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Advanced Air Mobility: Demand Analysis and Market Potential of the Airport Shuttle and Air Taxi Markets

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Abstract: Advanced air mobility (AAM) is a broad concept enabling consumers access to on-demand air mobility, cargo and package delivery, healthcare applications, and emergency services through an integrated and connected multimodal transportation network. However, a number of challenges could impact AAM's growth potential, such as autonomous flight, the availability of take-off and landing infrastructure (i.e., vertiports), integration into airspace and other modes of transportation, and competition with shared automated vehicles. This article discusses the results of a demand analysis examining the market potential of two potential AAM passenger markets—airport shuttles and air taxis. The airport shuttle market envisions AAM passenger service to, from, or between airports along fixed routes. The air taxi market envisions a more mature and scaled service that provides on-demand point-to-point passenger services throughout urban areas. Using a multi-method approach comprised of AAM travel demand modeling, Monte Carlo simulations, and constraint analysis, this study estimates that the air taxi and airport shuttle markets could capture a 0.5% mode share. The analysis concludes that AAM could replace non-discretionary trips greater than 45 min; however, demand for discretionary trips would be limited by consumer willingness to pay. This study concludes that AAM passenger services could have a daily demand of 82,000 passengers served by approximately 4000 four- to five-seat aircraft in the U.S., under the most conservative scenario, representing an annual market valuation of the 2.5 billion USD.

Keywords: advanced air mobility (AAM); urban air mobility (UAM); on-demand air mobility; market analysis; air taxi; vertical take-off and landing (VTOL)

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1. Introduction

A variety of technological advancements and industry investments in electrification, automation, vertical take-off and landing (VTOL) aircraft, unmanned aerial systems (UAS), and air traffic management are enabling innovations in aviation, such as new aircraft designs, services, and business models. Advanced air mobility (AAM) is a broad concept that enables consumers access to on-demand air mobility, goods delivery, and emergency services through an integrated and connected multimodal transportation network [1]. AAM can serve a variety of built environments (i.e., urban, suburban, and rural) and includes local use cases of about a 50-mile (80 km) radius in rural or urban areas and intraregional use cases up to a few hundred miles [2]. Other common terms include on-demand air mobility, urban air mobility (UAM), and rural air mobility.

In recent years, on-demand aviation services similar to transportation network companies (TNCs) (i.e., Uber or Lyft) are entering the marketplace. Globally, 12 app- and web-based, on-demand AAM passenger services using helicopters and fixed-wing aircraft were operational as of March 2020 [1]. A number of companies have announced plans to launch passenger AAM services using VTOL and other novel aircraft designs. A few planned services include: (1) Volocopter in Singapore in 2021; (2) EHang in Linz, Austria in 2021; (3) Vertical Aerospace in London in 2022; (4) Joby Aviation (also acquired Uber Elevate) in 2024 (cities to be announced); and (5) Lilium in Orlando, Munich, Nürnberg, and other cities around the world in 2024 [1]. A few companies with unannounced launch timelines include Archer, Wisk (formerly Kitty Hawk), and many others. Additionally, a number of automakers have announced investments in AAM, including Aston Martin, Audi, Daimler, Geely, General Motors, Hyundai, Porsche, Stellantis, and Toyota [1].

While AAM may be enabled by the convergence of several factors, several challenges, such as community acceptance, safety, social equity, issues around planning and implementation, airspace, and operations, could create barriers to mainstreaming. Moreover, while numerous societal concerns have been raised about these approaches (e.g., affordability, safety, privacy, multimodal integration, etc.), AAM has the potential to offer additional options for emergency services, goods delivery, and passenger mobility [1]. Several market studies forecast that AAM passenger and emergency services will begin to transition to VTOL and electric VTOL (eVTOL) aircraft in the mid to late 2020s. Broadly, these market studies estimate a passenger mobility market of 2.8 to 4 billion USD by 2030, and a global AAM market potential of 74 to 641 billion USD in 2035 [2–8]. Herman et al. [6] conducted a market study examining 74 global cities using a metanalysis approach of existing studies coupled with an analytical forecasting model that included variables such as city demographics, infrastructure costs, aircraft and supply chain, demand assumptions, and community and regulatory constraints. The study estimates a market potential of 318 billion USD across the 74 cities in 2040. Another study by Porsche Consulting estimates a global demand for 23,000 eVTOL aircraft in 2035. Using a gravity model, [7] forecasts demand in 2042 for regional air taxis (up to 300 km). Mayor and Anderson [8] estimates that air taxis could have upwards of 400 million enplanements representing 4% of domestic trips by 2050. Lineberger et al. [9] estimates that the U.S. AAM market will be valued at 115 billion USD and employ more than 280,000 workers by 2035. Market forecasts vary widely because of variations in study scope and assumptions, such as geography, timeline, market segmentation, and the inclusion of military applications of VTOL aircraft.

Estimating the demand and growth potential of AAM is important for three key reasons. First, understanding the potential demand for AAM helps private sector investments in eVTOL and infrastructure development. Second, understanding the potential demand for AAM is important to help inform planning, policy, and decision-making of the public sector. Finally, estimating the market size, demand, and growth potential of AAM helps public and private sectors understand the potential scale of externalities associated with AAM. Although a number of studies have attempted to estimate the demand and market potential of AAM, many of these studies focus on unconstrained forecasts, which can overestimate the market potential for AAM using optimistic assumptions. This study examines the demand and market potential of AAM by applying a series of constraints, including infrastructure availability and capacity, willingness to pay, the time of day for anticipated operations, and the weather. In addition to a constraint analysis, this study analyzes the market potential of AAM by overlaying a variety of scenarios including technology enhancements, network efficiency, autonomous flight, infrastructure improvements, varying values of time, competition with shared automated vehicles, telecommuting, and latent demand.

This article presents a demand analysis examining the market potential of two potential AAM passenger markets: (1) airport shuttles and (2) air taxis. The airport shuttle market envisions AAM passenger service to, from, or between airports along fixed routes. The air taxi market envisions a more mature and scaled service that provides on-demand point-to-point passenger services throughout urban areas. This article is organized into five sections. The first section provides an overview of the emerging literature on AAM market demand analysis. The next section describes the methodology used to analyze and forecast the AAM airport shuttle and air taxi markets. In the third section, the authors review key findings from the scenario and sensitivity analyses of both markets. In the fourth section, the authors discuss the findings from eight market scenarios. In the final section, the authors conclude with a discussion of how the global pandemic may impact the evolution of advanced air mobility and recommendations for additional research.

2. Overview of Studies Forecasting AAM Demand

A number of emerging studies have examined the market potential for AAM across different geographies using a variety of qualitative and quantitative methods. Broadly, these studies tend to use a variety of variables such as cost, journey time, wait time, number of connections, value of time, and vertiport density to quantify consumer demand, potential mode share, and price elasticity for AAM. Using a gravity model to estimate interurban demand, Becker et al. [7] identified potential AAM markets in 2042. Another study by NEXA Advisors [6] modeled AAM demand for a variety of different use cases, including air taxi, airport shuttle, corporate campus shuttle, emergency services, and regional air mobility. The model used a variety of variables including population, population density, gross domestic product (GDP) per capita, age, existing aviation activity, and the presence of large corporations. A similar study by Mayor and Anderson [8] models AAM using GDP and GDP growth; population and population growth; population density; income distribution and wealth concentration; among other factors. A qualitative study by Robinson et al. [10] identified potential locations for AAM using factors such as sprawl, urban density, geography, the number of existing airports, wealth, weather, surface transportation congestion, and the presence of various economic clusters. Using the cities identified in [8], Mayakonda et al. [11] estimated AAM passenger kilometer demand based on airfares, potential time savings, and vertiport density. The study estimated that AAM demand could achieve 3.2 to 8.5% mode share based on airfares of 0.30 USD per passenger kilometer. The range was attributed to various assumptions about the density of a vertiport network. However, the study also found that mode share quickly declines with increasing costs, particularly above 0.90 USD per passenger kilometer. At that price point, AAM mode share declines to 0.5 from 1.3% (again, the range was attributable to different assumptions about vertiport density).

Antcliff et al. [12] suggested that the San Francisco Bay Area could be an early adopter market for AAM because of the high percentage of long-distance or "super" commuters, among other factors such as weather and geography. Others have theorized that polycentric regions with multiple urban centers could support AAM demand associated with bidirectional traffic patterns that increase aircraft occupancies and reduce "deadhead" flights without paying passengers [13]. These studies theorize that the bidirectional demand from polycentric cities could also improve the operational efficiency and profitability of early operations, helping reduce traveler costs and creating a feedback loop that increases demand [14].

Finally, studies have also conducted exploratory demand modeling and travel time analyses, often comparing AAM with private vehicle use and other modes of transportation. Wei et al. [15] compared door-to-door travel times of private vehicles with short take-off and landing (STOL) aircraft. Using a case study of South Florida, the study found potential demand for AAM trips greater than 45 min. Other studies have found that air taxi trips need to be longer than 15 to 25 km to provide sufficient travel time savings over surface modes in order to generate AAM demand [16]. Using a case study of Melbourne, Australia, Swadesir, and Bil [17] compared the travel times and costs of air taxis to cycling, driving, and riding public transportation. Another study by Rothfeld et al. [18] found that surface transportation was typically only competitive with AAM travel times when trips were less than 10 km in length. Using a case study of the San Francisco Bay Area, Antcliff et al. [12] found that minimizing AAM access and egress times (e.g., enplaning/deplaning, security, delays, etc.) were an important factor the competitiveness of AAM door-to-door travel times. Kreimeier et al. [19] conducted an economic assessment of AAM in Germany and also found that air taxi demand is highly sensitive to cost and travel time. The study also found a willingness to pay of 0.5–0.8 EUR_{2015} per kilometer, depending on travel time and distance [19]. Fu et al. [20] modeled mode choice in Munich using a stated preference-based survey (n = 248) multinomial logit, nested logit, and mixed logit models. The study found a value of time of 27.55, 27.47, 32.57, and 44.68 EUR per hour for private vehicles, public transportation, shared automated vehicles, and autonomous air taxis, respectively. Al Haddad et al. [21] also concluded that the value of time savings, among other factors, were highly influential on the potential adoption and use of AAM. All of these studies suggest that AAM demand could be influenced by the quality of first- and last-mile connections because of their impacts on total travel time, cost, and convenience (i.e., number of connections) [12,15–21].

Cohen et al. [1] theorized that the AAM passenger mobility market segments may evolve from hub and spoke services to point-to-point air taxi services if the cost of flights decreases, adoption mainstreams, and infrastructure becomes more ubiquitous. However, Ref. [1] also cautions that although on-demand aviation may be enabled by the convergence of several factors, a number of challenges could constrain AAM's growth and mainstreaming, such as safety, air traffic management, noise, privacy, visual pollution, community acceptance, weather, environmental impacts, infrastructure limitations, and security, among others.

3. Methodological Overview

The authors began the study by conducting a comprehensive literature review documenting potential use cases and markets for AAM. The literature review was also used to document a variety of operational assumptions (e.g., aircraft and flight characteristics) as well as costs per passenger mile. As part of the literature review, 36 use cases were identified that could potentially be served by VTOL and eVTOL aircraft. In addition to reviewing use cases, the authors collected preliminary data on 486 urbanized areas considered for potential inclusion in the market study. Because of limited study resources, the researchers filtered out small urban areas to focus on larger metropolitan regions and urban air mobility. To do this, the researchers applied a population filter selecting metropolitan regions with more than one million inhabitants and applied a population density filter excluding low-density regions with less than 1000 inhabitants per square mile. The remaining urban areas were indexed based on travel time, commute stress, and annual congestion cost. Between summer 2017 and winter 2019, as part of a National Aeronautics and Space Administration (NASA) market study, the authors established a strategic advisory group (SAG) to solicit feedback on key assumptions from more than 50 public and private sector thought leaders to inform this research. SAG members included senior professionals and subject matter experts from NASA, the Federal Aviation Administration (FAA), the National Transportation Safety Board (NTSB), the North Carolina Department of Transportation, New York City, the city of Los Angeles, Los Angeles World Airports, the International Civil Aviation Organization (ICAO), and numerous manufacturers, startups, and academic institutions. Public sector participants included directors of the FAA's Aviation Plans and Policy Office, the Office of International Affairs, the Unmanned Aircraft Systems (UAS) Integration Office, and a former NTSB chairman. Manufacturers and startups representing a diverse set of planned airframes were also included as part of the SAG. In consultation with the SAG, it was decided that the market study would focus on ten metropolitan regions in the U.S. (Dallas, TX; Denver, CO; Honolulu, HI; Houston, TX; Miami, FL; New York, NY (including Newark, NJ); Phoenix, AZ; the San Francisco Bay Area, CA; Southern California (including Los Angeles, Orange, Riverside, and San Bernardino Counties); and Washington, DC (including Northern Virginia)).

The authors then applied these metrics to create a four-step process to analyze the airport shuttle and air taxi markets. Collectively, these four steps (described below) included calculating key business model and operational metrics, such as number of flights, potential revenue, operating costs, passenger volumes and distribution, and infrastructure availability (e.g., number, location, and capacity of a hypothetical vertiport network). Each of these steps are outlined below:

Step 1. The first step included defining operational assumptions. For example, both the airport shuttle and air taxi markets are defined by range, demand, infrastructure availability, aircraft capabilities, and similar operational characteristics. The process of defining operational assumptions included consideration of the complete trip concept, such as ground transportation and first- and last-mile connections to a vertiport, transfers, and the air taxi flight.

Step 2. The second step involved developing an operating model and calculating key performance metrics. To do this, the authors calculated the cost of passenger service for different aircraft types proposed to serve the air taxi and airport shuttle markets. Each cost, such as capital, maintenance, batteries, electric charging, and vertiports, was individually modeled. Weather adjustments, such as wind speed, temperature, and density for each urban area, were applied. The full methodology for the weather analysis can be found in [22]. Using the calculated cost of passenger service, the authors calculated demand using a demand model comprised of (1) trip generation, (2) scoping, (3) trip distribution, (4) mode choice, and (5) operational constraints.

Step 3. Third, the authors developed what-if scenario analyses using operational constraints, such as infrastructure capacity, time of day restrictions (e.g., limiting flights during the night to minimize adverse community impacts), and regulatory challenges to flying under instrument flight rules (IFR) conditions.

Step 4. In the final step, the authors performed a Monte Carlo sensitivity analysis to better understand the impact of these challenges and various assumptions on market size and viability. To do this, the authors simulated 10,000 randomly generated air taxi missions for each urban area. Eight scenarios were developed based on the current and future states of the air taxi system, including decisions by key stakeholders.

The methods and findings from each of these steps in the analytical process are described in greater detail in the following four subsections. All data used in the analysis was from 2018 unless otherwise noted.

3.1. Operational Assumptions

The authors assumed that initial airport shuttle and air taxi operations would have a pilot on board. Additionally, the authors assumed that aircraft used for airport shuttle and air taxi markets would have a maximum range of 50 miles on a single charge using an electric propulsion system. The nominal flight profile (Figure 1) and operational assumptions (Table 1) used to feed into the analysis were developed in consultation with the SAG.

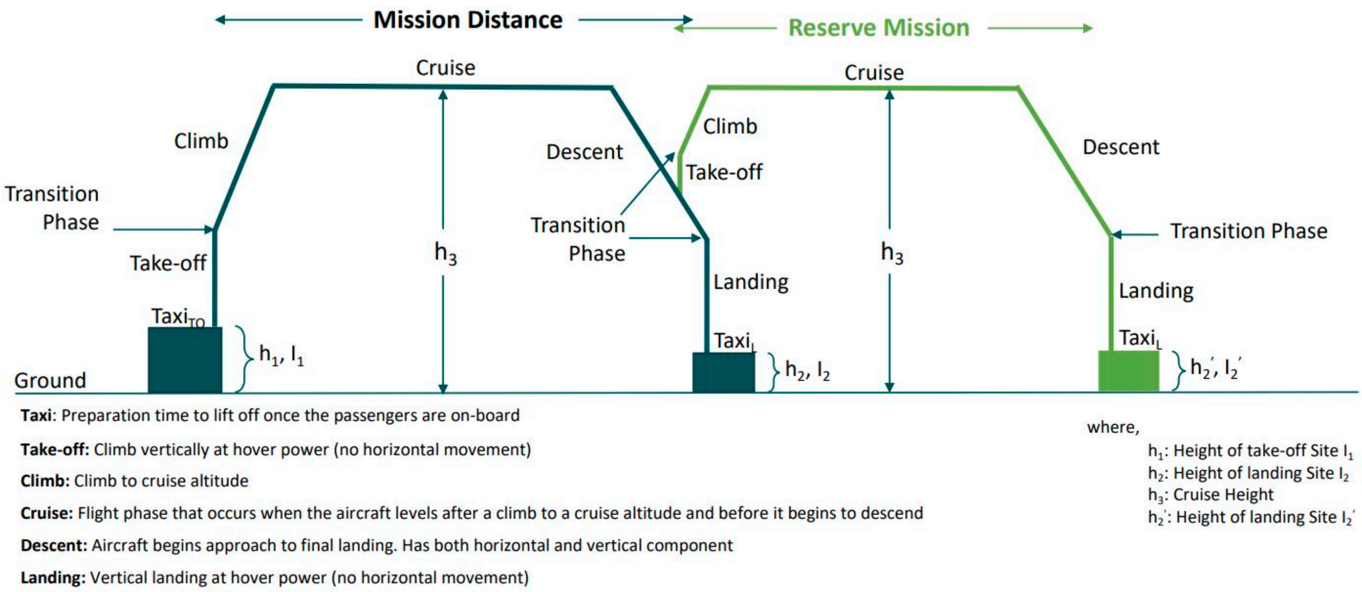

Figure 1. Flight profile of the airport shuttle and air taxi use cases.

Table 1. Operational profile of the airport shuttle and air taxi use cases.

Parameter	Definition	Minimum	Maximum
Aircraft seats (passenger seats = aircraft seats − 1)	Number of seats in aircraft. Initial years of operation assumed a pilot on-board, hence there was one seat less available to be occupied by a passenger.	1	5
Load factor (%)	Passenger load factor, which measures the utilization of the capacity of the eVTOL, i.e., the number of seats occupied by a revenue passenger divided by the total number of available seats.	50%	80%
Utilization (annual number of flights) for 2+ seat aircraft (number of flight hours per year)	Average numbers of hours in a year that an aircraft was actually in flight. Conservative utilization numbers were used to consider battery recharging/swapping times.	1000	2000
Utilization (annual number of hours) for 2-seat aircraft (number of flight hours per year)	For 2-seat aircraft (only one passenger seat), the aircraft was only flown when the passenger seat was filled. Therefore, the utilization range was adjusted by multiplying with the load factor of a 2+ seat aircraft, i.e., 1000 × 50%, 2000 × 80%.	500	1600
Max reserve (mins)	Flight time for reserve mission (outside of mission time) at a specified altitude.	20	30
Deadhead trips (%)	Ratio of non-revenue trips and total trips.	25%	50%
Detour factor (%)	Factor that captures the lateral track inefficiencies equal to the ratio of actual flight distance divided by the great circle distance between two vertiports.	5%	15%
Cruise altitude (ft)	Cruise altitude for AAM vehicles.	500	5000
Embarkation time (mins)	Time spent in the process of loading AAM vehicle with passengers and preparing them for flight.	3	5
Disembarkation time (mins)	Time required for passengers to disembark the AAM vehicle after the flight.	2	3
Battery depth of discharge (%)	Referred to the degree to which a battery was discharged in relation to its total capacity.	50%	80%

3.2. Price Per Passenger Mile

The authors analyzed nine different aircraft types using electric, hybrid, and JetA powertrains. The nine types of aircrafts considered included:

(1) Multirotor-a rotorcraft with more than two rotors (e.g., Ehang and Volocopter).
(2) Autogyro-a type of rotorcraft, which use an unpowered rotor in free autorotation to develop lift (e.g., Carter).
(3) Conventional helicopter—a type of rotorcraft in which lift and thrust are supplied by rotors (e.g., Robinson R22).
(4) Tilt duct—a eVTOL in which a propeller is inside a duct to increase thrust (e.g., Lilium Jet).
(5) Coaxial rotor—a design with rotors mounted one above the other (e.g., GoFly).
(6) Lift + cruise—a design that has independent thrusters for cruise and lift (e.g., Aurora Flight Sciences).
(7) Tilt wing—an aircraft that uses a wing that is horizontal for conventional forward flight and rotates up for vertical takeoff and landing (e.g., A3 Vahana).
(8) Compound helicopter—a design with a helicopter rotor-like system and one or more conventional propellers to provide forward thrust during cruising flight (e.g., HopFlyt).
(9) Tilt rotor—an aircraft type that generates lift and propulsion by way of one or more powered rotors mounted on rotating engine pods or nacelles (e.g., Joby Aviation).

For this analysis, the airport shuttle and air taxi markets were evaluated using electric aircraft because of the strong industry focus on eVTOL development, the potentially lower environmental impact (if powered by a clean energy grid), and lower operational costs. Next, the authors conducted a literature review and consulted with the SAG to review more than 70 aircraft designs and performance characteristics to develop a range of flight specifications, such as speed, range, weight, and other attributes. Aircraft specifications, such as cost and maximum take-off weight (MTOW) were calculated on a per seat basis and were extrapolated for aircraft with more than one seat.

The next step was to simulate the operation of these aircraft on randomly generated flights using an air taxi model (i.e., one or more passenger travels in an eVTOL between an origin and destination vertiport and pays on a per passenger mile basis). Ground transportation provides first- and last-mile connections between the traveler's origin and destination.

Next, the operating cost per passenger mile for each aircraft was calculated as a sum of the direct operating cost (DOC) and the indirect operating cost (IOC). The DOC includes capital, energy, battery, crew, maintenance, insurance, infrastructure, and route cost, whereas the IOC includes marketing and reservation costs. Next, the authors applied a pricing model and taxes to calculate the price per passenger mile (i.e., the cost to the passenger). Each of the cost components of the DOC were individually modeled for aircraft with two to five seats (a one-seat aircraft was not considered because of pilot requirements), whereas IOC was calculated as percent of the DOC (10–30%). To conduct the Monte-Carlo-based sensitivity analysis, 10,000 randomly generated iterations were performed. Table 2 outlines key steps, ranges, and assumptions used in modeling each cost component.

Table 2. Cost component assumptions.

Cost Component	Key Steps	Key Assumptions		
		Parameter	**Min**	**Max**
Capital and insurance cost	• Capital cost is the sum of the depreciation cost and the finance cost. Certification costs were included in the aircraft price. • Residual value of the aircraft was assumed to be negligible. • Aircraft insurance is the sum of liability and hull insurance, calculated as a % of aircraft price.	Vehicle life (flight hours)	12 k	15 k
		Depreciation rate (%)	5%	10%
		Finance rate (%)	5%	10%
Energy and battery cost	• Energy required was calculated as the sum of energy required in each phase of the flight. • Battery pack sizing was done based on the longest mission and battery recycling was assumed to be negligible.	Battery specific energy in Wh/kg	300	400
		Battery capacity specific cost (USD/kWh)	200	250
		Energy conversion efficiency (%)	90%	98%
Crew cost	• Assumed one full time equivalent pilot per aircraft and one full time equivalent ground crew member in the initial years of service. • Each crew member undergoes annual training.	Pilot salary per year (USD)	50 k	90 k
		Ground crew salary per year (USD)	20 k	30 k
Infrastructure cost	• Calculated infrastructure cost by extrapolating car parking garage style architecture and construction to fit an aircraft. • Same infrastructure was also used to park the aircraft overnight. A nightly parking fee was added.	Cost of one supercharger (USD)	200 k	300 k
		Cost of one regular charger (USD)	10 k	20 k
Maintenance cost	• Calculated based on per-mission basis by multiplying the ratio of maintenance man hours to flight hours and the mechanic wrap rate.	Mechanic wrap rate (USD per hour)	60	100
		Maintenance manhours per flight hour	0.25	1

The economic modeling found that the median operating cost per passenger mile decreased as the aircraft's number of seats increased because of economies of scale for maintenance costs, indirect operating costs, and capital costs. The factors used for consideration in the operational model are shown in Figure 2. Multirotor(s) were found to have a high operating cost per passenger mile because of lower cruise speeds compared to other types of eVTOLs. The authors used median values for each seat category. Uncertainty in the cost calculation was observed (shown by gray lines in Figure 3), largely because of assumptions about cruise speed and network efficiency (utilization, load factor, and deadhead trips used to reposition aircraft without paying passengers). Each of these variables has the potential to increase and lower the operating cost per passenger mile. Maintenance, capital expenditures, and personnel represented ~60–70% of the overall operating costs. Most costs on a per passenger basis decreased for aircraft with a greater number of seats.

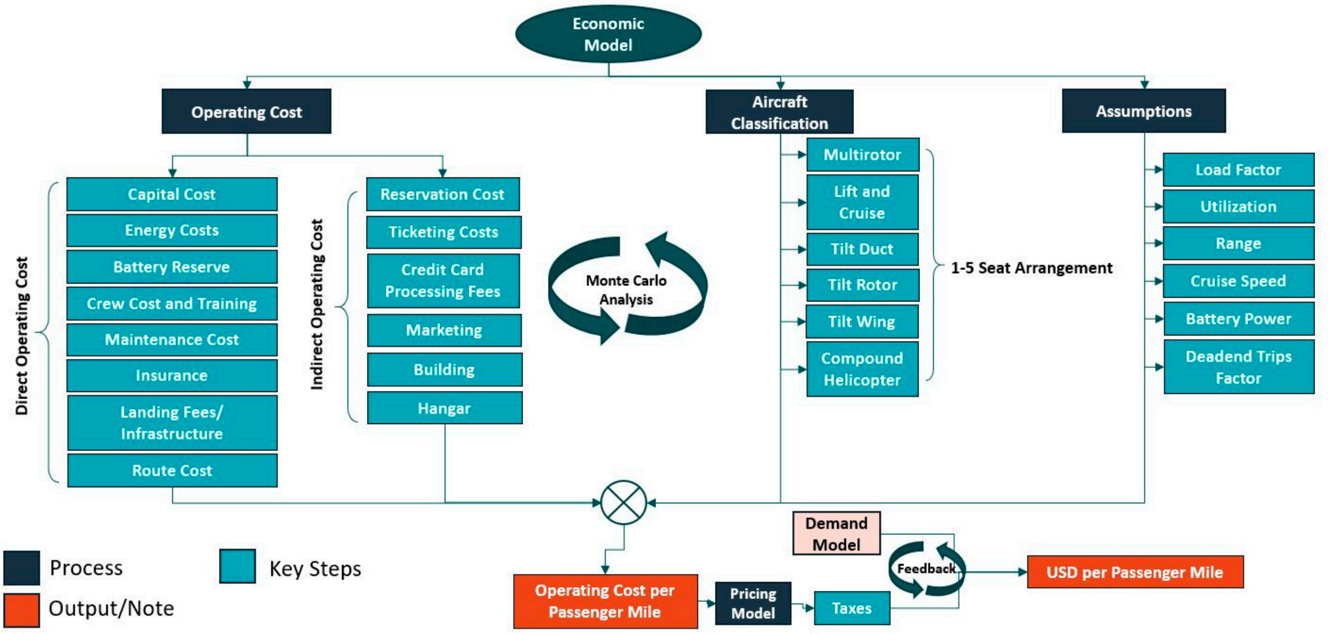

Figure 2. Structure of supply economic model for the air taxi and airport shuttle markets using eVTOL.

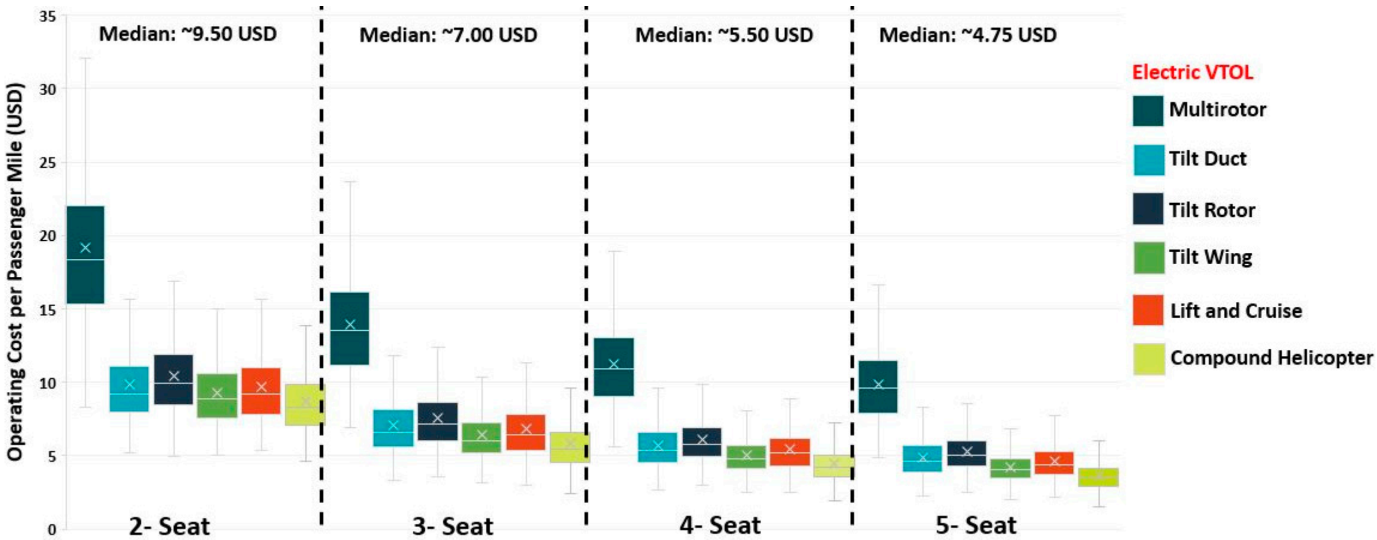

Figure 3. Operating costs per passenger mile.

Although service providers may use a variety of pricing strategies, for this analysis, the authors assumed a cost-plus profit pricing strategy for the operators with an assumed profit margin of 10–30%. Additionally, the authors assumed that both the air taxi and airport shuttle markets will be subjected to taxes and fees, comparable to taxis and TNCs. These taxes can include sales tax, motor vehicle fees, workers compensation, surcharges for public transportation, accessibility fees, licensing fees, inspection fees, environment taxes, and local/state property taxes. Although these taxes and fees vary by jurisdiction, the authors assumed taxes and fees ranging between 5% and 15%.

Based on these assumptions, the analysis concludes that a five-seat eVTOL is expected to cost around 6.25 USD per passenger mile in the near term with an uncertainty of +/−50%. This estimated cost is lower than comparable services offered by helicopters, but higher than all surface transportation services (Figure 4). However, increased operational efficiency and technological advancements such as autonomous flight could potentially reduce per passenger mile costs by 60%.

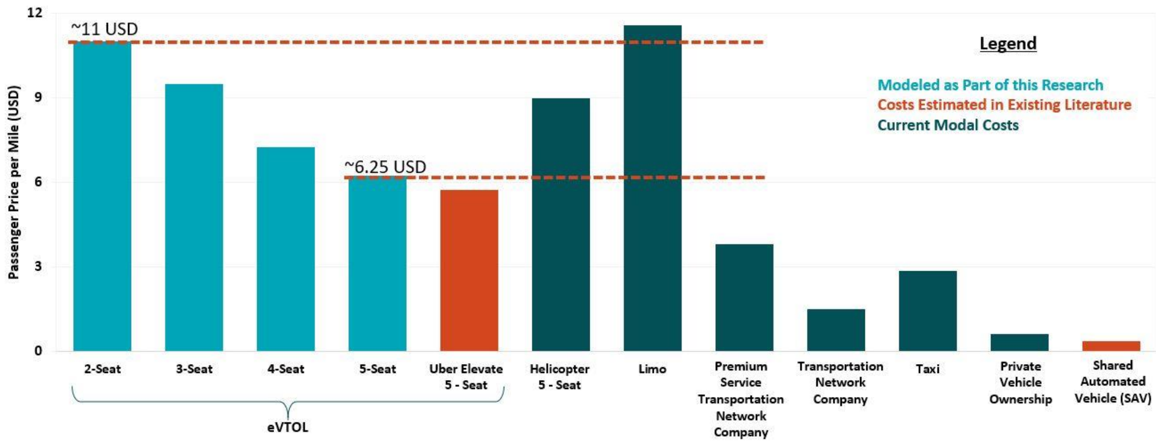

Figure 4. Price comparison of passenger AAM services with other modes of transportation.

3.3. AAM Travel Demand Model

Demand modeling was used through a five-step process of (1) trip generation, (2) scoping, (3) trip distribution, (4) mode choice modeling, and (5) application of constraints to assess market size, viability, and valuation for the air taxi and airport shuttle markets. This process is shown in Figure 5. Each of these steps are briefly described below.

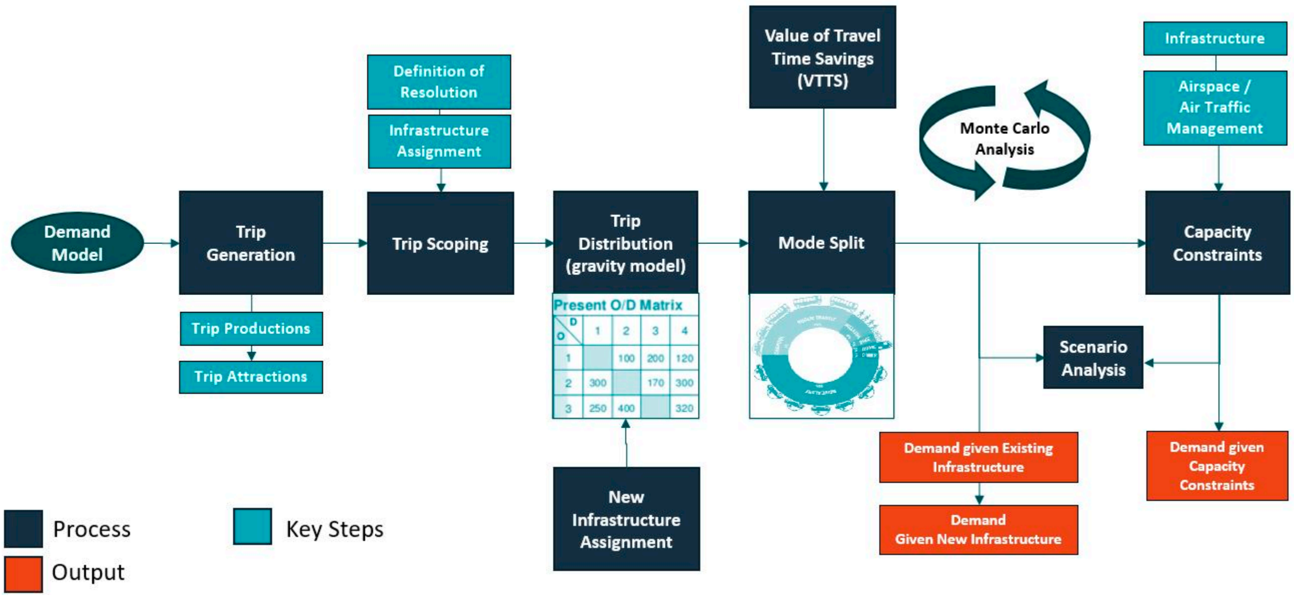

Figure 5. Demand side model for AAM.

Step 1. Trip generation is the first step in demand modeling and estimates the number of trips that are produced. For this step, the model was calibrated using the U.S. Department of Transportation data on mandatory trips (e.g., work-related) and discretionary trips (e.g., retail, leisure, etc.). For the air taxi analysis, works trips were generated using 2016 American Community Survey (ACS) commuting data and discretionary trips were generated using 2017′s National Travel Household Survey (NTHS) data. For the airport shuttle analysis, 2018 U.S. Bureau of Transportation Statistics (BTS) T-100 Market (All Carriers) data was used. Airport-specific trips were generated by proportionally distributing daily demand from each airport in an urban area to each census tract based on its population.

Step 2. Scoping was performed using ACS datasets available at different geographic levels (block groups, census tracts, place, county, and urban area) for various mode types. Temporal resolution of the datasets was limited to an average day of year. The authors first performed a tradeoff analysis between fidelity in results and computational speed for different combinations of geographic levels and mode types. The analysis was then conducted at a census tract level for mode types classified as driving, TNCs, taxi, public transportation, and walking. Next, the authors assumed that no new infrastructure would be constructed prior to early AAM operations. Existing infrastructure (i.e., heliports and airports) were obtained from the FAA's Aviation Environment Design Tool (AEDT) database. Capacity enhancements, such as additional vertiports and increased capacity per vertiports were evaluated in the Monte Carlo sensitivity analyses. Next, infrastructure was assigned to each census tract using a nearest neighbor algorithm. For the airport shuttle market, not all passengers arriving or departing at a major airport were considered potential customers of AAM because of various limitations, such as travel characteristics. For example, a family of four traveling a long distance with over 200 lbs. of baggage would be unlikely to use AAM, because of the high cost compared to other alternatives such as a rental car, and technically unable to use one AAM aircraft (because of performance limitations). Therefore, demand for the airport shuttle analysis focused on one to three passengers per air ticket.

Step 3. Trip distribution was performed by distributing trips between census tracts (origin–destination pairs) using a simplified gravity model assuming equal likelihood of individual trip interchanges between the tracts. All the trips where AAM total travel time was greater than the travel time for ground transportation were not considered for further analysis.

Step 4. Mode choice modeling was used to predict traveler mode choice while completing a trip. Air taxi and airport shuttle services were modeled to compete with personal cars, taxi, TNCs, and public transportation. Next, a utility function was developed based on two key attributes that influence choice of mode (i.e., travel time and travel cost per median household income per hour). Coefficients of the utility function were calibrated by fitting a logit model to the data generated using the 2016 American Community Survey. Having calibrated the utility function, a probabilistic choice model, the multinomial logit model (MNL), was selected to describe the preferences and choice of a user in terms of probabilities of choosing each alternative rather than predicting that an individual will choose a particular mode with certainty.

Step 5. Constraints based on existing data were applied based on passenger's willingness to pay (obtained from [23]) using a stated preference survey (n = 1722) in five U.S. cities), infrastructure availability and capacity, time of day, and visual flight rules operation restrictions. The process of applying constraints is show in Figure 6.

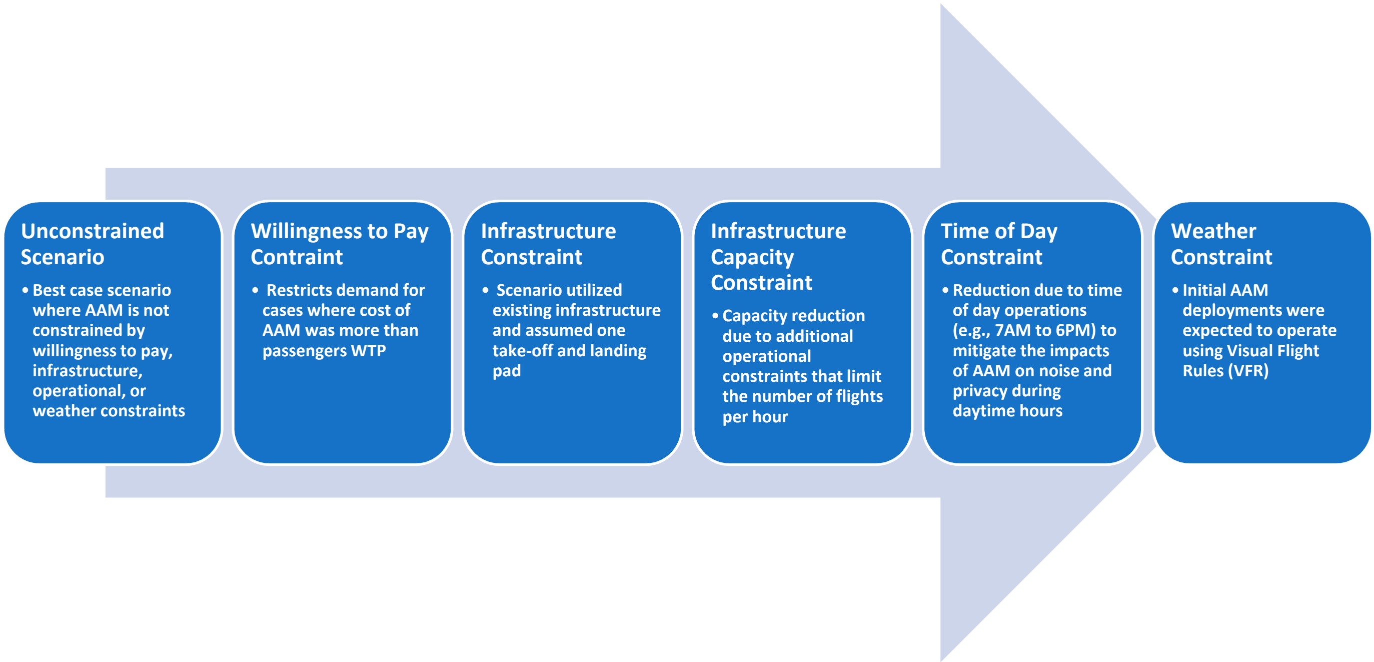

Figure 6. Process for applying constraints.

4. Findings and Discussion

Air taxi and airport shuttle markets were found to be viable across the sample of 10 urban areas considered in this analysis. However, after applying all constraints, approximately 0.5% of unconstrained trips (air taxi and airport shuttle combined) were captured using AAM. Infrastructure constraints (both the number of vertiports and capacity) were the greatest limitations for AAM demand. After applying constraints, AAM could replace mandatory trips greater than 45 min. However, no notable demand was observed for discretionary trips because of a low willingness to pay. Next, the price elasticity of demand modeled the sensitivity of the demand to changes in the price. Denver, Houston, and Honolulu were found to be more price sensitive than New York, Los Angeles, and Washington, D.C. Maximum revenue for each urban area was achieved at ~2.50–2.85 USD passenger price per mile.

By extrapolating the combined demand of the air taxi and airport shuttle markets for all 486 urban areas in the U.S., it was estimated that, in the early years of deploying AAM, the airport shuttle and air taxi markets will have a combined potential demand of 55,000 daily trips and 82,000 daily passengers. This potential demand had an annual market value of 2.5 billion USD and could be served by approximately 4000 four- to five-seat aircraft. Under a completely unconstrained scenario, there could be a potential demand of 11 million daily trips with a market valuation of 500 billion USD (Table 3). In particular, the air taxi market generates ~98% of its demand by capturing longer trips greater than 30 min in travel time served by ground transportation. In order to scale operations, additional vertiports with greater operational capacity would need to be built and lower operating costs realized. However, increased demand could raise a number of community concerns, such as noise, congestion, and other social, behavioral, environmental, and quality of life impacts.

Table 3. Market potential (size and valuation).

	Daily Trips	Daily Passengers	Total Number of Aircraft	Annual Market Valuation (Billion USD)
Unconstrained	11,000,000	16,000,000	850,000	500
Willingness to pay constraint	8,800,000	13,000,000	680,000	400
Infrastructure constraint	1,000,000	1,500,000	80,000	45
Infrastructure capacity constraint	80,000	120,000	6000	3.6
Time of day constraint	60,000	90,000	4500	2.75
Weather constraint	55,000	82,000	4100	2.5

4.1. Scenarios

A variety of factors, such as air traffic management capabilities, ground transportation, aircraft impacts (i.e., noise), and the regulatory environment could impact the growth and evolution of the air taxi and airport shuttle markets. The authors applied eight scenarios to forecast the impact different policy decisions and technological advancements could have on AAM passenger demand. Each of these scenarios are described in Table 4, and the impacts of these scenarios on AAM demand are shown in Figure 7.

Table 4. Summary of AAM policy and technology scenarios.

Scenario Name	Description
Technology advancements	This scenario estimated a reduction in aircraft costs due to falling battery prices and increasing aircraft production. This scenario forecasted a reduction in battery costs to 100–150 USD per kWh by 2025, with a 10 USD per kWh annual reduction. Additionally, this scenario assumes the cost of aircraft production is reduced by ~15% every 5 years by doubling production.
Increased network efficiency	This scenario assumed increasing network efficiency by (1) increasing aircraft utilization from ~4 h a day to ~7 h a day due to battery and charging improvements, (2) increasing load factors from ~65% to 80%, and (3) reducing deadhead trips from ~37.5% to ~20%.
Autonomous flight	This scenario assumed an on-board pilot is no longer needed, allowing each aircraft additional passenger capacity. Additional ground staff were added for safety briefings and passenger boarding.
Infrastructure improvements	This scenario estimated an increase in the number of vertiports and capacity, the latter enabled through improvements in air traffic management (i.e., unmanned traffic management (UTM)). This scenario doubled the number of vertiports and the operational capacity every five years to model these improvements.
Value of travel time	Increased productivity while traveling may result in a decrease in the value of travel time, thereby affecting the demand of AAM. This scenario evaluated the importance of travel time by introducing a significance factor in the utility function varying between 0 and 1. “0” represents no importance to travel time, and the user was expected to choose the mode entirely based on price, comfort, etc.
Competition with shared automated vehicles (SAVs)	This scenario examined the potential impacts of the adoption of SAVs on AAM passenger demand, based on a penetration rate of 0.5% and 10% in 2025 and 2035, respectively. The scenario assumed an average vehicle occupancy of ~65% (comparable to AAM) and a cost of 0.90 USD per passenger mile, which is approximately 35% less than private vehicle ownership.
Telecommuting	This scenario estimated the impacts of the growth of telecommuting on AAM passenger demand using a forecast longitudinal telecommuting growth rate of approximately ~10% annually.
Congestion and latent demand	Passenger AAM has the potential to contribute to new mobility patterns, such as de-urbanization and induced demand (because of the potential of reduced travel times), which encourages more people to use the service. Using a parametric analysis by varying average distances for each trip by −25% to +25% at an interval of 10%, this scenario estimated the potential impacts of induced demand. Note, a negative percentage indicates increased urbanization. In some cases, pooling and increased access to public transportation could also cause a reduction in congestion. This was explored by varying the average driving speed by −25% to 25% at an interval of 10%. A negative percent indicates increased congestion.

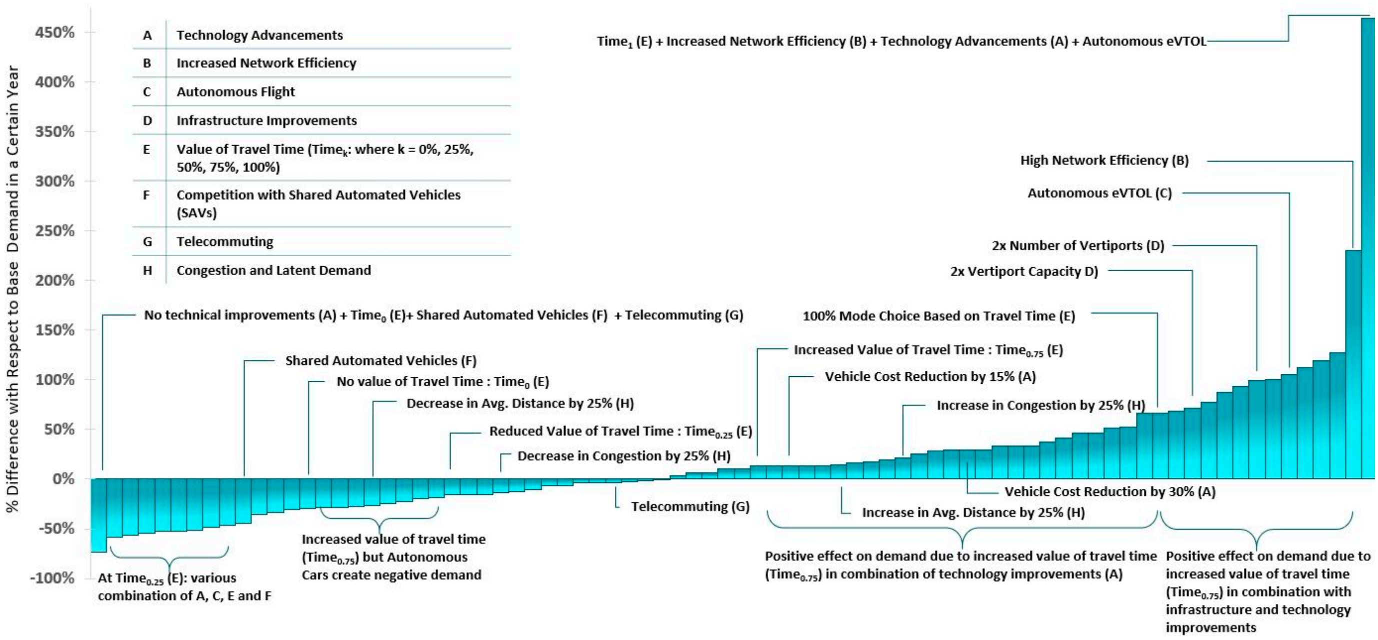

Figure 7. Air taxi and airport shuttle demand curve.

Based on these scenarios, additional vertiports and UTM may be needed to serve the airport shuttle and air taxi markets. Increased network efficiency, such as increased aircraft utilization, higher load factors, and reducing deadhead trips may help enable new capacity. Additionally, the value of time, greater congestion, other technological improvements such as autonomous flight may all support increased demand. However, the growth of SAVs and a decrease in the value of time could present notable constraints on demand for the air taxi market.

4.2. Limitations

Several limitations exist with this work. First, this work was exploratory, and estimating the potential demand for a conceptual and disruptive transportation service is difficult to assess. There are many unknowns about how the public (both users and non-users) may respond to AAM. Public concerns about equity, noise, and environmental impacts could lead to the development of policies that could impact or constrain the market in the future. Additionally, given this emerging topic and the vast number of planned deployments, the assumptions used to estimate market demand may evolve over time. Finally, the recovery from the global pandemic has the potential to reshape travel behavior in ways that are still unknown. The longer-term growth of e-commerce, telework, and potential shifts to suburban/exurban lifestyles could impact the demand for, and use cases envisioned, for AAM. However, in spite of these limitations this study provides a baseline estimate of market demand and a methodology for further analysis.

5. Conclusions

Based on this study, AAM passenger services could have a daily demand of 82,000 passengers served by approximately 4000 four- to five-seat aircraft in the U.S. under the most conservative scenario. Approximately 0.5% of unconstrained air taxi and airport shuttle trips were captured using AAM after applying all constraints. Moreover, about 98% of the demand generated for the air taxi market were trips greater than 30 min in travel time served by ground transportation. However, the scalability of AAM operations will depend on a number of factors, such as the ability to build more vertiports and reduce operating costs. Additionally, an increased demand and operations tempo could raise a number of community concerns, such as noise, aesthetics, congestion, and other impacts.

AAM has the potential to change how people travel and access goods in unintended ways. As such, AAM could have a variety of impacts on accessibility, social equity, vehicle ownership, vehicle kilometers/miles traveled (VKT/VMT), and greenhouse gas (GHG) emissions. Additionally, the impacts of AAM on travel behavior are highly uncertain. AAM has the potential to transform long trips into time saved. However, AAM could result in more or less congestion and emissions depending on how aircraft are used (e.g., traveling without passengers (deadheading), single passenger use, or pooled use). AAM could also shift consumer preferences in favor of living in less dense communities (e.g., suburbs, exurbs, and edge cities) resulting in a number of travel behaviors, land use, and other impacts.

Forecasting demand for a new mode of transportation is inherently difficult to do, particularly as the long-term impacts of the pandemic on travel behavior are uncertain. In spite of this study's limitations, the findings provide early insight in the market potential that stakeholders can use to help inform long-range planning and decision-making. The impacts (both positive and negative) of AAM could create a feedback loop that has the potential to stimulate or suppress demand. More research is needed to evaluate the potential social, travel behavior, environmental, equity, land use, and quality of life impacts on public acceptance and market demand for AAM.

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