UAV Scheduling Strategies in Multi-modal Last-Mile Urban Parcel Delivery

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Ang Li
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Ang Li, Mark Hansen
Department of Civil and Environmental Engineering
University of California Berkeley
Berkeley, CA, 94720
Email: angli@berkeley.edu; mhansen@ce.berkeley.edu

Bo Zou
Department of Civil, Materials, and Environmental Engineering
University of Illinois Chicago, Chicago, IL 60607
Department of Civil and Environmental Engineering
University of California Berkeley, Berkeley, CA, 94720
Email: bzou@uic.edu

***Abstract*— Urban parcel delivery has emerged as a high growth market, and the resulting delivery traffic can pose great challenges in dense urban areas. There is growing interest in supplanting the conventional model of a dedicated delivery person operating a van to alternatives featuring new classes of vehicles such as drones, autonomous ground vehicles, cargo bikes and non-motorized vehicles. This work proposes combined delivery strategies using trucks, cargo bikes and drones. We develop and compare multi-modal delivery strategies with various mode combinations. We work on zone-based multi-modal delivery strategies in multi-echelon networks. Then, we evaluate the benefit of multi-modal delivery in both uncongested and congested transportation networks. Results show that delivery models with multiple vehicles modes in both single- and multi-echelon networks are more efficient in terms of total delivery cost than truck only scenario. The multi- modal delivery strategies in two- echelon networks outperform other strategies in extremely congested situations. We suggest taking advantage of synergistic operation among emerging vehicle types, especially drones for more efficient parcel delivery.**

Keywords- Unmanned Aircraft Vehicles (UAVs), Multi-modal delivery, multi-echelon network, Continuous Approximations (CAs),

I. Introduction

With burgeoning e-commerce and rapid technological change in the parcel delivery system, conventional truck delivery is shifting to new classes of vehicles such as drones, autonomous ground vehicles, cargo bikes and non-motorized vehicles. Multiple modes can be operated synergistically to improve the efficiency of urban parcel delivery networks. One option of particular interest is drones, which shift traffic from the ground to the air. Replacing the last-mile truck delivery with drones helps mitigate traffic congestion results from truck traffic and double-parking. In order to attain the full potential of multi-modal delivery to reduce costs and increase convenience, it is necessary to develop efficient delivery strategies.

Existing literature on multi-modal transportation systems focused on location-routing problems [1, 2, 3], with explicit design of multi-echelon networks. However, limited research has studied the mode decision and demand assignment in the context of multi-modal delivery networks. The combination of trucks with cargo bikes and drones is rarely considered together for cooperative parcel delivery. In traditional single-mode logistics problems, Continuous Approximations (CAs) was widely used in warehouse location problems and delivery distribution strategies models. We apply the CAs method in the multi-modal strategies for delivery cost estimation by different modes. In summary, we propose generalized zone-based multi-modal delivery strategies in multi-echelon networks with different combinations of vehicle modes. Then, we evaluate the benefit of multi-modal cooperative delivery in both uncongested and congested transportation networks.

II. Literature Review

In the high growth parcel delivery market, dramatically increased traditional truck deliveries are contributing to traffic congestion, air pollution, noise, road deterioration, and safety concerns. The benefit of integrating multiple types of delivery vehicles, especially new types of vehicles including electric bikes, drones, and auto robots, has been explored recently. The truck-with-drone-onboard Vehicle Routing Problem (VRP) has been very popular and well-studied in the context of urban parcel delivery networks [4, 5, 6, 7, 8]. [4] design the truck with drone onboard delivery models under different settings, estimate costs using the CAs method, and compare the performance with truck-only delivery. It concludes that trucks with drones on board can be economically beneficial, especially with multiple drones onboard. Cargo bikes are also very popular in last-mile delivery networks [9, 10, 11]. The delivery route cost trade-offs between trucks and electric cargo bicycles are explored under multiple scenarios with different route characteristics [9]. The potential benefit of integrating autonomous robots is explored in [12] by developing scheduling procedures to determine the truck route along robot depots and drop-off points, such that the late customer deliveries are minimized. Though different multimodal delivery models have been proposed, limited existing research comprehensively summarizes and compares different combinations of multimodal delivery strategies.

A multi-echelon network with local transshipment centers is required in order to integrate cargo bikes, auto robots and other types of vehicles in last-mile delivery. Many existing papers worked on location routing problems for multi-echelon delivery networks and explored the benefit of such networks for inventory management [1, 2, 3, 13, 14, 15]. A two-echelon location-routing model is proposed in [1], and it suggests that transshipment platforms can significantly improve delivery process efficiency with proper fleet type and capacity. In [3], the authors design strategic last-mile three-tiered multi-modal delivery networks, estimate route costs and formulate facility location and routing models using a real-world case study. This reference considers all aspects of the multimodal delivery problem jointly and simultaneously in an integrated approach, including network design, location routing problem, cost approximation, model applications, etc. This work compares network design efficiency with different combinations of multiple delivery modes.

Cost estimation is required when comparing the performance of different multimodal delivery networks. Travel distance approximation is the main component of delivery cost estimation. [16, 17] approximated the single warehouse VRP tour distance by constructing a snaking swath route of near constant width, and analytically estimated the total travel distance in both L1 and L2 metrics using Continuous Approximations (CAs). The developed analytical distance formula is implemented in many delivery models [3, 4, 18, 19]. CAs method is commonly used in urban freight distribution management to generate analytical forms [20, 21, 22]. In our work, we integrate the CAs method of distance estimation to our optimization problems on demand distribution and mode decisions.

III. METHODOLOGIES

Here, we conceptualize and optimize the integrated delivery strategies combining trucks, electric cargo bikes, and UAVs. We focus on strategic same-day parcel delivery instead of instant food or grocery delivery. Thus, delivery time windows are not introduced to the models. Five zone-based delivery strategies with different mode combinations are conceptualized. These strategies include all-truck model, truck/drone model, truck-with-drones-on-board model, truck/cargo bike model, and truck and cargo bike/drone model. The first three models involve a single echelon delivery network while the last two involve a two-echelon network.

A. Single Echelon Delivery Scenarios

In the single echelon delivery network, delivery zones are identified and served independently. We work in a city- or county- level metropolitan region with a single hub warehouse. Delivery vehicles are assumed to depart directly from the hub warehouse to the delivery zones, and finish deliveries to customers within the zone, then go back to the hub warehouse. Thus, we need an efficient zone size to make good use of vehicle capacity. For same-day parcel delivery, parcel demand and destination are known at the beginning of the day. An efficient zone size is one for which one fully loaded vehicle can serve one day of delivery demand. Since trucks are involved in all three scenarios in the single echelon delivery network, the zone size will be determined by truck capacity and parcel demand density. We assume there are enough trucks at the warehouses. Three scenarios are considered in the single echelon delivery network, including all-truck scenario, truck or drone scenario, truck-with-drones-on-board scenario. The models determine the delivery vehicle mode, by estimating and comparing the total delivery costs.

a) Scenario 1: All Truck

In this scenario, only trucks are assumed to deliver parcels to all delivery zones. This scenario is used as the base case for later comparison of different combinations of multiple modes. The delivery network is divided into grid-based delivery zones in advance. Each truck trip is only responsible for one delivery zone and returns to the hub warehouse directly right after delivery.

The total delivery cost includes parcel handling cost and operational cost. The parcel handling cost involves parcel preparation, sorting, loading and unloading. Let n_z be the number of deliveries stops in zone z and ρ_z be the average number of dropped parcels per delivery stop in zone z. There are $n_z \cdot \rho_z$ total number of parcels to be delivered in zone z. For each delivery zone z, the total parcel handling cost H_z equals unit handling cost by truck per parcel c_T^H multiplying total number of parcels in the zone.

$$H_z = c_T^H \cdot n_z \cdot \rho_z \tag{1}$$

The operational cost can be calculated as the multiplication of unit time-based truck operational cost c_T^O and travel time. For each truck delivery trip, the total travel distance includes two-way linehaul distance d_z between hub warehouse and the zone, and VRP tour distance D_z in the zone. According to [17], with many randomly scattered demand points, a near optimal VRP tour can be constructed by lapping the region containing the points with nearly parallel laps. The entire zone can be covered by a snaking swath of near constant width, and points are visited along the swath. The optimal swath width that minimizes the expected total tour length can be calculated in both L1 and L2 metrics. Since we assume Manhattan distance as the truck travel distance metric, the VRP tour distance can be estimated as Equation 2.

$$D_z = 1.15 \cdot \sqrt{A_z \cdot n_z \cdot \rho_z} \tag{2}$$

where A is the area of zone z. Let v_l be the linehaul truck travel speed, and v_s be the inter-stop truck travel speed in VRP tour. The total travel distance per truck trip is $\frac{2d_z}{v_l} + \frac{D_z}{v_s}$. Let Ω_T be truck loading capacity. The number of truck trips in zone z can be calculated as $\frac{n_z \cdot \rho_z}{\Omega_T}$. The truck time-based operational cost O_z is expressed in Equation 3:

$$O_z = \frac{n_z \cdot \rho_z}{\Omega_T}\left(\frac{2d_z}{v_l} + \frac{D_z}{v_s}\right) c_T^O \tag{3}$$

Thus, total delivery cost for this scenario can be calculated:

$$Total\ cost = \sum_z c_T^H \cdot n_z \cdot \rho_z + \sum_z \frac{n_z \cdot \rho_z}{\Omega_T}\left(\frac{2d_z}{v_l} + \frac{D_z}{v_s}\right) c_T^O \quad (4)$$

b) Scenario 2: Truck/Drone

The second scenario has the same delivery network setup as the first scenario but with drone deliveries involved. Drones are operated independently from trucks. We assume drones depart from the hub warehouse, deliver a single parcel per trip, and go back to the warehouse. A mode decision is introduced in this scenario to determine whether each zone is served by either trucks or drones. If a zone is assigned to be served by drones, all parcels in the zone will be delivered by individual drone trips. The second scenario delivery model is formulated as an Integer Linear Programming. The decision variables and parameters are described in Table 1.

TABLE 1 Decision Variables and Parameters Description

Set	**Description**
Z	Delivery zones in the network
Decision Variable	**Description**
I_z	Binary variable. Equals 1 if zone z is served by trucks, otherwise drones.
Auxiliary Variables	**Description**
H_z	Parcel handling cost in zone z
O_z	Time-based operational cost in zone z
L_z	Drone launch and recovery cost in zone z
Parameters	**Description**
n_z	Number of deliveries stops in zone z
ρ_z	Average number of dropped packages in zone z
d_z	Average distance from warehouse to demand points in zone z. Linehaul travel distance.
D_z	VRP tour distance in zone z per truck trip
Ω_T	Truck loading capacity
v_l	Truck linehaul travel speed
v_s	Truck inter-stop travel speed in VRP tour
v_D	Drone speed
c_T^H	Truck handling cost per parcel
c_D^H	Drone handling cost per parcel
c_T^O	Unit time-based truck operational cost
c_D^O	Unit time-based drone operational cost
c_D^S	Launch and recovery costs per drone trip
U_D	Maximum drone travel distance within battery limit
ε	Delivery zone width

The delivery model is formulated as follows:

$$Min\ \sum_z (H_z + O_z + L_z) \quad (5)$$

s.t.

$$H_z = c_T^H \cdot n_z \cdot \rho_z \cdot I_z + c_D^H \cdot n_z \cdot \rho_z \cdot (1 - I_z) \quad (6)$$

$$O_z = c_T^O \cdot \frac{n_z \cdot \rho_z}{\Omega_T} \cdot \left(\frac{d_z}{v_l} + \frac{D_z}{v_s}\right) \cdot I_z + c_D^O \cdot n_z \cdot \rho_z \cdot \frac{2d_z}{v_D} \cdot (1 - I_z) \quad (7)$$

$$L_z = c_D^S \cdot n_z \cdot \rho_z \cdot (1 - I_z) \quad (8)$$

$$(2d_z + \varepsilon) \cdot (1 - I_z) \le U_D \quad (9)$$

$$I_z \in \{0,1\} \qquad \forall z \in Z \quad (10)$$

The objective function minimizes the total delivery cost. The total delivery cost is composed of parcel handling cost, operational cost, and drone launch and recovery cost. Constraint (6) defines the parcel handling cost. The first term calculates the handling cost if the zone is served by truck, while the second term for drone. Different handling cost coefficients are used as the parcel sorting, loading and unloading times are different for truck and drone. Constraint (7) defines the operational cost with the first term if the zone is delivered by truck and the second term if by drone. The first term is similar to that from scenario 1, the multiplication of cost coefficient, number of truck trips and trip travel time. For drones in the second term, the travel time is calculated as the two-way Euclidean distance between origin and destination divided by drone speed, and multiplying number of drone trips. Constraint (8) defines the extra launch and recovery cost for drone delivery, which is calculated as cost coefficient multiplying number of parcels in the zone. The unit launch and recovery costs are composed of drone launching, reaching cruising altitude, and landing. Constraint (9) limits that only delivery zones located within drone flying range from the warehouse will be considered for mode choice.

c) Scenario 3: Truck with Drones on Board

In this scenario, trucks are operated with drones on board in the same delivery trip. Each truck trip with drones on board is assigned to one delivery zone. Similar to previous scenarios, each delivery zone is assumed to be covered by a snaking swath of near constant width. We consider multiple drones on each truck. There are various operational possibilities with multiple drone deliveries [4, 23, 24, 25, 26]. Since we are exploring and comparing the benefit of different mode combinations for parcel delivery, we take the same setting of truck with multiple drones in [4]. We consider the situation where each truck is equipped with n drones. The truck will visit the first of $n+1$ stops every time iteratively by stop sequence in the swath. Then n drones launch from the truck at each truck stop, and each of the drones visit one of the following n stops and return to truck at $(n+2)^{th}$ stop. Figure 1 illustrates the example of a truck trip with three drones on board. Three drones launch from the truck at each truck stop and finish the following three deliveries, then return to truck at the fifth stop. Trucks are assumed to travel along road networks, which is approximated by Manhattan distance, while drones travel in Euclidean distance in the air.

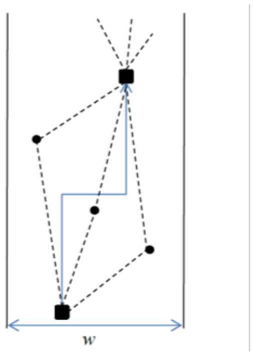

Figure 1. Truck with drones on board [4]

The total delivery costs include parcel handling cost, operational cost and drone launch and recovery cost. Similar to previous scenarios, the parcel handling cost can be calculated as Equation 1. Since package preparation and sorting, loading and unloading have been completed at the truck delivery stage, only truck parcel handling cost is considered. The drone launch and recovery cost can be express in Equation 11:

$$L_z = c_D^S \cdot n_z \cdot \rho_z \cdot \frac{n}{n+1} \tag{11}$$

where $n_z \cdot \rho_z \cdot \frac{n}{n+1}$ is the number of parcels delivered by drones in zone z. The time-based operational cost is calculated as:

$$O_z = c_T^O \cdot \left(\frac{n_z \cdot \rho_z \cdot D_Z^T}{v_s} + \frac{d_z}{v_l}\right) + c_D^O \cdot n_z \cdot \rho_z \cdot \frac{D_Z^D}{v_D} \tag{12}$$

where D_Z^T and D_Z^D are the expected truck and drone travel time per delivery respectively. The two expected travel times were estimated using continuous approximation methods in [4]. Let δ be the parcel demand density per unit area, w be the swath width, and n be the number of onboard drones. The expected horizontal travel distance between adjacent deliveries is $w/3$, and the expected vertical travel distance is $1/\delta w$. The expected truck travel distance per delivery can be calculated as:

$$D_Z^T = \frac{w}{3}\frac{1}{n+1} + \frac{1}{\delta w} \tag{13}$$

The expected drone travel distance per delivery is as follows:

$$D_Z^D = \frac{2n}{n+1}\sqrt{\left(\frac{w}{3}\right)^2 + \left(\frac{n+1}{2\delta w}\right)^2} \tag{14}$$

where $2\sqrt{\left(\frac{w}{3}\right)^2 + \left(\frac{n+1}{2\delta w}\right)^2}$ is the expected travel distance of each drone delivery trip, and there are n out of $n+1$ drone delivery trips in each truck stop cycle. In the square root term, the expected horizontal and vertical drone travel distances are $w/3$ and $\frac{n+1}{2\delta w}$ respectively. According to [4], the weighted average of the optimal swath widths for truck delivery (w_T^* that minimizes Equation 13) and drone delivery (w_D^* that minimizes Equation 14) is:

$$w^* = \sqrt{n+1}\sqrt{\frac{3}{\delta}\left(\frac{c_T^O+\sqrt{2}nc_D^O}{c_T^O+2nc_D^O}\right)} \tag{15}$$

The total delivery cost is $\sum_z (H_z + O_z + L_z)$.

B. *Two Echelon Delivery Scenarios*

In the two-echelon delivery network, a second-level facility, local transshipment center, is introduced (see Figure 2 for network definition). Figure 3 presents the delivery procedure in the multi-echelon network. First-level delivery vehicles are assumed to depart from hub warehouse to local transshipment center, transfer parcels to the second-level delivery vehicles, and return to hub warehouse. The second-level vehicles are responsible for parcel delivery from the local transshipment center to customers in each delivery zone. All the parcels are assumed to be delivered through local transshipment centers. Two delivery scenarios are considered in our two-echelon network. Trucks are used as first-level delivery vehicles in both scenarios. Scenario 4 considers only cargo bikes for the second-echelon delivery as the base case, while in scenario 5 each delivery zone is served either by drones or cargo bikes.

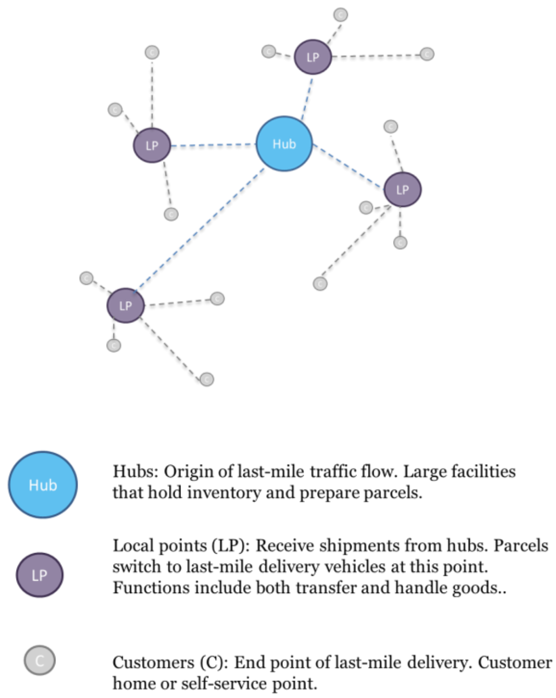

Figure 2. Multi-echelon network definition

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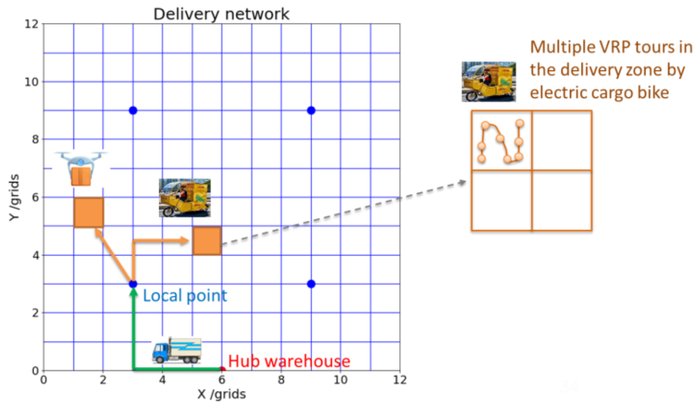

Figure 3. Multi-echelon network delivery procedure example

d) Scenario 4: Truck and Cargo Bikes

In scenario 4, truck and cargo bikes are operated cooperatively, where trucks deliver the first echelon from the hub warehouse to the local transshipment centers and cargo bikes finish the second echelon delivery tasks from local transshipment centers to individual customers in each zone. Parcels are resorted and transferred from the first level to the second-level vehicles at the local transshipment centers. A candidate list of local transshipment centers is predetermined. The delivery model determines which local transshipment centers will be in use and assigns delivery tasks from corresponding delivery zones to each local transshipment center.

In the first echelon, similar to previous scenarios, the delivery zone size is determined by demand density and truck capacity. One of the good zone size approximations is the area size that one full-loaded truck can exactly deliver one-day demand of the zone in a single VRP tour. However, in the second echelon, the cargo bike VRP tour can deliver much less parcels per trip because of its smaller loading capacity. Each delivery zone will be served by multiple cargo bike trips. It is more efficient in terms of total travel distance to further divide the delivery zone to many smaller cargo bike zones and have multiple VRP tours. The cargo bike zone size can be determined such that one full-loaded cargo bike can deliver one-day demand of the smaller zone.

The delivery model is formulated as an Integer Linear Programming. The new decision variable $\boldsymbol{I_{zl}}$ determines the corresponding delivery zones that will be served by each local transshipment center, as well as if each center will be in use or not. The additional variables and parameters are present in Table 2.

TABLE 2 Additional Decision Variables and Parameters Description for Scenario 4

Set	Description
$\boldsymbol{L}$	Local transshipment center candidates
Decision Variable	**Description**
$\boldsymbol{I_{zl}}$	Binary variable. Equals 1 if zone $\boldsymbol{z}$ is served by local transshipment center $\boldsymbol{l}$.
Auxiliary Variables	**Description**
$\boldsymbol{R_l}$	Parcel transfer cost at local transshipment center $\boldsymbol{l}$
Parameters	**Description**
$\boldsymbol{d_l}$	Distance from the hub warehouse local transshipment center $\boldsymbol{l}$
$\boldsymbol{d_{lz}}$	Distance from local transshipment center $\boldsymbol{l}$ to zone $\boldsymbol{z}$
$\boldsymbol{b_z}$	Number of cargo bike zones in delivery zone $\boldsymbol{z}$
$\boldsymbol{D_Z^C}$	Cargo bike VRP tour distance per trip
$\boldsymbol{\Omega_B}$	Cargo bike loading capacity
$\boldsymbol{v_{Bl}}$	Cargo bike linehaul travel speed
$\boldsymbol{v_{Bs}}$	Cargo bike inter-stop travel speed in VRP tour
$\boldsymbol{c_C^H}$	Cargo bike handling cost per parcel
$\boldsymbol{c_B^O}$	Unit time-based cargo bike operational cost
$\boldsymbol{c_l}$	Unit parcel transfer cost at local transshipment center $\boldsymbol{l}$
$\boldsymbol{U_l}$	Maximum number of parcels can be proceeded by local transshipment center $\boldsymbol{l}$.
$\boldsymbol{T}$	Maximum daily working time for human

The delivery model is formulated as follows:

$$Min\ \textstyle\sum_z (H_z + O_z) + \sum_l R_l \tag{16}$$

s.t.

$$H_z = (c_T^H + c_C^H) \cdot n_z \cdot \rho_z \tag{17}$$

$$O_z = \textstyle\sum_l \left(c_T^O \cdot \frac{n_z \cdot \rho_z}{\Omega_T} \cdot \frac{d_l}{v_l} \cdot I_{zl} + c_B^O \cdot b_z \cdot \left(\frac{2d_{lz}}{v_{Bl}} + \frac{D_Z^C}{v_{Bs}}\right) \cdot I_{zl}\right) \tag{18}$$

$$D_Z^C = 1.15 \cdot \sqrt{\frac{A_z}{b_z} \cdot \frac{n_z \cdot \rho_z}{b_z}} \tag{19}$$

$$R_l = \textstyle\sum_z c_l \cdot I_{zl} \cdot n_z \cdot \rho_z \tag{20}$$

$$\textstyle\sum_z I_{zl} \cdot n_z \cdot \rho_z \le U_l \tag{21}$$

$$\left(\frac{2d_{lz}}{v_{Bl}} + \frac{D_Z^C}{v_{Bs}}\right) \cdot I_{zl} \le T \tag{22}$$

$$\textstyle\sum_l I_{zl} = 1 \tag{23}$$

$$I_{zl} \in \{0,1\} \qquad \forall z \in Z \tag{24}$$

The objective function minimizes the total delivery cost. The total delivery cost is composed of parcel handling cost, operational cost, and parcel transfer cost. Constraint (17) defines the parcel handling cost, which includes handling cost for truck and cargo bike, since each parcel will be loaded on and unloaded from both truck and cargo bike. The cargo bike parcel handling cost will be much smaller because parcel preparation and sorting have been completed in the first echelon for truck. Constraint (18) defines the operational cost with the first term for trucks and the second term for cargo bikes. In the second term, $\frac{2d_{lz}}{v_{Bl}} + \frac{D_Z^C}{v_{Bs}}$ calculate total cargo bike travel time for zone z with first term for two-way linehaul travel time from local transshipment center to delivery zone and the second term for VRP tour time in smaller cargo bike zones. Similar to Equation (2), each cargo bike VRP tour distance can be estimated as Constraint (19). Constraint (20) defines the parcel transfer cost in the local transshipment center l, which includes cost for moving parcels from trucks to second-echelon vehicles. Constraint (21) limits the number of parcels been processed at each local transshipment center cannot exceed its capacity. Constraint (22) requires that each cargo bike VRP tour trip cannot be longer than daily working hour. Each delivery zone can only be assigned to one local transshipment center in constraint (23).

e) Scenario 5: Truck and Cargo Bikes/Drones

Multiple delivery modes are considered for the second echelon in scenario 5. Either cargo bikes or drones are used to finish the delivery from local transshipment centers to delivery zones. The delivery model is formulated in a generalized way that is able to consider more than two delivery modes in the second echelon, which may involve auto robots, crowdsourcing, etc. in the future. Similar to scenario 4, the delivery zone will be divided into many smaller cargo bike zones if cargo bikes are used. All parcels in the delivery zone will be delivered individually from the local transshipment center if drones are used. This delivery model determines both the delivery tasks assignment for local transshipment center, and the second echelon vehicle mode for each delivery zone. The model is formulated as an ILP, see variables and parameters in Table 3 and formulation as follows.

TABLE 3 Additional Decision Variables and Parameters Description for Scenario 5

Set	Description
M	Second echelon deliver mode choices set
Decision Variable	**Description**
I_{zlm}	Binary variable. Equals 1 if zone ***z*** is served by local transshipment center ***l***, and taking mode ***m*** in the second echelon.
Auxiliary Variables	**Description**
T_{zlm}	Second echelon total delivery travel time to serve zone ***z*** from local transshipment center ***l*** by mode ***m***
Parameters	**Description**
c_m^H	Handling cost per parcel by mode

$$Min\ \sum_z (H_z + O_z) + \sum_l R_l$$

s.t.

$$H_z = \sum_{l,m} (c_T^H + c_m^H \cdot I_{zlm}) \cdot n_z \cdot \rho_z \tag{25}$$

$$O_z = \sum_{l,m} (c_T^O \cdot \frac{n_z \cdot \rho_z}{\Omega_T} \cdot \frac{2d_l}{v_l} \cdot I_{zlm} + c_m^O \cdot T_{zlm} \cdot I_{zlm}) \tag{26}$$

$$T_{zl0} = b_z \cdot (\frac{2d_{lz}}{v_{Rl}} + \frac{D_Z^C}{v_{Rs}}) \tag{27}$$

$$D_Z^C = 1.15 \cdot \sqrt{\frac{A_z}{b_z} \cdot \frac{n_z \cdot \rho_z}{b_z}} \tag{28}$$

$$T_{zl1} = \frac{2d_{lz}}{v_D} \cdot n_z \cdot \rho_z \tag{29}$$

$$R_l = \sum_{z,m} c_l \cdot I_{zlm} \cdot n_z \cdot \rho_z \tag{30}$$

$$\sum_{z,m} I_{zlm} \cdot n_z \cdot \rho_z \le U_l \tag{31}$$

$$(\frac{2d_{lz}}{v_{Rl}} + \frac{D_Z^C}{v_{Rs}}) \cdot I_{zlm} \le T \tag{32}$$

$$(2d_{lz} + \varepsilon) \cdot (1 - I_{zlm}) \le U_D \tag{33}$$

$$\sum_{l,m} I_{zlm} = 1 \tag{34}$$

$$I_{zlm} \in \{0,1\} \qquad \forall z \in Z, l \in L, m \in M \tag{35}$$

The total delivery cost in the objective function is the same as scenario 4. Constraint (25) defines the parcel handling costs for both first and second echelon vehicles. Constraint (26) defines the operational cost with the first term for trucks and the second term for second echelon delivery vehicles. In the second term, travel time by either cargo bikes or drones T_zlm are specified in constraint (27) and (29) respectively. In constraint (27), the cargo bike VRP tour distance D_Z^C in smaller zones is calculated by constraint (28). Constraint (30) defines the parcel transfer cost, and constraint (31) limits the local transshipment center capacity. Constraint (32) requires that each cargo bike VRP tour trip cannot be longer than daily working hours. Constraint (33) specifies drone delivery range based on battery energy capacity.

IV. EXPERIMENTS

In this section, five multi-modal delivery strategies are compared in an idealized zone-based network under the scenarios of both with and without congestion effects. We work on a square network region divided into many grid squares, where each grid square is treated as a delivery zone in the model. We assume the hub warehouse is located on the middle point of the region edge (see red dot in Figure 4). Constant parcel demand density is assigned to the region using San Francisco data. In December 2019, around 100,000 packages are delivered in San Francisco daily [27]. Daily demand density is about 800 pkg/km2, given San Francisco area is 121 km2. The grid size of the idealized network is determined as the grid area contains daily parcel demand that can be delivered by exactly one full-loaded truck. Given truck loading capacity is 400 parcels [2], the grid width is set to be around 0.7 km. We work on an 8×8 km network with 12×12 delivery grid zones.

Comparisons of different multi-modal delivery models require reasonable parameter settings. Table 4 presents a set of parameter values we used in the experiments. The parcel handling costs by different modes are calculated as the product of hourly labor cost and average handling time per parcel by the mode [28]. The parcel handling cost includes parcel preparation and sorting, loading and unloading. Hourly California blue collar wage $22.77 [27] is used as the labor cost. We assume 10s average handling time per parcel for all modes in the experiments. The parcel handling cost coefficient is $0.06.

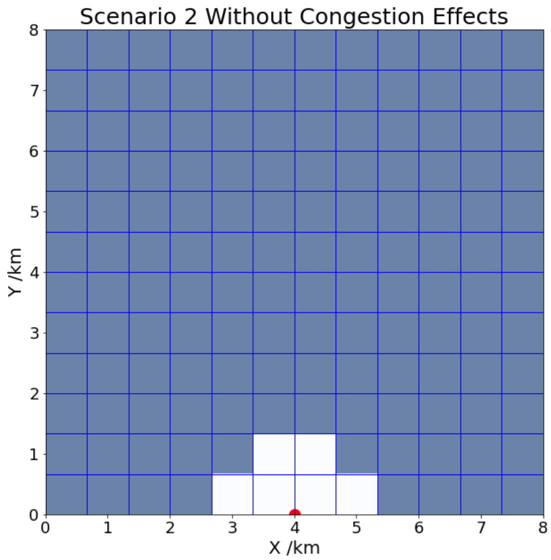

Figure 4. Multi-modal Assignment Results of Scenario 2

Notes: white grids are delivered by drones and blue grids by cargo bikes

TABLE 4 Parameters Values

Parameters	**Values**
Parcel handing cost	$0.06 /parcel
Parcel transfer cost at local point	$0.02 /parcel
Truck operational cost	$67/hr
Cargo bike operational cost	$39/hr
Truck capacity	400 parcels/ truck[2]
Cargo bike capacity	40 parcels/ truck [2]
Drone operational cost	$2.95/hr
Drone horizontal speed	67mph [33]
Drone takeoff speed	10m/s
Drone landing speed	5m/s
Drone launch and recovery cost	$0.02/ trip
Truck linehaul speed	40mph [3]
Truck inter-stop VRP speed	20mph [3]
Cargo bike linehaul speed	30mph [4]
Cargo bike inter-stop VRP speed	15mph [4]

Truck time-based operational cost coefficient includes two components, driver costs $30/hr and vehicle costs $37/hr [29], in total $67/hr. Driver costs include driver wages and benefits, and vehicle costs include fuel, truck lease or purchase payments, repair and maintenance, truck insurance premiums, permits and licenses, tires, tolls. The operational cost coefficient for electric cargo bike includes $30/hr driver cost and $9/hr vehicle costs [9]. For drone operational costs, we take into account $0.34/hr initial investment [30], $20/hr labor costs [31], and $0.94/hr vehicle costs [32], with total $21.28/hr. The initial investment per drone including software is $4000, and the drone has a lifespan of 5 years with 9-hour daily operation time and 5 days per week [30]. The drone vehicle costs include insurance, maintenance, and electricity for battery recharging. We assume each drone operator can monitor 12 drones at the same time [35]. The daily working hours per person are 8 hours, we use 6 hours as the maximum trip length limitation with extra 2 hours for trip preparation. For drone launch and recovery cost, we consider launching cost to the cruising altitude and landing cost. We use 180 feet as typical drone flying altitude according to Amazon Prime Air [34]. 10 m/s and 5m/s are used as takeoff and landing speed respectively [33]. The drone launch and recovery cost per trip can be calculated as takeoff and landing time multiplying drone operational cost coefficient, which is around $0.02/trip.

Results of five delivery models are compared in Table 5. Note that drone cost in the table includes both drone operational cost and drone launch and recovery costs. For scenario 3, we consider three onboard drones on each truck. For the first three single echelon network scenarios, delivery models with multiple modes have less total cost than the all-truck scenario. Trucks with drones on board model is more efficient than trucks or drones operated individually for different zones departed from the warehouse. Compared to trucks, drones have smaller unit operational cost, but need longer total trip time because of their limited loading capacity. The tradeoff is captured by the mode decision results of scenario 2 in Figure 4. The white grids are delivery zones served by drones, while blue grids are served by trucks. The one-way maximum drone flying distance is 10km, but the decision boundary is two grids away from the warehouse. Grids farther than the threshold will need longer total drone travel distance, which will cause much higher travel cost than trucks.

For two-echelon scenarios, we use the example case of four local transshipment centers located in the center of four squared subregions (see green dots in Figure 5). The results are shown in scenario 4 and 5. We also consider the extreme cases with the same number of local transshipment centers as the number of grids in scenario 4e and 5e. 144 local transshipment centers are located in the middle of each delivery zone. The more local transshipment centers, the less use of second-echelon vehicles traveling from local transshipment centers to the center of delivery zones. The extreme cases reveal the total cost lower bound of two echelon network delivery strategies, as it has the shortest total use time of second-echelon vehicles. Two-echelon network requires additional parcel transferring cost between first- and second- echelon vehicles. Besides, the total travel distance is longer with a detour to the local transshipment centers before arriving at delivery zones. However, the two-echelon network can reduce the number of truck trips dramatically, by comparing the truck cost between the first three scenarios and the last four. It removes truck traffic from road networks and reduces congestion from truck traffic and double-parking activities. The two-echelon network can be more efficient when congestion effect is considered. In scenario 4, grids are evenly assigned to four predetermined local transshipment centers. Choosing the closest local transshipment centers to the delivery zone results in smaller total travel time cost when there are many cargo bikes VRP tours at the second echelon. In scenario 5, even though both bikes and drones are provided for second-echelon delivery, only drones are used as the assumed drone unit operational cost is much smaller than that for bikes from selected literatures. Mode decision results are plotted in Figure 6 with bike/drone unit operational cost ratio equal to 6. Four closest delivery zones to each local transshipment centers are assigned to drones and farther to cargo bikes.

Further analysis is conducted to reveal the benefits of the multi-modal strategies in congested networks. In Figure 7, five multi-modal models are performed under different congestion levels, with reduced truck speed from congested road networks. Scenario 1 all-truck model is used as baseline case, and percentages of total cost savings are calculated for all other scenarios with truck speed from 20% to 100% of uncongested speed. All scenarios show greater savings in more congested road networks. Single echelon scenarios (scenario 2 and 3) always have savings compared to baseline. Some two-echelon scenarios (scenario 4, 5) cost more than baseline in uncongested situations, but start to save cost when road network getting more congested. They even generate more savings than single-echelon scenarios in extremely congested road networks. In addition, changing the number of local transshipment centers will also influence the savings. The comparisons results provide delivery service providers with suggestions of the most efficient network design and multi-modal delivery strategy based on the congestion levels of the interested area.

TABLE 5 Delivery Models Results Comparisons

Scenario	Total cost $	Handling cost $	Truck cost $	Drone cost $	Bike cost $
scenario 1: all truck	10011	3629	6382	/	/
scenario 2: truck/drone	9974	3629	6177	168	/
scenario 3: truck with drones on board	8742	3629	4005	1107	/
scenario 4: truck+ cargo bikes	14957	4781	1795	/	8382
scenario 5: truck+ cargo bikes/drones	12667	4781	1795	6091	/
scenario 4e: truck+ cargo bikes	8855	4781	1795	/	2279
scenario 5e: truck+ cargo bikes/drones	7899	4781	1795	1323	/

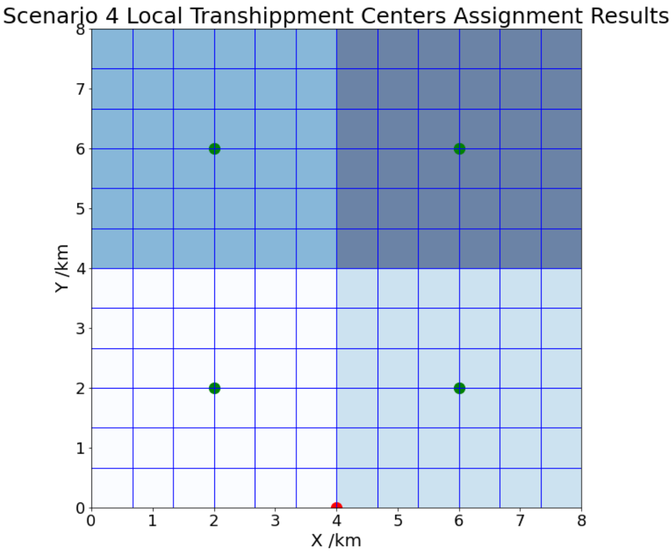

Figure 5. Local Transshipment Centers Assignment Results of Scenario 4

Notes: The color of grids represents the assignment of local points

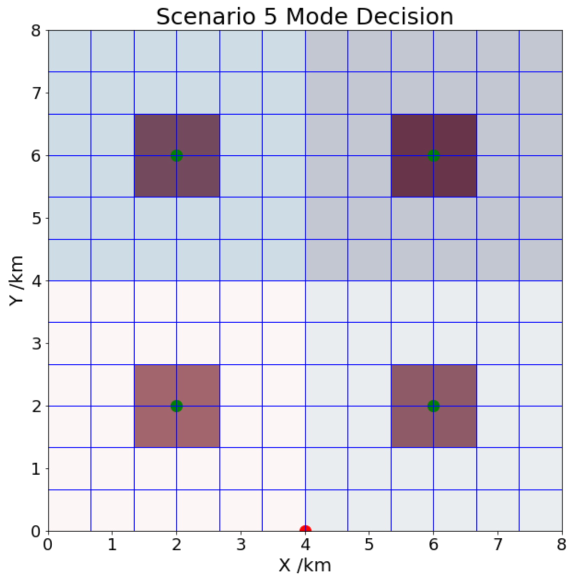

Figure 6. Multi-modal Local Transshipment Center Assignment and Mode Decision Results of Scenario 5

Notes: The entire region is evenly assigned to four local transshipment centers. Parcels will be shipped to local transshipment centers by trucks and delivered by either cargo bikes or drones to grid delivery zones. Purple grids will be delivered by drones in the second echelon, and others by cargo bikes.

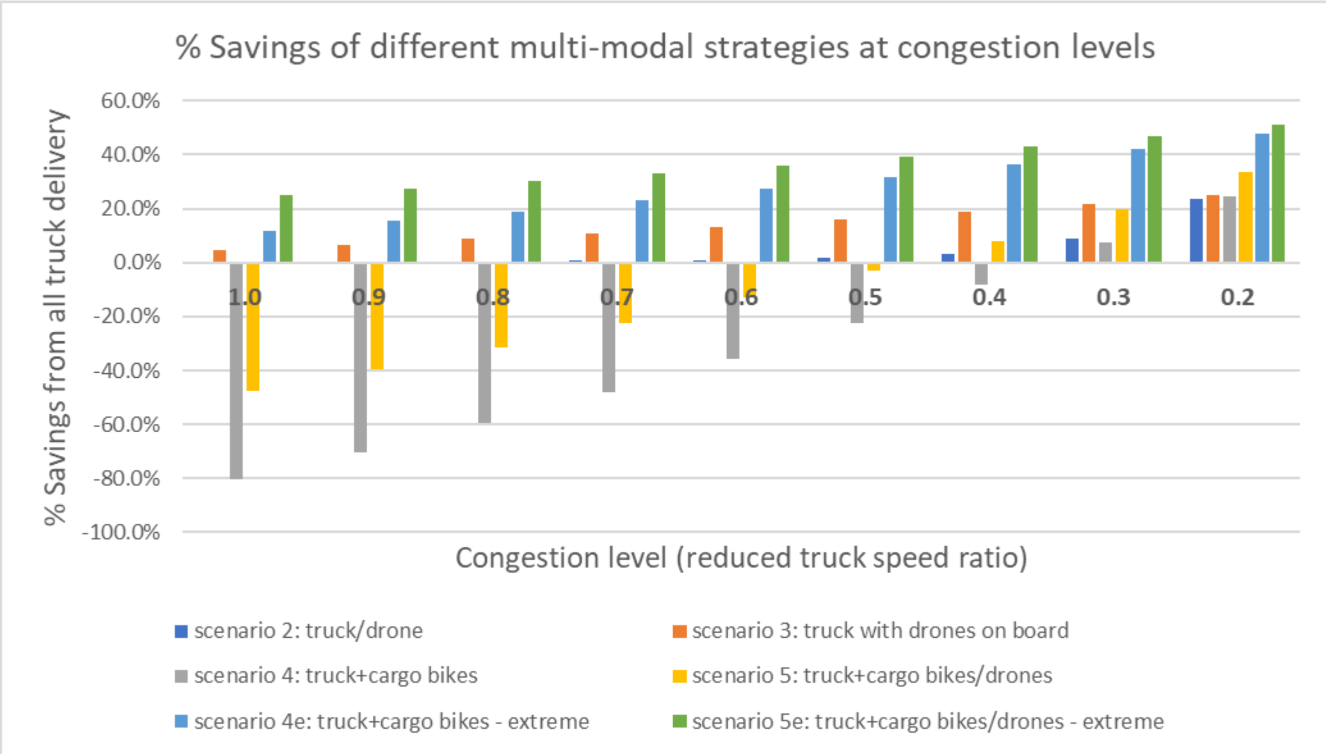

Figure 7. Multi-modal Assignment Results of Scenario 4

V. CONCLUSIONS

Multimodal delivery models with different combinations of vehicles are developed and compared in this work. Especially single- and two-echelon delivery networks including trucks, cargo bikes, and drones are proposed. We consider both the facility assignment and mode decisions under scenarios. We explicitly calculate the delivery costs mainly including parcel handling cost and vehicle operational costs. From our specific experiments, we found that delivery models with multiple vehicles modes in both single- and two- echelon networks are more efficient in terms of total delivery cost than truck only scenario. Single echelon delivery models generate less cost than that of two-echelon in uncongested road networks. The two-echelon multi-modal delivery strategies benefit the congested road network a lot by reducing truck traffic and double-parking activities. The results suggest that we can take advantage of synergistic operation among emerging vehicle types, especially nonmotorized vehicles, and drones for more efficient parcel delivery.

For future research, one direction is sensitivity analysis with different parameter settings and network design, then comparing delivery models under more scenarios. Besides, it would be interesting to apply the delivery models to real-world case studies and compare the multi-modal delivery efficiency with idealized situations. In addition, we can improve the current multimodal delivery models by integrating the congestion effects to the optimization model, and making decisions while evaluating the benefit of integrating multiple vehicle modes.

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