Using Autonomous Modular Vehicle Technology as an Alternative for Last-Mile Delivery

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***Abstract*—With the rise of e-commerce, there is an increasing demand for efficient and timely delivery of goods. The emerging Autonomous Modular Vehicle Technology (AMVT) may provide a promising solution to achieving greater efficiency and agility in last-mile delivery. In this system, vehicles can be coupled together to form a train, optimizing operational costs by creating pods and traversing links as a train. This connection will decrease fuel consumption and also reduce the number of cars in a city, thereby decreasing congestion. These vehicles, or "pods," will be dispatched to different zones and stations within specific time windows. Upon arrival, customers will be notified to pick up their packages. However, the efficiency of this technology and its benefits for last-mile delivery are not yet clear. The objective of this research is to evaluate the effectiveness and operational cost of the proposed system for package delivery. Additionally, the study aims to explore features that contribute to the cost reduction of this system in comparison to the current scenarios. A mixed-integer programming model is formulated to optimize pod use and determine optimal routes and schedules. Results show that using this system will add some waiting time to the system to allow a pod train to travel. However, it will decrease the overall operation cost of the system compared to classical depot-based methods where trucks deliver packages. Moreover, these cost savings are more significant in areas with higher demand variations and overall demand. Implementing this innovative approach can help delivery companies cut transportation costs while maintaining delivery times and service levels, promoting environmental sustainability to meet the demands of the growing e-commerce industry.**

***Index Terms*—Autonomous Modular Vehicle, Last Mile Delivery, Mobile Automated Parcel Station.**

I. Introduction

The rapid growth in urban development and the surge in e-commerce have exacerbated current transportation and congestion problems, particularly in the aftermath of the pandemic. Traditional depot-based truck delivery systems structure presents challenges when adapting to the demands of express delivery services in urban areas, which include significant transshipment delays and limitations on depot capacity [1], [2], [3]. To address these challenges, urban areas are increasingly exploring strategies to enhance the efficient management of freight transportation within cities [1]. In this regard, an emerging technology for last-mile delivery is using Automated Modular Vehicle Technology (AMVT), which revolves around the capability to manage a fleet of modular autonomous vehicles or pods that can be dynamically relocated, stationed, interconnected, and detached as needed [4].

AMVT facilitates the seamless integration of multiple autonomous vehicles (AVs), each potentially housing one or more Autonomous Modular Vehicles (AMVs), to create an extended AV without any inter-vehicle gaps [5]. Furthermore, considering the AMVT concept, there is a potential to improve the energy efficiency of urban mass transit systems by designing transportation systems with varying capacities over time [6]. Additionally, modularity offers numerous advantages to future automated mobility systems, such as increased flexibility, efficient use of vehicle space, energy conservation, and the provision of value-added services, among other benefits [7]. However, it's crucial to strike a balance between the various benefits of AMVTs. In this research, our goal is to minimize operational costs while maximizing modularity, and we aim to find a trade-off between these two objectives. In the context of last-mile delivery planning, AMVT serves two critical purposes: parcel delivery and the deployment of mobile automated parcel stations for convenient neighborhood parcel pickup and drop-off within the last 50 feet [7]. Our project, in particular, focuses on mobile automated parcel stations, which can be stationed at specific locations to provide neighborhood deliveries. This innovative approach has the potential to significantly reduce the need for trucks to navigate detours, search for parking, and idle on local streets [7]. The AMVT system offers the advantage of requiring minimal modifications to the existing road network, but the potential need for additional sidewalk space to accommodate mobile automated parcel stations and their pods during stationing should be carefully addressed in the system design [4].

In the domain of AMVT, several studies have explored the operational costs and design aspects related to either transit or parcel deliveries. Hatzenbühler et al. [8] conducted a comprehensive analysis of the potential benefits of modular vehicle concepts and consolidation for enhancing the efficiency of urban transportation, catering to both freight and passenger needs. Their research indicates that this system can result in cost savings exceeding 50%. It's worth noting, though, that their model assumes a fixed platoon configuration established at the beginning of a route, which remains constant throughout the entire journey. In this research, we explore the potential formation of platoon configurations at different nodes within the system. Our main objective is to assess the impact of employing AMVT for last-mile delivery, functioning as mobile automated parcel stations. Additionally, we aim to measure the total cost savings achieved by this system in comparison to depot-based delivery systems. We also seek to identify the specific features of the system area that maximize these cost savings.

II. Problem Formulation

In this study, we have developed a mixed-integer programming model to demonstrate how AMVT can result in operating cost savings compared to traditional delivery systems. To address this challenge, we introduce several crucial service components. The primary system element is the "Service Area." The term "service area" denotes a predefined geographic region under the management of a designated carrier. Our investigation concentrates on evaluating an urban service area. The second pivotal aspect of our system is the "Service Zone." The whole service area is subdivided into more compact geographical segments, referred to as service zones, based on specific criteria determined by the carrier. Inside each service zone, designated pods are strategically stationed at predetermined locations to efficiently address the zone's unique demands. The last element is the "Courier." Delivery pods are responsible for fulfilling the daily requirements originating from the depot within each service zone. This is achieved by situating these mobile, automated parcel stations at central points within the zone for a specified period. Customers are then alerted to collect their packages from these stations during the designated time frame. Furthermore, it is essential to establish the general framework of our problem. The fundamental characteristics and assumptions of our AMVT model are summarized as follows:

- ✓ Within a given service area, we divide it into distinct service zones, with each zone having a designated point (the zone's center) where pods are stationed to fulfill the demand.
- ✓ At the start of each operational day, all pods embark on their journey from the depot and return to the depot at the end of the day.
- ✓ The total daily demand is known at the beginning of the daily operations. Based on these demand forecasts, the required number of pods for each zone is calculated.
- ✓ Pods possess the capability to remain at designated locations, awaiting the arrival of other pods, allowing them to form pod trains that can collectively traverse along a specified route.
- ✓ Based on the mileage covered by pods when operating as a train, we calculate fuel reduction.
- ✓ To effectively meet demand, each pod will be stationed at each zone for a specific multiple of the required number of pods throughout the day for that zone. This approach ensures that the demand within each zone is sufficiently addressed.

For the mathematical formulation, we are addressing a vehicle routing problem to determine the most efficient routes for pods to station at each zone to fulfill demand. At each node, these pods possess the flexibility to either join or disjoin, enabling us to optimize costs. The model minimizes transportation costs and waiting times while concurrently maximizing the total mileage covered by pods when connected in pod trains. So, the proposed model incorporates the objective of maximizing the total number of interconnected pods and thereby reducing fuel consumption [9]. This integrated approach also considers environmental concerns, as traversing as a train helps reduce congestion [4]. The notations are introduced in table I and II.

$$\min Z = \sum_{(i,j)\in N} \sum_{v\in V} c_o \cdot t_{ij} \cdot x_{ij}^v + \sum_{j\in N} \sum_{v\in V} c_f \cdot x_{0j}^v + \sum_{i\in N} \sum_{v\in V} c_w \cdot W_i^v + \sum_{(i,j)\in N} c_s \cdot d_{ij} \cdot TNP_{ij} \quad (1)$$

Subject to:

$$\sum_{v\in V} \sum_{j\in N_c} x_{0j}^v \leq P \quad (2)$$

$$\sum_{v\in V} \sum_{j\in N_c} x_{j0}^v = \sum_{v\in V} \sum_{j\in N_c} x_{0j}^v \quad (3)$$

$$\sum_{j\in N} x_{ji}^v - \sum_{j\in N} x_{ij}^v = 0 \quad \forall i \in N_c, \forall v \in V \quad (4)$$

$$\sum_{j\in N} x_{ji}^v \geq y_i^v \quad \forall i \in N_c, i \neq j, \forall v \in V \quad (5)$$

$$\sum_{v\in V} y_i^v = D_i \quad \forall i \in N_c \quad (6)$$

$$\sum_{i\in N} x_{ij}^v \leq 1 \quad \forall j \in N, \forall v \in V \quad (7)$$

$$\sum_{j\in N} x_{ij}^v \leq 1 \quad \forall i \in N, \forall v \in V \quad (8)$$

TABLE I
MATHEMATICAL MODEL PARAMETERS

Parameters:	Description
V	Set of available pods, $V = \{1, 2, \dots, P\}$, where P is the maximum number of pods.
N_c	Set of nodes that pods can station at, $N_c = \{1, 2, \dots, i, \dots, j, \dots, n_c\}$.
N	Nodes where pods can be stationed, connected, or disconnected from a pod train, and the truck depot within the service area, $N = N_t \cup \{0\}$.
P	Total number of pods.
D_i	Total number of required pods to satisfy the demand of node $i \in N_c$.
L	Maximum number of connected pods in a pod train.
E	Maximum allowable hours that pods can remain outside the depot.
t_{ij}	Travel time on link (i, j) (hour) for $i \in N$, $j \in N$.
d_{ij}	Distance between node i and j (mile) for $i \in N$, $j \in N$.
T_i	Required time (hour) for a pod to stay in a node $i \in N_c$ to satisfy demand.
c_o	Travel cost ($/hr).
c_w	Penalty rate for waiting ($/hr).
c_f	Fixed cost of using a pod ($/ day).
c_s	Fuel reduction rate for traveling as a train ($ per mile per number of connections).

TABLE II
MATHEMATICAL MODEL DECISION VARIABLES

Decision Variables:	Description
x_{ij}^k	A binary variable that is equal to 1 if pod $k \in V$ travels on link (i, j) for $i \in N$, $j \in N$ and 0 otherwise.
δ_{ij}^{kv}	A binary variable that is equal to 1 if pods $k \in V$ and $v \in V$ join each other to travel on link (i, j) for $i \in N$, $j \in N$, and 0 otherwise.
y_i^k	A binary variable that is equal to 1 if pod $k \in V$ is assigned to (i.e. stations at) node $i \in N_c$ and 0 otherwise.
τ_i^k	Arrival time of pod $k \in V$ at node $i \in N$.
τd_i^k	Departure time of pod $k \in V$ at node $i \in N$.
W_i^k	Waiting time of pod $k \in V$ at node $i \in N$.
TNP_{ij}	Total number of connected pods in link ij for $i \in N$, $j \in N$.

$$\delta_{ij}^{kv} \leq x_{ij}^v \cdot x_{ij}^k \quad \forall i, j \in N, \forall v, k \in V \tag{9}$$

$$\tau_j^v = \sum_{i \in N} (\tau d_i^v + t_{ij}) \cdot x_{ij}^v \quad \forall j \in N, \forall v \in V \tag{10}$$

$$\tau d_i^v = \tau_i^v + y_i^v \cdot T_i + w_i^v \quad \forall i \in N, \forall v \in V \tag{11}$$

$$\tau_0^v \leq E \quad \forall v \in V \tag{12}$$

$$\sum_{v \in V} \sum_{k \in V} \delta_{ij}^{kv} \leq L \quad \forall i, j \in N \tag{13}$$

$$\tau_i^v \leq \tau_j^v \quad if \quad x_{ij}^v = 1 \quad \forall i, j \in N, \forall v \in V \tag{14}$$

$$TNP_{ij} = \frac{1}{2} \sum_{kinV} \sum_{vinV} \delta_{ij}^{kv} \quad \forall i, j \in N \tag{15}$$

$$W_i^k \geq 0, \quad \tau_i^k \geq 0, \quad \tau d_i^k \geq 0, \\ \delta_{ij}^{kv} \in \{0, 1\}, \quad x_{ij}^v \in \{0, 1\}, \quad y_i^k \in \{0, 1\} \tag{16}$$

The objective function (1) minimizes the overall cost of the system, comprising components that account for operational costs associated with vehicle travel time, fixed costs of vehicle departures from the depot, waiting costs for vehicles at each node to make a pod train, and fuel cost reduction related traveling as a train. As traveling as a train decreases fuel consumption and also the cost of the trip [9] [10], it is imperative to calculate the total mileage that pods have covered when operating as a train. Constraint (2) indicates that the total number of the pods departing from the depot to any other node $j \in N_t$ should not exceed the total number of pods. Moreover, based on constraint (3) all the pods should start from the depot and get back to the depot eventually. Constraint (4) ensures that no pod is left stationed at any node other than the depot. Constraints (5) and (6) ensure demand satisfaction by allowing pods to be stationed at nodes when they've entered via an input link. Moreover, The number of stationed pods is matched to each zone's demand. Constraints (7) and (8) ensure that each pod v can exclusively occupy a single link at any given time, applicable to all links (i,j) and all pods v. Constraint (9) ensures that pod k and pod v can only travel together on link (i, j) if both pods travel on that link. Constraints (10) and (11) encompass the arrival time, departure time, and waiting time for each pod at every node. It is noteworthy that if a pod traverses a link without connecting to any other pods, the waiting time is zero. Constraint (12) ensures that the arrival time of each pod to the depot is less than the maximum allowable hours that pods can remain outside the depot. Constraint (13) guarantees that the total number of pods traveling together on a link (i, j) remains within the specified limit, denoted by the parameter L. This restriction prevents an excessive number of pods from simultaneously using the same link. Constraint (14)ensures that if a specific pod traverses link ij, the arrival time at j must be greater than the arrival time at i. Constraint (14) calculates the total number of connected pods on each link, which is equal to half of the number of connections. Constraint (15) calculates the total number of connected pods on each link, which is equal to half of the number of connections on that link, and at the end constraint (16) enforces the non-negativity and binary nature of variables.

III. Solution Method

The mathematical model, as detailed in Section 3, is formulated as a mixed-integer mathematical model. It is important to note that this model poses challenges when attempting to find exact solutions for large-scale cases. As a result, we chose to address a single depot problem within a service area comprising six zones using an exact solution approach. To accomplish this, we employed the Gurobi optimizer, a widely recognized optimization tool known for its proficiency in handling complex objective functions; Gurobi utilizes highly efficient mathematical programming techniques to navigate through the solution space, allowing for accurate solutions in scenarios with various constraints and variables. [11], [12]. Furthermore, in the formulations, equations 10, 11, and 14 are nonlinear. In defining the model, we found it more straightforward to express certain constraints as non-linear equations, facilitating a clearer interpretation of the model. However, to expedite the solving process, we adopted a linearized approach by introducing new variables representing the products of these variables. Consequently, we formulated the problem using a linear representation and employed the Gurobi optimizer to derive optimal solutions efficiently.

IV. Numerical Experiment

For the numerical example, we consider a service area comprising six zones, where each 1x1 mile area is treated as an individual zone, and the pods are stationed at the center of each zone. The determination of the required number of pods and station times for each zone is based on the total demand of that zone and the capacity of each pod. The depot locations are strategically positioned just outside the service area, situated at a 1-mile distance from the boundary of four zones, selected randomly. In this model, at the start of the day, the number of required pods is calculated based on the demand of each zone. Subsequently, each pod begins its trip from the depot to fulfill the requests of the zone by stationing at the center of each zone. These pods have the capability to form platoons at these central points. The overall layout of the service area and zones is illustrated in Figure 1, while the values of other parameters are detailed in Table III. To provide a benchmark for comparison and calculate saving cost, we contrast the results with a base scenario wherein a depot-based package delivery system is employed. In this system, trucks initiate their trip at the beginning of the day from the depot, visit different zones, deliver packages to the microhubs, and at the end of the day, return to the depot without any connections or waiting time in their path.

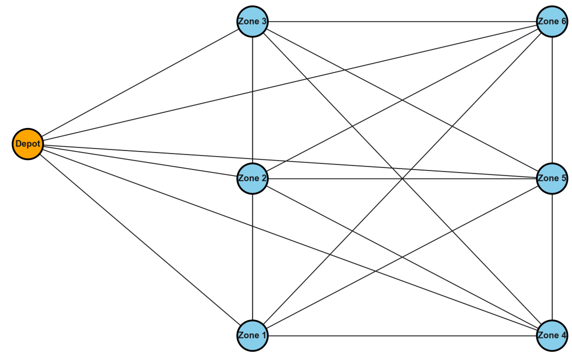

Fig. 1. Service Area, Station Locations, and Depot.

A. Results

Following the experiment outlined in Section 4, we conducted model runs for various values and distributions of demands. Initially, we compared the average total cost of the AMVT system with the baseline depot-based scenario, and the results are presented in Figure 2. The average is computed across various distributions of demand among different zones while maintaining a constant total demand within the service area. Notably, also this proposed system introduces waiting costs due to modularity but results in a significant reduction in the overall system cost. Furthermore, despite assuming equal operation costs for both scenarios and not accounting for reductions in driver costs, Figure 2 demonstrates that the proposed system effectively reduces the overall cost by about 12%. Subsequently, we aimed to identify the most crucial factors influencing cost savings and determine the scenario features where savings are maximized. It is worth noting that, across different scenarios, we measured the variance in demand between different zones to investigate any correlation between saving costs and demand variation. The saving costs for various scenarios are illustrated in Figure 3, indicating that an increase in the total required demand for the service area corresponds to an increase in total saving costs and

TABLE III
PARAMETERS

Parameter	Description	Value	Source
v	Speed of the pod (mph)	20	[13] [1]
c_w	Penalty rate for waiting ($/hr)	3	[1]
c_o	Travel cost ($/hr)	13.54	[1] [14]
c_s	Fuel reduction rate ($ per mile per number of connection)	-1.5	[10] [9]

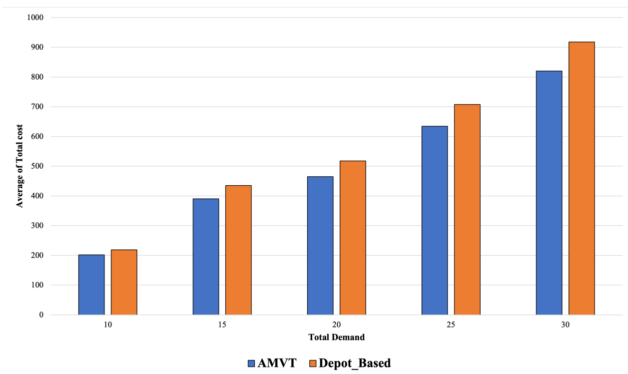

Fig. 2. Comparing average total cost of AMVT to Depot_Based.

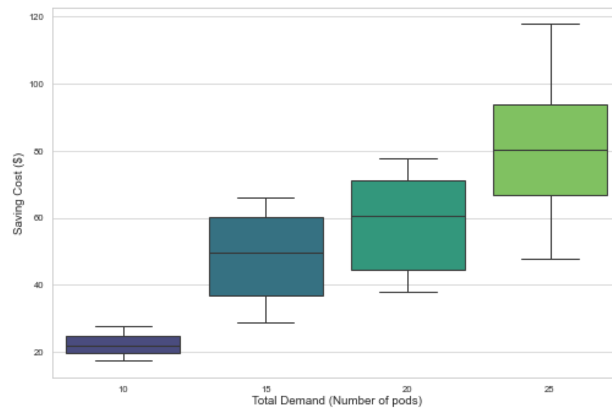

Fig. 3. Saving Cost Distribution for Different Total Demands.

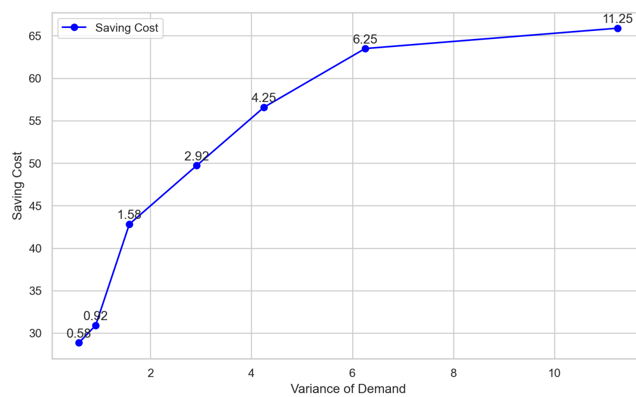

Fig. 4. Impact of demand variance on saving cost.

broadens the range of these saving costs. To gain a deeper understanding of the impact of demand distribution on saving costs, we conducted additional measurements in a scenario where the total demand for the service area remains constant but varies in distribution. Figure 4 illustrates the saving costs based on different variances of demand among zones when the total demand of the system is fixed at 15. The depicted results in Figure 4 demonstrate that an increase in the variance of demands in the service area leads to a corresponding increase in saving costs. Consequently, the findings suggest that both the total number of demands and the variance of demand positively influence saving costs, resulting in an overall increase.

V. Conclusion and Future works

This study delves into the application of AMVT for package delivery in urban areas. A mixed-integer mathematical formulation is developed to evaluate the efficiency of the proposed system, and the model is solved using the Gurobi optimizer to obtain an exact solution. The study conducts a comparative analysis between the total operational cost of AMVT and a depot-based scenario, calculating the cost savings resulting from the modularity feature of this new system. The results unveil a noteworthy 12% reduction in the total operational cost when employing AMVT. Additionally, the model is executed for various scenarios, revealing that cost savings increase as both the total demand of the service area and the demand variance between different zones rise. This finding highlights the adaptability and effectiveness of AMVT in diverse urban settings. Future research directions could include a more comprehensive analysis of modularity's effectiveness in dynamic demand situations, aiming to deepen our understanding of its significance under varying demand conditions. Furthermore, assessing the system's performance in larger-scale applications and conducting comparative analyses with conventional delivery systems would provide valuable insights for broader implementation and enhance our understanding of the scalability and adaptability of the proposed AMVT system.

REFERENCES

[1] S. Ballare and J. Lin, "Investigating the use of microhubs and crowd-shipping for last mile delivery," *Transportation Research Procedia*, vol. 46, pp. 277–284, 2020.

[2] G. Pohl, "Zipments thesis," *New North Center*, 2013.

[3] Q. Chen and J. Lin, "A preliminary investigation of sustainable urban truck routing strategies considering cargo weight and vehicle speed," in *the 2014 Transportation Research Board Annual Meeting, Washington DC, paper*, no. 14-3300, 2014.

[4] J. Lin, Y. M. Nie, and K. Kawamura, "An autonomous modular mobility paradigm," *IEEE Intelligent Transportation Systems Magazine*, vol. 15, no. 1, pp. 378–386, 2023.

[5] Q. Li and X. Li, "Trajectory planning for autonomous modular vehicle docking and autonomous vehicle platooning operations," *Transportation Research Part E: Logistics and Transportation Review*, vol. 166, p. 102886, 2022.

[6] Z. Chen, X. Li, and X. Zhou, "Operational design for shuttle systems with modular vehicles under oversaturated traffic: Continuous modeling method," *Transportation Research Part B: Methodological*, vol. 132, pp. 76–100, 2020.

[7] J. Lin, Y. M. Nie, and K. Kawamura, "An autonomous modular mobility paradigm," *IEEE Intelligent Transportation Systems Magazine*, vol. 15, no. 1, pp. 378–386, 2022.

[8] J. Hatzenbühler, E. Jenelius, G. Gidófalvi, and O. Cats, "Modular vehicle routing for combined passenger and freight transport," *Transportation Research Part A: Policy and Practice*, vol. 173, p. 103688, 2023.

[9] Q. Ye, X. Chen, R. Liao, and L. Yu, "Development and evaluation of a vehicle platoon guidance strategy at signalized intersections considering fuel savings," *Transportation Research Part D: Transport and Environment*, vol. 77, pp. 120–131, 2019.

[10] highways.dot.gov, "Develop truck platooning technology and conduct an inservice field operational test to assess the impacts in a real operational environment." *online Available at: https://highways.dot.gov/research/laboratories/saxton-transportation-operations-laboratory/Truck-Platooning*, 2017.

[11] V. Y. Muley, "Mathematical programming for modeling expression of a gene using gurobi optimizer to identify its transcriptional regulators," *Modeling transcriptional regulation: Methods and protocols*, pp. 99–113, 2021.

[12] Gurobi Optimization, LLC, "Gurobi Optimizer Reference Manual," 2023. [Online]. Available: https://www.gurobi.com

[13] D.-Y. Lee, V. M. Thomas, and M. A. Brown, "Electric urban delivery trucks: Energy use, greenhouse gas emissions, and cost-effectiveness," *Environmental science & technology*, vol. 47, no. 14, pp. 8022–8030, 2013.

[14] Bls.gov, "ight trucor delivery ervices drivers." *online Available at: https://.bls.gov/oes/current/oes3033.htm*, 2018.