

$$\min_{x_{i,d}^k, y_{i,d}^k, K} \sum_{0}^{K-1} \sum_{i=1}^{I} \left(|x_{i,d}^{k+1} - x_{i,d}^k| + |y_{i,d}^{k+1} - y_{i,d}^k| \right) \tag{4}$$

where $x_{i,d}^k$ and $y_{i,d}^k$ are coordinates denoting the relative lateral and longitudinal positions of autonomous modular bus i in time step k in the grid system. For instance, the location of the red bus in Fig. 4 will be denoted as (1,4).

In addition, the following constraints are introduced.

(1) Vehicle dynamics are constrained with Eq. (5) to Eq. (7), which define possible movements of each AMB at each time step, i.e., either changing one lane, moving forward or backward by one cell, or remaining the current position.

$$|x_{i,d}^{k+1} - x_{i,d}^k| = \begin{cases} 1 & \textit{if lane changes} \\ 0 & \textit{otherwise} \end{cases}, \forall i \in \mathscr{I}, d \in \mathscr{D}, k \in [0, 1, \cdots K-1] \tag{5}$$

$$|y_{i,d}^{k+1} - y_{i,d}^k| = \begin{cases} 1 & \textit{if accelerate/decelerate} \\ 0 & \textit{otherwise} \end{cases}, \forall i \in \mathscr{I}, d \in \mathscr{D}, k \in [0, 1, \cdots K-1] \tag{6}$$

$$|x_{i,d}^{k+1} - x_{i,d}^k| \bullet |y_{i,d}^{k+1} - y_{i,d}^k| = 0, \forall i \in \mathscr{I}, d \in \mathscr{D}, k \in [0, 1, \cdots K-1] \tag{7}$$

(4) Eq. (8) defines the final states of AMBs and passengers. Specifically, all AMBs are in desired lanes, and passengers are completely separated according to their turning needs.

$$x_{i,d}^K = d, m_{i,d} = 1, n_{i,e}^K = 0, \forall i \in \mathscr{I}, d \neq e, d, e \in \mathscr{D} \tag{8}$$

(5) The in-motion transfer behavior is modeled as follows. If two AMBs with the same turning direction are coupled, taking left-turning as an example, then only passengers with left-turning needs will move between two AMBs, with the purpose of balancing passenger load, as shown in Eq. (9). Note that other balancing strategies can also applied in our framework, such as empty of the modular buses. However, if two AMBs with different turning directions are coupled, passengers will move to their target AMBs according to turning needs, as defined in Eq. (10) to Eq. (13).

If $x_{i,d}^k = x_{j,e}^k, |y_{i,d}^k - y_{j,e}^k| = 1,\ m_{i,d} = m_{j,e} = 1,\ \textit{and}\ d = e,$

$$n_{i,d}^{k+1} = \left\lceil \frac{n_{i,d}^k + n_{j,e}^k}{2} \right\rceil, n_{j,d}^{k+1} = n_{i,d}^k + n_{j,e}^k - n_{i,d}^{k+1}, \forall i, j \in \mathscr{I}, d, e \in \mathscr{D}, \forall k \in \mathscr{K} \backslash K \tag{9}$$

If

$$x_{i,d}^k = x_{j,d}^k, |y_{i,d}^k - y_{j,d}^k| = 1,\ m_{i,d} = m_{j,e} = 1,\ \textit{and}\ d \neq e,$$

$$n_{i,d}^{k+1} = \max\left(n_{i,d}^k + n_{j,d}^k, c\right), \forall i, j \in \mathscr{I}, d, e \in \mathscr{D}, k \in \mathscr{K} \backslash K \tag{10}$$

$$n_{j,d}^{k+1} = \max\left(n_{i,d}^k + n_{j,d}^k - c, 0\right), \forall i, j \in \mathscr{I}, d, e \in \mathscr{D}, k \in \mathscr{K} \backslash K \tag{11}$$

$$n_{j,e}^{k+1} = \max\left(n_{i,e}^k + n_{j,e}^k, c\right), \forall i, j \in \mathscr{I}, d, e \in \mathscr{D}, k \in \mathscr{K} \backslash K \tag{12}$$

$$n_{i,e}^{k+1} = \max\left(n_{i,e}^k + n_{j,e}^k - c, 0\right), \forall i, j \in \mathscr{I}, d, e \in \mathscr{D}, k \in \mathscr{K} \backslash K \tag{13}$$

(6) Eq. (14) defines that if two AMBs are not located closely in the longitudinal direction, then no in-motion transfer happens.

If

$$|y_{i,d}^k - y_{j,d}^k| \neq 1$$

$$n_{i,d}^{k+1} = n_{i,d}^k, n_{j,d}^{k+1} = n_{j,d}^k, \forall i, j \in \mathscr{I}, d, e \in \mathscr{D}, k \in \mathscr{K} \tag{14}$$

By carefully examining the problem modeled in Eq. (4) to Eq. (14), we found that the problem can hardly be solved directly with commercial solvers, although we have a clear nonlinear programming formulation. The major reason is that the number of time steps required to complete in-motion transfers is unknown. This means that the number of decision variables, e.g., the location of AMBs and passenger states at each time step, is non-deterministic, leading to a challenge to use commercial solvers which usually requires a static number of decision variables (Raidl and Jakob, 2008). A natural thought for addressing this problem is to use an iterative method over the decision variable K, i.e., iterating K from one to a pre-defined large value and solve Eq. (1) with each iterated value of K. However, this iterative approach will introduce another issue related to a huge number of variables in applying solvers. Specifically, taking $K = 10$ as an example and further assume that there are 10 AMBs in total, the number of decision variables in this iteration alone can come up to 200 (10*10*2 = 200), which makes it inefficient to code and solve with commercial solvers.

To this end, we develop a solving algorithm to find optimal solutions for the AMB trajectory optimization problem. Recall that, in this stage, we seek to find optimal and cooperative trajectories for all AMBs with the purpose of facilitating in-motion transfers with minimal vehicle movements. Therefore, this is essentially a vehicle cooperation problem with unique constraints in a discrete grid system, which falls in the general category of sorting problems defined by Wu et al. (2020). However, the sorting algorithm in Wu et al. (2020) only addresses vehicle movement problems with no consideration of passenger movements. Thus, we develop a new model to address the cooperative design of vehicle trajectories and passenger transfer plans. A detailed description of the sorting algorithm is presented in the supplemental file for interested readers.

The very basic idea of the proposed algorithm is to consider the system state, which is jointly defined by AMB permutations and the composition of passengers with different turning needs in each AMB, as a node in a virtual graph. Any change to the AMB permutation or the passenger state will generate a new system state and thus a new node in the graph. The cost of changing from one state to another can be considered as the weight of arc linking two nodes that represent those states. Therefore, all system states and corresponding costs jointly constitute a graph and finding the optimal solution for the cooperative trajectory design problem is equivalent to finding the shortest path in the modeled graph, as shown in Fig. 5. In this paper, we apply the A* algorithm proposed by *Hart (1968)* in finding the shortest path, which uses a heuristic function to direct the searching. Constraints defined by Eq. (5) to Eq. (14) will also be used to further prune out graph branches and thus improve searching efficiency, and the algorithm will terminate when Eq. (8) is satisfied.

In the A* algorithm, each graph node will be marked with a value of cost function, which represents the estimated length of the shortest path if incorporating the current node. In this study, we define the cost function as:

$$D(a) = M\sum_{i=1}^{I}\sum_{d=1}^{D}\left(1-m_{i,d}^{*}\right)\left(n_{i,d}^{0}-n_{i,d}^{k}\right)+\sum_{0}^{k}\sum_{i=1}^{I}\left(|x_{i,d}^{k+1}-x_{i,d}^{k}|+|y_{i,d}^{k+1}-y_{i,d}^{k}|\right) \tag{18}$$

$$H(a) = M\sum_{i=1}^{I}\sum_{d=1}^{D}\left(1-m_{i,d}^{*}\right)n_{i,d}^{k}+\sum_{i=1}^{I}\left|x_{i,d}^{k}-\sum_{d=1}^{D}d\bullet m_{i,d}^{*}\right| \tag{19}$$

$$F(a) = D(a)+H(a) \tag{20}$$

where $F(a)$ is the estimated cost function marking the current node$a$; $D(a)$ is the length of the path from the initial node to node a, and $H(a)$ is the heuristic function.

In A* algorithms, the definition of the heuristic function largely determines the optimum performance of the algorithm. In this paper, the first term in Eq. (19) denotes the total number of passengers that need to transfer at time step k, and the second term

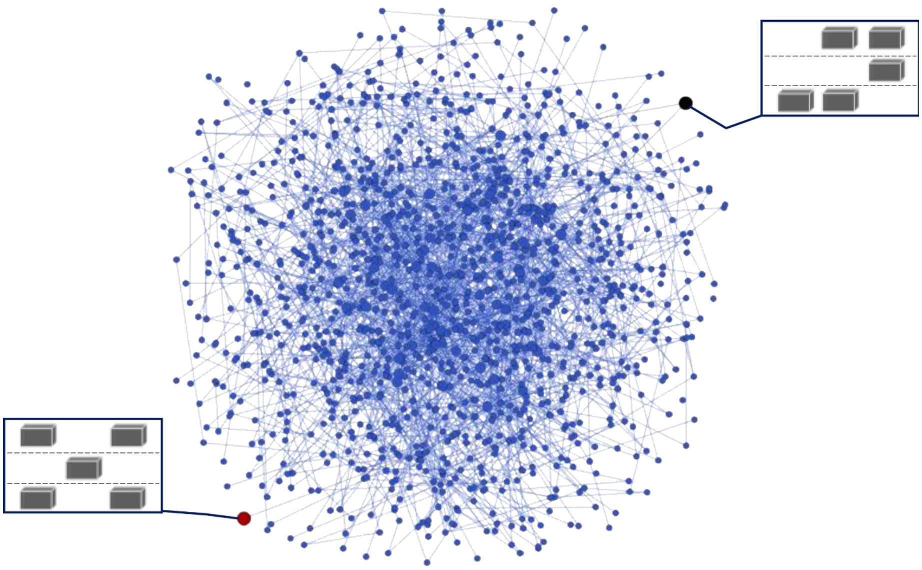


Fig. 5. An illustration of the graph state space.

represents the deviations of all AMBs from their desired lanes measured in a Manhattan distance manner. The parameter M is used to prioritize passenger movements and thus guarantee to achieve the optimal solution. We prove that the heuristic function in Eq. (19) is admissible in *Appendix B*, which means that the developed A* algorithm is optimal according to *Hart (1968)*.

5. Numerical experiments

In this section, we report the results from several numerical experiments to illustrate the operation of in-motion transfer and examine the operational performance of the proposed AMB-based transit system through a grid road network.

5.1. In-motion transfer before an intersection

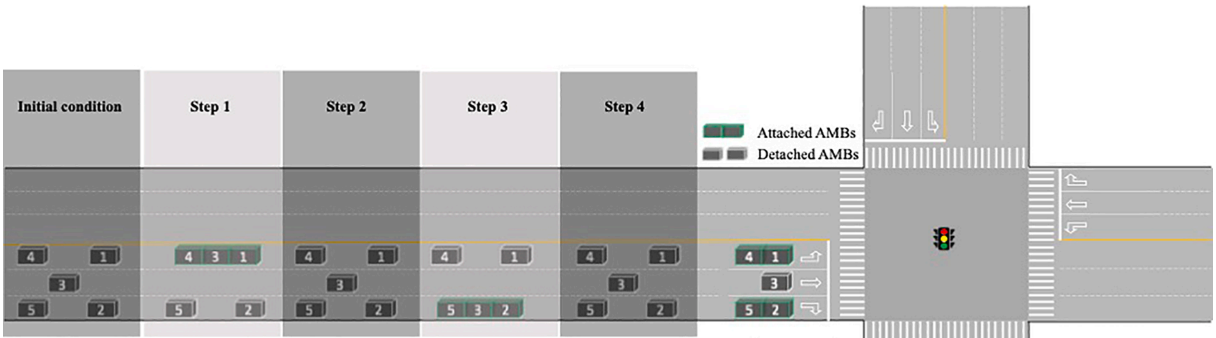
Consider an autonomous modular bus platoon as shown in Fig. 6. In the initial state, passengers with different turning desires are mixed in each autonomous modular bus. Since the proposed transit system operates without fixed routes, the turning decision at intersections of each AMB is not pre-determined. Instead, the turning directions are determined by the stage one problem. It turns out that AMB 1 and 4 need to turn left, and AMB 2 and 5 turn right, with AMB 3 to go straight.

Based on the proposed algorithm, AMB trajectories are designed to optimally perform in-motion transfers with minimal vehicle movements. As shown in Fig. 6, through two in-motion transfers involving all five autonomous modular buses, passengers are separated into three groups in exclusive AMBs according to their turning needs. In the case study, there are 18 ($3+4+6+3+2=18$) passenger transfers in total, and the average number of transfers per person equals approximately 0.35 (18/51 $\approx$0.35). For a conventional bus serving the same group of passengers, there will be at least 34 off-vehicle transfers, counting both alighting and boarding, which leads to an average number of transfer times of 0.67.

5.2. Operational performance in a grid network

In this section, we examine the operational performance of the proposed transit system from the passenger's perspective in a grid network as illustrated in Fig. 7. A conventional bus system is also operated separately with the same traffic demand in the same network as a benchmark. A major purpose of this case study is to address the intuitive concern that this flexible transit system may result in an excessive number of transfers on long trips, leading to unpleasant travel experiences and thus is impractical. Therefore, the average number of transfers (in-vehicle for AMBs and off-vehicle for conventional buses) and travel time are selected as the measure of performance. Common experimental setups in both groups are listed as follows:

- Passenger origins and destinations are endpoints of the network. In other words, internal demands are not considered for convenience.
- The link travel time between intersections is identical and equal to four minutes for both conventional buses and AMBs. In this study, we assume fixed link travel time for both conventional and modular buses to focus on the comparative analysis of these two modes. In practice, we can expect that AMBs drives with comparable speed to taxies which are normally faster than buses (SPECS, n.d.).
- We further assume that the road links are long enough so that in-motion transfers can always be completed.



ID	Number of Passengers in each AMB															Direction
	Initial			Step 1			Step 2			Step 3			Step 4			
	L	T	R	L	T	R	L	T	R	L	T	R	L	T	R	
AMB-1	8	3	0	9	0	0	9	0	0	9	0	0	9	0	0	Left
AMB-2	0	4	7	0	4	7	0	4	7	0	0	7	0	0	7	Right
AMB-3	3	6	3	0	12	3	0	12	3	0	18	0	0	18	0	Through
AMB-4	8	3	0	10	0	0	10	0	0	10	0	0	10	0	0	Left
AMB-5	0	2	4	0	2	4	0	2	4	0	0	7	0	0	7	Right

L- left-turning passengers; T- through-going passengers; R- right-turning passengers.

Fig. 6. In-motion transfer at a signalized intersection.

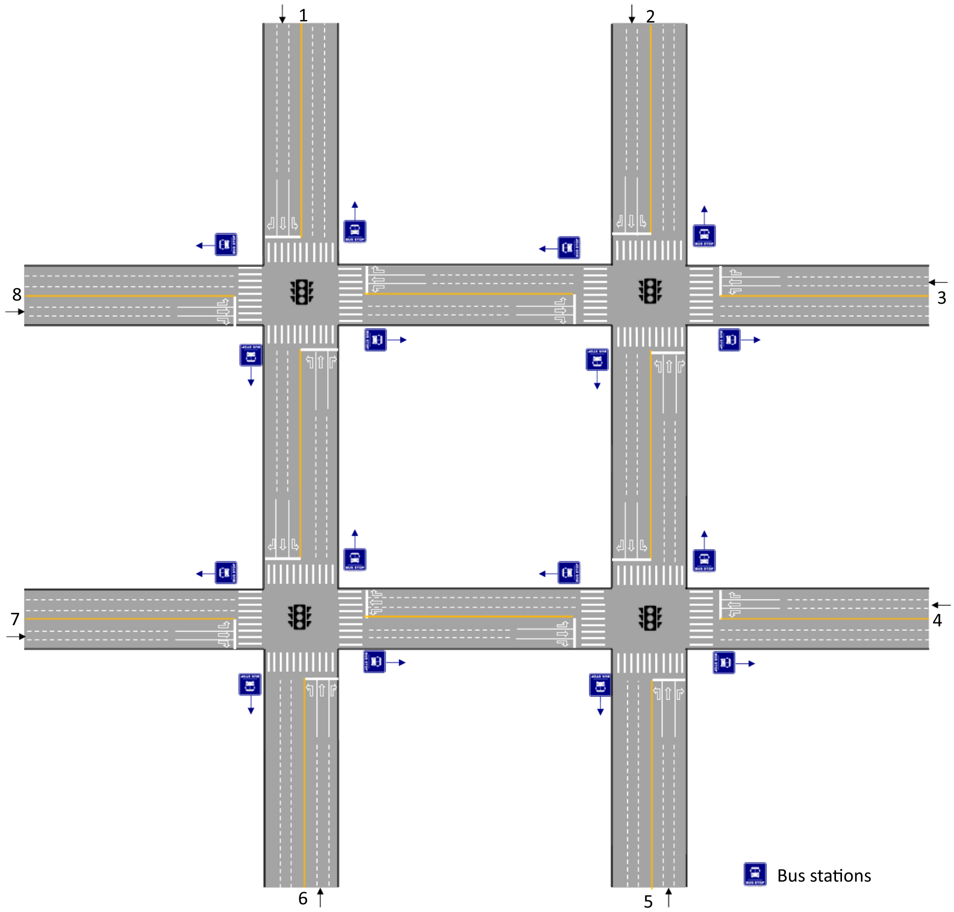


Fig. 7. Road network in the experiments.

- Passengers seek to travel in shortest paths in terms of travel time.
- The intersection delay is equal to one minute for both conventional buses and modular buses.

For the conventional bus group, every five minutes, a bus carrying a certain number of passengers will depart from each of the end points in the network. The bus enters the network from one of the endpoints and always adopts a route of a straight line until it reaches the other endpoint in the opposite direction, meaning that the conventional buses always go straight at intersections. The dispatch headway is used to optimally synchronize buses from different routes, which is commonly considered as an optimal timetable strategy in existing studies *(*Ceder et al., 2001; Yap et al., 2019*)*. With the synchronized timetable, most buses would arrive at intersections at the same time and wait at the bus station for the same time duration. Therefore, passengers could transfer seamlessly at bus stations, and the transfer time in the conventional group is minimized. We further assume that the capacity of the conventional bus is 90 passengers (42 seats) according to the current bus model Volvo 7900.

For the autonomous modular bus group, every five minutes, a platoon of six AMBs carrying the same number of passengers will depart from each of the endpoints in the network. Instead of off-vehicle transfer, the AMBs perform in-motion transfer and directly deliver passengers to their destinations. Several scenarios are simulated to investigate the performance of AMBs in various demands. We further assume that the capacity of each AMBs is 20 passengers (7 seats) according to the current test AMB model from NEXT Future Transportation inc.

5.2.1. Homogeneous demands

In this case, the demand between each pair of origin and destination points is identical. Specifically, there are 42 passengers in each conventional bus, and the average ridership in each AMB is 7 passengers, ranging from 5 to 9 passengers. Theoretically, there are $7 \times 8 = 56$ different trips with different origin and destination points. However, with homogeneous demand, several trips from symmetric OD pairs are inherently the same, such as the trips from station 1 to station 8 and station 5 to station 4. In this regard, 14 representative trips are selected to compare the performance of two groups. A simulation result of two hours is presented in Table 1.

The experiments show that the average travel time of the AMB group is 14.7 min, which is 16.6% less than the conventional bus group. More importantly, in such a network scale, the average number of transfers in the AMB group is 0.90, significantly smaller than the conventional bus group (1.06). This demonstrates that the proposed transit system could provide comparable or even better service than the conventional bus system. Furthermore, we have a particular focus on the average number of transfers on long trips. Surprisingly, trip 11 has the longest travel time but results in a smaller number of transfers compared with most of the other trips, especially considering the fact that passengers of trip 11 have passed through three intersections. However, there are eight passengers in trip 11 that experience three transfer times, which account for 26.7% of three-transfer passengers in all OD pairs. Nevertheless, considering that the percentage of three-transfer passengers is only 1.4% in trip 11 and 0.4% on all trips, we believe this is acceptable in practice with proper incentives.

5.2.2. Heterogeneous demands

In this case study, we increase the demand for trip 5 by seven times and examine the system's response to such a surge in demand. The results are presented in Table 2. It can be found that the average number of transfers for trip 5 is significantly reduced while the average number for all trips remains stable. This indicates that the proposed system has an adaptive ability to heterogeneous demands, without the need for demand prediction or centralized control. In other words, the system will automatedly assign more AMBs to trips with higher demand and maintain a reasonable level of service. The demands of multiple OD pairs are further changed to present results of more complicated heterogenous scenarios, as shown in Table 3. It can be found that the pattern is clear and consistent with that in Table 2, that is, passengers of the mainstream (with higher demand) always experienced a smaller number of transfers. It is also notable that in all 4 new cases, the AMBs remains a stable performance, further demonstrating the system's adaptive ability to demand variations.

We also increased the demand for all trips by the same amount of value, but the system performance remains stable. This phenomenon indicates that the performance of the

proposed transit is only sensitive to ratios of demands instead of absolute demands, as long as the capacity is sufficient.

5.2.3. The capacity and number of autonomous modular buses

In this case study, we vary the capacity of autonomous modular buses while maintaining the same traffic demands and examine the system performance. The results are shown in Table 4. It is evident that increasing the capacity cannot improve system performance. However, when the capacity of each AMB is reduced in the simulated scenario, the capacity shortage phenomenon started to occur. We summarize the frequency of such phenomenon in 100 simulations over different capacity setups under the same demand level, as shown in Table 5. The results in Table 5 suggest that the occupancy rate of AMBs should be carefully examined to avoid capacity shortage. Otherwise, certain incentive policies should be made to compensate detour passengers.

We further increase the number of AMBs and also maintain the same level of demand. The results are provided in Table 6. It can be found that increasing the number of AMBs leads to a substantial decrease in the average number of transfers. In extreme conditions when there are a huge number of AMBs, the system has a comparable performance to private cars, featured by zero transfer times.

The results in Table 4 and Table 5 also jointly indicate that, for the proposed system, increasing the fleet size is a more effective and flexible treatment against high demand and may not increase energy consumption. The major reason is that increasing modular bus capacity cannot improve the flexibility of in-motion transfers at intersections, while a larger fleet could better facilitate such operations.

6. Conclusion and discussion

In this study, we propose an innovative transit system with autonomous modular buses that is adaptive to dynamic traffic demands

Table 1
Travel time and the number of transfers under homogeneous demands.

ID	Modular Buses							Conventional Bus	
	0 transfers	1 transfer	2 transfers	3 transfers	Passenger #	avg transfer *	avg travel time (mins)	avg transfer *	avg travel time (mins)
All trips	2209	3879	1397	30	7515	0.90	14.7	1.06	17.09
trip_1	214	353	0	0	567	0.62	9	1.00	10
trip_2	127	309	124	0	560	0.99	14	0.00	15
trip_3	189	326	86	0	601	0.83	14	1.00	15
trip_4	219	213	95	8	535	0.80	19	1.00	25
trip_5	187	240	82	10	519	0.84	19	2.00	25
trip_6	115	269	176	0	560	1.11	14	1.00	15
trip_7	110	269	133	0	512	1.04	14	2.00	15
trip_8	135	293	78	0	506	0.89	14	2.00	15
trip_9	143	305	79	0	527	0.88	14	1.00	15
trip_10	194	215	88	4	501	0.80	19	1.00	25
trip_11	235	241	70	8	554	0.73	19	1.00	25
trip_12	126	303	108	0	537	0.97	14	0.00	15
trip_13	105	274	145	0	524	1.08	14	1.00	15
trip_14	110	269	133	0	512	1.04	9	1.00	10

* average number of transfers, defined as the total number of transfers divided by the total number of passengers.

Table 2
A performance comparison between the homogeneous demand scenario and the heterogeneous demand scenario.

ID	Homogeneous demands							Heterogeneous demands
	0 transfers	1 transfer	2 transfers	3 transfers	passenger	avg transfer	avg travel time (mins)	avg transfer
All trips	2209	3879	1397	30	7515	0.90	14.7	0.85
trip_1	214	353	0	0	567	0.62	9	0.63
trip_2	127	309	124	0	560	0.99	14	0.99
trip_3	189	326	86	0	601	0.83	14	0.99
trip_4	219	213	95	8	535	0.80	19	0.85
trip_5	187	240	82	10	519	0.84	19	0.52
trip_6	115	269	176	0	560	1.11	14	1.04
trip_7	110	269	133	0	512	1.04	14	1.03
trip_8	135	293	78	0	506	0.89	14	0.89
trip_9	143	305	79	0	527	0.88	14	0.92
trip_10	194	215	88	4	501	0.80	19	0.85
trip_11	235	241	70	8	554	0.73	19	0.73
trip_12	126	303	108	0	537	0.97	14	0.99
trip_13	105	274	145	0	524	1.08	14	1.01
trip_14	110	269	133	0	512	1.04	9	1.03

Table 3
Average number of transfers in different scenarios.

ID	Homogeneous	New Scenario 1	New Scenario 2	New Scenario 3	New Scenario 4
All trips	0.9	0.85	0.86	0.85	0.85
trip_1	0.62	0.63	0.61	0.63	0.66
trip_2	0.99	1.01	1.04	1.03	1.06
trip_3	0.83	0.91	0.98	0.97	0.97
trip_4	0.8	0.77	0.73	0.75	0.70
trip_5	0.84	0.59	0.66	0.64	0.67
trip_6	1.11	1.02	1.09	0.88	0.89
trip_7	1.04	1.13	0.97	1.00	1.08
trip_8	0.89	0.89	0.92	0.91	0.86
trip_9	0.88	0.87	0.93	0.96	0.93
trip_10	0.8	0.83	0.84	0.73	0.87
trip_11	0.73	0.75	0.70	0.80	0.73
trip_12	0.97	1.01	1.04	1.03	1.06
trip_13	1.08	1.02	0.96	1.05	0.94
trip_14	1.04	1.13	0.97	1.00	1.08

*Trips in color have increased demand by 400% compared with the homogeneous scenario.

Table 4
Performance comparison with different capacity setups.

ID	Average number of transfers per passenger			
	Baseline (20)	Capacity 25	Capacity 35	Capacity 45
All trips	0.90	0.91	0.89	0.90
trip_1	0.62	0.63	0.62	0.64
trip_2	0.98	0.99	0.96	1.02
trip_3	0.83	0.90	0.98	0.89
trip_4	0.80	0.69	0.78	0.77
trip_5	0.84	0.88	0.77	0.79
trip_6	1.11	1.02	1.09	1.01
trip_7	1.04	1.14	0.91	1.02
trip_8	0.89	0.95	0.98	0.80
trip_9	0.88	0.90	0.93	0.92
trip_10	0.80	0.86	0.77	0.82
trip_11	0.73	0.74	0.74	0.81
trip_12	0.98	0.99	0.96	1.02
trip_13	1.08	0.96	1.05	1.07
trip_14	1.04	1.14	0.91	1.02

and has the potential to provide better service than the conventional bus system. The proposed transit system is designed to provide door-to-door service and each autonomous modular bus can pick up any passenger regardless of desired destinations. A unique transfer operation is introduced in this paper which is performed to transfer passengers between coupled modular buses in motion. Through in-

Table 5
the frequency of capacity shortage in 100 simulations.

	Baseline (20)	Capacity 18	Capacity 16
Frequency	0.0084	0.027	0.095

Table 6
Performance comparison with different number of AMBs.

ID	Average number of transfers per passenger			
	Baseline (6)	15 modular buses	21 modular buses	42 modular buses
All trips	0.90	0.66	0.52	0
trip_1	0.62	0.67	0.61	0
trip_2	0.98	0.73	0.59	0
trip_3	0.83	0.67	0.53	0
trip_4	0.80	0.50	0.37	0
trip_5	0.84	0.56	0.43	0
trip_6	1.11	0.81	0.58	0
trip_7	1.04	0.79	0.55	0
trip_8	0.89	0.68	0.60	0
trip_9	0.88	0.60	0.54	0
trip_10	0.80	0.59	0.46	0
trip_11	0.73	0.49	0.37	0
trip_12	0.98	0.73	0.59	0
trip_13	1.08	0.77	0.61	0
trip_14	1.04	0.79	0.55	0

motion transfers, each passenger will be served smoothly by several autonomous modular buses and delivered in the shortest path with no off-vehicle transfers. We develop a nonlinear programming model to solve the joint design problem of passenger transfer plans and AMB trajectories. Numerical experiments demonstrate that the proposed transit system results in significantly shorter travel time and a reduced number of transfers. Sensitivity analysis indicates that the AMB-based system is highly sensitive to demand ratios. Numerical experiments indicate that the proposed MAATS system is more efficient than conventional buses in reducing travel time and the number of transfers. Moreover, compared with the prevailing flexible public transport services, such as CB and PRT, the AMB-based system is arguably more flexible and adaptive in operation and relieves the need for huge investment in infrastructure construction.

Simulation results also show that there is a trade-off between improving capacity usage and avoiding the capacity shortage phenomenon. Future studies could explore the possibility of making incentive policies to address this issue. Another advantage of autonomous modular buses that has not been investigated in this study is the efficient energy consumption compared with conventional buses. Taking Volvo 7900 and the modular bus designed by Next Transport Future as an example, the Volvo 7900 weights 19000 kg, with an average load of 42 passengers in our case studies, and the modular bus weights 2000 kg carrying 7 passengers on average. Assuming a linear relationship between vehicle mass and energy consumption *(*Basso et al., 2019*)*, only 13.4% of energy is used on carrying passengers with 86.6% energy hauling the heavy vehicle for the Volvo bus (assuming that the average weight of passengers is 70 kg). However, for the autonomous modular bus, 20% of energy is used on delivering passengers, which is a significant difference in a large-scale implementation point of view. The energy consumption didn't increase substantially in the modular bus system even though it is operated with more vehicles (5 times more than the number of conventional buses). For this case study, the energy consumption of the MAATS got reduced because the difference in mass is so significant that it becomes the dominant influencing factor in this case. Future studies are warranted to conduct a life cycle cost analysis of the proposed modular bus system.

Note that in this study, the pick-up and alighting problem of AMBs are not specifically addressed. The major reason is that there could be many possible solutions for such an underdeveloped system, and existing studies have indicated that the pick-up and alighting problem itself can be very complicated depending on the highly stochastic demand in both time and space, routing algorithms, incentives, etc. Therefore, in this study, we only consider the operational performance of the proposed system at major road networks assuming that passengers are already on board. Considering the current practice and travelers' familiarity, we present an optional way of picking up and alighting passengers. In low-demand areas or conventional first/last mile regions (e.g., communities relatively far away from corridors), the autonomous modular bus serves as a shared-ride service, picking up and alighting passengers upon requests through the mobile application, such as the service introduced by Hyland and Mahmassani (2020). After driving out of those regions to high-density areas, there are most likely multiple AMBs on each road to cooperate with each other and operate as a public transit system mentioned above.

The pick-up/alighting problem is also related to the station design problem of AMBs. As an innovative transit system that is still under development, the specific form of AMB stations can be very flexible. To the authors' best knowledge, the AMB station designed problem has not been specifically addressed in any of existing studies nor field tests. Most of the existing studies, such as Chen et al., (2019) and Cao and Ceder (2019), simply assume that the AMBs could use conventional bus stations in their models and case studies. Based on the analysis of the present paper, we propose that the AMBs station and pick-up/alighting services should be jointly considered in future investigations. For instance, in central areas with high demand, the AMBs could adopt the conventional bus stations. In suburbs or low-demand areas where the AMBs are more devoted to first-mile and last-mile services, the AMBs stations can be planned in a more scattered pattern and also smaller in size. Moreover, considering that most current test models of AMBs are electric vehicles, charging facilities should also be embedded in AMB stations to enable frequent charging for the purpose of battery maintenance and improving driving range. The joint station design and pick-up/alighting problem should be addressed in a more comprehensive way in future studies before the AMBs are deployed in practice.

It should also be noted that in oversaturated traffic when there is insufficient space for lane-changings, the AMBs will be most likely unable to completely transfer passengers. Thus, passengers will have to make a temporary detour and transfer at downstream undersaturated roads. In addition, the system requires a sufficient number of autonomous modular buses to guarantee that AMBs arrive at intersections to perform in-motion transfers cooperatively. This issue can be addressed by simply putting a large number of AMBs in a limited high-density area or developing advanced planning methods to coordinate trajectories of AMBs with such purposes. Another issue associated with the proposed system is that the OD information of passengers is only used for local optimization at signalized intersections. Global integration of travel data could reveal more benefits and thus we encourage more comprehensive investigations on this issue. Last but not least, the present paper evaluates the benefits of the AMB system merely from passengers' perspective. The operational cost of such an innovative transit system from service providers' point of view needs to be comprehensively investigated in future studies before it is widely implemented in practice.

CRediT authorship contribution statement

Jiaming Wu: Conceptualization, Methodology, Writing - original draft. **Balázs Kulcsár:** Methodology, Funding acquisition, Supervision, Writing - review & editing. **Selpi:** Methodology, Funding acquisition, Writing - review & editing. **Xiaobo Qu:** Methodology, Funding acquisition, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors acknowledge the contribution of Transport Area of Advance at Chalmers University of Technology under the project PUBS. The paper has been partially supported by Energimyndigheten through the project 'Operational Network Energy Management for Electried Buses' (46365-1), and the EU JPI project SMUrTS. We would also acknowledge the discussions with Tommaso Gecchelin, CTO of NEXT Future Transportation inc. with respect to the problem statement and potential implementations of the system. Fig. 2 is reproduced with the permission of Tommaso Gecchelin.

Appendix A

The capacity shortage phenomenon, i.e., when the number of AMBs are not sufficient to separate passengers to different directions, is most likely to happen only when all AMBs are almost fully loaded before transfer. In such scenarios, the system will not be able to completely separate passengers due to the capacity shortage in certain directions. As a compromise, several passengers may have to temporally deviate from their shortest paths and take a detour (i.e., turn to an undesired direction and then reroute at the next intersection), leading to increased travel time. In other words, several passengers have to turn to an undesired direction due to capacity insufficiency. In such scenarios, the optimization of passenger transfers can be formulated as follows:

$$\min_{m_{i,d}} \sum_{i=1}^{I}\sum_{d=1}^{D}\left(1-m_{i,d}\right)\left(n_{i,d}^{0}-\sum_{e=1}^{D}z_{i,d-e}^{0}+\sum_{e=1}^{D}z_{i,e-d}^{0}\right)+W\sum_{i=1}^{I}\sum_{d=1}^{D}\left(\sum_{e=1}^{D}z_{i,d-e}^{0}+\sum_{e=1}^{D}z_{i,e-d}^{0}\right) \tag{21}$$

Subject to

$$\sum_{d=1}^{D}m_{i,d}=1,\forall i\in\mathscr{I},m_{i,d}\in\{0,1\} \tag{22}$$

$$\sum_{i=1}^{I}c\bullet m_{i,d}\geq\sum_{i=1}^{I}\left(n_{i,d}^{0}-\sum_{e=1}^{D}z_{i,d-e}^{0}+\sum_{e=1}^{D}z_{i,e-d}^{0}\right),\forall i\in\mathscr{I},d\in\mathscr{D} \tag{23}$$

$$\sum_{d=1}^{D}\left(\sum_{e=1}^{D}z_{i,d-e}^{0}-\sum_{e=1}^{D}z_{i,e-d}^{0}\right)=0,\forall i\in\mathscr{I},d\neq e,d\in\mathscr{D} \tag{24}$$

$$\sum_{e=1}^{D}z_{i,d-e}^{0}\leq n_{i,d}^{0},\forall i\in\mathscr{I},d\neq e,d,e\in\mathscr{D} \tag{25}$$

$$\sum_{e=1}^{D} z_{i,d-e}^{0} \geq 0, \forall i \in \mathscr{I}, d \neq e, d, e \in \mathscr{D} \tag{26}$$

$$\sum_{e=1}^{D} z_{i,d-e}^{0} = 0, \forall i \in \mathscr{I}, d = e, d, e \in \mathscr{D} \tag{27}$$

$$W \geq 0 \tag{28}$$

where $z_{i,d-e}^{0}$ denotes the number of passengers that are temporarily reassigned from direction d to direction e in vehicle i at the current intersection; W is a weighting factor. The first term in the objective function denotes the total number of transfers in such scenarios, and the second term indicates the weighted number of detoured passengers in order to address the capacity insufficient problem. It is notable that the objective function is a non-linear function of decision variables. However, with the consideration that they are all positive integer or binary variables and the number of turning directions usually ranges from one to three in most real cases, the non-integer linear programming problem can be very simple and easily solved by most commercial solvers. The value of the weighting factor W can be determined based on incentives and promoting policies where future research is warranted.

Appendix B

Proposition 1:. *The heuristic function in Eq.* (19) *is admissible.*

Proof:. *It can be derived that*

$$\sum_{i=1}^{I} \sum_{d=1}^{D} \left(1 - m_{i,d}^{*}\right) n_{i,d}^{k} \leq \sum_{k}^{K-1} \sum_{i=1}^{I} \sum_{d=1}^{D} \left(1 - m_{i,d}^{*}\right) \left| n_{i,d}^{k} - n_{i,d}^{k+1} \right| \tag{29}$$

where the right-side term is the actual number of vehicle transfers. Since the second term in Eq. (19) adopts the Manhattan distance value which is the shortest distance between any two positions in a grid system, we have

$$\sum_{i=1}^{I} |x_{i,d}^{k} - \sum_{d=1}^{D} d \bullet m_{i,d}^{*}| \leq \sum_{k}^{K-1} \sum_{i=1}^{I} (|x_{i,d}^{k+1} - x_{i,d}^{k}|) \tag{30}$$

$$\sum_{i=1}^{I} |x_{i,d}^{k} - \sum_{d=1}^{D} d \bullet m_{i,d}^{*}| \leq \sum_{k}^{K-1} \sum_{i=1}^{I} (|x_{i,d}^{k+1} - x_{i,d}^{k}| + |y_{i,d}^{k+1} - y_{i,d}^{k}|) \tag{31}$$

Eq. (29) and Eq. (31) jointly guarantee that the heuristic function will never overestimate the actual cost to the goal state, and therefore proved that Eq. (19) is admissible by definition.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tra.2021.07.005.

References

Ainsalu, J., Arffman, V., Bellone, M., Ellner, M., Haapamäki, T., Haavisto, N., Josefson, E., Ismailogullari, A., Lee, B., Madland, O., Madžulis, R., Müür, J., Mäkinen, S., Nousiainen, V., Pilli-Sihvola, E., Rutanen, E., Sahala, S., Schønfeldt, B., Smolnicki, P., Soe, R.-M., Sääski, J., Szymańska, M., Vaskinn, I., Åman, M., 2018. State of the Art of Automated Buses. Sustainability-basel 10, 3118. https://doi.org/10.3390/su10093118.

Bagloee, S.A., Ceder, A. (Avi), 2011. Transit-network design methodology for actual-size road networks. Transp Res Part B Methodol 45, 1787–1804. https://doi.org/10.1016/j.trb.2011.07.005Bie, Y., Gong, X., Liu, Z., 2015. Time of day intervals partition for bus schedule using GPS data. Transp. Res. Part C Emerg. Technol. 60, 443–456. https://doi.org/10.1016/j.trc.2015.09.016.

Bie, Yiming, Xiong, Xinyu, Yan, Yadan, Qu, Xiaobo, 2020. Dynamic headway control for high-frequency bus line based on speed guidance and intersection signal adjustment. Comput-aided Civ. Inf. 35 (1), 4–25. https://doi.org/10.1111/mice:v35.110.1111/mice:12446.

Anderson, J. Edward, 2010. A review of the state of the art of personal rapid transit. J. Adv. Transp.

Basso, R., Kulcsár, B., Egardt, B., Lindroth, P., Sanchez-Diaz, I., 2019. Energy consumption estimation integrated into the Electric Vehicle Routing Problem. Transp. Res. Part D Transp. Environ. 69, 141–167. https://doi.org/10.1016/j.trd.2019.01.006.

Brake, J., Mulley, C., Nelson, J.D., Wright, S., 2007. Key lessons learned from recent experience with flexible transport services. Transp. Policy 14 (6), 458–466. https://doi.org/10.1016/j.tranpol.2007.09.001.

Cao, Z., Ceder, A. (Avi), 2019. Autonomous shuttle bus service timetabling and vehicle scheduling using skip-stop tactic. Transp. Res. Part C Emerg. Technol. 102, 370–395. https://doi.org/10.1016/j.trc.2019.03.018.

Cats, O., Yap, M., van Oort, N., 2016. Exposing the role of exposure: Public transport network risk analysis. Transp. Res. Part Policy Pract. 88, 1–14. https://doi.org/10.1016/j.tra.2016.03.015.

Carnegie, J. A., & Hoffman, P. S., 2007. Viability of personal rapid transit In New Jersey: final report, February 2007.

Ceder, A., Golany, B., Tal, O., 2001. Creating bus timetables with maximal synchronization. Transp. Res. Part Policy Pract. 35 (10), 913–928. https://doi.org/10.1016/S0965-8564(00)00032-X.

Ceder, Avishai, Wilson, Nigel H.M., 1986. Bus network design. Transp. Res. Part B Methodol. 20 (4), 331–344. https://doi.org/10.1016/0191-2615(86)90047-0.
Ceder, Avishai, 1987. Methods for creating bus timetables. Transp. Res. Part Gen. 21 (1), 59–83. https://doi.org/10.1016/0191-2607(87)90024-0.
Chebbi, O., Chaouachi, J., 2016. Reducing the wasted transportation capacity of Personal Rapid Transit systems: An integrated model and multi-objective optimization approach. Transp. Res. Part E Logist. Transp. Rev. 89, 236–258. https://doi.org/10.1016/j.tre.2015.08.008.
Chen, J., Liu, Z., Zhu, S., Wang, W., 2015. Design of limited-stop bus service with capacity constraint and stochastic travel time. Transp. Res. Part E Logist. Transp. Rev. 83, 1–15. https://doi.org/10.1016/j.tre.2015.08.007.
Chen, Y., Wang, H., 2018. Pricing for a last-mile transportation system. Transp. Res. Part B: Methodol. 107, 57–69. https://doi.org/10.1016/j.trb.2017.11.008.
Chen, J., Liu, Z., Wang, S., Chen, X., 2018. Continuum approximation modeling of transit network design considering local route service and short-turn strategy. Transp. Res. Part E Logist. Transp. Rev. 119, 165–188. https://doi.org/10.1016/j.tre.2018.10.001.
Chen, Xi, Wang, Yinhai, Wang, Yong, Qu, Xiaobo, Ma, Xiaolei, 2021. Customized bus route design with pickup and delivery and time windows: Model, case study and comparative analysis. Expert Syst. Appl. 168, 114242. https://doi.org/10.1016/j.eswa.2020.114242.
Chen, Zhiwei, Li, Xiaopeng, Zhou, Xuesong, 2020. Operational design for shuttle systems with modular vehicles under oversaturated traffic: Continuous modeling method. Transp. Res. Part B Methodol. 132, 76–100. https://doi.org/10.1016/j.trb.2019.05.018.
Chen, Z., Li, X., Zhou, X., 2019b. Operational design for shuttle systems with modular vehicles under oversaturated traffic: Discrete modeling method. Transp. Res. Part B Methodol. 122, 1–19. https://doi.org/10.1016/j.trb.2019.01.015.
Christian Shepherd, 2019. Chinese AI start-up DeepBlue takes self-driving buses global. < https://www.ft.com/content/72bf3046-bca0-11e9-b350-db00d509634e> (last accessed August 28, 2020).
Dai, Z., Liu, X.C., Chen, X., Ma, X., 2020. Joint optimization of scheduling and capacity for mixed traffic with autonomous and human-driven buses: A dynamic programming approach. Transp. Res. Part C Emerg. Technol. 114, 598–619. https://doi.org/10.1016/j.trc.2020.03.001.
Frei, C., Hyland, M., Mahmassani, H.S., 2017. Flexing service schedules: Assessing the potential for demand-adaptive hybrid transit via a stated preference approach. Transp. Res. Part C Emerg. Technol. 76, 71–89. https://doi.org/10.1016/j.trc.2016.12.017.
Guler, S.I., Menendez, M., 2014. Analytical formulation and empirical evaluation of pre-signals for bus priority. Transp. Res. Part B Methodol. 64, 41–53. https://doi.org/10.1016/j.trb.2014.03.004.
Guo, Xin, Sun, Huijun, Wu, Jianjun, Jin, Jiangang, Zhou, Jin, Gao, Ziyou, 2017. Multiperiod-based timetable optimization for metro transit networks. Transp. Res. Part B Methodol. 96, 46–67. https://doi.org/10.1016/j.trb.2016.11.005.
Guo, Q.-W., Chow, J.Y.J., Schonfeld, P., 2018. Stochastic dynamic switching in fixed and flexible transit services as market entry-exit real options. Transp. Res. Part C Emerg. Technol. 94, 288–306. https://doi.org/10.1016/j.trc.2017.08.008.
Guihaire, Valérie, Hao, Jin-Kao, 2008. Transit network design and scheduling: A global review. Transp. Res. Part Policy Pract. 42 (10), 1251–1273. https://doi.org/10.1016/j.tra.2008.03.011.
Huang, Di, Liu, Zhiyuan, Fu, Xiao, Blythe, Philip T., 2018. Multimodal transit network design in a hub-and-spoke network framework. Transp. Transp. Sci. 14 (8), 706–735. https://doi.org/10.1080/23249935.2018.1428234.
Huang, D., Liu, Z., Liu, P., Chen, J., 2016. Optimal transit fare and service frequency of a nonlinear origin-destination based fare structure. Transp. Res. Part E Logist. Transp. Rev. 96, 1–19. https://doi.org/10.1016/j.tre.2016.10.004.
Huang, D., Gu, Y., Wang, S., Liu, Z., Zhang, W., 2020. A two-phase optimization model for the demand-responsive customized bus network design. Transp. Res. Part C Emerg. Technol. 111, 1–21. https://doi.org/10.1016/j.trc.2019.12.004.
Hyland, M., Mahmassani, H.S., 2020. Operational benefits and challenges of shared-ride automated mobility-on-demand services. Transp. Res. Part Policy Pract. 134, 251–270. https://doi.org/10.1016/j.tra.2020.02.017.
Irving, J. H., Bernstein, H., Olson, C. L., & Buyan, J., 1978. Fundamentals of personal rapid transit.
Stein, Joshua, Goebel, Nicole, 2019. Germany: Berlin tests driverless buses. accessed August 28, 2020. <https://www.dw.com/en/germany-berlin-tests-driverless-buses/a-50055426>(last.
Kim, M. (Edward), Schonfeld, P., 2013. Integrating bus services with mixed fleets. Transp. Res. Part B Methodol. 55, 227–244. https://doi.org/10.1016/j.trb.2013.06.013.
Kim, M. (Edward), Schonfeld, P., 2014. Integration of conventional and flexible bus services with timed transfers. Transp. Res. Part B Methodol. 68, 76–97. https://doi.org/10.1016/j.trb.2014.05.017.
Kim, M. (Edward), Schonfeld, P., 2015. Maximizing net benefits for conventional and flexible bus services. Transp. Res. Part Policy Pract. 80, 116–133. https://doi.org/10.1016/j.tra.2015.07.016.
Kreutzberger, E.D., 2003. Impact of Innovative Technical Concepts for Load Unit Exchange on the Design of Intermodal Freight Networks. Transp. Res. Rec. 1820, 1–10. https://doi.org/10.3141/1820-01.
Liu, T., Ceder, A. (Avi), 2015. Analysis of a new public-transport-service concept: Customized bus in China. Transp. Policy 39, 63–76. https://doi.org/10.1016/j.tranpol.2015.02.004.
Li, Y., Liu, Y., Xie, J., 2020. A path-based equilibrium model for ridesharing matching. Transp. Res. Part B: Methodol. 138, 373–405.
Liu, X., Yuan, Q., Miao, R., Ma, X., 2020. Customized Commuting Bus Route and Timetable Optimization Using Mobile Internet Data. In: International Conference on Transportation and Development 2020. American Society of Civil Engineers, Reston, VA, pp. 13–24.
Lyu, Y., Chow, C.-Y., Lee, V.C.S., Ng, J.K.Y., Li, Y., Zeng, J., 2019. CB-Planner: A bus line planning framework for customized bus systems. Transp. Res. Part C Emerg. Technol. 101, 233–253. https://doi.org/10.1016/j.trc.2019.02.006.
Kim, Myungseob, Levy, Joshua, Schonfeld, Paul, 2019. Optimal zone sizes and headways for flexible-route bus services. Transp. Res. Part B: Methodol. 130, 67–81.
Lees-Miller, John D., Wilson, R. Eddie, 2012. Proactive empty vehicle redistribution for personal rapid transit and taxis. Transp. Plan Techn. 35 (1), 17–30. https://doi.org/10.1080/03081060.2012.635414.
Ma, Wanjing, Liu, Yue, Yang, Xiaoguang, 2013. A Dynamic Programming Approach for Optimal Signal Priority Control Upon Multiple High-Frequency Bus Requests. J. Intell. Transp. S 17 (4), 282–293. https://doi.org/10.1080/15472450.2012.729380.
Ma, Xiaolei, Miao, Ran, Wu, Xinkai, Liu, Xianglong, 2021. Examining influential factors on the energy consumption of electric and diesel buses: A data-driven analysis of large-scale public transit network in Beijing. Energy 216, 119196. https://doi.org/10.1016/j.energy.2020.119196.
Mageean, J., Nelson, J.D., 2003. The evaluation of demand responsive transport services in Europe. J. Transp. Geogr. 11 (4), 255–270. https://doi.org/10.1016/S0966-6923(03)00026-7.
Mueller, K., Sgouridis, S.P., 2011. Simulation-based analysis of personal rapid transit systems: service and energy performance assessment of the Masdar City PRT case. J. Adv. Transp. 45, 252–270. https://doi.org/10.1002/atr.158.
Niu, H., Zhou, X., 2013. Optimizing urban rail timetable under time-dependent demand and oversaturated conditions. Transp. Res. Part C Emerg. Technol. 36, 212–230. https://doi.org/10.1016/j.trc.2013.08.016.
Narayan, Jishnu, Cats, Oded, van Oort, Niels, Hoogendoorn, Serge, 2020. Integrated route choice and assignment model for fixed and flexible public transport systems. Transp. Res. Part C Emerg. Technol. 115, 102631. https://doi.org/10.1016/j.trc.2020.102631.
Nourbakhsh, Seyed Mohammad, Ouyang, Yanfeng, 2012. A structured flexible transit system for low demand areas. Transp. Res. Part B Methodol. 46 (1), 204–216. https://doi.org/10.1016/j.trb.2011.07.014.
Pratt, A.N., Morris, E.A., Zhou, Y., Khan, S., Chowdhury, M., 2019. What do riders tweet about the people that they meet? Analyzing online commentary about UberPool and Lyft Shared/Lyft Line. Transp. Res. Part F Traff. Psychol. Behav. 62, 459–472. https://doi.org/10.1016/j.trf.2019.01.015.
Qiu, Guo, Song, Rui, He, Shiwei, Xu, Wangtu, Jiang, Min, 2019. Clustering Passenger Trip Data for the Potential Passenger Investigation and Line Design of Customized Commuter Bus. Ieee T. Intell. Transp. 20 (9), 3351–3360. https://doi.org/10.1109/TITS.697910.1109/TITS.2018.2875466.
Qu, X., Wang, S., 2021. Communications in Transportation Research: Vision and Scope. Commun. Transp. Res. 1, 100001.
Raidl, G.R., Puchinger, J., 2008. Combining (integer) linear programming techniques and metaheuristics for combinatorial optimization. In: Hybrid Metaheuristics. Springer, Berlin, Heidelberg, pp. 31–62.

Susilo, Y., Chee, P.N., Darwish, R., Pernestål Brenden, A., 2018. Early Lessons From an Autonomous Bus Deployment on a Public Road in Stockholm. In Nationell konferens I transportforskning 2018.

SPECS, SPECIFICATIONS. < https://www.next-future-mobility.com/specs> (last accessed January 19th, 2021).

Spera, E., 2016. CAREEM to Bring Driverless Transportation Solutions to the MENA Region through Partnership with NEXT Future Transportation. Linkedin. <https://www.linkedin.com/pulse/careem-bring-driverless-transportation-solutions-mena-emmanuele-spera > (last accessed August 28th, 2020).

Shen, Y., Zhang, H., Zhao, J., 2018. Integrating shared autonomous vehicle in public transportation system: A supply-side simulation of the first-mile service in Singapore. Transp. Res. Part Policy Pract. 113, 125–136. https://doi.org/10.1016/j.tra.2018.04.004.

Sproule, William J., Neumann, Edward S., 1991. The morgantown PRT: It is still running at West Virginia University. J. Adv. Transp. 25 (3), 269–279. https://doi.org/10.1002/atr.v25:310.1002/atr.5670250303.

Suh, S.D., 2001. Automated People Movers. Moving Through the Millennium 1–16. https://doi.org/10.1061/40582(2001)17.

Shi, Xiaowei, Chen, Zhiwei, Pei, Mingyang, Li, Xiaopeng, 2020. Variable-Capacity Operations with Modular Transits for Shared-Use Corridors. Transp. Res. Rec. J. Transp. Res. Board 2674 (9), 230–244. https://doi.org/10.1177/0361198120928077.

Sun, Huijun, Wu, Jianjun, Ma, Hongnan, Yang, Xin, Gao, Ziyou, 2019. A Bi-Objective Timetable Optimization Model for Urban Rail Transit Based on the Time-Dependent Passenger Volume. Ieee T. Intell. Transp. 20 (2), 604–615. https://doi.org/10.1109/TITS.2018.2818182.

Tao, S., Corcoran, J., Rowe, F., Hickman, M., 2018. To travel or not to travel: 'Weather' is the question. Modelling the effect of local weather conditions on bus ridership. Transp. Res. Part C Emerg. Technol. 86, 147–167. https://doi.org/10.1016/j.trc.2017.11.005.

Tong, Lu (Carol), Zhou, Leishan, Liu, Jiangtao, Zhou, Xuesong, 2017. Customized bus service design for jointly optimizing passenger-to-vehicle assignment and vehicle routing. Transp. Res. Part C Emerg. Technol. 85, 451–475. https://doi.org/10.1016/j.trc.2017.09.022.

Tegnér, G. (2007). PRT in Sweden: from feasibility studies to public awareness.

Tyrinopoulos, Yannis, Antoniou, Constantinos, 2008. Public transit user satisfaction: Variability and policy implications. Transp. Policy.

Varga, B., Tettamanti, T., Kulcsár, B., Qu, X., 2020. Public transport trajectory planning with probabilistic guarantees. Transp. Res. Part B Methodol. 139, 81–101. https://doi.org/10.1016/j.trb.2020.06.005.

Wu, Jianping, Hounsell, Nick, 1998. Bus Priority Using pre-signals. Transp. Res. Part Policy Pract. 32 (8), 563–583. https://doi.org/10.1016/S0965-8564(98)00008-1.

Wu, Jiaming, Ahn, Soyoung, Zhou, Yang, Liu, Pan, Qu, Xiaobo, 2021. The Cooperative Sorting Strategy for Connected and Automated Vehicle Platoons. Transp. Res. Part C Emerg. Technol. 123, 102986. https://doi.org/10.1016/j.trc.2021.102986.

Yap, M., Luo, D., Cats, O., van Oort, N., Hoogendoorn, S., 2019. Where shall we sync? Clustering passenger flows to identify urban public transport hubs and their key synchronization priorities. Transp. Res. Part C Emerg. Technol. 98, 433–448. https://doi.org/10.1016/j.trc.2018.12.013.

Xu, Q., Wang, J., Wang, B., Yan, X., 2020. Modeling and simulation of intersection quasi-moving block speed guidance based on connected vehicles. J. Intell. Connected Vehicles 3 (2), 67–78.

Yan, Yadan, Liu, Zhiyuan, Meng, Qiang, Jiang, Yu, 2013. Robust Optimization Model of Bus Transit Network Design with Stochastic Travel Time. J. Transp. Eng. 139 (6), 625–634. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000536.

Yoder, Supin L., Weseman, Sidney E., DeLaurentiis, John, 2000. Capital Costs and Ridership Estimates of Personal Rapid Transit. Transp. Res. Rec. 1704 (1), 58–67. https://doi.org/10.3141/1704-09.

Zhang, Zhenhao, Tafreshian, Amirmahdi, Masoud, Neda, 2020. Modular transit: Using autonomy and modularity to improve performance in public transportation. Transp. Res. Part E: Logist. Transp. Rev. 141, 102033. https://doi.org/10.1016/j.tre.2020.102033.

Zheng, H., Peeta, S., 2015. Network design for personal rapid transit under transit-oriented development. Transp. Res. Part C Emerg. Technol. 55, 351–362. https://doi.org/10.1016/j.trc.2015.02.012.

Zheng, Y., Li, W., Qiu, F., Wei, H., 2019. The benefits of introducing meeting points into flex-route transit services. Transp. Res. Part C: Emerg. Technol. 106, 98–112. https://doi.org/10.1016/j.trc.2019.07.012.