Modeling and Evaluating Multimodal Urban Air Mobility

Center for Transportation, Environment, and Community Health
Final Report

by
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16. Abstract

Traffic congestion has been one of the leading issues around the world. The emerging concept urban air mobility (UAM) is expected to provide a new solution by making use of the three-dimensional airspace to transport passengers and goods in urban areas. UAM application is based on a new type of electric aircraft that is enabled to take off and land vertically (eVTOL) and embedded with advanced autonomous and distributed propulsion technology. Compared to traditional aircraft like helicopters, eVTOL will provide safer, more efficient, and quieter air transportation service in urban areas. One of the greatest identified challenges for UAM application is to build well-distributed infrastructures to support eVTOL aircraft operations. Those infrastructures are vertiports (or skyports), where eVTOL aircrafts takeoff and land, onboard or disembark passengers, and get charged. On the one hand, dense land use in urban areas, aircraft operation requirements and community acceptance among many other factors severely restrict the number of vertiports and make it impossible to provide door-to-door (DtD) services through pure air transportation. On the other hand, vertiport locations should be carefully selected with consideration of its impact on potential UAM demand and system performance. In this project, we plan to develop mathematical models to design operation network for on-demand UAM service. Specifically, we solve the problem of vertiport optimal location identification and user allocation to vertiports with consideration of interactions between vertiport locations and potential UAM travel demand. We will also incorporate performance uncertainty of transportation network into consideration and extend the static model to stochastic programming. A case study based on the Tampa Bay area will be conducted to demonstrate the effectiveness of the proposed models.

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1. Introduction

Traffic congestion is a leading sustainability issue in transportation around the world. According to a report published by INRIX, Inc., Americans spent an average of 97 h in congestion in 2018, costing them nearly $87 billion, an average of $1348 per driver [1]. Meanwhile, the effect of traditional roadway capacity expansion has been swamped by growth in population and vehicle ownership, and the increase in vehicle miles traveled (VMT) due to urban sprawl. Recent efforts have focused on implementing emerging technologies and concepts to mitigate congestion by using the existing roadway system more efficiently. For example, autonomous and connected vehicles are expected to smooth traffic flows, reduce vehicle operation headways, and enhance the capacity of the existing roadway system. Sharing mobility, pooling functions of transportation network companies (TNCs) that encourage customers to share trips, and micromobility— including bicycles, e-scooters, and e-bicycle sharing—that can use sidewalk and bike lanes have been implemented and are expected to help reduce VMT. Government agencies and research communities are realizing the needs and possibilities of developing and using low-altitude space— a valuable resource of the national transportation system that is currently underused. In 2017, National Aeronautics and Space Administration (NASA) embraced the concept of urban air mobility (UAM) and called for a market study of this transportation mode. Since then, significant efforts have been invested into this mode from different entities, including government agencies, manufacturers, and research communities. The concept of UAM dates back to the 1960s, when several companies used aircraft to provide point-to-point commuting service within and around metropolitan areas in Los Angeles, San Francisco, New York, and Chicago in the United States [2]. These carriers were ultimately forced to significantly reduce or terminate their operations due, in large part, to community acceptance issues, fatal accidents, and financial challenges [3], which still restrict the large-scale development of UAM. The UAM concept proposed in recent years is based on a new type of electric aircraft that can take off and land vertically, known as electric vertical take-off and landing vehicles (eVTOLs). This new type of aircraft, at its mature stage, integrates advanced autonomous and distributed electric propulsion technologies and can provide safer, quieter, and more efficient air transportation service in low-altitude space. Predictions from some industry companies are relatively positive, as they believe that potential adoption can be significant, as the service price can be well-controlled with economies of scale [4,5]. Some studies claim that there could be an annual market of almost $2.5 billion for air taxi and airport shuttle service considering different constraints [6] and that the service cost will be comparable to that of using UberX with enough market penetration [4]. However, public perception, infrastructure availability and accessibility, service quality, and service cost, among many other variables, can impose significant uncertainties on UAM potential demand. Thus, researchers are not so optimistic about the adoption rate and believe that the percentage of trips switching from current ground modes to UAM service will be limited due to the high cost of making UAM financially sustainable, station-based operation that requires access and egress using ground transportation modes, and low reliability when weather conditions prohibit eVTOL operation. Despite various uncertainties that may influence future UAM adoption, studies from government authorities and academia have reached a consensus that UAM will provide an alternative form of transportation for travelers with greatly improved mobility by overcoming the geographic constraints of ground mobility modes [2]. For example, Antcliff et al. [7] demonstrate that UAM service has the potential to reduce traveler daily long-distance door-to-door commute time by about one-third of that for ground transportation, using Silicon Valley areas as a case study.

Numerous efforts have been made to encourage the advancement of the novel UAM service. NASA and the Federal Aviation Administration (FAA) have been leading a market feasibility study and the promotion of UAM [6]. More than 70 manufacturers worldwide, including Boeing, Airbus, and Bell Helicopters, have been devoted to better design of eVTOL aircraft, and a more than $1 billion investment has been made as of September 2018 [8]. Demonstration flights of various types of aircraft have been conducted in the United States, China, United Arab Emirates, and Singapore [9–11]. In addition, high-profile events have been organized around the world to discuss challenges and solutions for UAM applications, such as Uber Elevate and LA City's Mayors Gathering [8]. The potential market for UAM can be, but is not limited to, ambulance service, air taxi service, airport shuttle service, tourism, inspections and surveys, goods delivery, and more [8].

Significant progress has recently been made toward UAM concept definition, potential market analysis, and application constraint identification [4,7,8,12,13]. One of the biggest challenges faced by UAM on-demand service is building a well-distributed ground infrastructure to support eVTOL aircraft operations [4,12]. For on-demand UAM serving passenger needs, the main ground infrastructure is vertiports (or skyports) from which eVTOL aircraft take off and land, board or disembark passengers, and get charged. Dense land use in urban areas, aircraft operation requirements, community acceptance, and other factors severely restrict the number of vertiports and make it impossible to provide door-to-door (DtD) services through pure air transportation [8]. Therefore, network design of UAM needs to integrate multiple transportation modes: ground transportation for vertiport access and egress, and air transportation between vertiports. This multimodal nature increases the complexity of UAM network design. Also, the number and location of vertiports will attract different levels of users. The interaction of supply and demand needs to be explicitly considered in UAM network design. In this study, we focus on the network design of UAM on-demand service. More specifically, this study uses integer programming and a solution algorithm to determine optimal locations of vertiports, user allocation to vertiports, and vertiport access- and egress-mode choices while considering the interactions between vertiport locations and potential UAM travel demand. We also analyze key incentives for potential UAM demand from the supply side and different pricing strategies for UAM operators. A case study based on simulated disaggregate travel demand data of the Tampa Bay area in Florida, USA was conducted to demonstrate the effectiveness of the proposed model.

The remainder of this paper is organized as follows. Section 2 summarizes the existing literature on vertiport location identification and factors that influence user adoption of UAM service. Key assumptions of this study and the modeling framework are discussed in Section 3, and Section 4 presents a numerical study of the Tampa Bay Region. Section 5 concludes the study and discusses future research directions.

2. Literature Review

2.1 Perception, acceptance, and adoption of UAM

Public perception, acceptance, and adoption are among the most critical factors that determine the success of UAM service, from vehicle certification and operation regulation to potential market identification. Much effort has been made by NASA and FAA to understand the potential disturbance of eVTOL operation on communities through various demonstration projects, such as the US Department of Transport (DOT) Integration Pilot Program (IPP) [14]. The importance of community engagement for the success of UAM service has also been repeatedly emphasized by the industry [15]. In the academic field, recent studies used survey instruments and econometrics

modeling to estimate potential UAM demand and to study near-term UAM market size under competition with tradition ground transportation and long-term UAM market size under competition with both ground autonomous vehicles and traditional vehicles. These surveys were distributed in five major cities in the United States and focused on groups with a certain income and commute time thresholds [16–19]. Stated preference surveys were also used to understand public perception of the potential benefits, concerns, and desired operating characteristics of UAM service in the United States [20]. The authors found that a time-saving benefit was recognized by most respondents and that safety was their primary concern. Eker et al. [21] adopted a bivariate-ordered probit model to identify how demographic features and previous travel behaviors may influence public perception of the benefits and concerns of using UAM service. Age, gender, income level, education background, and daily driving habits, among many other factors, were found to be statistically significant. Al Haddad et al. [22] estimated the factors that would impact the time horizons of the public adopting UAM service using factor analysis and discrete choice models. In general, most respondents were positive regarding adoption of the service within five years, with only 3.17% of respondents indicating that they would not use the service and 21.27% being unsure. Among the factors that influenced adoption, safety concerns were the most important, followed by cost, trip duration, on-time reliability, and operation characteristics.

Fu et al. [23] attempted to understand the public's potential adoption of UAM service considering mode choice competition with private automobiles, public transportation, and autonomous taxi service [23]. Several multinomial logit models based on market segmentation were estimated, and the results indicated that safety, travel time, and travel cost were among the most critical factors that would influence the public's choices. UAM users were expected to place the highest value on time in comparison with the users of other ground transportation modes. Another study conducted a meta-analysis of urban mode choice factors from 52 studies from 1980 to 2017 to identify demand and acceptance drivers for UAM [24]. The authors proposed three different operation concepts of UAM in accordance with different user segment needs such as service cost, comfort, and flexibility.

Finally, a series of studies summarized the efforts of developing a simulation tool by extending the existing multi-agent transport simulation (MATSim) framework to integrate UAM service into the existing transportation system [25–28]. Although the travel mode choice behavior of the extended simulation framework was achieved by applying discrete choice models, the simulation tool was able to identify how different vehicle design scenarios (i.e., speed and capacity) and operation configuration may influence the potential demand for UAM service. The simulation tool was used to test cases studies in Sioux Falls, South Dakota, USA and Zurich, Switzerland. In the simulation, the UAM operation network (i.e., the location of vertiports) in each city was configured as given inputs.

2.2 UAM network design

A well-designed ground infrastructure system is the foundation of UAM operation. To establish such a system, optimal locations for vertiport construction must be identified in order to serve the potential demand of users and support the operations of eVTOL aircraft. Vertiport placement should first take into account the physical constraints of nearby land use and the operational requirements of eVTOL aircraft. Antcliff et al. [7] used Silicon Valley in California as an example to illustrate how to achieve these goals by analyzing the features of existing infrastructure and aircraft operation regulations. Vascik and Hansman [13] proposed co-locating vertiports with different types of existing infrastructure in order to increase vertiport availability and reduce UAM first/last mile distance. The factor of demand distribution was considered for identifying potential

vertiport locations; Lim and Hwang [29] used a *k*-means clustering algorithm to identify potential locations of vertiports in Seoul, Republic of Korea. Each identified cluster contained travel demands co-located with each other, and the centroids of clusters were regarded as reasonable locations for vertiports. Fadhil [30] conducted a geographic information system (GIS)-based approach to place vertiports, by considering factors that influence commuting demand in the study area and the existing available infrastructure. In that study, different weights were assigned to factors based on expert judgment, and locations with different probabilities to be selected as vertiports were identified. Optimization models may provide more insights for UAM network design in terms of providing optimal locations for vertiports and analyzing UAM operational characteristics. Daskilewicz et al. [31] proposed integer programming with the objective of minimizing system travel time, given the travel demand of the studied area. However, the formulation of the mathematical model was not provided in the published paper, and the authors were unable to identify optimal solutions. Another model was proposed by Rath and Chow [32], who applied the modeling structure of a traditional hub location problem for vertiport placement in New York City, USA serving trips from downtown to three airports in the New York and New Jersey area that originally used cab services [32]. A critical drawback of their model was that they purely applied the classical modeling structure without incorporating the operation features of UAM service. Some studies have looked into the willingness to pay of potential UAM users. As noted in Ref. [33], according to a survey, UAM service users may be willing to pay about 2–2.5 times the price of a taxi in the United States and Germany for a 50% reduction in travel time. Similar mode choice conclusions—that users are willing to pay more for UAM service to save travel time—can also be found in other stated preference studies [4,23].

Realizing gaps in the existing literature, we proposed to solve the UAM network design problem explicitly by taking mode competition into the modeling structure. Specifically, given disaggregated travel needs in a region and considering the interactions between demand attracted by UAM service and vertiport locations, the network design problem of on-demand UAM was modeled as a *p*-median hub-and-spoke network problem with special constraints reflecting an individual's mode choice between ground transportation and multimodal UAM service. We also propose a preprocessing method to reduce the feasible region of the decision variables, which decreases the computational time significantly and makes the problem tractable and the network design of UAM scalable. In addition, a sensitivity analysis was conducted to demonstrate the impact of critical factors—such as the access and egress time of UAM and the pricing of UAM services—on the outcomes of the network design. The findings from this study offer in-depth planning and managerial insights for municipal decision-makers and UAM operators.

3. Problem formulation

For an eVTOL on-demand service, given the disaggregate travel demand of an urban area, this study determined the location of vertiports, the corresponding travel demand for switching from ground transportation to UAM, traveler allocation to each vertiport, and ground mode choices for vertiport access and egress. In the mathematical modeling of the network design, the objective was to minimize the generalized travel cost for all travelers, including those who choose to use multimodal UAM service and those who continue to use the existing ground transportation network. However, it should be noted that the modeling allows each traveler to choose the best mode with the lowest generalized travel cost.

3.1 Assumptions

The following assumptions were made for UAM network design in this study:

(1) Users will choose between pure ground transportation and multimodal UAM service and will not use UAM service if the value of the saved travel time is less than the additional cost of multimodal UAM compared with pure ground transportation.

(2) Pure ground transportation in this study included only driving personal vehicles, using public transit, and using a for-hire service provided by transportation network companies (TNCs) or taxi companies. Transportation modes available for vertiport access or egress included driving personal vehicles, using transit bus service, walking, using a for-hire service, using a bike-sharing service, and e-scooter service.

(3) This study did not consider the trans-shipment of travelers at vertiports—that is, one trip goes through only two vertiports, with one trip close to the traveler's origin and the other close to the destination.

(4) For multimodal UAM service, congestion was not considered, and the speed of walking, biking, riding e-scooters, taking a bus, and flying was assumed to be constant; the speed of driving a personal vehicle or using a for-hire service was the same as the average speed of the corresponding ground trips.

(5) The cost of an air trip was composed of a base fixed cost and a variable cost, which is linear to the cruise distance. The cost of ground transportation depended on the travel mode selected (see Table 1 for cost composition and corresponding parameter settings for each travel mode.)

(6) This study did not consider possible additional waiting time of UAM travelers due to the capacity constraints of vertiports or shortages of eVTOLs.

(7) The study also did not consider different fare rates when UAM users choose a single-occupancy eVTOL or share the eVTOL with other users.

Table 1. Pricing schemes for different transportation modes

Travel Mode	Pricing Scheme	Values
eVTOL	Base cost + unit distance cost × trip distance	Base cost: $30, unit distance cost: $2
Transit	With transit pass	$1
	Without transit pass	$2
Personal vehicle	Gasoline cost per mile × trip distance + parking cost	Gasoline cost per mile: $0.11
For-hire service	Base cost + unit time cost × trip time + unit distance cost × trip distance	Base cost: $2.3, unit time cost: $0.28 per minute; unit distance cost: $0.8
Bike-sharing service	Base cost + unit time cost × trip time	Base cost: $1, unit time cost: $0.25
E-scooter	Unit time cost × trip time	Unit time cost: $0.29

For assumption (1), the value of the saved travel time and the additional travel cost were identified as the most significant factors that may influence a user's decision to choose UAM service, as described in the literature [23]. In assumption (2), only users of three primary transportation modes were considered as potential UAM users, as walking, biking, and e-scooters are mainly used for short trips. The travel modes that were assumed to be available for vertiport access and egress were potential mode choices for short-to-medium trips in practice. The rationale behind assumption (3) was that trans-shipment will add more waiting time and inconvenience to traveler trips and will reduce the attractiveness of multimodal UAM service for urban travel. However, if regional air

mobility is considered, trans-shipment may be allowed. An average constant travel speed for walking, biking, e-scooter, and aircraft was reasonable in assumption (4), as these modes are generally free of congestion, and their speed is either from a manufacturers' expected vehicle configuration or existing service data [4,34,35]. The assumption regarding the effect of congestion on ground vehicle trips can be relaxed by considering the uncertainty of travel time in a future study. The current pricing scheme for TNCs is commonly composed of a base fixed cost plus a variable cost [36], which was adopted for UAM air trips in assumption (5). The base cost and variable cost are set to match those of trips served by UberBlack, as predicted in Ref. [4]. This pricing strategy can be relaxed by incorporating many other factors in practice, such as time of day, travel time, and booking fees, and can follow a similar surge charging algorithm as that adopted by TNCs, which will be studied in future research. For ground trips, the cost of bus transit service depends on whether users have a transit pass or not. The cost of a for-hire service was simplified from the pricing scheme for UberX [36]. For the cost of bike-sharing and e-scooter service, the pricing schemes came from existing operators in Tampa Bay [37,38]. The cost of driving personal vehicles included gasoline cost and potential parking cost. Unit gasoline cost can be regarded as a deterministic value, but potential parking cost varies in different scenarios and was assumed in this study, as presented in Table 2, to depend on trip purpose, population density, and parking type [39]. It should be noted that the ownership cost of private vehicles was not included because when travelers make mode choice decisions for a specific trip, they do not take that cost into consideration. The capacity of the vertiports restricts the number of eVTOLs that can land and take-off from the vertiports. If the capacity is limited, passengers may have to wait. In addition, if the operator cannot provide enough eVTOLs, passengers will be delayed. Assumption (6) shows that we only assumed constant transfer time at vertiports and did not take these uncertainties into consideration. Assumption (7) shows that, in this study, we did not distinguish between the UAM service fares per traveler that may vary due to different occupancy rates of eVTOLs, similar to Uber and Uber Pool. For near-term implementations, if pilots are required to operate eVTOLs, there will be a significant fixed cost and the fare variation due to a different occupancy rate could be limited. With the ongoing effort, ultimately, we want to develop a planning and evaluation tool for emerging UAM, where the varied fare based on different occupancy rates can be captured and the impact on network design can be analyzed.

Table 2. Parking cost in different scenarios.

Trip purpose	Population density	Parking type	Value
Shopping, medical, and home	/	/	None
Work	High	Off-street parking	$13.00
	Median		$10.00
	Low		$6.75
School	/	Off-street parking	$1.00
Recreational	/	/	$5.00
Social	High	2 h off-street parking	$9.00
	Medium		$5.5
	Low		$3.00
Meal	High	1 h on-street parking	$1.25
	Medium		$1.00
	Low		$0.75

3.2 Modeling approach

The components of the modeling structure for UAM on-demand service are depicted in Fig. 1. There are three primary sources of initial inputs in the modeling structure. The first includes lidar data and land use information of the study area and regulation policies. Specifically, lidar data can be used to extract the elevations of the study area while developing the three-dimensional (3D) map; land use information works as the basis for identification of available ground spaces for vertiport construction, and regulation policies indicate operation constraints for the aircraft. GIS was used to combine the inputs for identifying candidate vertiport locations (see Section 3.3 for methodology details of the GIS tool). Simulation output from the Tampa Bay Regional Planning Model (TBRPM) was another primary source of input, providing travel demand data such as origin and destination (OD), travel time, and ground transportation mode for each traveler (see Section 4 for a more detailed description of the TBRPM and its output). The last input was socio-demographic information for travelers, which revealed the spatial distribution of the value of time of travelers. Candidate vertiport locations, travel demand, and spatial value of time distribution together served as the input for the network design model. Preprocessing techniques were used to reduce the feasible region of the network design model before using commercial solvers to solve the optimization problem. Finally, optimal locations of vertiports to be constructed, demand for UAM service, allocation of travelers to vertiports for UAM service, and traveler mode choices for vertiport access and egress were obtained.
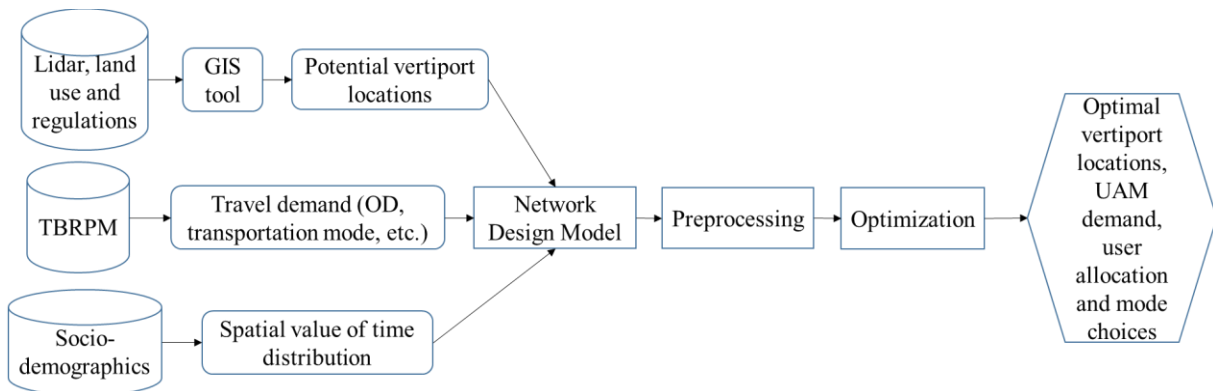

Figure 1. Components of the network design model for on-demand urban air mobility.

It should be mentioned that no interaction is considered between the TBRPM and the network design model in this study. The TBRPM was simulated once for a typical weekday to obtain mobility data for the study region, and it is assumed that traveler mode choice behaviors between ground transportation and UAM service do not influence the output of the TBRPM, as the shifted demand to UAM is expected to take only an extremely small amount of the total demand. Induced demand caused by emerging UAM is discussed in Section 5, and future research directions are suggested.

3.3 Potential vertiport identification using GIS tools

Before applying the proposed model for a specific UAM network design, potential candidate vertiport locations must be identified, which are restricted to various physical and regulation constraints. We obtained lidar data for Florida and processed the data for the Tampa Bay Region into a 3D map of the region. We then applied GIS tools to identify candidate locations based on existing land use restrictions and aircraft operational requirements. Based on land use restrictions,

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only categories considered to be suitable as potential vertiports were considered, such as commercial and industrial areas, vacant lots, and public-owned sites. Residential communities, including residential buildings in the downtown area, and preserved areas were excluded to alleviate vertiport impact on communities. The operational requirements for aircraft are primarily FAA regulations for helipad design, considering helicopter operation characteristics. The specific steps for identifying candidate vertiport locations are as follows:

(1)   Collect lidar data and develop a 3D map of the study area. Lidar data can be obtained from Ref. [40], where the National Oceanic and Atmospheric Administration (NOAA) provides the elevation data for coastal areas in the United States.

(2)   Import the map of the studied area into the GIS tool as the base map; the basic composition element of the map is parcel.

(3)   Add the layer of land use for the studied area to the base map, filter out eligible land use categories, and combine them with the parcel-level base map.

(4)   Add another layer that divides the studied area into hexagons of 500 ft (1 ft = 0.3048 m) from side to side. The size of the hexagons is selected based on FAA regulations that provide instructions for helipad design. Each hexagon is assumed to provide sufficient land for one eVTOL. If the FAA develops specific regulations for eVTOL vehicles, the size of the hexagons should be changed according to the new regulations.

(5)   Combine the layer of hexagons with the layer of land use types. If hexagons are not contained within parcels with eligible land use categories, they are removed and will not be considered as vertiport candidates.

(6)   Identify urban area high-rise buildings with sufficiently large rooftop space. For suburban areas without high-rise buildings, hexagons with a maximum altitude of 20 ft are parsed out; that is, if the maximum altitude is less than or equal to 20 ft, it is considered that no buildings or other structures are present and, therefore, a surface vertiport could be added.

(7)   Combine adjacent eligible hexagons into a single potential vertiport location to avoid an excessive number of candidates.

3.4 UAM hub-and-spoke network design

For multimodal UAM service, let N denote a set of nodes representing origins (O) and destinations (D) of traveler trips in urban or suburban areas. Let P denote a set of OD pairs, M denote a set of candidate locations for vertiports, and F denote a set of available travel modes for vertiport access and egress. Travelers can travel directly by pure ground transportation between any OD pair or by using multimodal UAM service through vertiports (i.e., accessing from the origin to a vertiport, flying from one vertiport to another, and egressing from the other vertiport to the destination), where vertiports are equivalent to hubs. Fig. 2 illustrates a transportation network with UAM service.
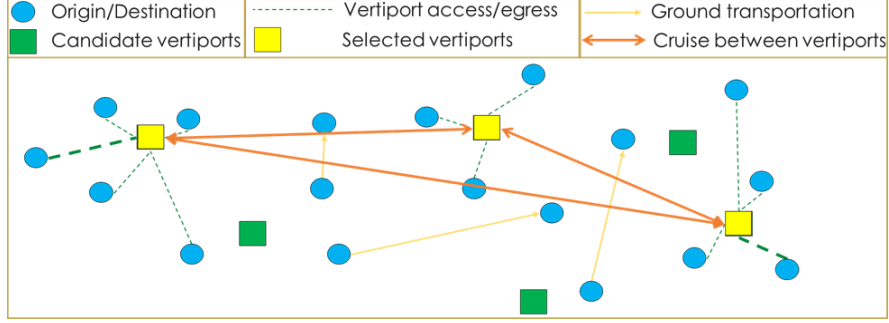
Figure 2. UAM hub-and-spoke network.

Such a network is similar to the hub-and-spoke network that has been extensively studied by the aviation research community, in which traffic between any two airports is not transported directly for all pairs of nodes but is transferred via designated trans-shipment nodes called hubs [41,42]. Thus, we borrowed the modeling structure of a p-median hub-and-spoke network problem. The decision variables of UAM network design problems are y_k, z^p, x_{kd}^p, g_{ak}^p, and h_{ed}^p, $\forall k, d \in M$, $\forall p \in P, \forall a, e \in F$, all of which are binary variables: y_k takes on a value of 1 if location k ($k \in M$) is selected as a vertiport; z^p takes on a value of 1 if trip p is through pure ground transportation; x_{kd}^p takes on a value of 1 if trip p is through multimodal UAM service that goes through two vertiports k and d with the order of k to d; g_{ak}^p takes on a value of 1 if trip p accesses vertiport k using travel mode a; and h_{ed}^p takes on a value of 1 if trip p egresses from vertiport d using travel mode e. Note that each trip p contains information of a pair of OD nodes (i, j), $\forall i, j \in N$.

As noted earlier, the number of vertiports to be built is limited due to various constraints. Let u be the planned number of vertiports; therefore:

$$\sum_{k \in M} y_k = u, \forall k \in M \tag{1}$$

To reach the destination, each traveler must make a choice between pure ground transportation and multimodal UAM service. Therefore:

$$P \tag{2}$$

It is obvious that site k cannot be in the route $i \rightarrow k \rightarrow d \rightarrow j$ unless k is selected to be a vertiport. Thus:

$$\sum_{k \in M, d \neq k} x_{kd}^p + \sum_{d \in M, d \neq k} x_{dk}^p \leq y_k, \forall k \in M, \forall p \in P \tag{3}$$

Usually, the demand of single-allocation hub-and-spoke network problems is assumed to be given as a constant value (deterministic programming) or as a set of variables with probability (stochastic programming). However, in this study, given the total number of individual trips, we considered the competition between the ground transportation mode and the multimodal UAM mode, which is affected by the decisions on vertiport locations, the allocation of travelers to the vertiports, and the mode choices for vertiport access and egress. In the following section, the formulation of the competition between different modes is introduced.

3.5 UAM concept of operation and mode choice

The concept of the operation of a multimodal UAM service has been defined in many studies [7,12,43] and can be described as the process presented in Fig. 3. At each vertiport, there will be

access and egress sites for passengers to transfer from/to ground transportation, areas for travelers waiting for eVTOL aircraft, boarding and disembarking areas for passengers getting on and off the eVTOL, and touchdown and liftoff pads (vertipads) for aircraft landing and take-off. It should be noted that, if travelers are required to disembark or board at vertipads, no specific boarding and disembarking areas are needed. For the multimodal UAM service process, travelers will first use ground transportation to get to their allocated vertiport. After arriving at a vertiport, travelers will experience a transfer process to the waiting areas, where they may wait for some time before boarding through corresponding gates. The eVTOL aircraft takes off from a vertipad and cruises to another vertiport after reaching a certain altitude. Once the eVTOL aircraft lands at the vertipad at the destination vertiport, travelers go through a similar transfer process before taking ground transportation to their destinations.
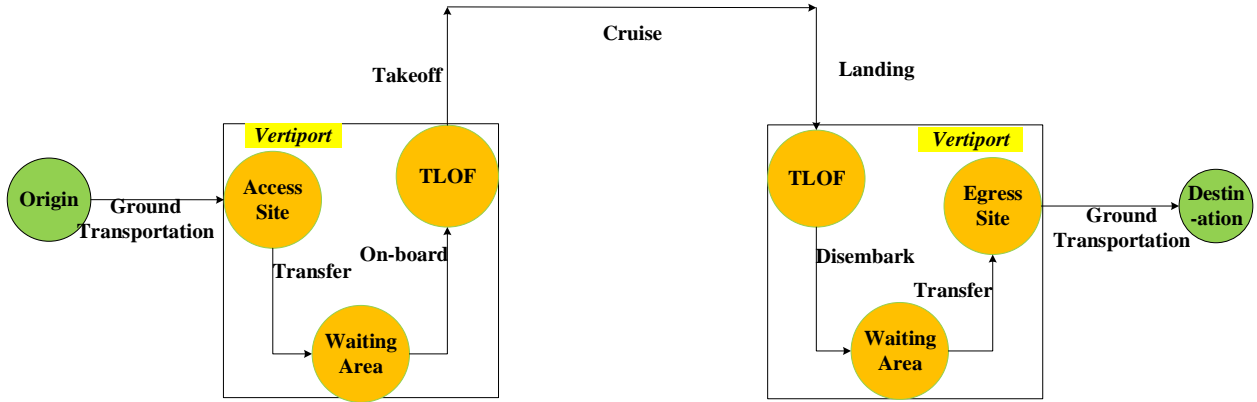

Figure 3. UAM concept of operation. TLOF: touchdown and liftoff area.

The travel time of multimodal UAM depends not only on the transfer process time and cruise time, but also on the access and egress times. Therefore, vertiport access- and egress-mode choices were also modeled in this study. It should be noted that it was assumed that only one transportation mode was selected for accessing or egressing a vertiport. Eqs. (4) and (5) show that if one trip involves multimodal UAM, then the ground transportation mode must be selected for accessing exactly one origin vertiport and for egressing one destination vertiport.

$$\sum_{k}\sum_{d \neq k} x_{kd}^{p} = \sum_{a}\sum_{k} g_{ak}^{p}, \forall p \in P \tag{4}$$

$$\sum_{k}\sum_{d \neq k} x_{kd}^{p} = \sum_{e}\sum_{d} h_{ed}^{p}, \forall p \in P \tag{5}$$

Also, it is necessary to ensure that access and egress modes will serve the exact two vertiports of the selected UAM service route, which can be restricted by the constraint in Eq. (6).

$$2x_{kd}^{p} \leq \sum_{a} g_{ak}^{p} + \sum_{e} g_{ed}^{p}, \forall k, d \neq k \in M, \forall p \in P \tag{6}$$

Given the relationship discussed above, travel time and travel cost for multimodal UAM service can be calculated. Let c_{air}^{p} and t_{air}^{p} denote the total UAM service cost and service time for trip p; c_{kd} and t_{kd} respectively represent the travel cost and travel time between two vertiports through eVTOL aircraft; and c_{ak}^{p} and t_{ak}^{p} represent the travel cost and travel time to allow access to or egress from vertiport k for trip p using ground transportation a. Let t_{tw} represent the time

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passengers spend transferring, waiting at vertiports, and boarding or disembarking eVTOLs; t_{tl} is the time required for eVTOLs to take off and land. Eqs. (7) and (8) are applied to calculate the overall travel time and travel cost for the UAM service.

$$c_{\text{air}}^p = \sum_k \sum_{d \neq k} c_{kd}^p \cdot x_{kd}^p + \sum_a \sum_k g_{ak}^p c_{ak}^p + \sum_e \sum_d h_{ed}^p c_{ed}^p \tag{7}$$

$$t_{\text{air}}^p = \sum_k \sum_{d \neq k} (t_{kd} + t_{tw} + t_{tl}) \cdot x_{kd}^p + \sum_a \sum_k g_{ak}^p t_{ak}^p + \sum_e \sum_d h_{ed}^p t_{ed}^p + t_{tw} + t_{tl} \tag{8}$$

where travel time and travel cost for vertiport access and egress and for the air trip can be obtained based on the cost calculation equation and travel speed assumptions discussed in Section 3.1. Finally, the criteria for traveler mode choice between pure ground transportation and UAM service is defined. The value of saved travel time is a major criterion used by the US Department of Transportation (DOT) for cost-effectiveness analysis when it plans to determine new actions that benefit travelers by reducing time spent in traveling [43]. Comparison between the value of time and travel cost is a fundamental criterion for travelers to choose from different modes. The value of the saved time is calculated as the saved time multiplied by the traveler's value of time. Let c_g^p and t_g^p represent travel cost and travel time for pure ground transportation, respectively; γ^p represents the value of time for a traveler in trip p. As revealed in the constraint in Eq. (9), users will not choose to use the UAM service when the value of saved travel time is less than the additional cost.

$$(c_{\text{air}}^p - c_g^p) \leq \gamma^p \cdot (t_g^p - t_{\text{air}}^p), \forall (i,j) \in W, \forall k, d \in M, \forall p \in P \tag{9}$$

3.6 Mathematical model for on-demand UAM service network design

The objective function of the integer program is to minimize the generalized travel cost for all users, including the costs for pure ground transportation and multimodal UAM service. The generalized travel cost is the combination of the monetarized travel time and the travel cost. Based on the discussion above, the complete formulation of integer programming (IP) for UAM network design is as follows (P1):

$$\min \sum_{p \in P} \left\{ (t^p \cdot \gamma^p + c^p) \cdot z^p + \sum_k \sum_{d \neq k} \left[c_{kd} + (t_{kd} + t_{tw} + t_{tl}) \gamma^p) \right] \cdot x_{kd}^p + \sum_a \sum_k g_{ak}^p (t_{ak}^p \cdot \gamma^p + c_{ak}^p) + \sum_e \sum_d h_{ed}^p (t_{ed}^p \cdot \gamma^p + c_{ed}^p) \right\}$$

s.t.

$$\sum_k y_k = u, \forall k \in M$$

$$z^p + \sum_k \sum_{d \neq k} x_{kd}^p = 1, \forall p \in P$$

$$\sum_{d \in M, d \neq k} x_{kd}^p + \sum_{d \in M, d \neq k} x_{dk}^p \leq y_k, \forall k \in M, \forall p \in P$$

$$\sum_k \sum_{d \neq k} x_{kd}^p = \sum_a \sum_k g_{ak}^p, \forall p \in P$$

$$\sum_{k}\sum_{d\neq k}x_{kd}^{p}=\sum_{e}\sum_{d}h_{ed}^{p},\forall p\in P$$

$$2x_{kd}^{p}\leq\sum_{a}g_{ak}^{p}+\sum_{e}g_{ed}^{p},\forall k,d\neq k\in M,\forall p\in P$$

$$\left[t^{p}-\sum_{k}\sum_{d\neq k}\left(t_{kd}+t_{tw}+t_{tl}\right)\cdot x_{kd}^{p}-\sum_{a}\sum_{k}g_{ak}^{p}t_{ak}^{p}-\sum_{e}\sum_{d}h_{ed}^{p}t_{ed}^{p}\right]\cdot\gamma^{p}$$
$$\geq\sum_{k}\sum_{d}c_{kd}^{p}\cdot x_{kd}^{p}+\sum_{a}\sum_{k}g_{ak}^{p}c_{ak}^{p}+\sum_{e}\sum_{d}h_{ed}^{p}c_{ed}^{p}-c^{p},\forall p\in P$$

$$z^{p}\in\{0,1\},y_{k}\in\{0,1\},x_{kd}^{p}\in\{0,1\},g_{ak}^{p}\in\{0,1\},h_{ed}^{p}\in\{0,1\}$$

$$z^{p}\in\{0,1\},y_{k}\in\{0,1\},x_{kd}^{p}\in\{0,1\},g_{ak}^{p}\in\{0,1\},h_{ed}^{p}\in\{0,1\},\forall k,d\in M,\forall p\in P,\forall a,d\in F \qquad (10)$$

3.7 Preprocessing procedures for a large network problem

The traditional hub-and-spoke problem has been proved to be non-deterministic polynomial (NP)-hard in many references [41,42,44–46], which means that the problem cannot be solved in polynomial time. The proposed mathematical model P1 is developed by combining the modeling structure of the traditional hub-and-spoke problem and the mode choice modeling of individual travelers, which makes the IP problem even more challenging to solve. Nevertheless, by analyzing the nature of the network design problem and the UAM trip characteristics, an additional constraint was proposed and preprocessed along with the constraint in Eq. (9) to largely reduce the feasible region of the IP problem. Thus, although the modeling structure is still more complex than that of a traditional hub-and-spoke network, the problem size of the proposed UAM network design can be significantly reduced, which makes it possible to solve large UAM network design problems. The preprocessing procedure is described as follows.

The objective of the mathematical model proposed in P1 is to minimize the system generalized cost with UAM service. As travel time and travel cost for all candidate trips using pure ground transportation are given and we are attempting to identify candidate trips that will switch to UAM service, the objective function of P1—that is, minimizing the total generalized cost of all trips—is equivalent to maximizing the saved generalized cost, as shown below:

$$\max\sum_{p\in P}\left\{\sum_{k}\sum_{d\neq k}\left[c_{kd}+\left(t_{kd}+t_{tw}+t_{tl}\right)\gamma^{p}-t^{p}\cdot\gamma^{p}-c^{p}\right]\cdot x_{kd}^{p}+\sum_{a}\sum_{k}g_{ak}^{p}\left(t_{ak}^{p}\cdot\gamma^{p}+c_{ak}^{p}\right)+\sum_{e}\sum_{d}h_{ed}^{p}\left(t_{ed}^{p}\cdot\gamma^{p}+c_{ed}^{p}\right)\right\}$$

(11) We know from Eq. (9) that travelers will not use the UAM service if the value of the saved time is less than the addition cost (i.e., $\sum_{k}\sum_{d\neq k}x_{kd}^{p}=0$. As a result, trips for which x_{kd}^{p} must be 0 can be excluded. Then, we can define set W_{1}:

$$W_{1}=\left\{\left(p,k,d,a,e\right)\Big|\left[t^{p}-\left(t_{kd}+t_{tw}+t_{tl}\right)-t_{ak}^{p}-t_{ed}^{p}\right]\cdot\gamma^{p}\geq c_{kd}^{p}+c_{ak}^{p}+c_{ed}^{p}-c^{p},\forall p\in P,\forall k,d\in M,p\in P\right\}$$

(12)

where $\left(p,k,d,a,e\right)$ in W_{1} represent candidate trip p with k, d as the origin and destination vertiports, respectively; a,e are the vertiport access and egress modes, respectively; and x_{kd}^{p} can take on a value of 1.In addition, another constraint can be proposed through observation of UAM

service process. Without loss of generality, any trip from origin i to destination j using UAM service through two given vertiports k, d can be illustrated by Figs. 4(a) and (b).
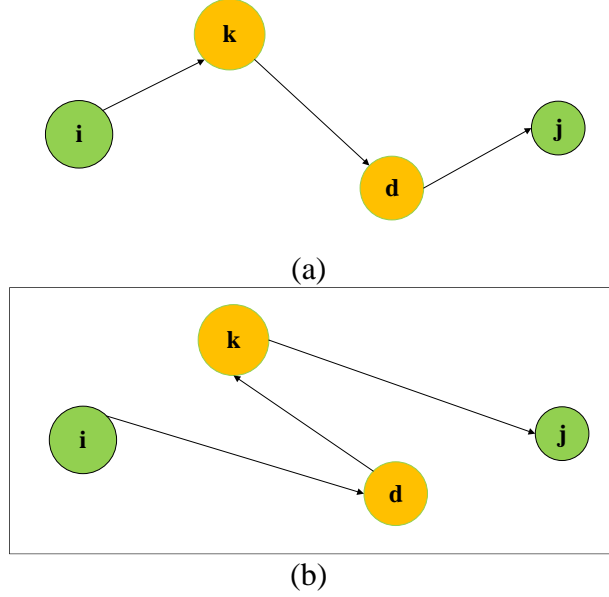

(a)

(b)

Figure 4. Relative position of any origin and destination pair and two candidate vertiports.

Given any two vertiports (k,d), the air trip distance is constant regardless of which vertiport is selected as the origin vertiport. Therefore, users will always select the trip route with the shorter trip distance for any given vertiport ($i \to k \to d \to j$ in this case), and the trip with a longer trip distance ($i \to d \to k \to j$ in this case) will not be feasible. Otherwise, the combination of straight-line distance for vertiport access and egress will even be longer than the straight-line distance between the origin and destination. This relationship can be expressed by the constraint in Eq. (13).

$$d_{kd}^p \geq d_{dk}^p \cdot x_{dk}^p, (p,k,d) \in W_1 \tag{13}$$

where d_{kd}^p represents the trip distance for trip p through vertiport $k \to d$. Then, we can define set W as:

$$W = \left\{ (p,k,d,a,e) \middle| d_{kd}^p \leq d_{dk}^p, (p,k,d) \in W_1 \right\} \tag{14}$$

In this way, we can further reduce the feasible region of the original model P1, and P1 can be replaced by the following mathematical model (P2):

$$\max \sum_{p \in P} \left\{ \sum_k \sum_{d \neq k} \left[c_{kd} + (t_{kd} + t_{tw} + t_{tl}) \gamma^p - t^p \cdot \gamma^p - c^p \right] \cdot x_{kd}^p + \sum_a \sum_k g_{ak}^p (t_{ak}^p \cdot \gamma^p + c_{ak}^p) + \sum_e \sum_d h_{ed}^p (t_{ed}^p \cdot \gamma^p + c_{ed}^p) \right\}$$

s.t.

$$\sum_k y_k = u, \forall k \in M$$

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$$\sum_k \sum_{d \neq k} x_{kd}^p \leq 1, \forall (p,k,d) \in W$$

$$\sum_{d \in M, d \neq k} x_{kd}^p + \sum_{d \in M, d \neq k} x_{dk}^p \leq y_k, \forall (p,k,d) \in W$$

$$\sum_k \sum_d x_{kd}^p = \sum_a \sum_k g_{ak}^p, \forall (p,k,d,a,e) \in W$$

$$\sum_k \sum_d x_{kd}^p = \sum_a \sum_k g_{ak}^p, \forall (p,k,d) \in W$$

$$\sum_k \sum_d x_{kd}^p = \sum_e \sum_d h_{ed}^p, \forall (p,k,d,a,e) \in W$$

$$2x_{kd}^p \leq \sum_a g_{ak}^p + \sum_e g_{ed}^p, \forall (p,k,d,a,e) \in W$$

$$z^p \in \{0,1\}, y_k \in \{0,1\}, x_{kd}^p \in \{0,1\}, g_{ak}^p \in \{0,1\}, h_{ed}^p \in \{0,1\}, (p,k,d,a,e) \in W$$

(15)

4. Numerical study

To demonstrate the effectiveness of the proposed methodology, a numerical study was conducted based on travel demand data simulated from the TBRPM, which has been used to forecast future travel demand by Florida Department of Transportation (FDOT) District Seven (D7) and metropolitan planning organizations (MPOs). The study area for the TBRPM corresponds with the FDOT D7 jurisdiction and includes Hillsborough, Pinellas, Pasco, Hernando, and Citrus counties, as presented in Fig. 5(a).
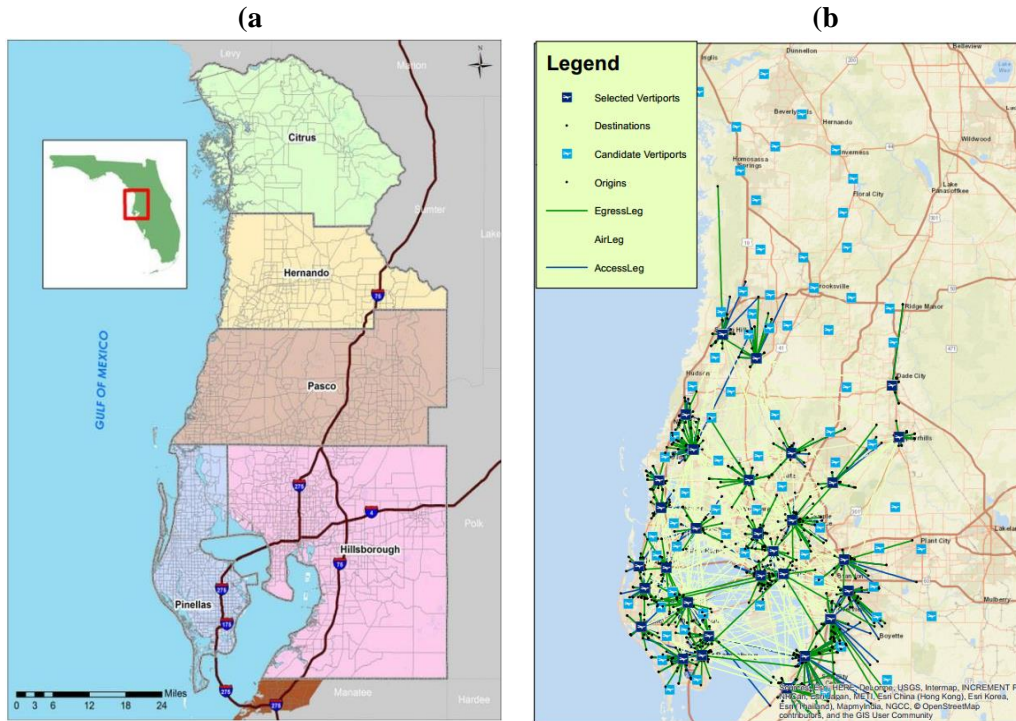
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Figure 5. (a) The study region of TBRPM and (b) optimization results of selected vertiport locations and UAM trip distributions.

4.1 Data description

Travel demand data from the TBRPM is at the parcel level and focuses on trips from each individual traveler as a result of the TBRPM running a simulation for 24 h for a typical weekday. The data provides the OD coordinates of all forecasted trips in the studied area and their corresponding network travel time and travel distance. Other information such as household income, number of household workers, travel mode, trip purpose, and transit pass holder, is also available. Trips were filtered, and those with more than 10 miles of driving distance and 30 min of travel time were retained, assuming that trips shorter than this threshold would be less appealing for eVTOL flights. As a result, 266 734 trips remained as potential UAM trips. Descriptive statistics of these trips are presented in Table 3. As shown, the travel time and travel distance of these trips are unevenly distributed, and there is a significant number of trips with extremely long travel time (≥41.74 min) or long travel distance (≥29.46 miles).

Table 3. Descriptive statistics for candidate trips.

| Statistics	Travel time (min)	Travel distance (mile)
Mean	38.48	25.95
Standard deviation	8.79	7.41
Minimum value	30.00	10.00
25th percentile	32.40	20.52
50th percentile	35.80	24.44
75th percentile	41.74	29.46

Maximum value	179.85	103.10

In total, 100 candidate vertiport locations were selected by following the aforementioned process using the GIS tool. Based on the household income and number of workers for each household from the TBRPM input data, an average annual wage was obtained for each traveler; the corresponding distribution is presented in Fig. 6(a). This distribution is very close to that for all of Florida [47], and the value of time for each traveler can be calculated by dividing the general working hours of a year (2080 h) accordingly, with the distribution presented in Fig. 6(b). Other parameters used for the model estimation in the numerical study are presented in Table 4.
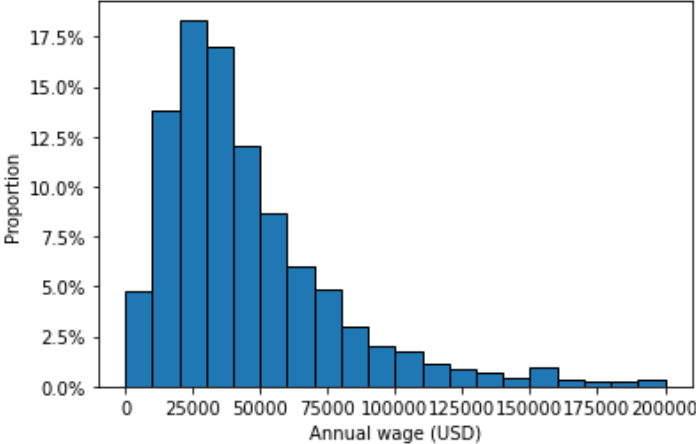
(a)
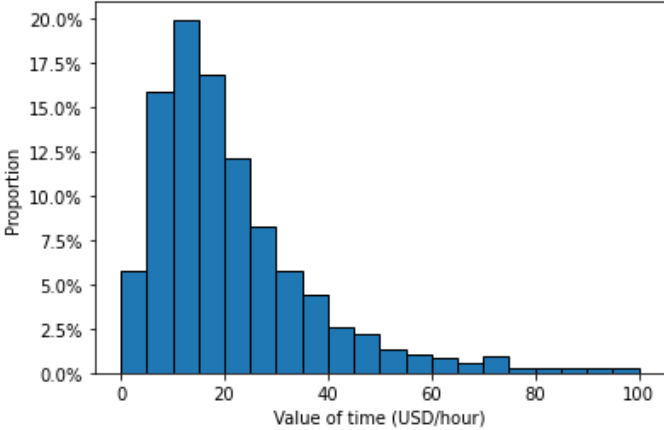
(b)

Figure 6. Average wage distribution and (b) value of time distribution for travelers in the study area.

Table 4. Value of parameters in the numeric study.

Parameters	Value
Average bus speed (mph)	12.10
Average e-scootering speed (mph)	6.00
Average biking speed (mph)	5.09

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Average walking speed (mph)	3.13
Cruise speed of eVTOL aircraft (mph)	150.00
Number of vertiports to be built	30
Transfer time at vertiport (min)	5.0
Aircraft operation at vertiport (min)	2.5
Coefficient to transfer straight line to driving distance	1.4
Coefficient to transfer straight line distance to walking/biking/e-scootering distance	1.1

4.2 Result analysis

The integer program was solved using Python and Gurobi v9.0 solvers on a 3.60 GHz Dell computer with 16 GB RAM under a 64-bit Windows 10 operating environment. Preprocessing took 2 h 34 min, and the mathematical model took 245 s (around 4 min) to obtain the optimal values. The identified locations of 30 vertiports and the corresponding UAM trips are illustrated in Fig. 5(b). In summary, preprocessing resulted in 1 124 travelers as potential UAM service users, and the optimization results indicate that 532 were finally selected—around 0.20% of the 266 734 trips—at a generalized cost-saving of $9 783. The demand at each selected vertiport is summarized in Table 5, and the vertiport access- and egress-mode choices are summarized in Table 6. As shown, the demand at the vertiports was unevenly distributed, with the highest at 65 and the lowest at 13 in the current parameter settings. Demand for UAM service was found to be mainly along the coastal areas. For vertiport access- and egress-mode choices, driving a personal vehicle was the primary choice for vertiport access, and driving a personal vehicle and using a for-hire service were the primary mode choices for vertiport egress. In addition, the travel time and distance distributions of UAM users were reviewed if they continued using ground transportation to verify whether the threshold defined to filter the candidate trips for UAM service (30 min and 10 miles) was reasonable. As shown in Figs. 7 and 8, the average trip distance of UAM users was around 30 miles, and the average trip time of UAM users was close to 50 min, indicating that the selection of threshold is reasonable.

Table 5. Number of trips through each selected vertiport.

Vertiport index	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Demand	52	64	39	45	21	25	35	39	64	48	31	43	27	30	41
Vertiport index	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Demand	20	34	26	33	42	26	36	54	25	21	25	32	13	65	27

Vertiport index	Demand	Vertiport index	Demand
1	52	16	20
2	64	17	34
3	39	18	26
4	45	19	33
5	21	20	42
6	25	21	26

7	35	22	36
8	39	23	54
9	64	24	25
10	48	25	21
11	31	26	25
12	43	27	32
13	27	28	13
14	30	29	65
15	41	30	27

Table 6. Transportation mode choices for vertiport access and egress.

Item	Transportation mode	Value
Vertiport access	Personal vehicle	495
	For-hire service	10
	Bicycle	1
	E-scooter	10
	Transit	16
Vertiport egress	Personal vehicle	161
	For-hire service	329
	Transit	42
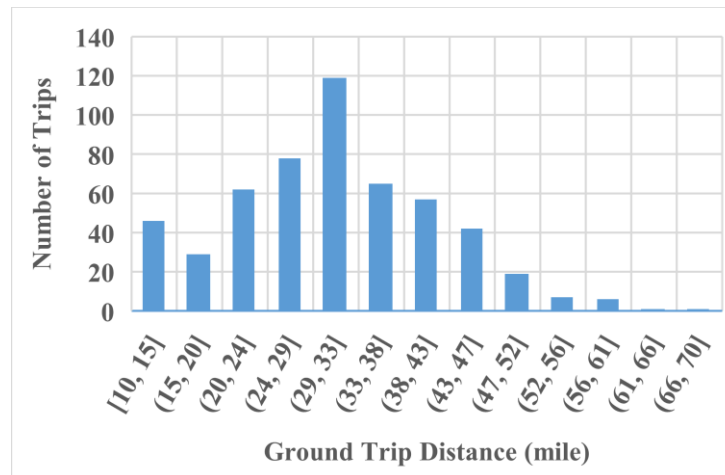
Figure 7. Travel distance distribution for UAM users if using pure ground transportation.
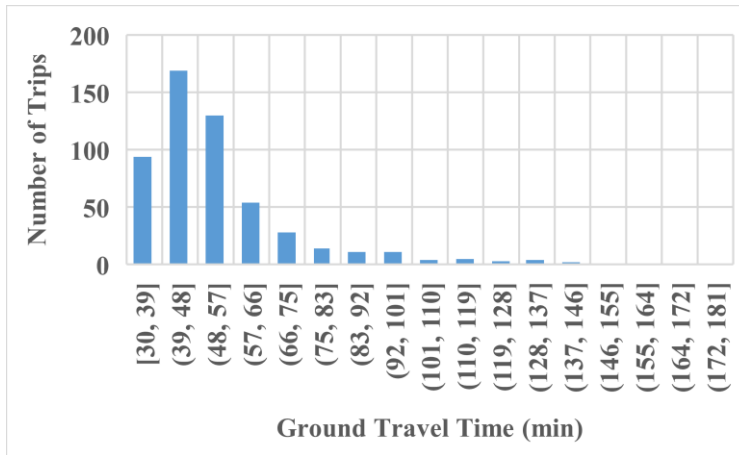
Figure 8. Travel time distribution for UAM users if using pure ground transportation.

The characteristics of the multimodal UAM trips were analyzed, and the results are presented in Figs. 9–12. As shown in Fig. 9, the majority of UAM trips are 10–40 miles, with the longest being around 60 miles. Use of the UAM service can save 8–40 min for most users, with the longest time saved at more than 120 min, according to Fig. 10, indicating a significant travel time-saving benefit of UAM service. The ratio of time consumption was calculated for each part of a multimodal UAM trip compared with its total service time; the corresponding distribution is illustrated in Fig. 11. As shown, on average, the air trip time comprises around 30% of the total UAM service time, which indicates potential to further increase UAM service efficiency by expanding vertiport locations to improve vertiport accessibility. As for the trip purposes, it is observed from Fig. 12 that home- and work-based trips are the primary trip purposes for UAM service.
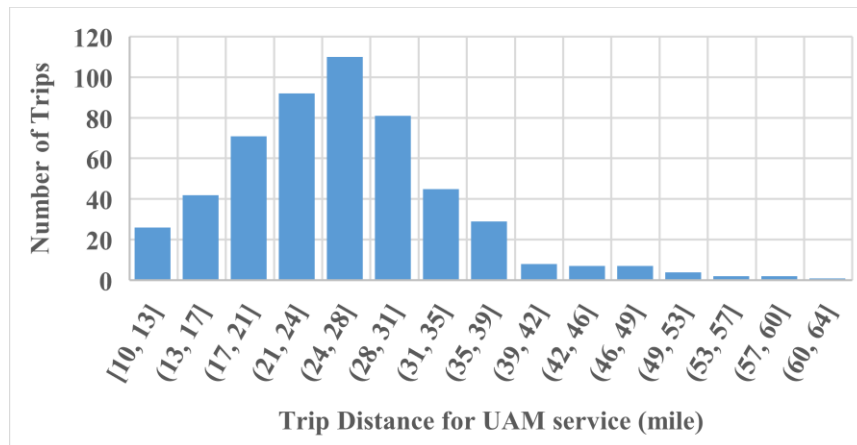

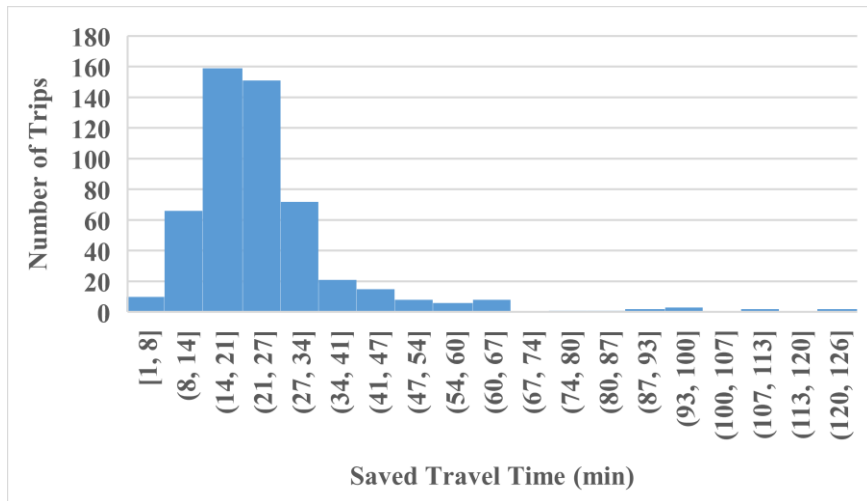Figure 9. Multimodal UAM travel distance distribution.

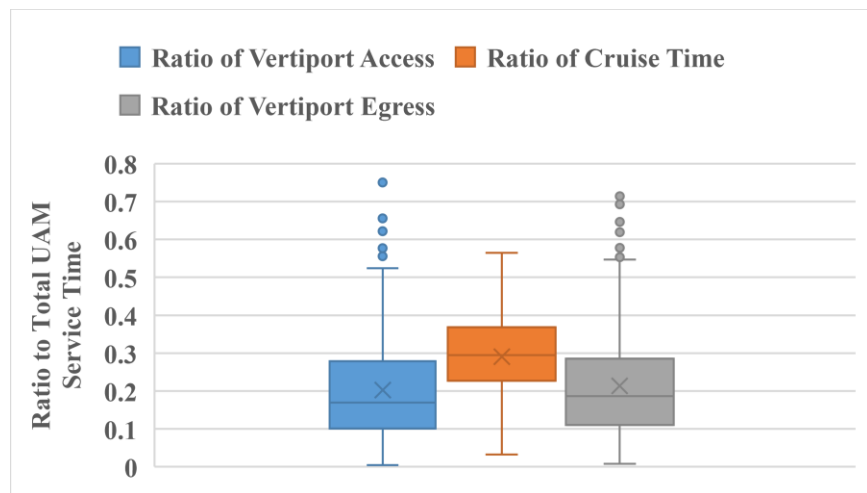Figure 10. UAM travel time-saving distribution.

Figure 11. Comparison of the ratio of service time for each part of UAM operation to the total service time.
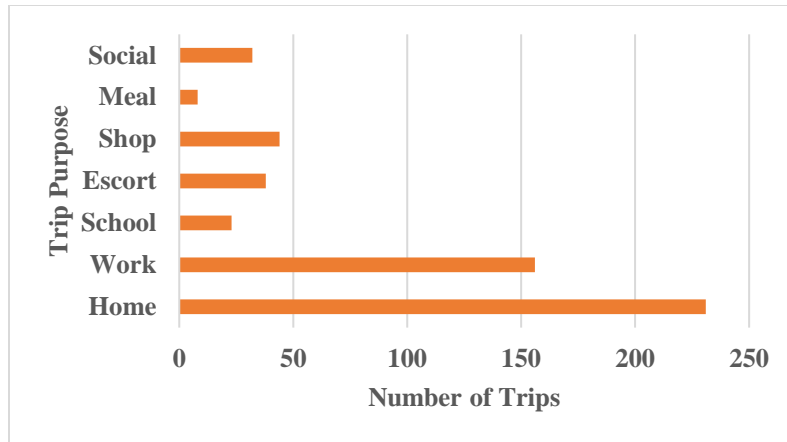
Figure 12. Comparison of trip purposes for selected UAM service.

4.3 Sensitivity analysis

Several sensitivity analyses were conducted in order to understand how some critical parameter variations may influence traveler mode choice behaviors and UAM service performance. For each sensitivity analysis, the value of one parameter was varied, as shown in Table 4, and the values were kept fixed for others. The first parameter to be observed was the number of vertiports to be built; the results are presented in Figs. 13–17. The number of vertiports can significantly influence user accessibility to vertiports, and thus affects users' potential adoption of UAM service. As shown in Fig. 14, with an increasing number of vertiports available, the portion of vertiport access and egress time to total UAM service time decreases, even though some "outlier" trips will always exist, revealing increasing user accessibility to vertiports. Therefore, it is reasonable to expect that improved accessibility leads to growth of UAM adoption, as illustrated in Fig. 13. The number of UAM users increases by around 900, making up about 0.34% of the total trips as the number of vertiports increases from 10 to 100; this effect slows down after the number of vertiports reaches above 80, indicating that UAM adoption is also constrained by other factors. An increasing number of UAM users also corresponds to an increase in the generalized cost-savings of the system. In addition, increased availability of vertiports results in decreased demand at each vertiport for a majority of vertiports, whereas extreme high and low demand always exist at a few vertiports (see Fig. 17); the demand is most evenly distributed when the number of vertiports is 60. Increasing vertiport accessibility does not favor increasing the adoption of non-motorized travel modes (i.e., e-scooter, bicycle, and walking) for vertiport access and egress, as revealed in Figs. 15 and 16. As shown, driving personal vehicles is always the primary choice for vertiport access; for vertiport egress, users favor hire-service the most, followed by driving a personal vehicle. In addition, a significant number of users would use bus transit for vertiport egress. The second parameter tested was passenger transfer time at vertiports. Transfer time represents the efficiency of operation management at vertiports, and increased transfer time offsets the time-saving advantage of UAM air trips. The overall UAM service time of the selected trips increases with increasing transfer time (see Fig. 19), and the travel time replaced by pure ground trips is more unevenly distributed with a higher percentage of long trips (see Fig. 20). This indicates that longer transfer times make UAM service less efficient and less competitive with pure ground transportation for shorter travel time trips. For UAM adoption, Fig. 18 shows that when the transfer time increases from 2 to 10 min,

more than 600 travelers switch back to pure ground transportation, which is more than 0.2% of the total demand, and the generalized cost-saving increases by around $900.
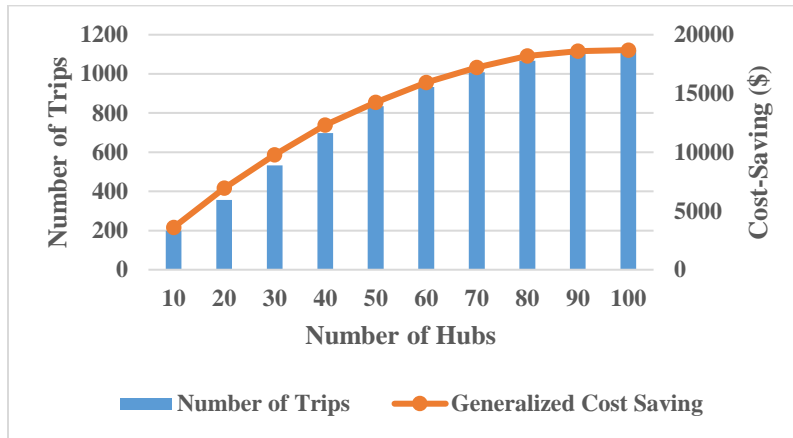

Figure 13. Generalized cost-saving and number of UAM trips variation with different number of vertiports.
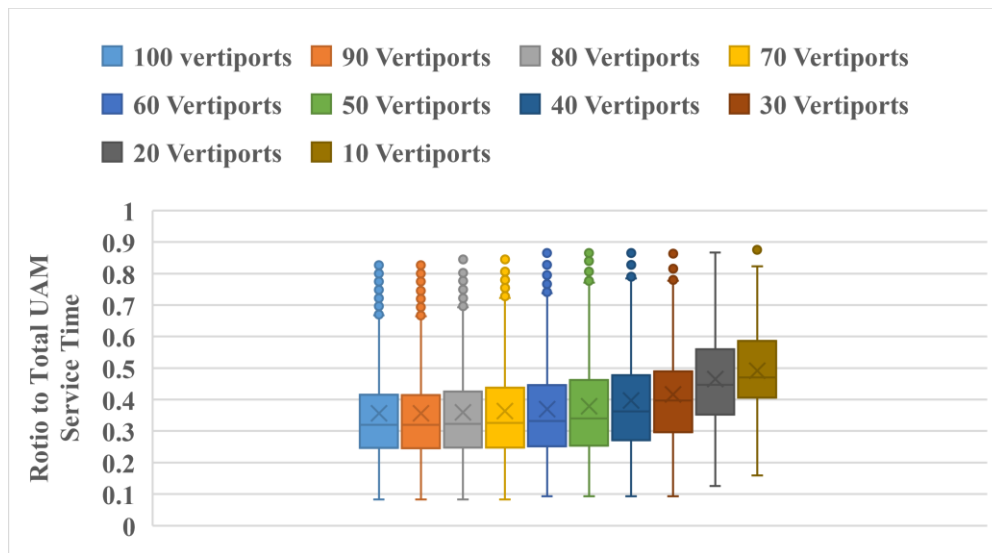

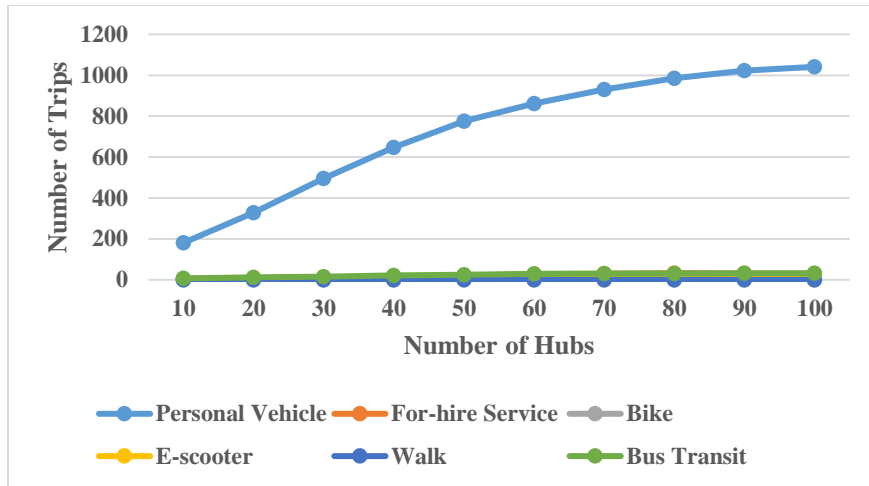Figure 14. Vertiport access and egress time with different number of vertiports.

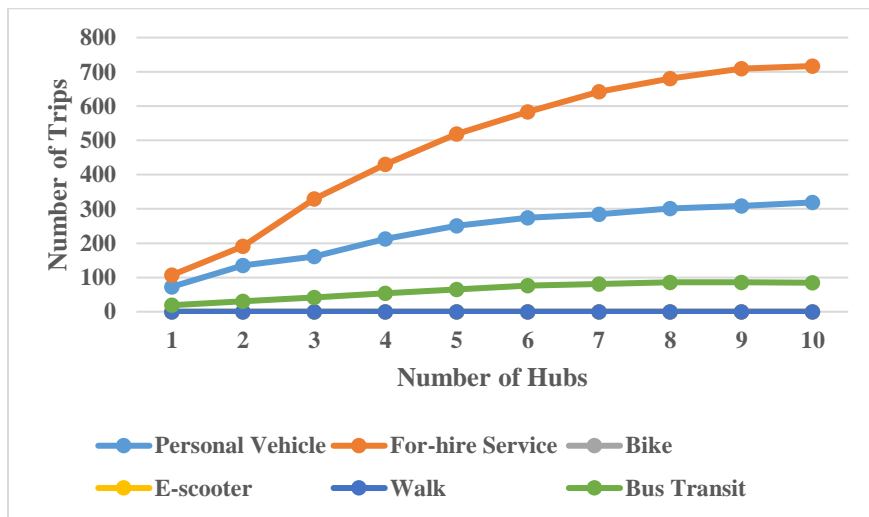Figure 15. Vertiport access choices with different number of vertiports.

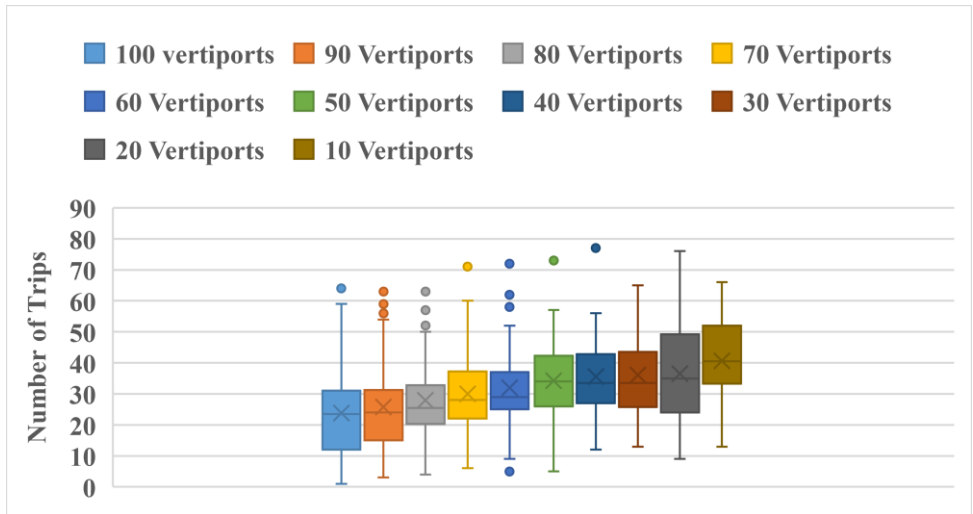Figure 16. Vertiport egress choices with different number of vertiports.

Figure 17. Vertiport demand distribution variation with different number of vertiports
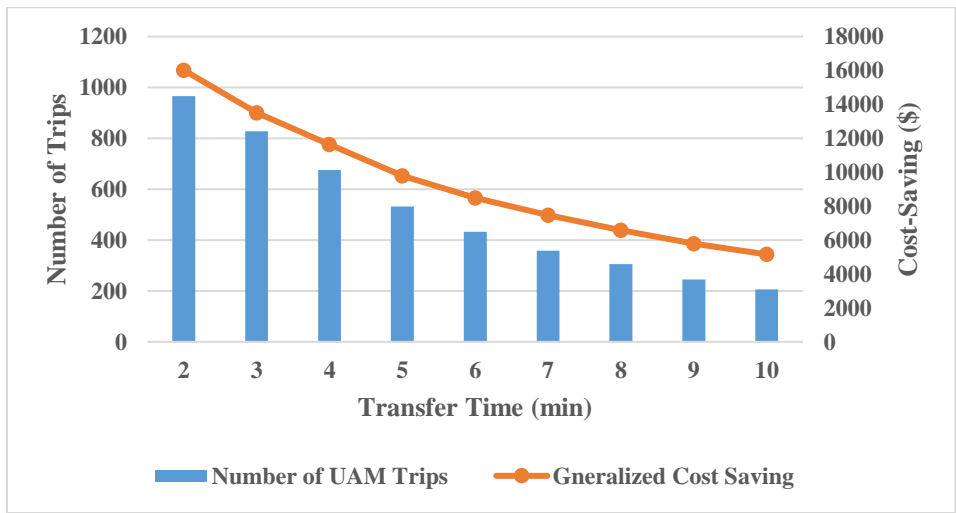

Figure 18. System travel time and UAM adoption variation with different transfer time.
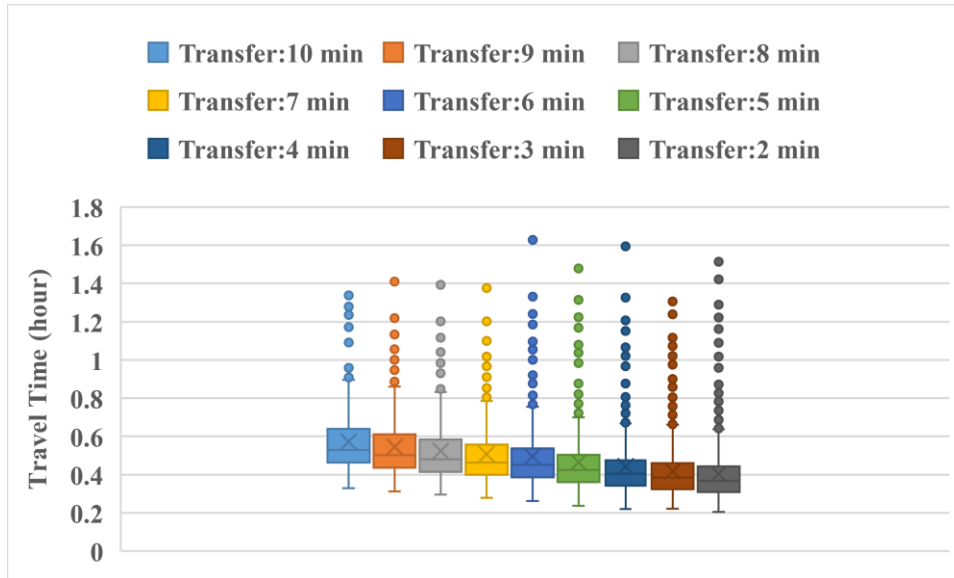
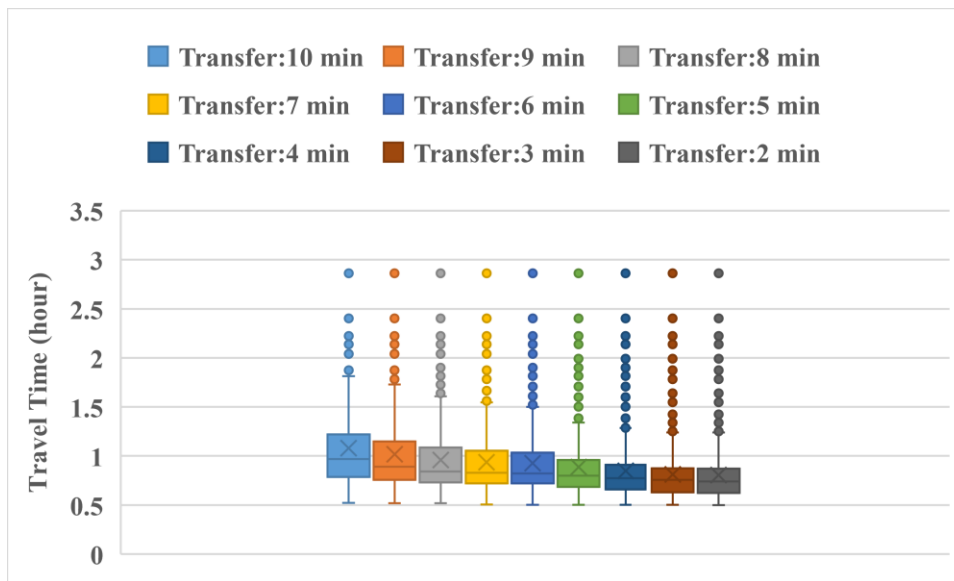Figure 19. UAM trip time distribution variation.

Figure 20. Travel time distribution variation if UAM users continue to use to ground transportation.

How the UAM pricing scheme would influence UAM adoption and the corresponding system performance, as well as the total revenue generation for UAM operators, was also tested. We assumed different UAM air trip price setting scenarios for a baseline number of vertiports. The results of this sensitivity analysis are presented in Figs. 21 and 22.

As revealed in Fig. 21, when the number of vertiports is fixed, UAM adoption is extremely sensitive to air trip price. The adoption rate reaches up to 5000 when the base cost is $10 and the unit air trip cost is $1 but drops to less than 1000 when the base cost is $30 and the unit air trip cost is $2. UAM adoptions of scenarios with a lower base cost are more sensitive to an increase in unit air trip cost. For example, the adoption of UAM service with a base cost of $10 decreases from 5000 to less than 2000 when the unit air trip cost increases from $1 to $2; for a scenario with

a base cost of $30, the change is from around 2000 to less than 600 with the same increase in unit air trip cost. The variation of generalized cost-savings follows a similar trend.

Another significant insight is about revenue generation for UAM operators. As illustrated in Fig. 22, when the number of vertiports is fixed, the total revenue generated for the UAM operator will monotonically decrease with the increase of either unit cost or base cost, which means that an increased unit air trip cost distracts potential users and the lost revenue cannot be compensated for by charging customers a high fare. It should be noted that, when service adoption is high, additional operating costs related to the vehicle fleet size demand, operation, and management may occur, which will offset revenue. Further information needs to be collected and an analysis needs to be performed to understand the impacts of these parameters to UAM operator profit—that is, the difference between revenue and cost.
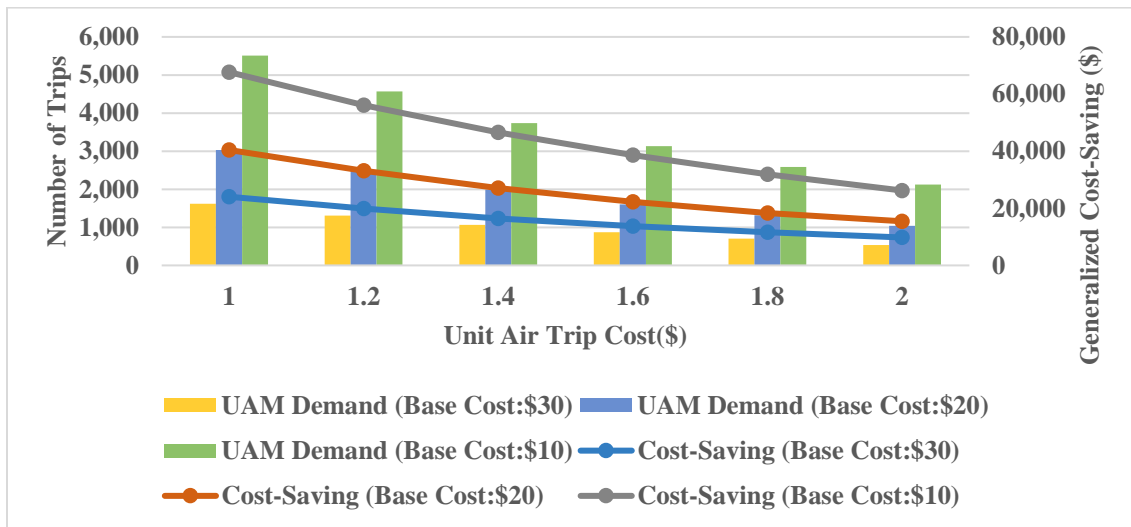

Figure 21. Generalized cost-saving and UAM adoption variation with respect to different pricing schemes.
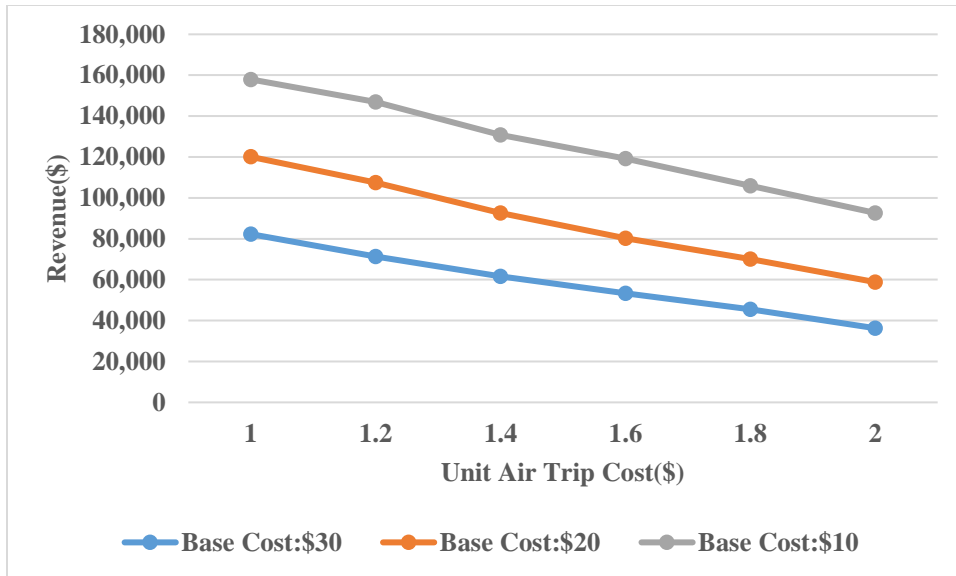
Figure 22. Variation of total revenue generated for UAM operators with respect to different pricing strategies.

Finally, the combined effects of infrastructure supply and pricing strategies in the long run were also explored. In Figs. 23–25, system travel time, air trip revenue generation, and total UAM demand variances were analyzed, with different numbers of vertiports and different unit price settings given a base cost of $30. Overall, the variation in UAM demand, generalized cost-saving, and revenue generation are comparably more sensitive to the unit air trip cost than to the number of vertiports. The marginal effect decreases with an increase in the number of vertiports and the unit air trip cost.

Figure 23. UAM demand variation with different unit air trip cost and number of vertiports.
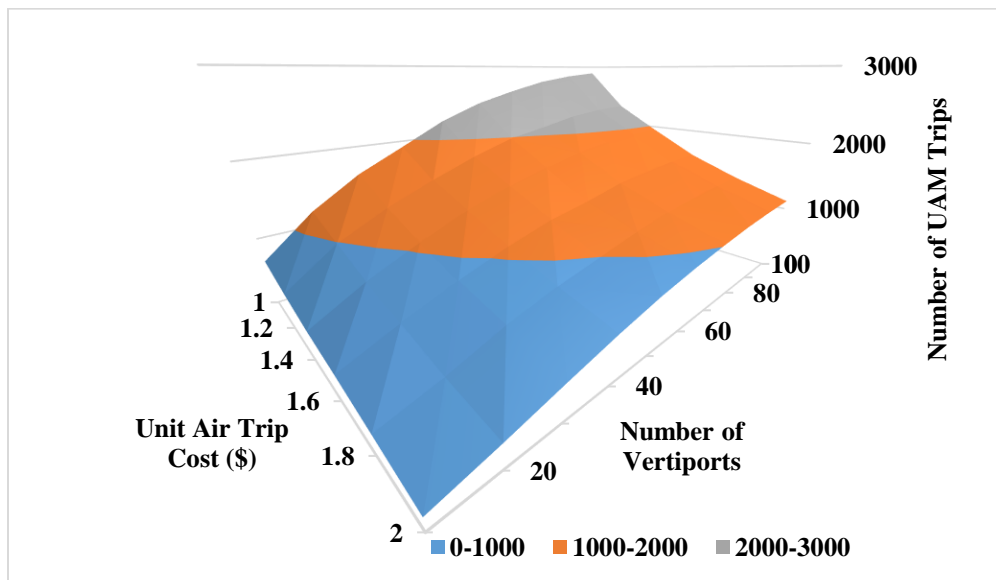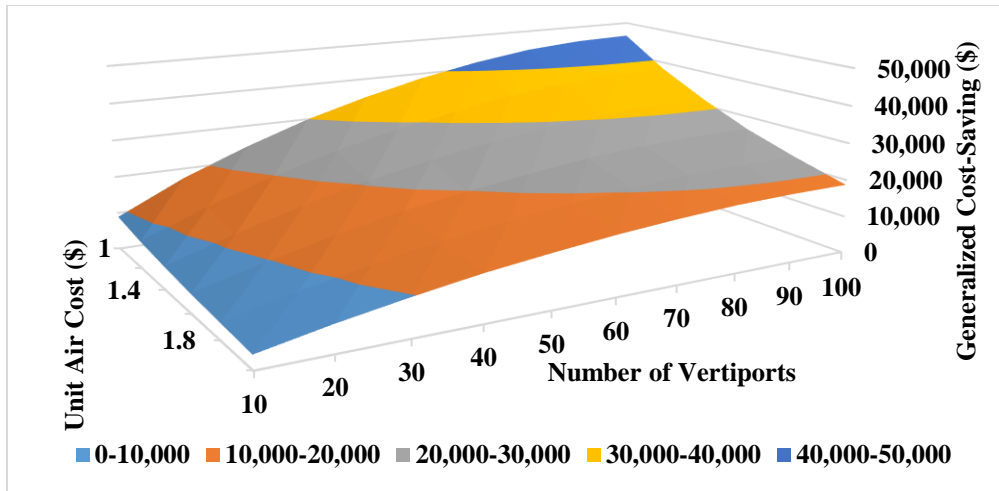
Figure 24. Generalized cost-saving variation with different unit air trip cost and number of vertiports.
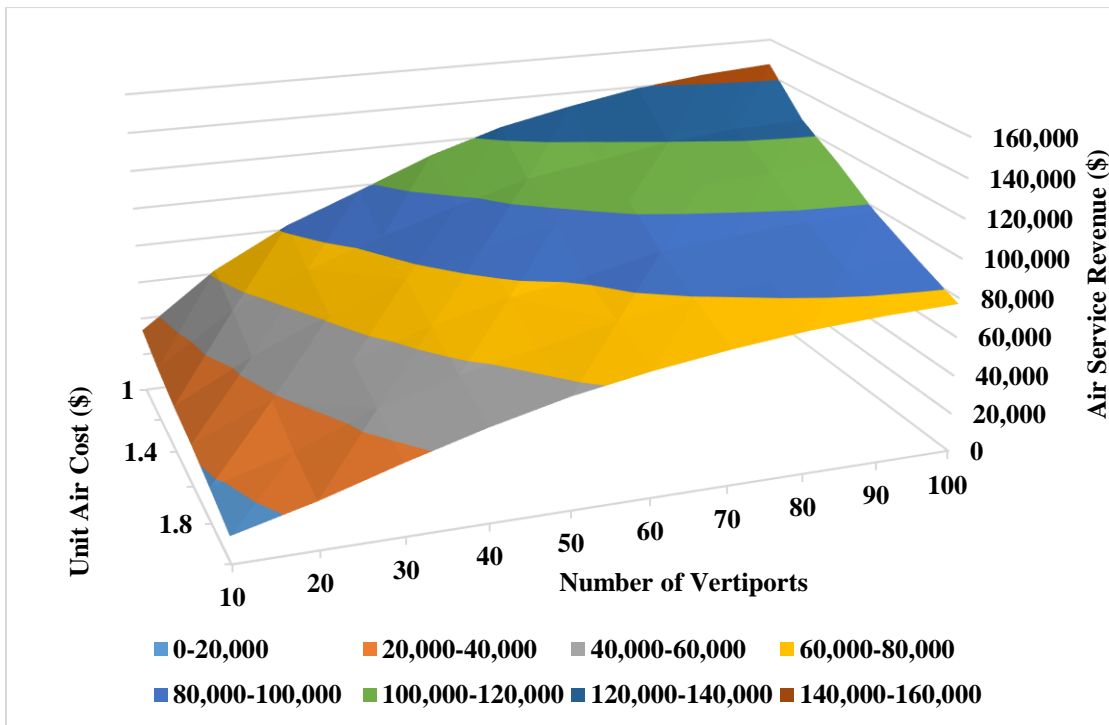
Figure 25. Revenue variation with different unit air trip cost and number of vertiports.

5. Conclusions

This study examines the network design of eVTOL on-demand UAM service. A deterministic IP model was formulated by combining the modeling structure of the traditional hub-and-spoke problem and the mode choice modeling of individual travelers. By analyzing the nature of the network design problem and the UAM trip characteristics, an additional constraint was proposed and preprocessed along with other constraints in order to largely reduce the feasible region of the

IP problem. The optimization results show significant time savings due to the introduction of UAM service and a non-uniform distribution of demand at different vertiports. Sensitivity analyses were conducted to explore the effects of critical factors from the supply side of UAM adoption and service performance. It was observed that although increasing the number of vertiports improves vertiport accessibility and thus increases UAM adoption rates, the case study shows that when the number of vertiports exceeds 80, the marginal effect becomes insignificant. Also, an increase in transfer time between ground modes to UAM drastically discourages travelers from switching from ground transportation to UAM and decrease UAM service performance. Furthermore, different pricing schemes were tested and revealed significant impacts on UAM adoption rates and revenue generation. A combined analysis of the effects of the number of vertiports and pricing strategies indicates that price imposes greater influence than any other factors, from system performance to revenue generation. The proposed modeling framework and sensitivity analysis can provide city managers and UAM operators with a better understanding of emerging on-demand UAM and can provide insights for designing future UAM service in terms of infrastructure requirements and pricing strategies.

This study focused on the infrastructure needs of future UAM service. To integrate this new mode into existing transportation systems, many challenging research problems remain to be addressed. The induced demand caused by the system performance improvement due to the introduction of UAM includes induced ground traffic demand due to mitigated traffic congestion and induced demand of UAM service due to improved mobility. In this study, induced demand was not considered; however, the results of vertiport locations will not be affected by this caveat. For the first type of induced demand, because the number of trips switching to UAM service was very limited in the case study, congestion relief will be minimal and induced demand could be negligible. For the second type, if induced demand follows the same geographic distribution of daily trips used in the study, the optimal locations of vertiports will be the same. In future research with a higher market penetration of UAM, induced demand should be considered. One way of handling this is to modify the framework to enable interactions between the TBRPM model and the network design model. UAM service can be coded into the TBRPM as a new transportation mode according to the network configuration obtained from the network design model. The entire model will then run iteratively with the demand output from the TBRPM as the inputs of the network design model until the UAM demand and network configuration remain relative stable. The induced demand can then be obtained by comparing it with the results from the modeling with no interaction.

This study can be improved and extended in several directions. In this work, when calculating vertiport access and egress time using ground transportation, possible traffic congestion was not taken into consideration. Taking randomness into the problem formulation and proposing a more reliable UAM network design is a future research interest. Also, fleet planning was not studied; instead, it was assumed that there are enough eVTOLs to serve the passenger demand accessing at each vertiport. In addition, fare rates that may vary due to different occupancy rates were not distinguished; that is, passengers would pay a higher fare if they choose to travel alone or a lower fare if they are willing to share with other passengers. An ongoing study is addressing the operational management of UAM service and addressing the need to reposition eVTOL vehicles from the planning and tactical operation perspectives. In that study, eVTOLs are modeled with different occupancy rates, and passengers pay for the service based on their travel distance and the eVTOL occupancy rate. That study is also investigating the charging scheduling of eVTOLs in order to ensure the continuous services of UAM. With this ongoing effort, ultimately, the intention

is to develop a planning and evaluation tool for emerging UAM with which to capture more realistic features of UAM service and performance scenario analyses and offer insights to stakeholders.

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