

An Autonomous Modular Mobility Paradigm

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Abstract—In the United States, public transit vehicles have a very low average load factor (10.1–12.4%), resulting in an excessive waste of seat capacity and poor fuel economy per passenger mile served. This problem is gravely exacerbated by the COVID-19 pandemic, which at its peak had caused more than 70% reduction in transit ridership nationwide. On the other hand, the rapid uptake of e-commerce, also accelerated by the pandemic, has put tremendous pressure on last-mile delivery. A *co-modality* system that integrates transit services with last-mile logistics offers a promising solution to better utilization/sharing of vehicle capacity and supporting infrastructure. Here we show such a system may be implemented based on Autonomous Modular Vehicle Technology (AMVT). At the core of AMVT is the ability to operate a fleet of modular autonomous vehicles or pods that can be moved, stationed, joined, and separated in real time. Coupling modularity with autonomy is poised to enable co-modality and beyond. We describe an AMVT bimodality system that provides integrated public transit and last-mile logistics services with a fleet of pods and discuss relevant research challenges and opportunities, research approaches, and real-world adoption issues.

Introduction and Motivation

The public transportation infrastructure and service paradigm have, for decades, focused on fixed-route and fixed-schedule services provided by large vehicles (buses and train cars). In the United States, the average bus load factor was between 10.1% and 12.4% between 2006 and 2015 [1]. As a standard bus has a capacity of 40 seats [2], such a low utilization rate translates to an excessive waste of seat capacity, resulting in extremely poor fuel economy per passenger mile served by buses [3]. The problem has severely worsened during the COVID-19 pandemic in 2020, which at its worst inflicted a 76% reduction nationwide in unlinked transit trips compared to 2019 [4]. The overall reduction in travel due to the pandemic also caused a significant drop in the federal fuel-tax revenue that funds about 80% of the federal aid to transit agencies. It is not an exaggeration to say that transit services in many cities are facing an existential threat that calls for drastic actions. On the freight side, the e-commerce boom, which rapidly accelerated during the pandemic [5], has put tremendous pressure on last-mile delivery. As last-mile delivery is the least efficient component in freight transportation—accounting for 41% of the overall logistics cost [6]—this uptake of e-commerce has ramifications for energy consumption, greenhouse gas emissions, and traffic congestion. Integrating transit services with last-mile logistics—referred to as *co-modality* hereafter—offers a promising solution to better utilization/sharing of vehicle capacity and supporting infrastructure. Yet the implementation of this idea requires not only technological breakthroughs but also a systems approach that transcends the boundaries between the two highly siloed sectors in the transportation industry.

Now, envision a future co-modality mobility system enabled by *Autonomous Modular Vehicle Technology (AMVT)*. Figure 1 shows a six-seat AMVT prototype that debuted in Dubai in 2018 [7], [8]. These modular autonomous vehicles (MAVs), also known as *pods*, are powered by electric batteries. Pods run on existing road infrastructure individually or as a connected pod train. As illustrated in Fig. 2, AMVT promises exciting multifaceted mobility services that are flexible and customizable due to its two attractive features: *modularity* and *autonomy*. AVs are widely expected to be a game changer in transportation. Coupling modularity and autonomy, AMVT is poised to shape a new transportation paradigm.

AMVT-Based Mobility Services

A wide range of new mobility services could become viable with AMVT. With modularity, transit vehicle capacity can be adjusted in real time according to passenger demand, by forming or breaking off pod trains [Fig. 2(a)]. Forming a pod train can facilitate en-route transfer anywhere and anytime [Fig. 2(b)]. It can also effectively improve road uti-

lization efficiency (by compressing the gap between pods and increasing the vehicle occupancy rate) and save energy (by reducing air drag). Thus, pods can facilitate a wide



FIG 1 An AMVT prototype pod. (Source: [7]; used with permission.)

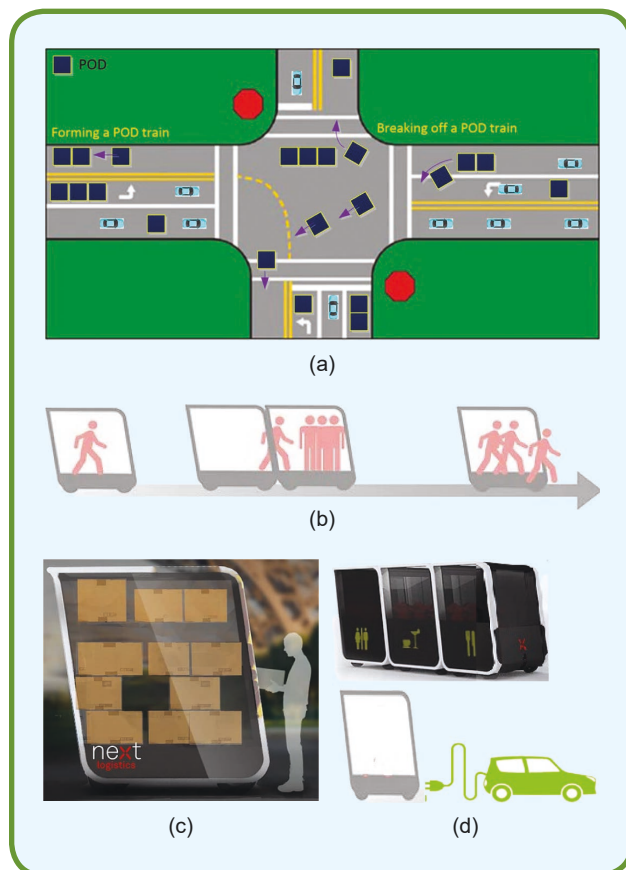


FIG 2 AMVT-based multifaceted mobility services. (a) En-route pod train forming and break-off. (b) En-route transfer. (Source: [7]; used with permission.) (c) Parcel delivery and MAPSs. (Source: [7]; used with permission.) (d) Value-added services, such as mobile pharmacy/dining pods (top) and a mobile electric vehicle (EV) charging pod (bottom).

range of transit services, including first/last-mile feeder service, paratransit, and ridesharing.

Pods can be similarly applied to parcel delivery [Fig. 2(c)]. They can also be deployed as mobile automated parcel stations (MAPSs) to collect and store parcels [Fig. 2(c)]. Autonomy and modularity make pods an ideal “last 50 ft” pick-up/drop-off platform in residential and commercial neighborhoods, which could significantly reduce truck detouring, parking, and idling on local streets.

Pods can also provide exciting value-added service opportunities, such as recreational uses, mobile pharmacies, and mobile charging stations for electric vehicles (EVs) [Fig. 2(d)]. The last application is especially appealing as the world is currently racing to electrify transportation [9].

The mobility services described previously are part of an envisioned system of AMVT-based mobility services. In this article, we will focus on two primary applications of AMVT—public transit and last-mile logistics, separately and integrally. We refer to this system as the *AMVT-based bimodality (BM) system*, or *AMVT-BM*. Traditionally, passenger transportation and goods transportation are operated by separate entities with proprietary fleets and infrastructures, often leading to significant underutilization owing to the lack of coordination. Modularity and co-modality hold the key to effectively addressing the fundamental dilemma facing many public transit systems in the United States today: the coexistence of a poor level of service and the severe underutilization of system capacity. They could also substantially reduce truck cruising, parking, and idling on neighborhood streets for last-mile delivery, which have important implications for traffic management and environmental sustainability. With the rapid growth in e-commerce and consumers’ demand for express delivery, the need for innovative solutions to last-mile delivery is urgent.

An AMVT-BM system could, in principle, benefit operators, users, and the society at large. However, its implementation requires a concerted effort of planning, design, management, finance, and regulation. If successful, AMVT-BM will transform future transportation systems; enable new business models; and make mobility services more efficient, flexible, ubiquitous, scalable, customizable, and sharable. The rest of this article discusses the research challenges and opportunities in the design and operation of various AMVT systems. We first address transit and last-mile delivery applications separately and then consider an application of co-modality, i.e., AMVT-BM. We also touch on issues related to planning, infrastructure design, and business models. Given the exploratory nature of the subject, the discussion will stay at the conceptual level and focus on the key tradeoffs. Much of the implementation detail is left out not only because of space limitations but also to avoid unproductive speculations of an emerging technology that is still evolving.

Challenges and Opportunities

The envisioned AMVT-BM paradigm builds on the premise that modularity brings extra benefits to future automated mobility systems: flexibility, optimal utilization of vehicle capacity, energy efficiency, and value-added services, to name a few. However, only a few studies, as we demonstrate later in this section, have convincingly demonstrated whether and how the technology benefits a bimodal system. Despite the promises of AMVT, its application in a complex system involves tradeoffs that are not well understood, let alone fully accounted for. For example, while pod trains offer flexibility and aerodynamic benefits, they may need to slow down for pod joining and disjoining operations. Thus, it is unclear that a modularized fleet would necessarily outperform existing transit systems for meeting the demand, especially during peak hours. These trains may also disrupt traffic when they are formed and broken off. AMVT’s en-route transfer capability is another attractive feature at the first glance. Yet such a dynamic transfer scheme may be hard to implement and inconvenient or difficult to use, which could compromise efficiency and user experience. There could be other hidden tradeoffs that are difficult to even anticipate for such a new and complex system.

To take advantage of autonomous modularity, the operator needs to group and break pods and to transfer passengers (or parcels if so equipped), all in real time. There are two limiting cases. On the one hand, each pod operates individually like regular shared AVs, which likely provides a high level of service (in terms of convenience) but low efficiency (in terms of service capacity and congestion). On the other hand, if the pods form as long trains as the technology allows, the road space can be better utilized thanks to economies of scale, and en-route transfer can be more easily arranged. The downside of operating longer pod trains, however, is inflexibility for both users and the operator as it would require lower dispatching frequency (or longer headway). Like larger vehicles, such as buses, trolleys, and trucks, long pod trains can also cause traffic disruptions that are likely to increase nonlinearly with their length. It is almost certain that neither of these extreme scenarios provides an optimal balance among level of service, operating cost, and traffic disruptions. Seeking this balance, therefore, is central to gauging the impact of modularity.

In the rest of the section, we present a list of research challenges and opportunities, research approaches, and real-world adoption issues. It is worth noting that the following discussion assumes that the basic vehicle technology and communication infrastructure that enable AMVT pod train operation are a given, such as the AMVT pod itself, the 5G communication network, and the technology enabling pod joining and disjoining, and therefore, they are not included in the discussion.

Modularity in Transit Service Design and Operation

A small but growing literature has explored the design and operational features of AMVT-based transit service, ranging from minimum fleet size (MFS), optimal dispatching strategies, and en-route transfer to the applications of flex-route and feeder services. Liu et al. [10] investigated an MFS problem for an autonomous modular public transit (AMPT) system and proposed a deficit function (DF) theory-based solution for a single-line AMPT system. The results show that the DF approach is effective in solving the MFS problem. Dakic et al. [11] designed an optimal dispatching strategy for modular bus units using a 3D macroscopic fundamental diagram. Liu et al. [12] presented an MAV-based flex-route transit system of self-adaptive capacity and flexible service mode. The design is formulated as a mixed-integer linear program (MILP) and solved heuristically through a two-stage solution framework. Zhang et al. [13] designed an automated modular transit feeder service that serves local demand and connects travelers to main modules for long-distance trips.

Gecchelin and Webb [14] described a modular dynamic ride-sharing (MDRS) system composed of pods operating individually for off-peak, low-capacity last-mile feeder services or forming a pod train as a quasi-rapid transit system. They envision that MDRS has the potential to reduce congestion through decreasing the size and number of vehicles and increase cost-effectiveness and convenience. Wu et al. [15] investigated en-route transfer strategies for a modular, adaptive, and autonomous transit system (MAATS) and demonstrated that the MAATS has a shorter travel time and reduced number of transfers than the conventional bus system without substantially increasing energy consumption. Similarly, Caros and Chow [16] compared a hub-and-spoke modular autonomous transit system with and without en-route transfer to quantify the potential benefits of en-route transfer.

Chen et al. [17] investigated a time-varying capacity design problem for one-to-one modular mass transit systems. A tactical level continuum approximation (CA) model was proposed to shed light on fundamental analytical properties in the optimal design. In another study, Chen et al. [18] extended the theoretical investigation of using the CA method for the operational design of MAV-based urban mass transportation with spatiotemporally varying passenger demand. They showed that the CA model can achieve near-optimal solutions (with gaps lower than 4% for most cases) with negligible computation time (lower than 10 ms) for large-scale instances and thus provided a good approximation to problems with complex system operation constraints whose exact optimal solution can hardly be found with discrete modeling methods. Most recently, Chen and Li [19] solved the same problem as in [18] but formulated it as an MILP and used an improved branch and bound algorithm to solve it. The study may serve as a benchmark for other research.

In a nutshell, most existing studies subscribe to the notion that AMVT can bring a range of operational benefits to passenger transportation and set out to demonstrate how it may work in an isolated, and sometimes highly simplified, service system. The concern with this approach is twofold. First, it relies on a premise of the benefits that have yet to be proven. Second, it often fails to capture the tradeoffs that take place at the system level, e.g., the (negative) impact of pod-related operation on mobility (e.g., average travel speed) or intersection operations.

To understand the impact of modularity in transit design and operation at a system level, one could start with a hypothetical hybrid transit network that consists of a fixed-route service and a flexible feeder service, as illustrated in Chen and Nie [20]. In the model, it is critical to capture the essence of dynamic pod train formation and break-off. One possibility is to maintain two separate services but allow the trains for each service to swap pods at stops so that boarding and alighting passengers can have truly “seamless” transfers between the two. A second possibility is to operate a single “flexible” fixed-route service, which will let some pods break away or rejoin at stops when passengers need to alight or board.

There are several directions to extend the analysis. First, other route structures, such as ring-radial, can be considered. Second, competition between the pod-based hybrid transit with other modes, such as pod-based ride hailing that provides direct door-to-door service, can be analyzed. Third, the impact of pod train formation and break-off on network traffic can be incorporated to capture cross-mode interactions. Fourth, the pod-based hybrid systems can be evaluated in a wide variety of scenarios defined by demand pattern, city size, route structure, and other factors.

Modularity in Last-Mile Delivery Service Design

In a last-mile delivery design, two essential services by AMVT are considered: parcel delivery and MAPSs for neighborhood (i.e., “last 50 ft”) parcel pickup and drop off. One design is to have two dedicated sets of pods providing those two last-mile delivery services separately. Under such a setup, the problem becomes two independent subproblems, a vehicle routing problem (VRP) for delivery pods and a resource rebalancing problem (RRP) for MAPS pods (plus a location choice problem if the MAPS location varies). Both have been studied extensively in the literature. Operationally speaking, this design is simple but may not be cost-effective. Therefore, an integrated design in which all pods may be optimally assigned to either service dynamically in a daily operation is necessary.

There are two technical elements in the integrated design—the *routing* of the pod trains and the *stationing* of the MAPSs. The pod train routing problem (PTRP) is a considerable deviation from the classical VRP in two important aspects. The first is that the cost objective function in

pod routing no longer involves a driver cost (driverless), and thus, the traditional objective of minimizing travel distance or time as a surrogate for minimizing driver cost does not work well. An important consideration in pod train formation is to reduce the overall energy consumption of the pods, similar to the effect of vehicle platooning on reducing energy consumption. On the other hand, pod train joining and disjoining may cause an additional delay. Therefore, the overall objective of the PTRP should be to minimize the total energy consumption and delay induced by pod train joining and disjoining. The second deviating aspect of the PTRP is pod train formation during routing. This defines a unique subproblem of determining an optimal strategy to form pod trains en route between the hub and the service zones.

Keeping consistent with the overall objective of the PTRP, this subproblem can be solved by maximizing the total shared distance of the pods, as illustrated in Fig. 3, of a pod train formation graph [21], [22]. Each node represents a preformed pod train (with one or more pods). Each train is assigned the shortest path between the hub and its service zone. An edge connecting two nodes indicates that the two pod trains (nodes) are eligible for joining into one pod train en route if they have a nonzero sharable portion of their respective routes spatially and temporally (i.e., within an ε of time window). Each edge is assigned two values; the first is the total combined number of pods from the two pod trains, and the second represents the total shared distance (>0) by the two pod trains. Thus, the pod train formation subproblem becomes one that maximizes the total shared distance in the graph, subject to constraints such as the maximum train length defined by the pod technological limitations, e.g., 4–15 pods are joinable depending on the road conditions and regulation according to the specifications of the prototype shown in Fig. 1 [7].

The stationing of the pods may involve a pod rebalancing problem (PRP), i.e., pods with unused capacity in some MAPS zones moving to the others with a high parcel drop-

off demand to provide an additional deposition capacity. The RRP has been studied extensively, for example, in the form of the bike sharing rebalancing problem (BRP) (e.g., [23]–[30]) and mobility-on-demand vehicle routing and rebalancing problem (MoD VRRP) (e.g., [31]–[37]) in recent years. The BRP is often formulated as a one-commodity pickup and delivery problem with split loads. A queueing model is a common approach to MoD VRRP. The PRP in this study can be formulated as a variant of the MoD VRRP.

The routing and stationing of the pods could be modeled jointly in a bilevel structure. In the lower level, stationing is formulated to minimize the total fleet size of pods needed for the MAPS service to meet the parcel collection demand, considering that some pods may return to the depot directly after delivery if an excessive MAPS capacity for parcel collection is determined, or additional pods may be dispatched directly to serve as MAPSs to meet an excessive parcel collection demand. This decision will then feed into the upper-level model to optimize the PTRP objective stated previously.

Co-Modality Service Design and Operation

Designing and implementing an AMVT-BM system that integrates the transit and last-mile delivery services described previously defines the very core of the research challenges and opportunities. Foremost, how can last-mile delivery be combined with public transit, given the very different design and operating features of the two subsystems? Is it operationally feasible? What are the tradeoffs? For example, would this integrated system increase detour time and delay and subsequently lower the quality of service for both subsystems? How can the pod fleet be managed to serve both services efficiently? These are a few examples of the key questions that need to be addressed.

Co-modality is not a new concept. He and Yang [38] provided a recent review of the studies that aim at integrating passenger and freight transportation. They also proposed a collaborative delivery scheme using both buses and trucks and demonstrated its benefits through a case study in a Chinese city. They found that it is not only cost-effective but also reduces congestion and emissions. Co-modality scenarios explored by recent studies involve urban rail transit [39], [40], crowdshipping using urban bus riders [41]–[44], and drone delivery using urban transit vehicles [45].

Integrating AMVT-based transit and last-mile delivery services can take various forms. At the minimal level of integration, there could be two dedicated fleets of pods serving people and goods separately, and they jointly operate on streets by forming pod trains as needed to take advantage of energy efficiency. The scheduling and dispatching decisions are made independently between the two subsystems, but real-time routing is jointly considered. At the maximum level of integration, there could be one

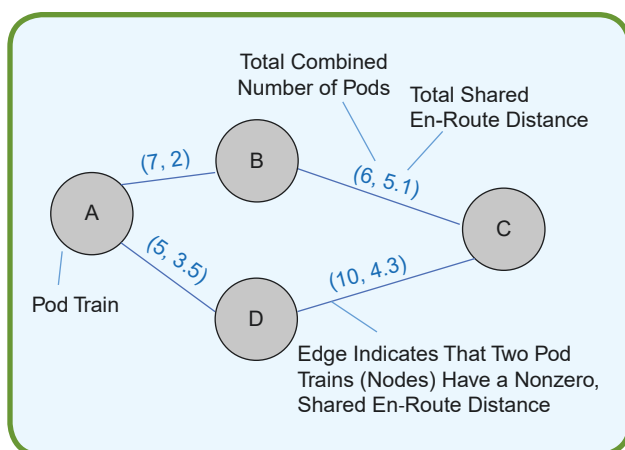


FIG 3 A pod train formation graph.

centrally managed fleet of pods, and all aspects of the planning and operation (scheduling, dispatching, and routing) are determined simultaneously for the two services. Practically speaking, a pod may carry either passengers or parcels but not both on a given service run, subject to the pod size and configurations (e.g., seating or parcel shelving); when a pod completes a service run, it returns to a depot for its next dispatching as either a passenger or parcel pod. There may be some simple assembly work in the pods related to replacing seats with parcel shelves and vice versa, which may incur minor labor costs. Another practical consideration is how to arrange passenger and/or parcel pods in a pod train such that en-route transfer of either is not blocked. For example, all parcel (or passenger) pods may be allowed to join only at the end of the train so that they form an uninterrupted block.

Optimizing the design and operation of AMVT-BM poses formidable computational and analytical challenges that likely require a modeler to introduce simplifications or focus on subsystems. Yet these very strategies may well undermine the ability to detect the tradeoffs that arise only from complexity. Simulation is a powerful solution to this dilemma: it can investigate the performance of the AMVT-BM system under a wide range of configurations and inputs, and simultaneously, evaluate its impacts on the network-wide traffic.

The idea can be tested using a crude prototype that retains the main features (e.g., modularity and co-modality) but leaves out the integrated optimization of system design and operation. The joint simulation results will identify opportunities where coordination/integration (e.g., capacity sharing or schedule synchronization) promises improvements. These opportunities will be ranked and used to guide the development and evaluation of local collaborative strategies between the two service systems. For example, whether or not to use two dedicated sets of pods or one combined set of pods for parcel and passenger delivery, the pods could travel together to reap the fuel efficiency benefits of forming trains and detach only for the last mile. These strategies can be developed and tested individually at first. Then, they can be combined to form different strategy packages. The search for a near-optimal strategy package will then become a combinatorial optimization problem.

Other Operational Issues

In addition to the technical issues and challenges discussed previously, there is a host of other operational issues that need to be considered. For example, parcel loading and unloading and en-route transfer (from one pod to another) are all critical aspects of the operation. While these operations will likely be automated by the time AMVT technology becomes mature (see [46] for an illustration), the form and extent of such automation and also the magnitude of

associated benefits remain highly uncertain, and thus, not discussed in detail here. Another problem concerns the potential of en-route interaction between passengers and freight. Transporting passengers and freight in the same pod would likely raise safety, security, and possibly legal concerns for both transit and freight operators. One way to solve this problem is to never mix passengers and parcels in the same pod. In fact, as discussed in the “Co-Modality Service Design and Operation” section, we may even sort passenger and parcel pods such that they form their own blocks in the pod train. Alternatively, a technology-based solution, such as smart locks that can secure a subspace to hold parcels as needed, may be the answer.

Large-Scale Real-Time Planning Issues

AMVT-BM is essentially a demand responsive mobility-as-a-service paradigm. Fulfilling both passenger and parcel delivery requests on demand in a timely fashion requires a thorough investigation. There are many algorithms in the literature to handle real-time on-demand requests (e.g., [47]–[49]), typically with invariable unit vehicle capacity, making them inapplicable to AMVT. In addition, servicing an entire city with potentially thousands of demands and pods might lead to a scalability issue, which encourages some degree of decentralized planning. Hence, a novel framework/algorithm might be required to accommodate on-demand requests in pod trains.

Infrastructure Design Issues

One advantage of the envisioned AMVT-BM system is that it requires very little modification to the existing surface road network that the existing transit and delivery vehicles operate on. Nonetheless, additional space may be needed to accommodate pod train formation and break-off as well as en-route transfer due to the expected slowdown of pods during such operations. In addition, MAPs may require additional sidewalk space; distributed micro-depots for pods may bring additional benefits to the AMVT-BM system operation. Curbside space management may be another issue in AMVT-BM. All these issues must be taken into consideration in the system design.

Business Models

The success of the envisioned AMVT-BM systems depends on the discovery and creation of a suitable business model. Possible arrangements include but are not limited to: 1) a private integrator, like transportation network companies (TNCs); 2) an own/lease contractual relationship (e.g., the U.S. freight-passenger rail system), 3) a co-ownership arrangement; or 4) public-private partnership [50]–[54]. Examples of critical issues for future investigation are system and service integration (or separation) strategies, level of service, social equity, pricing strategies, compensation policy, and capital investment strategies.

Stakeholder Receptiveness

An AMVT-BM system would require changing the conventional mindset and breaking down the institutional, operational, and financial silos that currently entrench the transportation industry. Would the potential stakeholders see the shift to the AMVT-BM paradigm as opportunities or threats? Is it even possible for transit agencies to work with companies that deliver parcels within the current regulatory framework, and if so, in what form and capacity? What should be the government's role in facilitating the adoption of the technology? The answers to these questions will profoundly shape the future of AMVT-BM. Here, the stakeholders include transit agencies, city officials, logistics companies, and technology/auto companies. To the best of our knowledge, no study has sought the answers to these questions, which are crucial to the reception of the stakeholders. Actively engaging the stakeholders will forge meaningful conversations and collaborations that could break down the existing barriers.

Final Remarks and Outlook

AMVT could profoundly reshape urban mobility and the way we design and operate transportation systems. To realize the potential of the technology, there is a need to fully understand the tradeoffs that modularity and co-modality bring to bear on mobility service system design and operation. The research findings will lay the foundation for future full-scale studies of AMVT-BM and beyond, which could significantly influence the direction of research in network modeling, traffic flow theory, transit design, and logistics. Co-modality in AMVT-BM requires the cooperation and commitment of traditional stakeholders to share the use of resources and the development of new business models. There is also a role for governments to play in facilitating such paradigm shifts. With the right ingredients—proper planning, design, finance, and government policy—modularity and co-modality can deliver a more efficient, flexible, ubiquitous, scalable, customizable, and sharable mobility future.

Acknowledgment

The research is funded by the National Science Foundation (#2127677) Civil Infrastructure.

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