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Package delivery by electric vertical takeoff and landing aircraft? An attractiveness assessment

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ABSTRACT

Electric vertical takeoff and landing aircraft (eVTOLs) are gaining growing interest recently. However, limited attention has been paid to the prospect of using eVTOLs for package delivery. To fill this void, this paper explores the attractiveness of eVTOL-based package delivery in terms of cost, energy consumption, and CO_2 emissions. Given that eVTOLs cannot take off/land at customer doorsteps, a two-leg system design is proposed and formulated as an optimization model. To implement the model, we consider multiple plausible eVTOL and ground vehicle types, their cost economics, and energy use and CO_2 emission characteristics. Applying the model in the Chicago metro region, we find that the attractiveness of eVTOL-based package delivery depends critically on the eVTOL and ground vehicle types. With an appropriate eVTOL-ground vehicle combination, eVTOL-based delivery can be attractive compared to van-only delivery in terms of total shipping cost, but not necessarily so from the energy and emission perspectives. This highlights the need for future R&D to further enhance the energy efficiency of eVTOLs. When designing eVTOL-based package delivery systems, the importance to account for the potential interactions between eVTOL traffic and commercial air traffic should also be recognized.

1. Introduction

Electric vertical takeoff and landing aircraft, or eVTOLs, have gained much interest with the advent of Advanced Air Mobility (AAM). While most of the research focus is drawn to personal travel, limited attention has been paid to the prospect of using eVTOLs for package delivery. On the other hand, because of faster speed, point-to-point flying, and avoidance of road traffic, eVTOLs are being considered recently by the freight logistics industry as a promising alternative to today's ground-based package delivery. Several eVTOL manufacturers have developed prototype eVTOLs and been actively testing their use with major logistics service providers (LSPs) (Sabrewing Aircraft Company, 2021; Reed, 2022; Garrett-Glaser, 2020; Klisauskaite, 2021; FedEx, 2022). For example, in partnership with Beta Technologies, UPS is conducting extensive eVTOL tests for small package delivery and heavier cargo transport to reduce the environmental impact of its logistics operations (UPS, 2021). This partnership includes exploring the integration of eVTOLs into UPS's existing network to transform UPS's supply chain. FedEx is also investing in eVTOL-based logistics, by leveraging this new type of aircraft to enhance express delivery services and reduce carbon emissions (FedEx, 2022). Amazon has made multiple rounds of investment in the eVTOL company Beta Technologies, with its eVTOL test flight flying between Amazon's Air Hub facilities (Alcock, 2022a).

Despite the industry interests, it remains unanswered as to whether eVTOL-based package delivery will be attractive from the economic, energy, and CO_2 emission perspectives, especially in comparison with today's ground-based delivery. Answering this question is critical to justify, support, and guide future eVTOL research and development (R&D) in the freight logistics sector. To answer this question, specifying the plausible operational context for eVTOL-based delivery is needed. Because eVTOLs cannot take off and land at customer doorsteps, this paper considers two-leg operations for eVTOL-based delivery. In the first leg, eVTOLs fly from a central distribution point (CDP) to intermediate stops, termed *vertiports* where eVTOL take off and land. At a vertiport, packages are transferred to local transportation modes (*e.g.*, vans and passenger cars) for the second leg to deliver packages to final customers.

Much like today's package delivery businesses, eVTOL-based delivery is expected to be operated by private LSPs. As such, it is reasonable to assume that eVTOL-based delivery operations seek to minimize cost while meeting the demand. Under a two-leg system design, cost

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minimization will involve decisions on where vertiports can be located, how many vertiports are actually built, how many eVTOL flights are dispatched from the CDP to each of the vertiports for the first leg, and how ground-based delivery is performed for the second leg. As vertiports for eVTOL takeoff hold some footprint, only limited locations in an area will be suitable for vertiport building, *e.g.*, parking lots of large shopping centers. In this paper, such locations are termed candidate vertiport locations.

In addition to vertiport-related decisions, the cost efficiency of the two-leg system design depends on what eVTOL and ground vehicles are used. Different combinations of eVTOLs and ground vehicles for the two legs can result in distinct outcomes of where and how many vertiports to build, how many eVTOL flights and ground vehicles to dispatch, and consequently total shipping cost. Moreover, cost minimization does not necessarily account for the operation outcomes that are of public concern, particularly energy consumption and CO_2 emissions, which are essential to determining whether eVTOL-based package delivery will be not only economically desirable but socially beneficial. For this, it is also important to recognize different possible operation scenarios and the inherent uncertainties in the parameters of eVTOL-based package delivery.

In view of the above, this paper aims to make three contributions:

- First, we develop and adopt a suite of methods to identify the optimal eVTOL-based delivery system design from a cost minimization perspective and assess the associated system total shipping cost, energy consumption, and CO_2 emissions. We approach the system design by formulating an optimization model that combines the determination of vertiport locations, assignment of vertiport to delivery zones, and the number of eVTOL flights to dispatch for the first leg, with approximate computation of the second-leg delivery operations, to reduce computational complexity while preserving the essence of the design.
- Second, we demonstrate the use of the methods by applying them to a prospective eVTOL-based package delivery system, in the Chicago metro region in the US. We examine multiple scenarios that vary by eVTOL and ground vehicle type, plus a benchmarking scenario where only ground vehicles are used for delivery. Total shipping cost, energy consumption, and CO_2 emissions are computed and compared across the scenarios. Sensitivity analysis is further conducted to understand how the system performance responds to key system parameters.
- Third, based on the numerical results, a series of policy discussions is conducted. These discussions encompass (1) the desired eVTOL type, (2) the desired ground vehicle type, (3) the overall promise of eVTOL-based package delivery, and (4) operation density implications for potential public support. The policy discussions help inform future system development of eVTOL-based package delivery that is beneficial both economically and socially.

In the rest of the paper, we review the relevant literature and identify the research gaps in Section 2. In Section 3, an optimization formulation is proposed for the system design of eVTOL-based package delivery. Section 4 is dedicated to characterizing eVTOLs and ground vehicles, in terms of their cost economics and operational characteristics including energy consumption and CO_2 emissions. This is followed by numerical application of the methods in the previous two sections to examine the prospect of eVTOL-based package delivery in the Chicago metro region in Section 5. Section 6 summarizes the results, discusses further the implications, and suggests directions for future research.

2. Literature review and research gaps

2.1. Existing relevant research

While eVTOLs have been argued for freight logistics (Goyal et al., 2018; Cohen and Shaheen, 2021; Doo et al., 2021), its prospect has received much less attention than for passenger transportation in the Advanced Air Mobility literature. To our knowledge, German et al. (2018) is probably the first study that explores the operational possibility of eVTOL-based package delivery. The authors claim the benefits of eVTOL-based package delivery to include augmented ability to meet increasing demand, reduced customer waiting time, and expedited delivery, which all contribute to greater customer convenience. In the study, an integer programming model is developed to select vertiports to maximize the demand served. However, how to dispatch eVTOL flights toward the vertiports is not part of the decision-making. In another study, German and Daskilewicz (2018) propose four concepts, intra-city point-to-point, intra-city hub-and-spoke, regional hub-and-spoke, and city to/from airport, to describe the possible delivery scenarios of eVTOL-based package delivery.

Focusing on the demand side of eVTOL-based cargo delivery, Gunady et al. (2022) take a system-of-systems approach to explore using eVTOLs as an alternative to trucks for middle-mile logistics. The authors propose methodologies to generate freight demand and estimate transportation mode choice in the presence of eVTOLs. In Rimjha et al. (2020), a 10-step procedure is proposed to estimate cargo demand in the Northern California region using eVTOLs. A parametric analysis concerning the market share of on-demand air mobility is conducted. Recognizing the lack of relevant information from publicly available data, the authors highlight the uncertainties in predicting eVTOL cargo demand.

While our study is intended for package delivery using eVTOLs, it is worth noting that eVTOL-based passenger transportation bears some similarities. For example, both package delivery and passenger transportation can involve vertiport location decisions (Schweiger and Preis, 2022; Brunelli et al., 2023; Rath and Chow, 2022) present a hub location problem to select skyports for air taxi accessing airports. Vertiport location decision-making is modeled as a modified single-allocation p-hub median location problem in Willey and Salmon (2021), which incorporates elements of subgraph isomorphism to choose vertiports and vertistops. Macias et al. (2023) develop an integrated vertiport placement model incorporating vehicle sizing and queuing, and demonstrate its use in a case study of hypothetical UAM implementation in London. The vertiport network design problem is also tackled in Wu and Zhang (2021), which involves determining vertiport location, traveler allocation to vertiports, and vertiport access/egress mode choices, while considering the interaction between vertiport location and eVTOL travel demand. Apart from the above studies, Lim and Hwang (2019) use k-mean clustering, Rajendran and Zack (2019) adopt iterative constrained clustering, Daskilewicz et al. (2018) formulate an integer linear program, and Fadhil (2018) employs a GIS-based analysis to investigate vertiport locations for their respective case studies. These research efforts notwithstanding, none of them explicitly consider eVTOL flight dispatching as part of the decision-making process. Nor do they address local routing for vertiport access/egress, which is especially important for eVTOL-based package delivery given that the second leg from vertiports to customers involves local touring of delivery vehicles.

Because eVTOLs cannot fly to customer doorsteps, the integration of eVTOL services with ground transportation is needed and critical for the operational efficiency of the overall air-ground system. Existing research on air-ground integration has exclusively focused on passenger transportation. Shon et al. (2024) perform optimal planning of an AAM system with explicit consideration of ground access to vertiports, emphasizing the importance of system-wide optimization to achieve minimum travel time and cost. A multi-objective optimization framework is proposed in Zhao and Feng (2024) to integrate vertiports into the existing mobility hubs like metro and train stations. The authors show that seamless transfers between air and ground modes could result in significant time savings, up to 80% compared to driving in a case study in Beijing, China. Mudumba et al. (2021) highlight the environmental benefits of integrating AAM with electric ground

Table 1
Sets, variables, and parameters.

Sets	Description
$\mathbb{V}$	set of candidate vertiport sites
$\mathbb{Z}$	set of delivery zones
Variables	**Description**
x_i	binary variable indicating whether candidate site i is selected to construct a vertiport
x_{ij}	binary variable indicating whether candidate site i is selected to serve delivery zone j
y_i	number of eVTOL flights per day from CDP to site i
Parameters	**Description**
$c_{i,1}$	vertiport daily cost if candidate site i is selected to construct and operate a vertiport
$c_{i,2}$	eVTOL flying cost for a round trip from CDP to candidate site i
c_3	vertiport daily cost at CDP
c_0	unit cost of using ground mode for line-haul movement of the second leg (in \$/mile)
c_0'	unit cost of using ground mode for local movement of the second leg (in \$/mile)
κ_1	carrying capacity (in tons) of an eVTOL aircraft
κ_2	carrying capacity (in tons) of the ground delivery mode
$\bar{\rho}_{ij}$	average distance from candidate site i to delivery zone j
Q_j	delivery demand (in tons) per day for zone j
A_j	size of zone j (sq. miles)
$\bar{\omega}$	average weight of a package (tons)

vehicles, suggesting that coordinated networks of eVTOLs and electric cars could significantly lower CO_2 emissions. Wu and Zhang (2021) employ integer programming to identify optimal vertiport locations, AAM traveler allocation, and ground access and egress modes. Applying to the Tampa Bay area, the authors demonstrate the crucial role of efficient multi-modal integration in the success of AAM.

In addition to package delivery and passenger transport, eVTOLs have been considered for mission-critical uses. Silva and Solis (2024) discuss how eVTOLs may be adapted for public services, emphasizing the needed design modifications to meet different mission requirements. Conley et al. (2024) examine the technological gaps for eVTOL-based emergency missions, suggesting enhancing eVTOL performance and utility in challenging environments like wildfire. The potential of eVTOLs for public services is also investigated by Doo et al. (2021) considering diverse eVTOL applications including law enforcement and disaster relief. The authors highlight the integration of eVTOL-based public services with existing urban infrastructure. The operational and economic challenges of using eVTOLs as air ambulance are discussed by Goyal and Cohen (2022), who also propose technological improvements to enhance the reliability and cost-effectiveness of eVTOL-based air ambulance.

From the modeling standpoint, the system design of eVTOL-based package delivery can be viewed as a one-to-many distribution problem with transshipments. In the literature, two approaches to this problem exist. The first approach is based on continuous approximation (Daganzo and Newell, 1986; Campbell, 1993; Daganzo, 2005). This approach provides operation guidelines and ensures near minimum system cost with light computation (Daganzo and Newell, 1986), but does not give detailed and specific operations. The second approach is based on formulating and solving integer programs for two-echelon vehicle routing problems, in which freight is moved in two echelons with transfers at intermediate facilities (*e.g.*, Crainic et al., 2009; Perboli et al., 2011). In our context, vertiports can be viewed as the equivalent of intermediate facilities. Because this approach seeks detailed routing of all vehicles on both echelons, it is computationally more challenging and often requires heuristics to obtain approximate solutions (Sluijk et al., 2023). In our study, the focus is on eVTOL-based delivery system design, by selecting locations to build vertiports and determining how many eVTOL flights to fly from a CDP to the vertiports. Detailed routing from the vertiports to final customers is not essential. A hybrid approach is thus taken, with detailed modeling of vertiport site selection, delivery zone-to-vertiport assignment, and eVTOL flight frequency determination. Meanwhile, continuous approximation is used for the second-leg delivery from the vertiports to final customers.

2.2. Research gap identification

Based on the above review, three research gaps in the literature are identified. First, to our knowledge, no existing research has modeled vertiport location and flight dispatching decisions simultaneously when designing an eVTOL-based delivery system. Second, while eVTOLs are expected to be used in conjunction with ground vehicles for package delivery, given that eVTOLs cannot take off and land directly at customers' doorsteps, there remains a gap in the existing literature regarding the optimal integration of these two transport modes for package delivery. Third, given that eVTOLs are still developing and eVTOL-based package delivery is yet to be implemented, inherent uncertainties exist. But the impact of the uncertainties on the attractiveness of eVTOL-based package delivery have not been examined. Filling these gaps is important to answer the question of whether eVTOL-based package delivery will be attractive from economic, energy, and CO_2 emission perspectives. This is what we intend to do in this paper.

3. System design model

This section develops a model for the system-level design of eVTOL-based package delivery. As mentioned earlier, the conceived operations consist of two legs. In the first leg, eVTOLs are dispatched from a CDP to transport packages to vertiports, where packages are transferred to the ground delivery mode for the second-leg delivery to final customers. In the first leg, eVTOLs fly back-and-forth between the CDP and vertiports. The second leg involves the touring of ground vehicles to deliver packages to customers. The service area is divided into delivery zones. The system design involves selecting from a set of candidate sites for vertiport construction and operation, and assigning delivery zones to each of the vertiports for the second-leg delivery.

We consider that eVTOLs to fly back and forth between the CDP and vertiports, rather than visiting multiple vertiports in a single trip, for two reasons. First, we expect a much larger number of packages assigned to a vertiport than a single eVTOL flight can carry. Thus, it is intuitive to load an eVTOL flight with packages destined to the same vertiport. This form of operation is appealing from the cost perspective, given that performing additional takeoff/landing operations by visiting more vertiports in a trip will incur significantly more energy and thus further cost. Second, the back-and-forth flying is simple to perform, which is important at the early stage of eVTOL-based package delivery operations. Nonetheless, allowing an eVTOL to stop at multiple vertiports in a trip may provide operational flexibility. Exploring this will be left for future research.

With the above setup, we now present the optimization model for the eVTOL-based package delivery system design. The optimization model is a mixed-integer linear program (MILP) shown in (1)–(8). The notations used in the MILP are given in Table 1.

$$\min \sum_{i\in\mathbb{V}} c_{i,1}x_i + \sum_{i\in\mathbb{V}} c_{i,2}y_i + \sum_{i\in\mathbb{V}}\sum_{j\in\mathbb{Z}} \left(c_0\frac{2\bar{\rho}_{ij}Q_j}{\kappa_2} + 0.57c_0'\sqrt{\frac{A_jQ_j}{\bar{\omega}}} \right) x_{ij} + c_3 \quad (1)$$

s.t.

$$y_i \leq M x_i \qquad \forall i \in \mathbb{V} \quad (2)$$

$$\kappa_1 y_i \geq \sum_{j\in\mathbb{Z}} Q_j x_{ij} \qquad \forall i \in \mathbb{V} \quad (3)$$

$$\sum_{j\in\mathbb{Z}} x_{ij} \leq M x_i \qquad \forall i \in \mathbb{V} \quad (4)$$

$$\sum_{i\in\mathbb{V}} x_{ij} = 1 \qquad \forall j \in \mathbb{Z} \quad (5)$$

$$x_i \in \{0,1\} \qquad \forall i \in \mathbb{V} \quad (6)$$

$$x_{ij} \in \{0,1\} \qquad \forall i \in \mathbb{V}, j \in \mathbb{Z} \quad (7)$$

$$y_i \in \mathbb{N} \cup \{0\} \qquad \forall i \in \mathbb{V} \tag{8}$$

In the MILP, the objective function (1) minimizes the system's total shipping cost per day, which is the sum of three summation terms. The first summation term expresses the fixed cost of using vertiports. If a candidate site i is selected to construct a vertiport, the fixed cost $c_{i,1}$ includes the daily capital cost associated with vertiport construction and the daily operating cost of the constructed vertiport. The second summation term expresses the eVTOL flying cost between the CDP and the vertiports (the first leg). Different from the first summation term, the second summation term is a function of the number of eVTOL flights made (y_i). The third summation term expresses the cost of second-leg delivery by ground vehicles from the vertiports to final customers (the second leg). The last term is a constant, expressing the daily capital cost associated with the construction of a larger vertiport at the CDP, which is termed "vertibase". Note that this constant term does not affect the optimization results. It is included in the objective function only for completeness of the system total shipping cost.

The second-leg delivery cost is the sum of line-haul movement cost (from vertiport i to zone j) and local movement cost (within zone j), expressed respectively by $c_0 \frac{2\bar{\rho}_{ij} Q_j}{\kappa_2}$ and $0.57 c_0' \sqrt{\frac{A_j Q_j}{\bar{\omega}}}$. The expression of the second-leg cost follows the continuous approximation approach (Daganzo, 1984, 2005), which provides a simple and effective approximation for the vehicle touring length even when the zone shape is irregular and demand in the zone is not uniform. In the expression, $\frac{2\bar{\rho}_{ij} Q_j}{\kappa_2}$ corresponds to the total line-haul travel distance from vertiport i to reach the center of the demand points in zone j, obtained by multiplying the average line-haul distance in one tour, $2\bar{\rho}_{ij}$, by the number of tours $\frac{Q_j}{\kappa_2}$. $0.57\sqrt{\frac{A_j Q_j}{\bar{\omega}}}$ captures the total local travel distance between the demand points within zone j. Note that the line-haul distance and the local distance are multiplied by different unit cost factors c_0 and c_0', measured in \$/mile. One reason is that drivers of the ground mode are typically paid by \$/hr. As line-haul and local travel have different speeds (*e.g.*, line-haul travel is likely to use freeways and highways, while local travel will mainly occur on local roads with frequent stops), the time needed to travel one mile will be different between line-haul and local travel. Consequently, the cost of traveling one mile will also differ.

The minimization of system total shipping cost is subject to a set of constraints. Constraint (2) specifies that eVTOL flights to a vertiport occur only if the vertiport is constructed. M is a big number here. Constraint (3) describes the inflow–outflow relationship at each vertiport. Specifically, as we dispatch an integer number of eVTOL flights to a vertiport (which is specified by constraint (8)), it is likely that eVTOL flights are not fully loaded. Thus, multiplying the number of eVTOL flights that fly to a vertiport by the carrying capacity of an eVTOL aircraft should give a tonnage greater than or equal to the tonnage carried by the second-leg delivery mode from the vertiport to the assigned delivery zones. Constraint (4) specifies that second-leg delivery trips from a candidate vertiport site i exist only if a vertiport is constructed at the site. More specifically, if a vertiport is constructed at site i, *i.e.*, $x_i = 1$, then there are second-leg delivery trips from the vertiport to at least one delivery zone, *i.e.*, $\sum_{j \in \mathbb{Z}} x_{ij} \geq 1$. If vertiport i is not constructed, *i.e.*, $x_i = 0$, then there must be no second-leg delivery trips from site i to any delivery zone j, *i.e.*, $\sum_{j \in \mathbb{Z}} x_{ij} = 0$. Constraint (5) limits the number of vertiports serving a zone to one. Constraints (6)–(8) describe the binary and non-negative integer requirements for the decision variables.

4. eVTOL and ground vehicle characterization

4.1. Cost economics of evtols and ground vehicles

Currently, a few eVTOL types exist for freight transportation. While they all bear some similarities, two distinct eVTOL types are specifically considered: Sabrewing Rhaegal B and Beta Alia 250 shown in Fig. 1. These two eVTOL types are chosen as relevant aircraft performance parameters are available and both types have attracted quite a bit of industry interest, with Ameriflight purchasing 35 Sabrewing Rhaegal and UPS testing Beta Alia in their respective cargo operations (UPS, 2021; Stoner, 2023). Sabrewing Rhaegal is designed for only freight transportation. It does not have a pilot onboard. It uses ducted electric motor fans for lifting and forwarding flight. In some way, Sabrewing Rhaegal can be viewed as a large drone. The unit operating cost of Sabrewing Rhaegal is \$1.46/mile, with a carrying capacity of 5400 lb (Alcock, 2022b). The design of Beta Alia is very different from Sabrewing Rhaegal. It is a piloted eVTOL with a lift-plus-cruise design. The eVTOL can be used for both passenger and freight transportation. Beta Alia has a carrying capacity of 1400 lb and a unit operating cost of \$550/hr, which includes crew cost, avionics costs, vehicle maintenance cost, energy cost, and acquisition cost (Howard et al., 2021; Aerospace Technology, 2022). These eVTOL parameter values, along with the maximum flying ranges, are documented in Table 2.

Apart from eVTOLs, it is also important to specify the cost characteristics of ground vehicles for the second-leg delivery. We consider three ground vehicle options. The first two options are delivery vans, powered by gasoline and electricity respectively. The third option is crowdshipping, which is about soliciting ordinary people who have spare time and use their private cars to perform delivery to earn income. Delivery vans are the most commonly used transportation mode for local delivery to customers (Perboli and Rosano, 2019; Boysen et al., 2021; Mohammad et al., 2023). Crowdshipping is considered as it is an emerging mode for "last mile" delivery and has gained significant interest in package delivery in recent years (Kafle et al., 2017; Le et al., 2019; Farazi et al., 2022; Ahamed et al., 2021; Zou and Kafle, 2023).

For the first ground vehicle option, the unit operating costs of a gasoline van are estimated at \$0.78/mile for line-haul and \$1.96/mile for local travel, based on different travel speeds of 30 mph for line-haul and 10 mph for local travel, as detailed by Shojaei et al. (2022). Fuel costs are \$0.11/mile. Maintenance costs are \$0.08/mile. The driver's wage is set at \$17/hour, which results in labor costs of \$0.57/mile for line-haul and \$1.70/mile for local travel, depending on travel speeds. The vehicle's capital cost is calculated assuming a purchase price of \$24,275, a service life of 20 years, a 3% discount rate, and 300 days of operation per year, yielding capital costs of \$0.02/mile for line-haul and \$0.07/mile for local travel. Summing up these components, the total operating costs are \$0.78/mile for line-haul and \$1.96/mile for local travel. The carrying capacity and maximum range of the gasoline van are 1510 lbs and 380 miles, respectively (Edmunds, 2020).

For the second ground vehicle option, the unit operating costs for an electric delivery van, differing between line-haul and local travel, are estimated at \$1.13/mile and \$3.06/mile, respectively, based on Choubassi et al. (2016). Energy (electricity) costs are \$0.05/mile. Maintenance costs are \$0.117/mile. The driver's wage is \$28/hr, translating to \$0.93/mile for line-haul and \$2.80/mile for local travel. The vehicle's capital cost, assuming a purchase price of \$32,301, a 3% discount factor, and a 20-year service life (with 300 operating days per year and 8 h per day), is estimated to be \$0.03/mile for line-haul and \$0.09/mile for local travel. Summing up these components, the total unit operating costs are \$1.13/mile for line-haul and \$3.06/mile for local travel. The carrying capacity and maximum travel range of a gasoline van are assumed to be 1679 lbs and 178 miles, as also noted by Choubassi et al. (2016).

For the third ground vehicle option, the unit operating cost to the LSP for using crowdshipping is based on the payments to crowdshippers. Considering Amazon Flex's pay range of \$18–25/hr, we take the midpoint of \$21.5/hr (Pourrahmani and Jaller, 2021). Dividing this rate by line-haul and local travel speeds results in unit costs of \$0.72/mile and \$2.15/mile, respectively. For the carrying capacity of a crowdshipper, we consider that crowdshippers use the trunk of their cars to load packages. The capacity of a car trunk is assumed to be 150 kg (331 lb) (Qi et al., 2018). A car's maximum travel range is estimated at 480 miles, assuming a fuel economy of 40 mpg and a 12-gallon tank.

(a) (b)

Fig. 1. The two eVTOL types considered in our numerical analysis: (a) Sabrewing Rhaegal B and (b) Beta Alia 250.
Source: (Vertical Magazine, 2020; Adams, 2020)

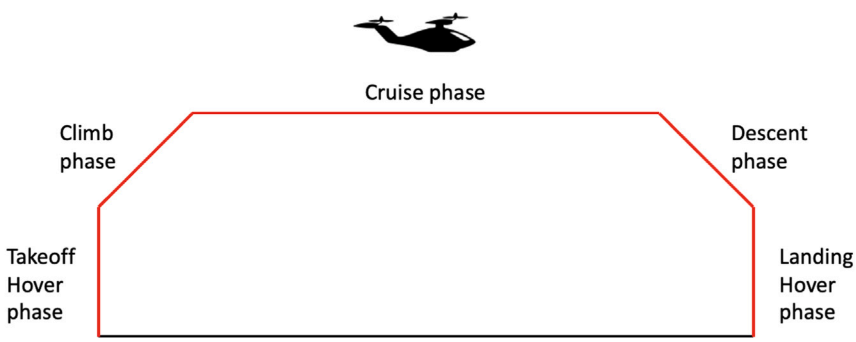


Fig. 2. eVTOL flight profile.

Table 2
Operational characteristics of eVTOLs, delivery vans, and crowdshipping.

	Sabrewing Rhaegal B	Beta Alia 250	Gasoline van	Electric van	Crowdshipping
Unit operating cost	\$1.46/mile	\$550/hr	\$0.78/mile (line-haul) \$1.96/mile (local)	\$1.13/mile (line-haul) \$3.06/mile (local)	\$0.72/mile (line-haul) \$2.15/mile (local)
Carrying capacity	5,400 lb	1,400 lb	1,510 lb	1,697 lb	331 lb
Maximum flying range	1,151 miles	288 miles	380 miles	178 miles	480 miles
Source(s)	Alcock (2022b)	Howard et al. (2021) Aerospace Technology (2022)	Shojaei et al. (2022) Edmunds (2020)	Choubassi et al. (2016)	Pourrahmani and Jaller (2021) Qi et al. (2018) Wong (2017)

4.2. eVTOL flight energy and emission modeling

In addition to cost economics, the energy consumption of eVTOL-based package delivery is also of our interest. In this subsection, we characterize the energy use of an eVTOL flight, drawing information from Kasliwal et al. (2019). An eVTOL flight consists of five phases: takeoff hover, climb, cruise, descent, and landing hover (Fig. 2). The energy use of a flight is the sum of energy use in the five phases. In each phase, the energy use is calculated as the required power multiplied by the time spent in the phase.

Let us first look at the required power during hover, which is the most energy-intensive phase of an eVTOL flight profile. Based on the momentum theory, the hover power P_{hover} is specified as:

$$P_{\text{hover}} = \frac{mg}{\eta_h}\sqrt{\frac{\delta}{2\rho}} \tag{9}$$

where m is the eVTOL mass (which is the eVTOL weight plus the load weight), g is gravity constant, η_h is hover system efficiency, δ is disk loading, and ρ is sea-level air density. Following Kasliwal et al. (2019) and Zhao et al. (2022), we assume that the power used during takeoff hover and landing hover is the same.

For the cruise phase, the required power P_{cruise} is specified as:

$$P_{\text{cruise}} = \frac{mg}{\frac{L}{D}}\frac{V}{\eta_c} \tag{10}$$

where V is cruise speed, L/D is the lift-to-drag ratio, and η_c is cruise system efficiency.

For the climb and descent phases, we model them in the same way as cruise for three reasons (Kasliwal et al., 2019). First, the energy required in excess of cruise performance to climb and accelerate is approximately balanced out by the lower energy required during the descent and deceleration segment, so that assuming cruise performance for the whole duration is a good approximation. Second, limited data are available indicating how eVTOL speed and L/D would change throughout climb and descent. Third, the climb and descent phases are expected to take only a small fraction of the total flight time, especially in comparison with the cruise time. In this study, we consider that eVTOLs cruise at an altitude of 1000 ft with the rate of climb/descent at 1000 feet/minute. Thus, the climb and descent phases take only one minute each. The total energy consumption during climb, cruise, and descent is calculated by multiplying Eq. (10) by cruise time plus two minutes.

Table 3
Parameter values for eVTOL energy calculation.
Source: Kasliwal et al. (2019); Sabrewing Aircraft Company (2019); Aerospace Technology (2022)

Parameter	Symbol	Value (Unit)
Sabrewing Rhaegal B maximum gross weight (fully loaded)	m_{SR}	8836 lbs (4016 kg)
Beta Alia 250 maximum gross weight	m_{BA}	6000 lbs (2721 kg)
Gravitational acceleration	g	9.81 ($\frac{m}{s^2}$)
Cruise speed	V	150 mph (67.06 $\frac{m}{s}$)
Hover system efficiency	η_h	0.63
Cruise system efficiency	η_c	0.765
Cruise lift-to-drag ratio	$\frac{L}{D}$	17
Sea-level air density	ρ	1.225 ($\frac{kg}{m^3}$)
Disk loading	δ	450 ($\frac{N}{m^2}$)
Battery charge–discharge efficiency	CD	0.9
Primary-to-delivered electricity efficiency	PD	0.408

Overall, the required energy for a flight is computed by the following formula:

$$E = \frac{P_{\text{hover}} \cdot t_{\text{hover}} + P_{\text{cruise}} \cdot (t_{\text{cruise}} + 120)}{1000 \cdot CD \cdot PD} \tag{11}$$

where t_{hover} is hover time, which is assumed to be 30 s for both takeoff hover and landing hover. t_{cruise} is cruise time, obtained by dividing the line distance between the CDP and the vertiport of interest by eVTOL cruise speed. As mentioned above, two minutes (120 s) are added to capture the time for climb and descent. CD is the battery charge–discharge efficiency. PD is primary-to-delivered electricity efficiency. The values of the parameters in Eq. (9)–(11) are documented in Table 3.

It should be noted that for a round trip between the CDP and a given vertiport, the eVTOL is loaded during the outbound flight and empty during the inbound flight. As a result, the required power is calculated for the outbound and inbound flights separately. To be more specific, Eq. (9)–(10) will use different m's when calculating the power requirements of an outbound flight vs. an inbound flight, which are subsequently used by Eq. (11) to calculate the energy consumption of an outbound vs. an inbound flight. It is worth noting that the parameter values related to efficiency in Table 3 are the average values. The use of the average values is consistent with the focus of the study, which is to assess the overall attractiveness of eVTOL-based package delivery at the strategic level. For this kind of strategic-level assessment, detailed operational variations are often not needed. Nonetheless, when it comes to more detailed day-to-day operational planning, variations in the efficiency values should be explicitly taken into account.

Once the energy consumption of an eVTOL flight is obtained, CO_2 emissions of the flight are calculated next. In this study, we focus on CO_2 emissions associated with the generation and consumption of the energy used by eVTOL. As eVTOL flying consumes electricity and does not emit CO_2, CO_2 emissions occur only during the generation of electricity. Thus, the CO_2 emissions of a flight are calculated by multiplying the energy consumption by the emission factor of electricity generation. Given that our numerical application is in the Chicago metro region, the emission factor of electricity generation for the state of Illinois is used, which is 0.314 kg CO_2/kWh (Energy Information Administration, 2022).

4.3. Energy and CO_2 emission statistics of ground vehicles

Shifting focus to ground vehicles, we analyze the energy and CO_2 emission statistics for electric vans, gasoline vans, and crowdshipping cars. Like eVTOL CO_2 calculations, we focus on emissions from energy generation and consumption by ground vehicles. For electric vans, we use the Nissan EV200, which consumes 0.398 kWh/mile for line-haul and 0.233 kWh/mile for local travel (Electric Vehicle Database, 2021). CO_2 emissions from electric vans come from electricity production, calculated by multiplying these energy consumption values by the emission factor of 0.314 kg CO_2/kWh, resulting in 0.125 kg CO_2/mile for line-haul and 0.073 kg CO_2/mile for local travel.

Table 4
Ground vehicle energy consumption factors (kWh/mile).

	Line-haul	Local
Electric van	0.398	0.233
Gasoline van	1.248	1.404
Crowdshipping car	0.887	1.204

Table 5
Ground vehicle CO_2 emission factor (kg CO_2/mile).

	Line-haul	Local
Electric van	0.125	0.073
Gasoline van	0.408	0.459
Crowdshipping car	0.290	0.393

For gasoline vans and crowdshipping cars, one gallon of gasoline contains about 33.7 kWh of energy (Department of Energy, 2021). We compute energy consumption per mile by dividing the energy per gallon by the vehicle's miles-per-gallon (mpg) efficiency. Gasoline vans achieve 27 mpg for line-haul and 24 mpg for local travel (Edmunds, 2020), while gasoline cars get 38 mpg for line-haul and 28 mpg for local travel (Edmunds, 2022).

Table 4 lists these values. CO_2 emissions are calculated by summing the "well-to-use" emission factor of 2.136 kg CO_2/gallon (US Department of Energy, 2023b)[1] and the tailpipe emission factor of 8.997 kg CO_2/gallon (US Department of Energy, 2023a), for a total of 11.023 kg CO_2/gallon. Dividing by the appropriate mpg yields the per mile CO_2 emission factors for gasoline vans and crowdshipping cars, shown in Table 5 alongside the values for electric vans.

5. Numerical application

To demonstrate the use of the model and methods described in Sections 3–4, this section applies them to investigate a prospective eVTOL-based package delivery system in the north suburbs of the Chicago metro region. We first describe the numerical setup, including the study area, delivery demand, candidate vertiport sites, and related cost parameters. Then, the system design results are presented for multiple scenarios that vary by the eVTOL and ground vehicle types considered. The results are compared with a benchmarking scenario that uses only ground vehicles for delivery. The results include system total shipping cost, vertiport site selection, energy consumption, and CO_2 emissions. We also perform sensitivity analysis with respect to key system parameters. For the interest of space, the sensitivity analysis results are presented in Appendix. The modeling and analysis are performed on a Macbook Pro (MacOS) with Intel core i5 2.3 6 Hz dual-cone processor and 8 GB memory. The MILP is coded in Spyder Python 5.4.2 and solved by the SCIP optimization suite.

5.1. Numerical setup

5.1.1. The study area

The study area is the north suburbs of the Chicago metro region, shown in Fig. 3a. The area has 37 cities and villages, each treated as a delivery zone. In this area, major shopping centers are the candidate sites for vertiport construction. Such shopping centers typically have large parking spaces, of which a small fraction could be converted for vertiport construction. Fig. 3b shows locations of the 13 major shopping centers that are outside of the eVTOL no-fly zones (which are further described below) in the study area.

[1] In doing so, the gasoline type of E10, which blends up to 10% ethanol and is the most widely used in Illinois and the US, is assumed.

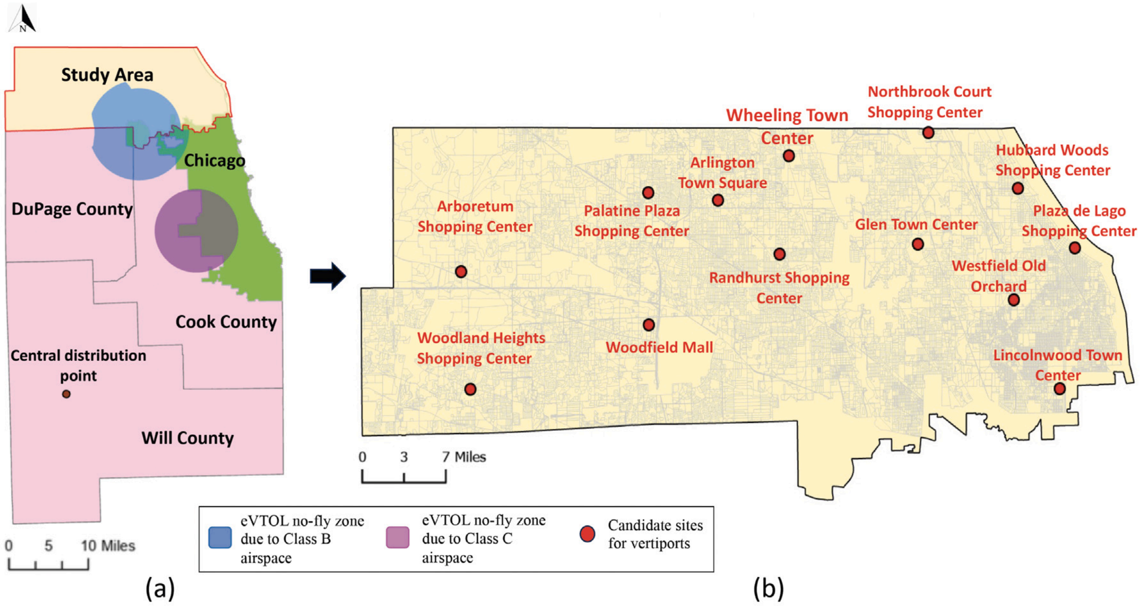


Fig. 3. (a) The study area and its location in the Chicago metro region, and (b) candidate sites for vertiports in the study area.

According to the 2017 National Household Travel Survey, the study area has over 440,000 households and generates 70,000 package delivery requests on an average day (US DOT, 2017). We assume that the LSP under study is responsible for delivering 20,000 packages per day. Considering just a portion of the total delivery requests is sensible, as it is likely that the study area is served by multiple LSPs. Moreover, even with eVTOL-based package delivery, there may still be a sizeable portion of packages delivered by traditional ground-based modes. While detailed information on the spatial distribution of the package delivery demand in the study area is not available, the best guess we could make is to spatially distribute the demand over the 37 cities and villages in the study area in proportion to the populations of the cities and villages. We consider that all packages are sent from a CDP located in Will County, an area that is southwest of Chicago and has many logistics facilities (Fig. 3a). The location is a Walmart fulfillment center. Within and surrounding the fulfillment center, abundant land and space exist making it appealing for eVTOL operations.

It is worth noting that airspace constraints are present the study area and more generally in the Chicago metro region, due to the presence of two major airports: O'Hare International Airport and Midway International Airport. These two airports are associated with Class B and Class C controlled airspace. The Class B airspace in the study area, which is centered around O'Hare, has a layered, upside-down wedding cake structure (FAA, 2024). The first (and innermost) layer, extending from the surface to 10,000 ft Mean Sea Level (MSL), has a circle-like shape with a horizontal radius of 5–6 nautical miles. The next layer extends from 1900 ft MSL to 10,000 ft MSL with a 10-nautical mile radius, followed by additional layers with greater starting MSLs and radii (Sky Vector, 2023). Recall that the eVTOL cruise altitude is considered to be at 1000 ft. Thus, it suffices to consider the first (innermost) layer of the Class B airspace as the eVTOL no-fly zone at this cruise altitude. Also, on the surface no candidate vertiport sites should be within the area delimited by the first (innermost) layer. This results in 13 major shopping centers considered as the candidate vertiport sites, as indicated by the red dots in Fig. 4.

In addition to the Class B airspace around O'Hare, we further consider the Class C airspace around the Midway International Airport. While the airport is not in the study area, the presence of Class C airspace can present air traffic control challenges as well if eVTOLs fly through the airspace from the central distribution point located in the south of the Chicago metro region to the vertiports in the north of the region. For this reason, we also consider the Class C airspace as an eVTOL no-fly zone. For the Class C airspace around Midway, the first (and innermost) layer extends from the surface to the lower boundary of the O'Hare Class B airspace, with a 5-nautical mile radius. The next layer extends from 1900 ft MSL (for the part above Lake Michigan, the layer extends from 2300 ft) also to the lower boundary of the O'Hare Class B airspace, with a 10-nautical mile radius (Sky Vector, 2023). As eVTOLs cruise at an altitude of 1000 ft, again it suffices to consider the first (innermost) layer of the Class C airspace as the eVTOL no-fly zone at this cruise altitude.

Given the two eVTOL no-fly zones around O'Hare and Midway, the shortest eVTOL flying path from the central distribution point to each of the candidate vertiport sites is no longer a straight line but needs to circumvent the no-fly zones. The corresponding distances are calculated using ArcGIS Pro.

5.1.2. Vertiport cost parameters

When a vertiport is built on the parking space of a shopping center, we expect relatively minor infrastructure upgrades on the converted parking spaces, such as pavement resurfacing, sign marking, and possibly installation of some communication equipment. Moreover, the size of a vertiport is expected to be small given the early stage of eVTOL-based package delivery. Johnston et al. (2020) provides different plausible vertiport sizes. We consider the smallest vertiport size in that study, which consists of one takeoff/landing pad and two pads for parking, charging, and maintenance. The total footprint of a vertiport will be about 100 ft × 60 ft. Following Yedavalli and Cohen (2022), the construction cost of a vertiport of this size is assumed to be $200,000.

Besides construction cost, operating a vertiport incurs daily operating cost, estimated to be in the range of $600,000–900,000 per year for a vertiport of the size we consider (Johnston et al., 2020). Given that the operations of a vertiport for package delivery use are simpler than those for passenger use — involving mainly package loading/unloading versus passenger boarding/alighting, waiting, ticketing, and security checks, we adopt the lower-bound value of $600,000. Adding the annual operating cost with the annualized cost associated with constructing a vertiport, for which we assume a service life of 30 years, 300 days of operations per year, and a discount factor of 3%, yields a vertiport daily cost of $2034, *i.e.*, $c_{i,1} = \$2,034$.

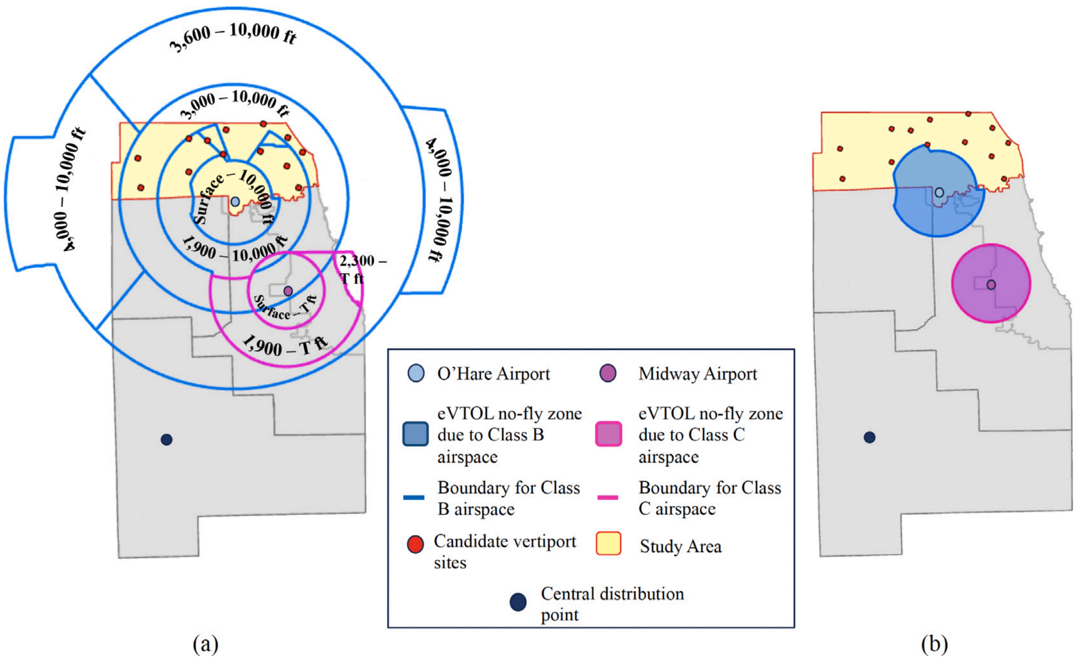


Fig. 4. (a) Classes B and C airspace in the Chicago metro region, and (b) identification of the eVTOL no-fly zones.

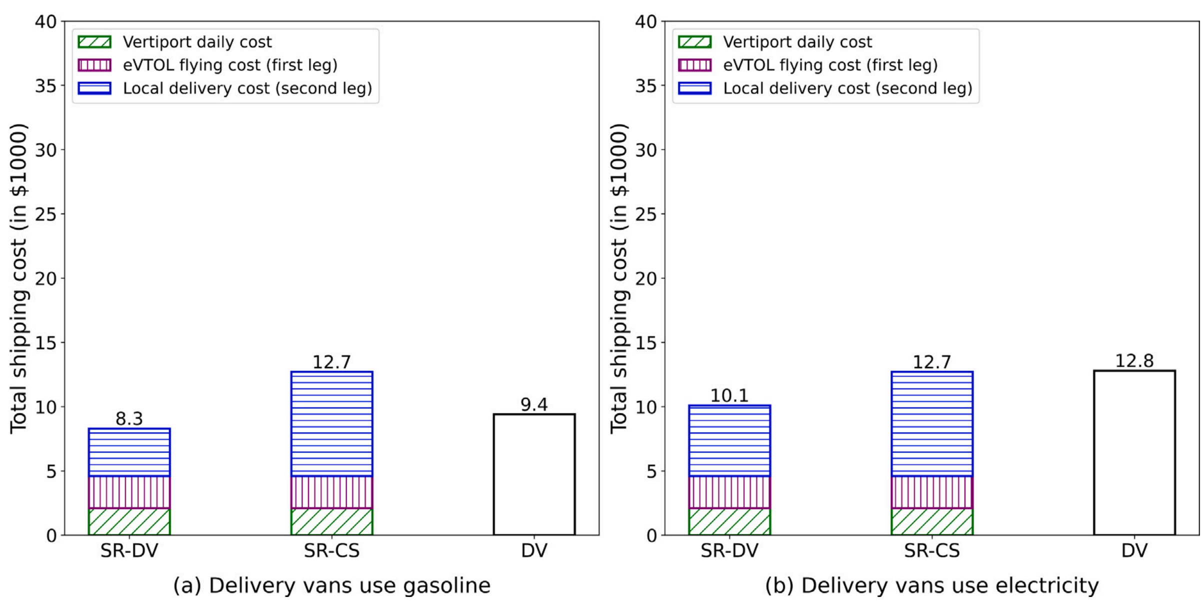


Fig. 5. Total shipping cost for the Sabrewing Rhaegal eVTOL (SR)-based scenarios and the van-only scenario.

The above daily cost pertains to vertiports that are newly built. At the fulfillment center, a larger vertibase will also be needed. Following Johnston et al. (2020), the footprint of a vertibase is about 230 ft × 100 ft, comprised of three takeoff/landing pads and six parking pads. The construction cost for a vertibase is $500,000. As eVTOLs replace some ground vehicles for delivery, the incurred operating cost associated with the vertibase is assumed to be canceled out by the cost savings due to no longer using traditional ground vehicle-based delivery. Again considering a discount factor of 3%, a service life of 30 years, and 300 days of operations per year, the vertibase daily cost at the fulfillment center is $85, *i.e.*, $c_3 = \$85$.

5.2. Total shipping cost

Because two eVTOL types and three ground vehicle options are considered, we present results from six scenarios. These six scenarios are short-named as: SR-DV (DVs are either gasoline powered or electric; thus two scenarios), SR-CS, BA-DV (DVs are either gasoline powered or electric; thus two scenarios), and BA-CS. SR denotes Sabrewing Rhaegal, BA denotes Beta Alia, DV means delivery van, and CS means crowdshipping. Apart from the six eVTOL-based package delivery scenarios, a benchmarking scenario, termed "DV", is considered as well where delivery vans are used to move packages from the fulfillment center directly to customers. To estimate the total shipping cost of this scenario, we use continuous approximation assuming that each van is

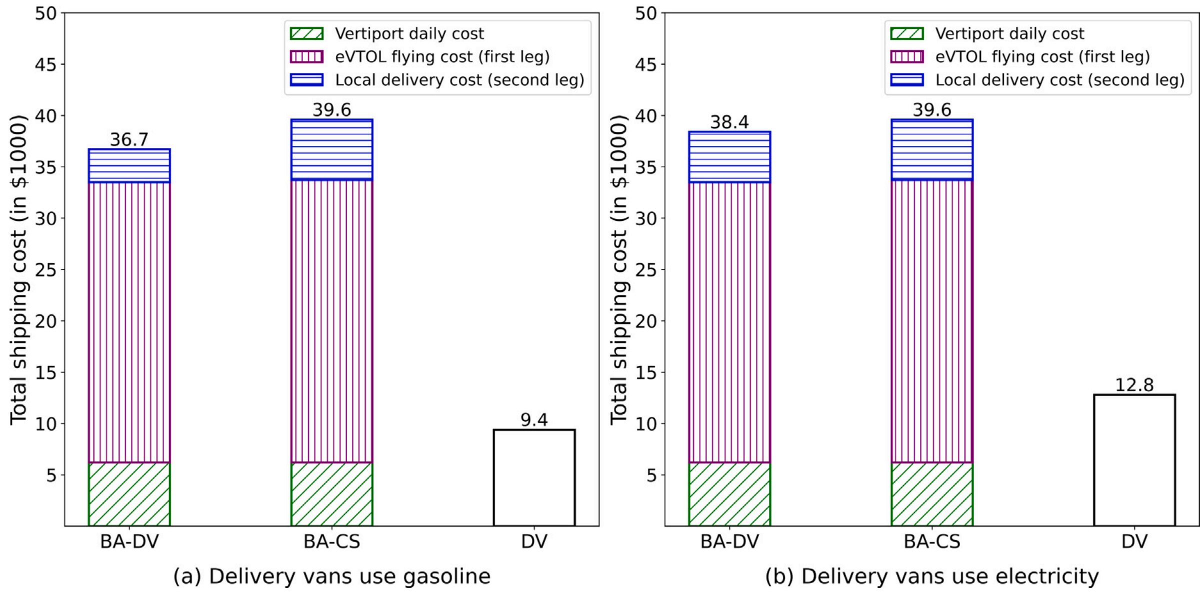


Fig. 6. Total shipping cost for the Beta Alia eVTOL (BA)-based scenarios and the van-only scenario.

fully loaded and dispatched for delivery in a specific zone. A delivery van will first travel a line-haul distance from the fulfillment center to the center of the intended delivery zone, and then travel locally visiting the customers in the zone. The total shipping cost can be estimated by $\sum_{j\in\mathbb{Z}}(c_0\frac{2\bar{\rho}_j Q_j}{\kappa_2}+0.57c_0'\sqrt{\frac{A_j Q_j}{\bar{\omega}}})$. This expression is similar to the third summation term in the objective function (1), except that $\bar{\rho}_{ij}$ is changed to $\bar{\rho}_j$ which represents the average distance from the fulfillment center to zone j. When computing the routing cost, the distance traveled for the ground modes uses the shortest distance path on the actual road network. eVTOLs are assumed to fly point-to-point between the fulfillment center and each of the vertiport sites.

The total shipping cost results are reported in Figs. 5–6. Fig. 5 reports SR-DV and SR-CS along with DV scenarios. Fig. 6 reports BA-DV and BA-CS along with DV scenarios. In each figure, the left part corresponds to using gasoline powered delivery vans, while the right part corresponds to using electric vans. Note that the SR-CS and BA-CS scenarios do not involve delivery vans but only passenger cars. Thus, the same SR-CS scenario is presented in Fig. 5a and Fig. 5b. Similarly in Fig. 6. All the scenarios involving eVTOLs can be solved within four seconds. The DV scenario does not require solving the optimization model. As a result, its solution is obtained much faster, within 0.1 s.

We find that, when gasoline vans are considered, using Sabrewing Rhaegal-gasoline van (SR-DV) yields the lowest total shipping costs ($8200 per day as shown in Fig. 5a). The reasons are as follows. First, Sabrewing Rhaegal has a much lower per mile operating cost than Beta Alia, while having almost four times more carrying capacity. Second, for ground transportation, while per mile operating cost by delivery van is slightly higher than crowdshipping, a delivery van can load way more packages than a crowdshipping car. Consequently, the cost per package using a delivery van will be lower. Because of the greater carrying capacity of Sabrewing Rhaegal than a delivery van, SR-DV also yields a lower total shipping cost than using delivery vans only (DV), by 14%. Similar findings can be said when electric vans are used (Fig. 5b). In particular, using SR-DV with electric vans yields a total shipping cost that is 25% lower than using electric vans only. Because of the higher unit operating cost (see Table 2), the total shipping cost is increased when using electric vans compared to using gasoline vans, as displayed between Fig. 5a and Fig. 5b.

Overall, while the total shipping cost is influenced by eVTOL and ground vehicle choices, Figs. 5–6 show that eVTOL choice is the more influential factor. Sabrewing Rhaegal is the better eVTOL choice given its greater carrying capacity and lower unit operating cost than Beta Alia and delivery vans. In contrast, the carrying capacity of a Beta Alia eVTOL is only comparable to a delivery van, while the unit operating cost is much higher, making it not competitive compared to van-only delivery. The distinction can be attributed to the different designs of Sabrewing Rhaegal and Beta Alia: as mentioned before, Sabrewing Rhaegal can be viewed as a large drone with no pilot onboard, whereas Beta Alia is piloted with a lift-plus-cruise design and tailored for dual use of passenger and freight transportation. The different designs suggest greater avionics and mechanical sophistication and consequently higher operating cost for Beta Alia. In contrast, drone-like Sabrewing Rhaegal, which is cheaper to operate, offers a more appealing alternative to van-only package delivery.

5.3. *Vertiport sites and flight distribution among the vertiports*

In addition to the first- and second-leg operating costs, Figs. 5–6 show that the scenarios incur different costs for vertiport construction and operations as well. This results from different numbers of vertiports built in different scenarios. Conceptually, there exists a trade-off between building vertiports and vehicle (eVTOL and ground vehicle) operations: having more vertiports can help reduce vehicle travel distances and consequently vehicle operating cost; however, this incurs more costs for vertiport construction and operations. When Sabrewing Rhaegal is used, because of its larger carrying capacity than Beta Alia, fewer flights will be flown, which lead to cheaper eVTOL flying cost and a smaller number of vertiports constructed. This is shown in Figs. 7–8. Note that for the SR-DV scenario, the vertiport choice and the distribution of eVTOL flights to the vertiports are the same, regardless of whether delivery vans are gasoline powered or electric.

Figs. 7 shows that under the SR-based scenarios, only one vertiport is constructed at Woodfield Mall. The total number of eVTOL flights is always 21. Under the BA-based scenarios, the total number of eVTOL flights is substantially, increased from 21 to 79, as Beta Alia has a smaller carrying capacity than Sabrewing Rhaegal. Moreover, because flying Beta Alia eVTOL is more expensive than flying Sabrewing Rhaegal, it is not surprising that more (three instead of one) vertiports are constructed which help reduce the flying distance, at Lincolnwood Town Center, Woodfield Mall, and Woodland Heights Shopping Center, as shown in Fig. 8. Between the BA-DV and the BA-CS scenarios, the distribution of flights among the three vertiports varies, due to the difference in carrying capacity and operating cost of delivery vans

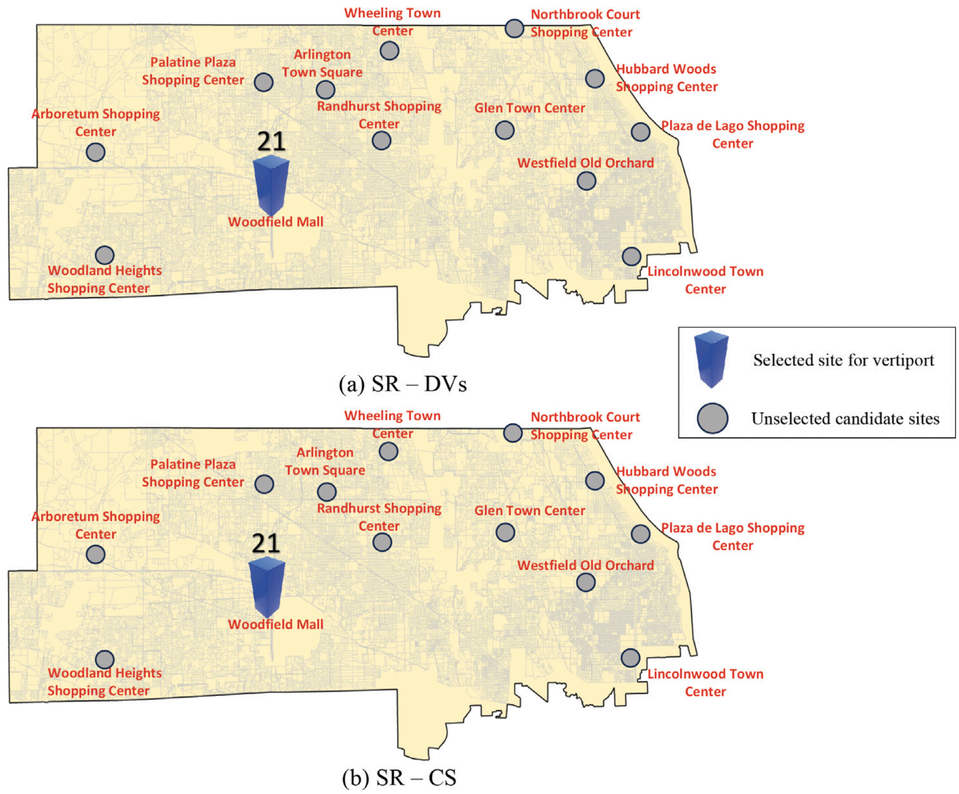


Fig. 7. Selected candidate site for vertiport building and the number of eVTOL flights to the vertiport (SR-based scenarios).

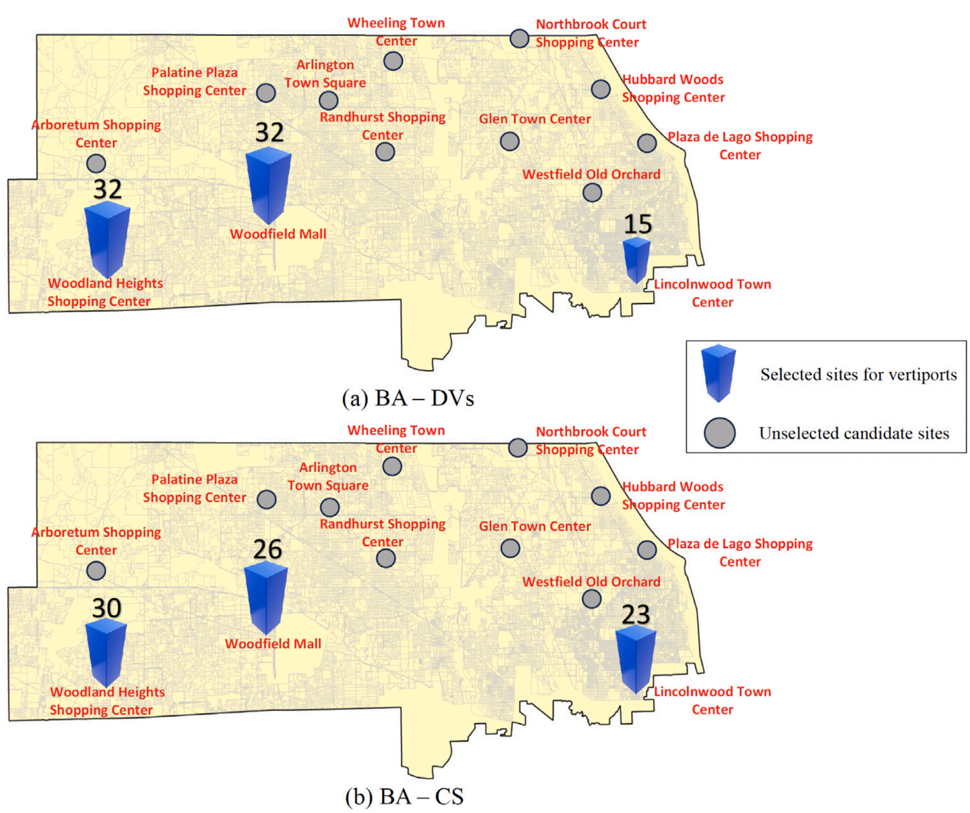


Fig. 8. Selected candidate sites for vertiports building and the number of eVTOL flights to the vertiports (BA-based scenarios).

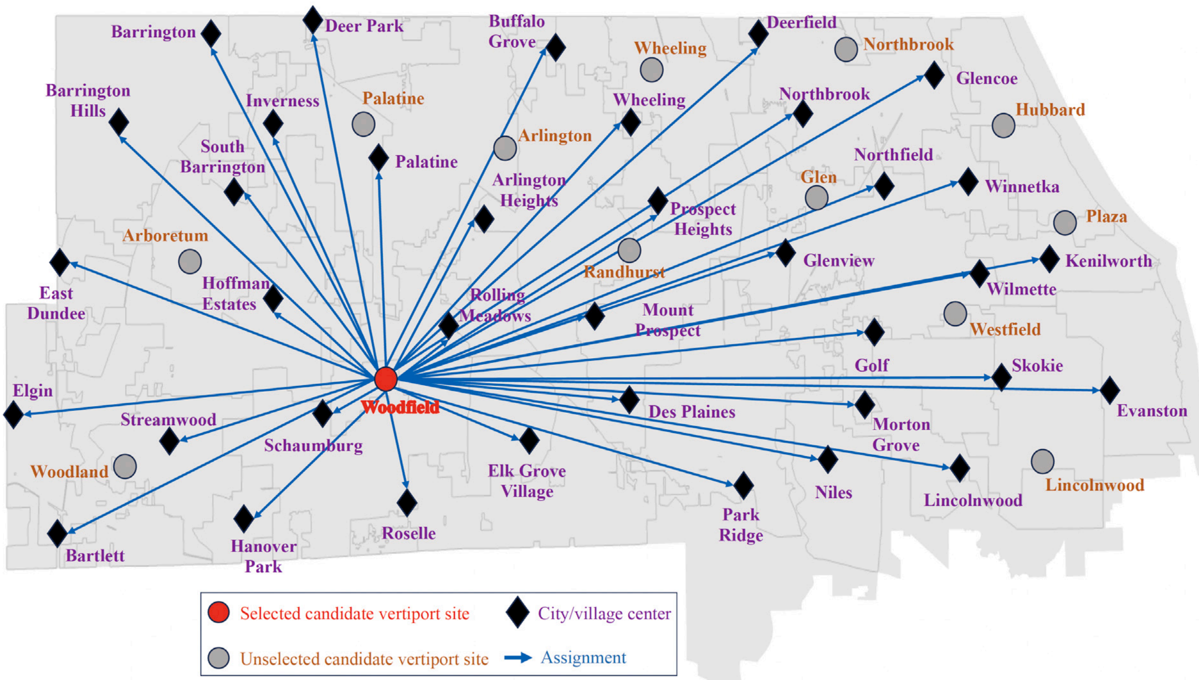


Fig. 9. Vertiport-city/village assignment for the SR-based scenarios.

and crowdshipping cars. Under all scenarios, the maximum number of eVTOL flights accommodated by a vertiport is 32. Given that the operation is for one day, accommodating up to 32 flights is unlikely to impose any capacity constraints at a vertiport (with eight operation hours in a day, on average a vertiport will only handle four eVTOL flights per hour).

Figs. 9–11 illustrates the assignment of the 37 cities/villages to the constructed vertiports under the various scenarios. In the figures, the black diamonds denote the geographic centers of the cities/villages. For the candidate vertiport sites, short names are presented for the purpose of figure clarity.[2] The three SR-based scenarios (SR-DV with gasoline vans, SR-DV with electric vans, and SR-CS) yield the same assignment results, as shown in Fig. 9. When Beta Alia is used, the assignment results differ somewhat by the second-leg transportation mode choice, as shown in Fig. 10 (second leg uses delivery vans) and Fig. 11 (second leg uses crowdshipping cars). Given that flying eVTOLs is expensive and the fulfillment center is located in the south of the Chicago metro region (Fig. 3), the chosen vertiports are always located at the southern end of the study area, which are closer to the fulfillment center. Most cities/villages are assigned to their closest vertiport. A few exceptions exist (*e.g.*, Schaumburg assigned to Woodland instead of Woodfield in Figs. 10–11), which is not surprising as minimizing total shipping cost needs to account for not only the second leg ground transportation cost but also the cost incurred in the first leg of eVTOL flying.

With the city/village-vertiport assignment results, the average package delivery time under the different scenarios are further estimated and compared. In doing so, we assume on average 20 min of package loading time at the CDP and another 20 min of package transfer time at the vertiport. The eVTOL flying time follows the flight profile specified in Section 4.2. For the average time a package spends during a ground vehicle tour in the second leg, it is estimated to be half of the sum of the vehicle tour time and stopping times during the tour, for which we assume that each stop takes two minutes. The number of stops in a ground vehicle tour is estimated at $\frac{\kappa_2}{\bar{\omega}}$.

Table 6
Average package delivery time under different scenarios.

Scenario	Delivery time (min)
SR-DV (gasoline)	87.4
SR-DV (electric)	87.7
SR-CS	86.8
BA-DV (gasoline)	78.9
BA-DV (electric)	79.5
BA-CS	77.4
DV (gasoline)	146.8
DV (electric)	148.2

Table 6 reports the estimated average package delivery time under the different scenarios. As eVTOLs fly at a much faster speed than delivery vans travel on the ground, it is not surprising that the eVTOL-based scenarios result in reduced delivery time compared to van-only scenarios, by over 40%. The difference between SR- and BA-based scenarios is due to the difference in vertiport locations, which results in different air and ground travel distances. Given an eVTOL type, the time difference among using gasoline and electric delivery vans and crowdshipping cars in the second leg stems from the different carrying capacities of these vehicles, which lead to different lengths of a vehicle tour and the number of stops in a tour. But overall, these differences are small compared to the differences between eVTOL-based and van-only scenarios.

5.4. Energy consumption

Following the description in Section 4.2, the energy consumption of each eVTOL flight is computed. For a given scenario, we sum the energy consumption of the individual flights to obtain the total eVTOL energy consumption. The energy consumption for ground vehicles is

[2] Their corresponding full names are: Arboretum Shopping Center (Arboretum), Woodfield Mall (Woodfield), Westfield Old Orchard (Westfield), Arlington Town Square (Arlington), Northbrook Court Shopping Center (Northbrook), Randhurst Shopping Center (Randhurst), Wheeling Town Center (Wheeling), Glen Town Center (Glen), Hubbard Woods Shopping Center (Hubbard), Plaza del Lago Shopping Center (Plaza), Woodland Heights Shopping Center (Woodland), Palatine Plaza Shopping Center (Palatine), and Lincolnwood Town Center (Lindcolnwood).

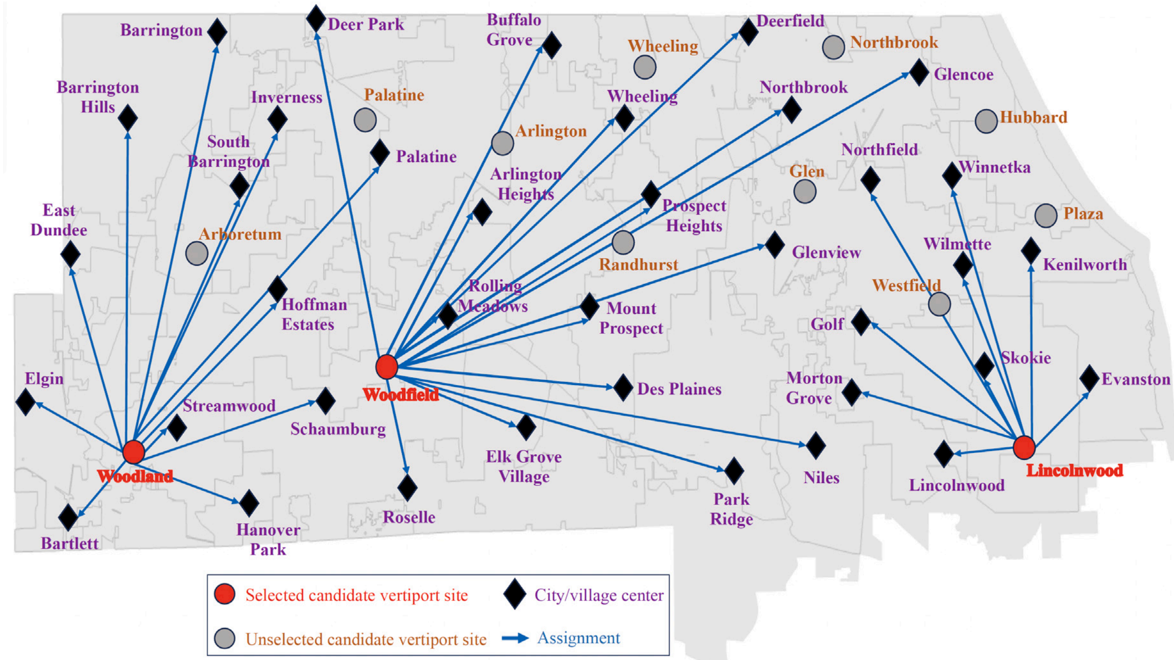


Fig. 10. Vertiport-city/village assignment for the BA-DV scenario (both gasoline and electric vans).

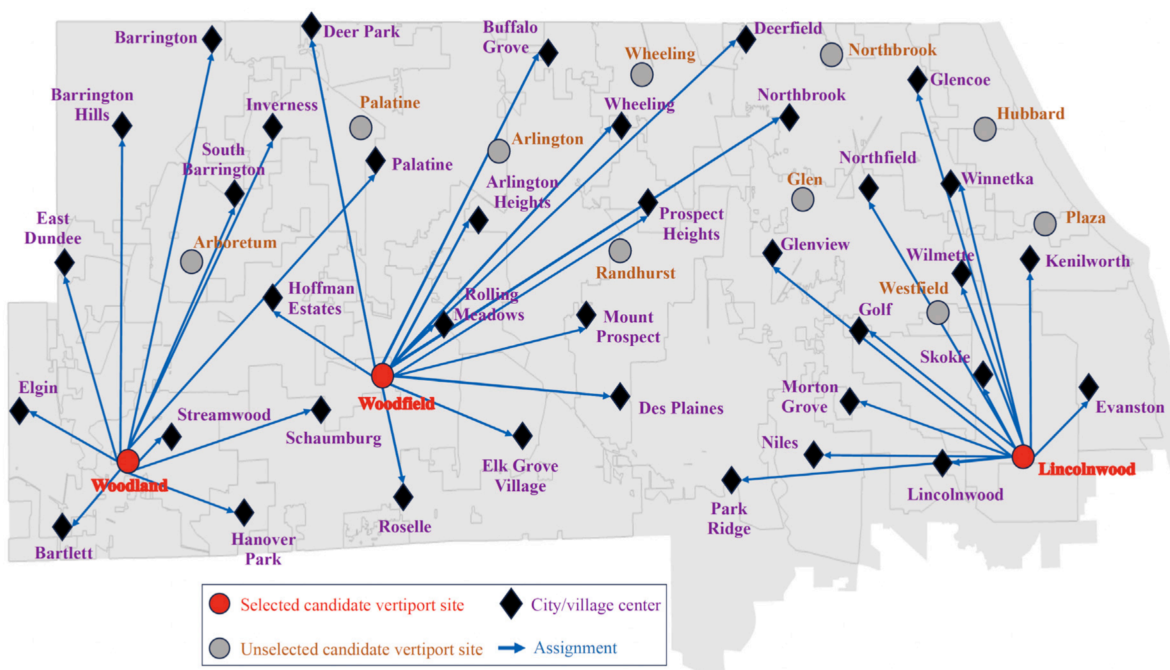


Fig. 11. Vertiport-city/village assignment for the BA-CS scenario.

calculated by multiplying the appropriate energy consumption factors in Section 4.3 by the corresponding ground vehicle miles traveled in line-haul and local travels, and then summing the energy consumption in the two parts. The system energy consumption for all scenarios is shown in Fig. 12.

Two observations are worth noting in Fig. 12a. First, for the first leg, the energy consumption by Sabrewing Rhaegal is much lower than Beta Alia (only about one third). This reaffirms the advantage of using Sabrewing Rhaegal, which has a drone-like design and a larger carrying capacity. Second, using Sabrewing Rhaegal along with ground vehicles for the second leg will consume less overall energy than using gasoline vans only. This is invariant to whether the second leg uses vans or crowdshipping cars, although using vans, which have larger carrying capacity, leads to lower energy consumption. However, the finding becomes different if electric vans are used (Fig. 12b). If vans are electric, the van-only delivery scenario results in the minimum energy consumption due to substantially reduced energy consumption factors, as shown earlier in Table 4.

This finding is not surprising to us, as flying eVTOLs in the air requires greater energy intensity. Following the calculation in Section 4.2, the required power for cruise for a fully loaded Sabrewing Rhaegal flight is 203.1 kW. Under the assumption of cruising at 150

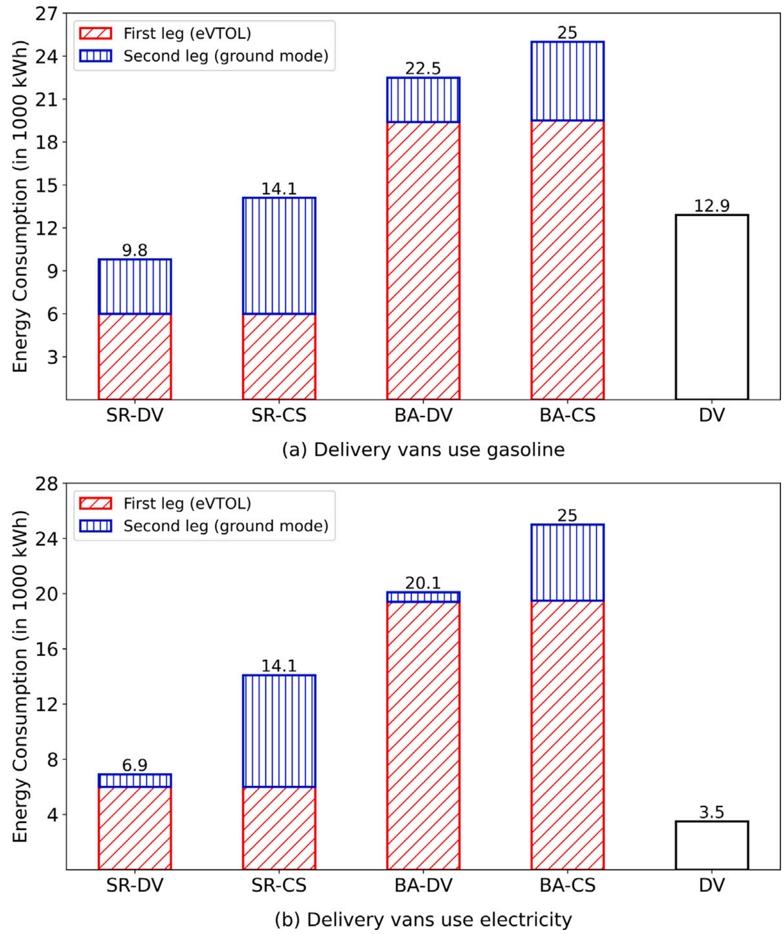


Fig. 12. Energy consumption under different scenarios.

mph, the energy use is 1.35 kWh per mile, almost four times the per mile energy use of an electric van (0.35 kWh per mile). On the other hand, the ratio of the carrying capacity of a Sabrewing Rhaegal flight and an electric van is less than four times. Moreover, an eVTOL flight involves the non-cruise phases of takeoff/landing hover, climb, and descent, which consume additional energy. Fig. 13 shows the energy consumption breakdown for a Sabrewing Rhaegal flight from the fulfillment center to the vertiport site that is chosen under the SR-based scenarios (Fig. 13a), and for a Beta Alia flight from the fulfillment center to one of the vertiport sites chosen under the BA-based scenarios (Fig. 13b). It can be seen that the four non-cruise phases, despite their very short time, account for nearly 30% of the total energy consumption of a flight. This is because of the greater power required during the non-cruise phases. For example, the required power during hover and cruise for a fully loaded Sabrewing Rhaegal flight is 847.5 kW and 203.1 kW, respectively. For a Beta Alia flight, the required power during hover and cruise is 574.2 kW and 137.6 kW, respectively. The power ratio is always greater than four.

5.5. CO_2 emissions

As CO_2 emissions are closely related to energy consumption, the estimation of system CO_2 emissions gives a similar picture as energy use, as shown in Fig. 14. Fig. 14(a) corresponds to using gasoline vans, while Fig. 14b reports the results of vans being electric. When gasoline vans are used, the SR-based scenarios yield lower CO_2 emissions than the van-only scenario. Using Sabrewing Rhaegal for the first leg and delivery vans for the second leg generates the minimum emissions, of 3200 kg per day. The use of Beta Alia with crowdshipping generates the highest CO_2 emissions per day of 8000 kg. However, if vans are electric, the van-only scenario becomes the least emission scenario, with the total CO_2 emission at 1100 kg per day. Thus, while using the drone-like Sabrewing Rhaegal can reduce CO_2 emissions compared to gasoline van use, it will not be environmentally competitive against electric vans, at least based on the current technologies.

6. Discussions and conclusion

While much of the existing AAM research focuses on using eVTOLs for passenger movement, limited attention has been paid to using eVTOLs for package delivery. Our paper fills this gap by developing and adopting methods and performing an extensive numerical application to assess the attractiveness of eVTOL-based delivery. The developed methods seek to design the eVTOL-based delivery system in a cost-optimal manner, while also estimating the energy consumption and CO_2 emissions. The numerical application implements the methods for package delivery in the north suburbs of the Chicago metro region. Multiple scenarios are examined, to understand how system total shipping cost, energy consumption, and CO_2 emissions would be and change under the scenarios.

We find that Sabrewing Rhaegal, which has a drone-like, pilotless, and freight-dedicated design with a large carrying capacity, will be quite attractive compared to piloted, passenger-freight dual use Beta Alia eVTOL. The drone-like design, together with the removal of an onboard pilot, results in reduced aircraft weight and operating cost.[3]

[3] The aircraft weights without package loading for Sabrewing Rhaegal and Beta Alia are 3436 and 4600 lbs respectively, by subtracting the carrying capacity in Table 2 from the maximum gross weight in Table 3.

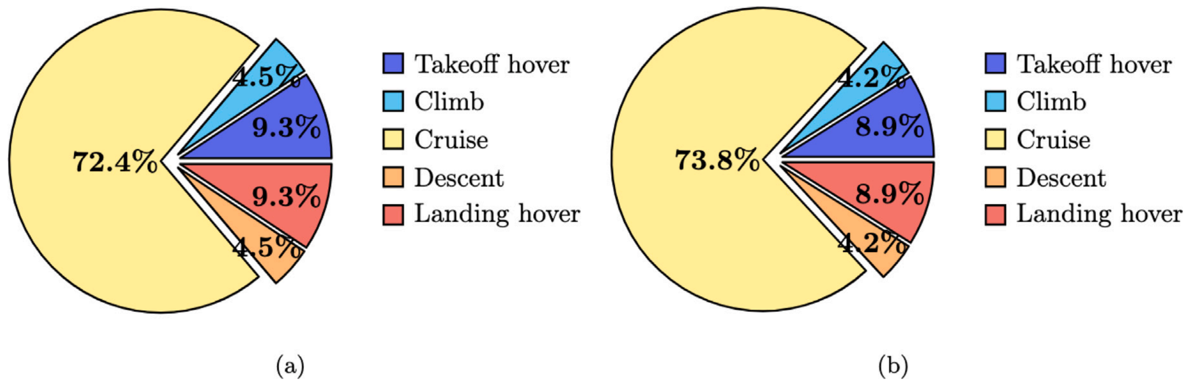


Fig. 13. Energy consumption breakdown for (a) fully-loaded Sabrewing Rhaegal flight profile from the fulfillment center to the vertiport at Woodfield Mall and (b) fully-loaded Beta Alia 250 flight profile from the fulfillment center to the vertiport at Lincolnwood Town Center.

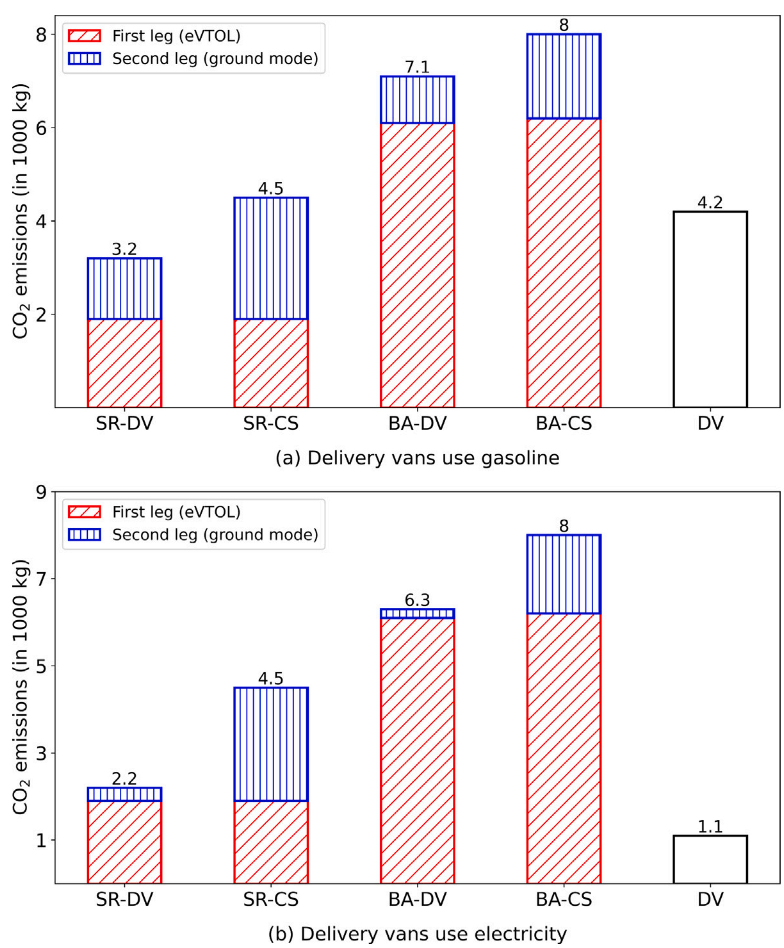
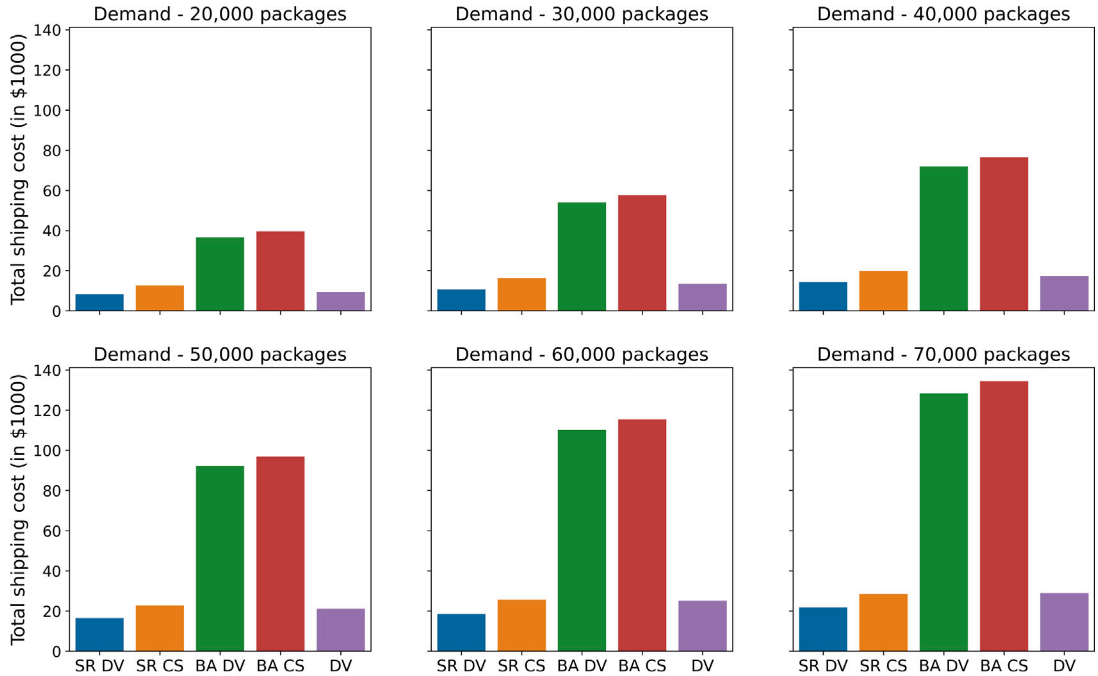


Fig. 14. CO_2 emissions under different scenarios.

The reduced aircraft weight leads to lower energy consumption and CO_2 emissions per unit weight carried for the same distance traveled. Thus, eVTOL-based freight policies should be directed to facilitate and encourage the adoption of pilotless cargo eVTOLs, including enabling clear and expedited cargo eVTOL certification pathways. Public investment in further developing and commercializing drone-like, pilotless, and freight-dedicated eVTOLs and pilot demonstrations will also help accelerate the adoption and scale-up.

Compared to the cost advantage, the implications of eVTOL-based delivery for energy use and CO_2 emissions seem more uncertain. If delivery vans are gasoline powered, eVTOL-based delivery will be a more attractive alternative to van-only delivery. However, with the current trend of electrification, delivery vans are likely to be electrified, in which case eVTOL-based delivery would not be attractive even in the best case (Sabrewing Rhaegal in combination with delivery vans). This is attributed to the high energy intensity of eVTOL operations. While LSPs and eVTOL manufacturers are pursuing sustainability while considering eVTOLs (*e.g.*, Randall, 2021; Aerial eVTOL, 2024; Texeira, 2024 Texeira2024), compelling advantages must be demonstrated over electric van-based delivery for large-scale adoption of eVTOL-based delivery. For this, future R&D should focus on enhancing the energy efficiency of eVTOLs. Given that eVTOL-based delivery already shows a plausible cost advantage over van-only delivery, public policies



(a) Delivery vans use gasoline

(b) Delivery vans use electricity

Fig. A.15. Total shipping cost analysis under different demands.

should better align the economic and sustainability outcomes of eVTOL-based delivery, *e.g.*, by enacting higher eVTOL energy use standards to encourage further energy efficiency of eVTOLs.

Moreover, by accounting for the potential interference of eVTOL operations with commercial air traffic in the vicinity of the busy airports, in this study we preclude eVTOLs from flying into specific classes (B and C) of the airspace. As an alternative to this approach, AAM corridors could be designed and deployed that transit airspace classes. Within an AAM corridor, it is expected that industry-defined and regulator-approved practices will be performed to direct the manner of interactions across different airspace users (FAA, 2023). As AAM continues to develop, air traffic operational concepts, rules, and procedures will also evolve toward highly cooperative, smooth, and automated management of mixed air traffic. In view of these, future modeling of the attractiveness of eVTOL-based package delivery may further incorporate the extent to which eVTOL traffic will be efficiently routed, managed, and integrated into the national airspace system. This can be a fruitful area for future research.

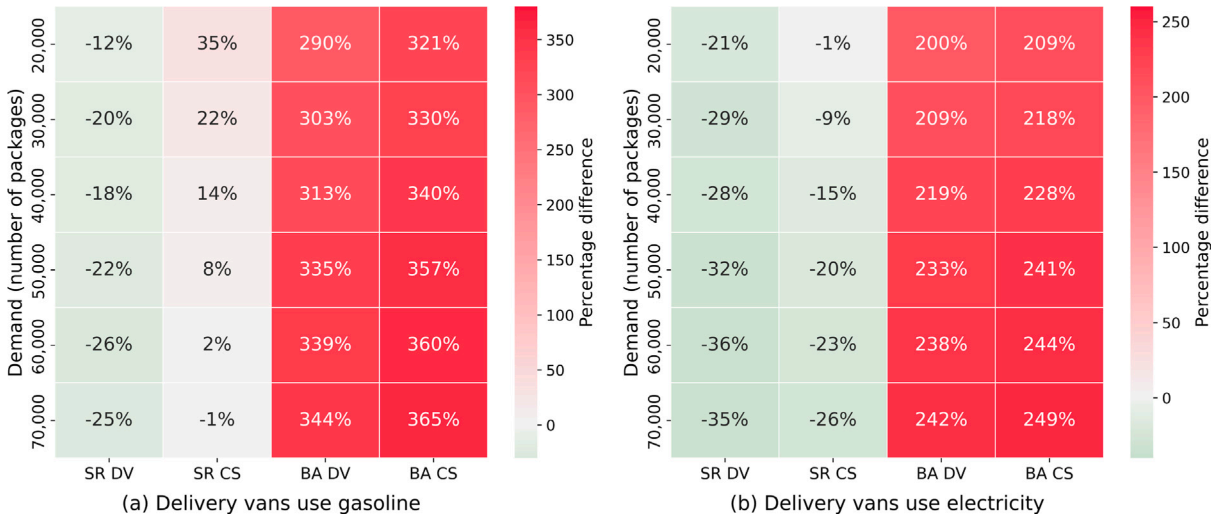


Fig. A.16. Percentage difference of total shipping cost between eVTOL-based scenarios and van-only scenario, under different demand levels.

In addition to the above, the research can be extended in a few other directions. First, in our system design, delivery zones are the same as cities and villages in the study area. Alternative delivery zone sizes and shapes could be conceived that may further improve delivery system performance. Second, efforts can be directed to collecting further information on eVTOL unit operating cost, including what cost components are considered, which will enable more accurate and detailed cost comparison across different eVTOL types. Third, the focus of the current study is on assessing the attractiveness of eVTOL-based delivery under regular eVTOL operations, not what would happen if eVTOLs cannot fly. This can present a limitation as irregular operations are inevitable, especially in adverse weather-prone regions like Chicago. In such situations, a backup plan, *e.g.*, using only ground vehicles for delivery, would need to be implemented. How to incorporate irregular operations in the attractiveness assessment would be another interesting direction for future research.

CRediT authorship contribution statement

Daniel Perez: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Bo Zou:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Nahid Parvez Farazi:** Writing – review & editing, Investigation.

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Appendix. Sensitivity analysis

The performance of the proposed eVTOL-based delivery system depends on values of the system parameters. Given that the system does not exist, the parameter values are subject to uncertainties. In this appendix, we examine how the system performance would change in response to three key system parameters: demand, unit eVTOL operating cost, and eVTOL power requirement.

A.1. eVTOL package delivery demand

Recall in Section 5.1 that we assume 20,000 package deliveries per day, while the study area generates 70,000 daily package delivery requests. In this subsection, we vary the package delivery demand from 20,000 to 70,000 in an increment of 10,000. Fig. A.15 illustrates the resulting changes in total shipping cost. Comparing a specific bar across different sub-figures, we can see that for all scenarios, the total shipping cost increases linearly with the package delivery demand.

As the attractiveness of eVTOL-based delivery against van-only delivery is of our particular interest, we further plot the heat map in Fig. A.16 which shows the percentage difference of the total shipping cost of each eVTOL-based scenario from the total shipping cost of the van-only scenario. It is observed that, as demand increases, SR-based scenarios become more competitive than the van-only scenario, as evidenced by the more negative percentages. For instance, when gasoline vans are used, the total shipping cost under the SR-DV scenario will change from 12% lower to 25% lower than the total shipping cost under the van-only scenario, as demand increases from 20,000 to 70,000.

The increased cost advantage of the SR-DV scenario as demand increases can be attributed to three factors. First is the fixed vertiport/vertibase cost. When a vertiport/vertibase is in place, the daily cost is a constant. Thus, as long as the vertiports remain the same, the vertiport daily cost borne by each package will be smaller as demand increases. This is indeed our case. For example, for the SR-DV scenario, the number of vertiports is the same for demand levels at 20,000 and 30,000 (one vertiports) and for demand levels at 40,000, 50,000, and 60,000 (two vertiports). Second, when we have more vertiports as demand increases, the average flying distance of an eVTOL flight is reduced, which reduces the total shipping cost. Third, because the second-leg cost is nonlinear with respect to Q_j (see the third summation term in the objective function (1)), demand increase can also trigger reassignment of zones to vertiports to reduce the total shipping cost further. For example, in the SR-DV scenario, 28 eVTOL flights fly to Woodfield Mall and 13 to Westfield Mall when the demand is 40,000. When the demand increases to 50,000, the number of vertiports remains the same (two). However, 32 eVTOL flights fly to Woodfield Mall and 20 to Westfield Mall.

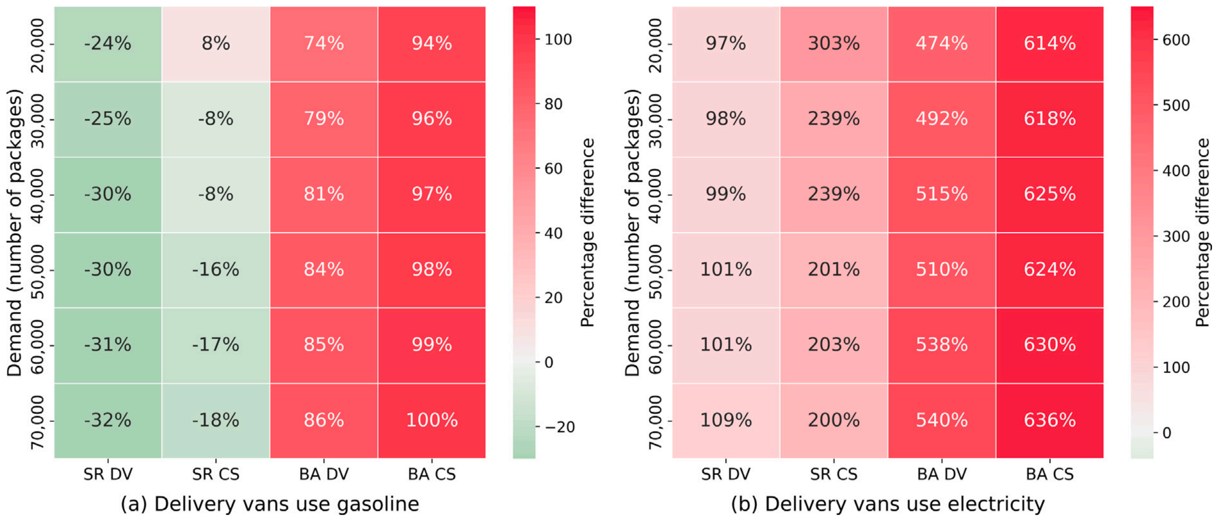

Fig. A.17. Percentage difference of energy consumption between eVTOL-based scenarios and van-only scenario, under different demand levels.

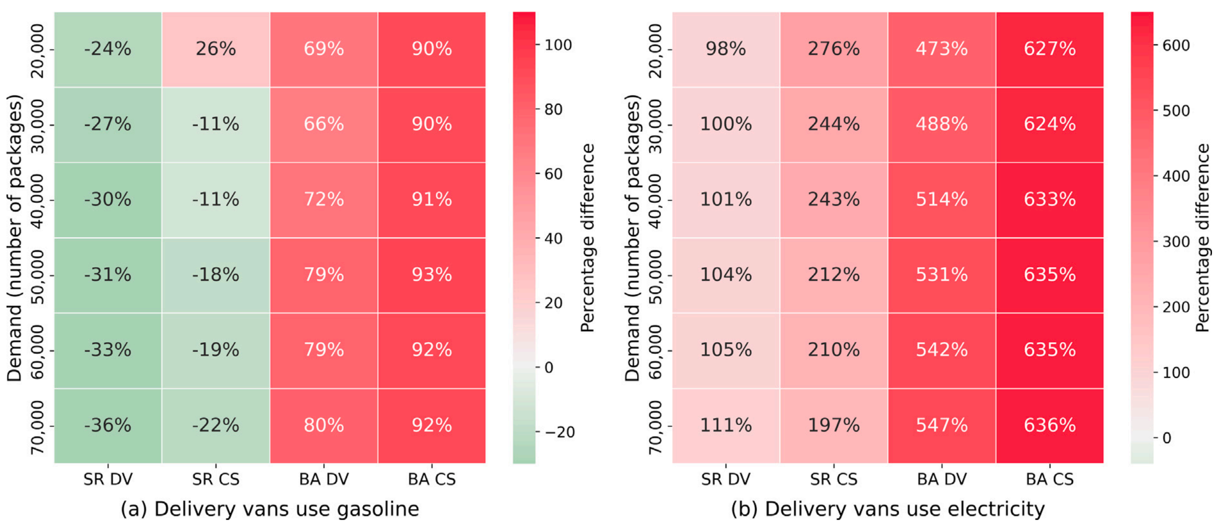

Fig. A.18. Percentage difference of CO_2 emissions between eVTOL-based scenarios and van-only scenario, under different demand levels.

For the same reasons, the SR-CS scenario will change from incurring 35% greater cost to 1% less cost, as demand increases from 20,000 to 70,000. On the other hand, using Beta Alia is more costly than using delivery vans. The increase in demand necessitates flying more eVTOL flights, which further exacerbates the cost disadvantage of BA-based delivery. As an example, when electric vans are used, the percentage cost difference of the BA-DV scenario from the van-only scenario increases from 200% at the demand level of 20,000 to 242% at the demand level of 70,000.

Similar trends can be said about the percentage difference in energy consumption and CO_2 emissions under the eVTOL-based scenarios from the van-only scenario, as shown in Figs. A.17–A.18. As demand increases, the SR-based scenarios will generally become more attractive in terms of both energy consumption and CO_2 emissions than van-only delivery, when gasoline vans are considered. When electric vans are considered, the gap with the van-only scenario will be widened, though not significantly. For BA-based scenarios, an increase in demand will further disadvantage BA-DV and not improve the competitiveness of BA-CS. Overall, as eVTOL-based delivery gains popularity with greater demand, picking the right eVTOL type is even more critical.

A.2. Unit operating cost of eVTOLs

One key factor for the success of eVTOL-based delivery is the unit cost of operating eVTOLs. In Section 5, we find that Sabrewing Rhaegal can be economically attractive, especially when combined with delivery vans. However, it is important to understand how the total shipping cost could decrease further as the unit operating cost of eVTOLs reduces. This reduction is likely as eVTOL technologies mature and economies of scale are realized over time. To this end, we consider lowering the unit operating cost of Sabrewing Rhaegal from \$1.46/mile to \$0.6/mile and lowering the unit operating cost of Beta Alia from \$550/hr to \$200/hr. For both eVTOL types, the largest reduction is by about 60%. The resulting total shipping costs are shown in Figs. A.19–A.20, which correspond to using gasoline and electric vans, respectively.

In Fig. A.19, we observe that the extent of cost reduction is more significant for the BA-based scenarios than the SR-based scenarios. For example, with gasoline vans, the maximum reduction in the total shipping cost will be from \$8,300 to about \$7,000 for the SR-DV scenario, or about 15% reduction. In contrast, for the BA-DV scenario, the maximum cost reduction will be from \$36,700 to about \$22,500, or about 38% reduction. The greater reduction for the BA-DV scenario is understandable, as eVTOL holds a substantially larger portion of

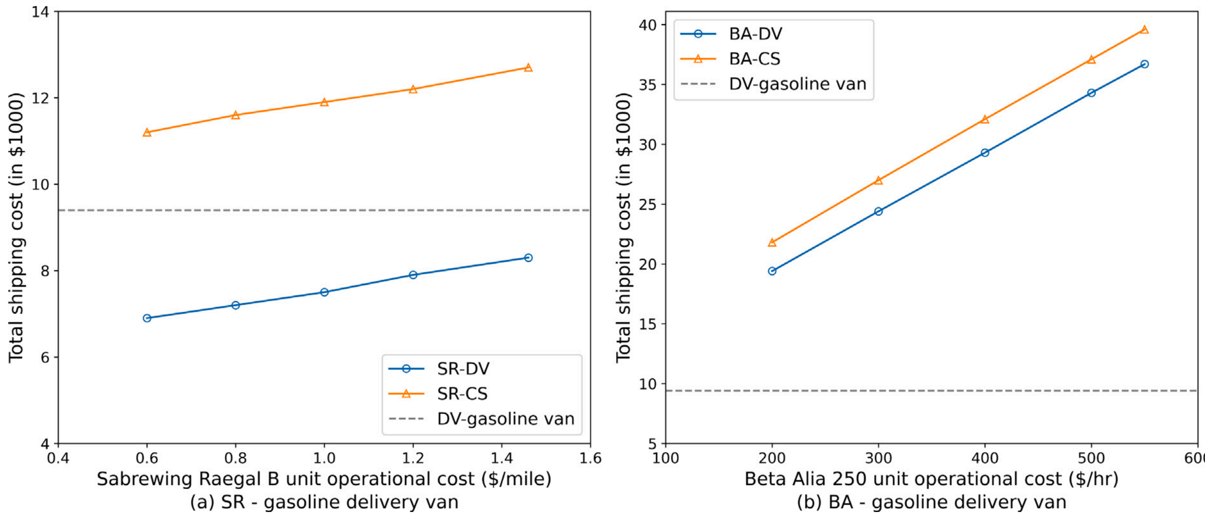

Fig. A.19. Sensitivity of total shipping costs to unit eVTOL operating cost, with gasoline vans.

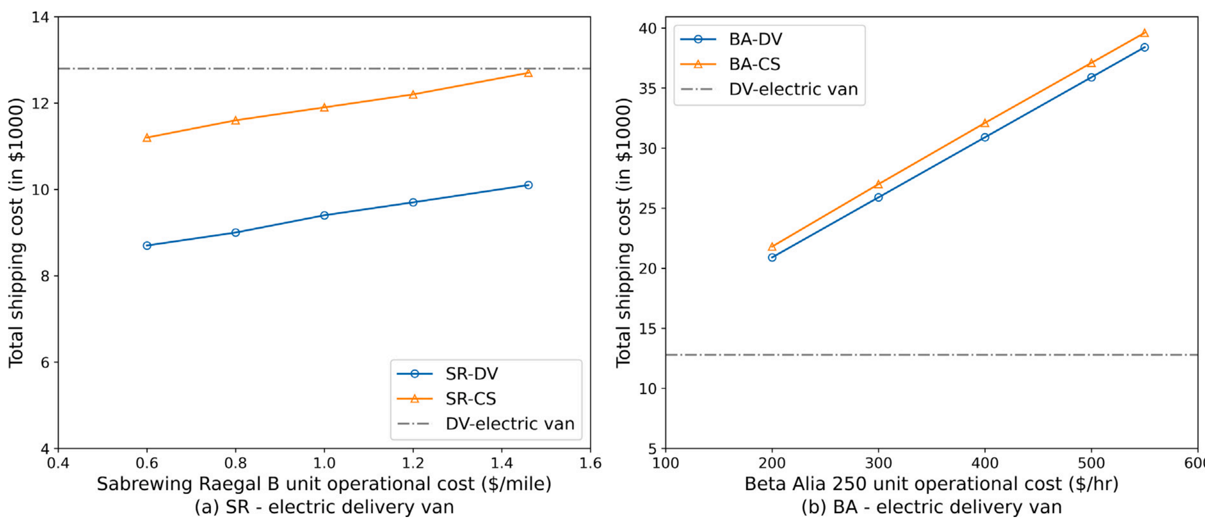

Fig. A.20. Sensitivity of total shipping costs to unit eVTOL operating cost, with electric vans.

the total shipping cost under the BA-DV scenario than under the SR-DV scenario (as shown in Figs. 5–6). On the other hand, even if the unit eVTOL operating cost is substantially reduced, using Beta Alia will still not be cost competitive compared to van-only delivery given its much higher base value for its unit operating cost. This reaffirms Sabrewing Rhaegal as a more suitable eVTOL type in the context of package delivery considered in our paper.

A.3. eVTOL power requirement

Finally, we examine how reduction in the needed power, which is plausible as eVTOL technology advances, would affect the energy consumption of eVTOL-based delivery scenarios. Specifically, we consider reducing the power for all phases of an eVTOL flight simultaneously by 0%–50% in a decrement of 10%. As the reduction in power requirement leads to a decrease in energy use, we need to account for the associated energy cost saving. For each round trip, we first calculate the saved energy under a given power reduction percentage, and then multiply the energy saving by the unit electricity cost of $0.0684 per kWh in Illinois (EIA, 2023), to obtain the energy cost saving. The energy cost saving is subtracted from $c_{i,2}$, to yield the updated eVTOL flying cost for a round trip from the fulfillment center to each candidate vertiport site i. Then, we use the updated eVTOL flying cost to re-solve the optimization model, which gives the new total shipping cost, energy consumption, and CO_2 emissions.

Fig. A.21 plots the resulting energy consumption under different scenarios. The dashed horizontal line indicates the energy consumption with van-only delivery. Again, two sub-figures are presented for delivery vans using gasoline and electricity, respectively. We can see that the reduction of the needed eVTOL power significantly affects the energy consumption and CO_2 emissions. The reduction is more significant with Beta Alia than with Sabrewing Rhaegal, which is due to the greater share of energy consumption by eVTOL in the system total when Beta Alia is used. With gasoline delivery vans, the energy consumption of the SR-DV scenario will be always below that of the van-only scenario. When the required power for eVTOL flying decreases by 50%, the energy consumption by Beta Alia along with delivery vans will also fall below the energy consumption if only vans are used. With electric vans, the SR-DV scenario will become almost the same as the van-only scenario in terms of energy consumption when eVTOL power requirement is reduced by 50%. Very similar findings can be said for CO_2 emissions, as shown in Fig. A.22. Overall, the results underscore the importance of substantially reducing power requirements, in order for eVTOL-based delivery to be competitive against van-only delivery in energy consumption and CO_2 emissions.

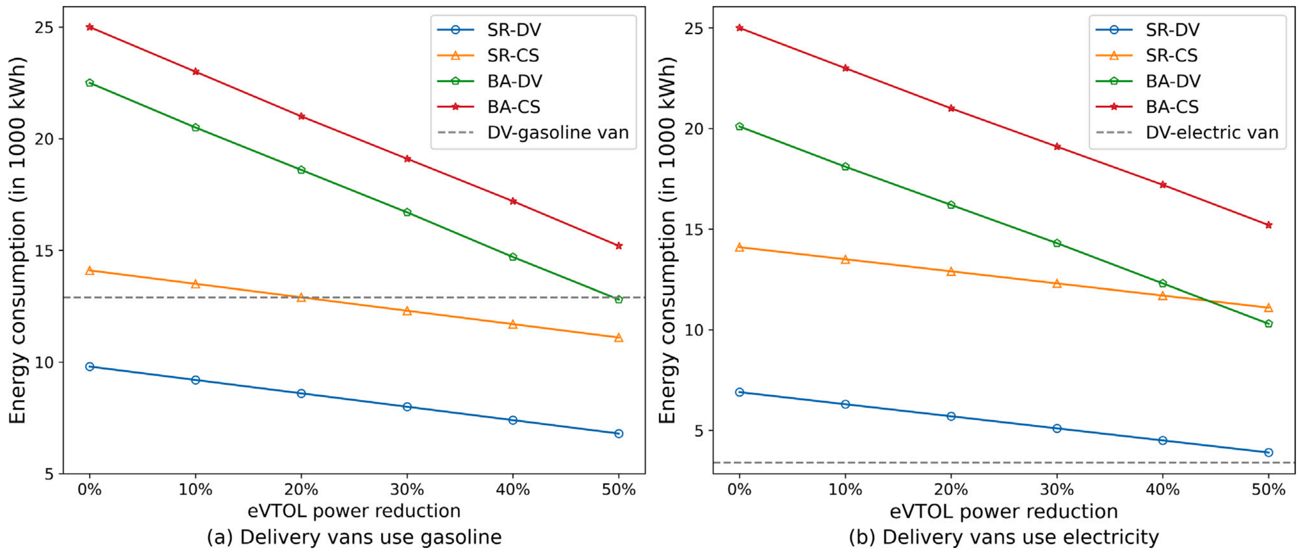

Fig. A.21. Sensitivity of energy consumption to eVTOL power reduction.

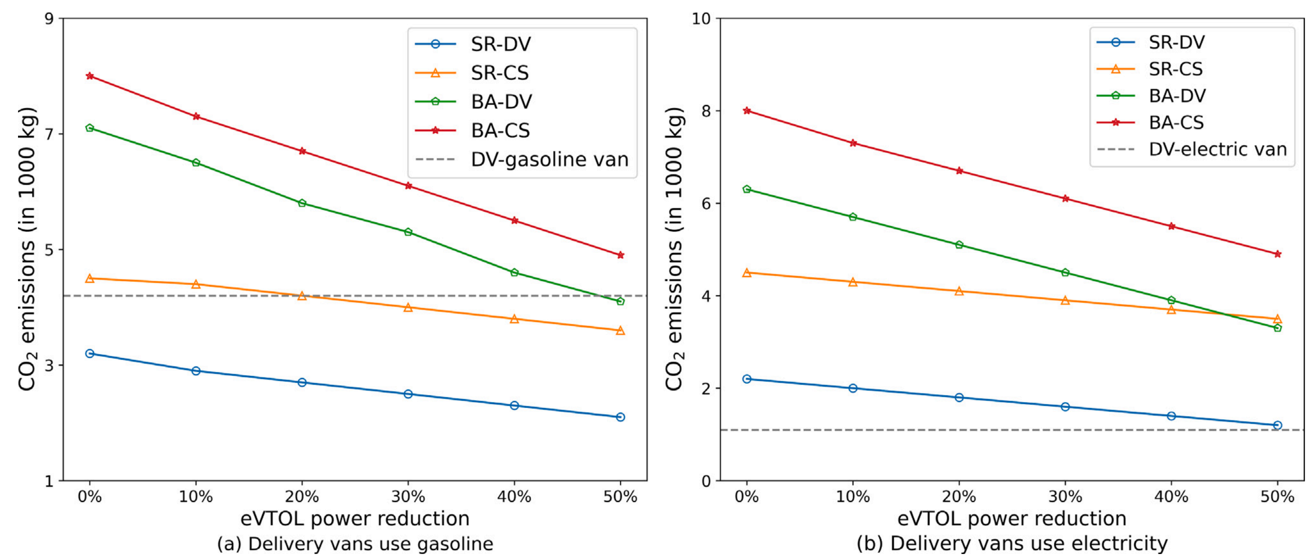

Fig. A.22. Sensitivity of CO_2 emission to eVTOL power reduction.

Data availability

Data will be made available on request.

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