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Urban air mobility: A comprehensive review and comparative analysis with autonomous and electric ground transportation for informing future research

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ABSTRACT

Urban air mobility (UAM), if successful, will disrupt urban transportation. UAM is not the first disruptive technology in transportation, with recent examples including electric ground vehicles (EVs), autonomous ground vehicles (AVs), and sharing services. In this paper, we conduct a *meta*-analysis of about 800 articles in the UAM, EV, and AV areas that have been published from January 2015 to June 2020, and compare and contrast research thrusts in order to inform future UAM research. Alongside this effort, we conduct an in-depth review of articles related to demand modeling, operations, and integration with existing infrastructure. We use insights from the *meta*-analysis and comprehensive review to inform future UAM research directions. Some of the potential research directions we identify include: (1) developing more refined demand models that incorporate the timing of when individuals will adopt UAM; (2) developing high-fidelity simulation models for UAM operations that capture interactions among vertiport locations, vertiport topology, demand, pricing, dispatching, and airspace restrictions; (3) explicitly considering one-way demand and parking constraints in demand and operational models; and (4) developing more realistic time-of-day energy profiles for UAM vehicles in order to assess whether the current electrical grid can support UAM operations.

1. Introduction

In recent years, there has been exponential growth in the number of publications related to aerial on-demand mobility[1]. A search of conference papers and journal publications in the American Institute of Aeronautics and Astronautics (AIAA) database shows that from 2015 to 2019, the number of annual publications in this area grew from 4 to 94. Interest in this area, commonly referred to as urban air mobility (UAM) or advanced air mobility (AAM)[2], is driven in part by advancements in battery, distributed electric propulsion, and autonomy technologies that are leading to the development of a new class of aircraft, commonly referred to as electric vertical takeoff

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[1] The number of UAM-related articles included in our review from 2015 to 2019 by year are 6, 11, 15, 74, and 120. An exponential curve fit through these datapoints is y=exp(1.0194x) with an R^2 of 0.86.

[2] On March 23, 2020, the U.S. National Aeronautics and Space Administration (NASA) began referring to its on-demand aerial activities as AAM instead of UAM to reflect a more inclusive vision for both urban and rural applications (NASA, 2020). We will use UAM throughout the paper.

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and landing (eVTOL) aircraft. These new eVTOL air taxis are expected to be safer, quieter, and less expensive to operate and maintain than existing vertical takeoff and landing aircraft, i.e., helicopters. Given current battery limitations, much of the research to date has focused on intracity or urban travel; however, extensions to regional and intercity missions are envisioned in the coming decades.

UAM represents a disruptive new technology, particularly if information-enabled platforms such as ride-hailing apps similar to those used by transportation network companies such as Lyft or Uber are used to connect operators with demand in real time. Never before has the potential for large-scale aerial operations within our cities been so real, as evidenced by the fact that in 2019 there were over 1,000 test flights of full-size eVTOL aircraft, and as of March 2020 at least 12 eVTOL aircraft were in the process of obtaining certification from the U.S. Federal Aviation Administration (FAA) (Dietrich and Wulff, 2020). To date, much of the research in UAM has been driven by the aerospace field and has focused on aircraft technology and aircraft operations, including the interface of UAM in the national airspace system (NAS); however, to be successful, UAM will need to integrate with our existing city infrastructure in ways that are acceptable to local communities, while providing service levels that offer time savings over existing modes at a price point that individuals are willing to pay.

UAM is not the first disruptive technology in transportation. Electric and/or autonomous ground vehicles (EVs and/or AVs) are new technologies that are disrupting travel and share many similar characteristics with UAM. For example, like UAM, EVs and AVs need to integrate with existing urban infrastructure; their operations are heavily dependent on battery charging and fast-charging capabilities; and their profitability is influenced by factors including community acceptance and consumer willingness to pay. Additionally, because UAM is typically envisioned to employ fleets of shared-use aircraft, there are many similarities to ride sharing concepts from ground transportation, particularly shared autonomous vehicles (SAVs) and shared autonomous electric vehicles (SAEVs). Owing to these similarities, insights gained from the EV, AV, and ride sharing research communities will be applicable to the UAM community and can help inform future UAM research directions. The broad interrelationships between autonomous, electric, and sharing technologies in the transportation literature—and UAM's place in this landscape—are illustrated in Fig. 1.

The objective of this paper is to provide a comprehensive review of UAM publications that have been published from 2015 to 2020 and to conduct a comparative analysis with publications during this same time period on EVs and AVs in order to help inform future UAM research. First, we compile a database of about 800 publications in the UAM, EV, and AV areas and classify their primary area(s) of research. Next, we conduct a *meta*-analysis comparing the overall research thrusts of the two communities. Finally, we conduct a more detailed analysis comparing the research approaches and results related to demand modeling, operations, and integration with existing infrastructure across the UAM and EV/AV areas. We use the comparative analysis to identify important factors that should be considered in the design and operation of UAM systems and areas of research that will potentially be important for the UAM community to investigate. To the best of our knowledge, our paper represents the first comprehensive review of UAM-related topics that conducts a comparative analysis of the ground vehicle and aircraft literatures for the purposes of identifying research opportunities and needs within UAM.

Multiple reviews have previously been conducted related to autonomous vehicles (Fagnant and Kockelman, 2015), shared autonomous vehicles (Narayanan et al., 2020), charging infrastructure and operational strategies for electric ground vehicles (Funke et al., 2019; Hardman et al., 2018; Shen et al., 2019), adoption of electric ground vehicles (Rezvani, Jansson and Bodin 2015; Hardman, 2019), carsharing (Meisel and Merfeld 2018; Illgen and Höck, 2018) and ride-hailing (Tirachini, 2019). Our paper differs from these prior reviews in that we focus on identifying papers from the EV and AV areas that contain ideas, modeling assumptions, methods, or results that are applicable and can help inform UAM research. Our paper complements other reviews of UAM research, most notably that of Straubinger et al. (2020), that classifies UAM research areas into eight broad areas: air vehicles, regulation, infrastructure, operations, market actors, integration, acceptance, and modeling. It is our hope that our paper will become a resource document for those currently pursuing UAM research and will spur new interdisciplinary UAM research.

The balance of this paper contains seven sections. Section 2 provides a brief history of UAM and an overview of different eVTOL aircraft designs. Section 3 documents the methodology we used to conduct our review and the results from the *meta*-analysis. The comparative analysis of UAM, EV, and AV research over a five-year period and directions for UAM research related to demand modeling, integration with existing infrastructure, and operations are discussed in Sections 4, 5, and 6, respectively. The paper concludes with a summary of main conclusions and limitations of the analysis.

2. History of UAM and eVTOL aircraft designs

This section provides an overview of current and prior UAM services and the different classes of eVTOL aircraft that are under development. The discussion explains the perceived market potential for UAM and points to the different business and operational strategies that aircraft manufacturers and UAM operators are pursuing.

2.1. History of UAM service and value estimates for the emerging eVTOL UAM market

The concept of urban air mobility is not new, with examples of UAM services using helicopters dating to the 1940s. From 1947 to 1971, Los Angeles Airways used helicopters to transport people and mail in the Los Angeles area, including between Disneyland and the Los Angeles International Airport (LAX). Los Angeles Airways experienced two accidents caused by mechanical failure in 1968 and subsequently ceased operations (Harrison, 2017, as referenced in Thipphavong et al., 2018). From 1953 to 1979, New York Airways used helicopters to fly passengers between Manhattan locations and the three major airports in New York City (Newark Liberty International Airport [EWR], LaGuardia Airport [LGA], and John F. Kennedy International Airport [JFK]). This service similarly ceased due to several accidents caused by mechanical failure (Witken, 1979, as referenced in Thipphavong et al., 2018; Mayor and Anderson,

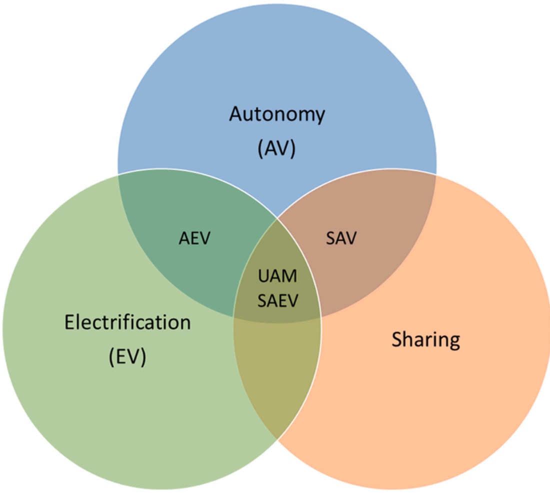

Fig. 1. Interrelationship of autonomous, electric, and sharing technologies in the transportation literature.

2019). The cost of a passenger ticket on a New York Airways shuttle was between $5 and $9, or about $47 to $86 in 2019 dollars (Mayor and Anderson, 2019). These early UAM operations successfully operated for more than two decades, ultimately ceasing operations due to safety concerns. These historic examples provide evidence of the potential value to consumers for similar (albeit safer) UAM services today.

Several helicopter operators are providing on-demand urban passenger air service. BLADE operates[3] between various locations in Manhattan and one of the three main airports in New York City (JFK, LGA, and EWR). Flights are bookable within 30 min of departure and the one-way cost is $195; additional charges starting at $85 apply for baggage above 25 lb (that is transported via a ground service), last-minute bookings, and cancellations received within three hours of departure (BLADE, 2020). In 2019, Uber partnered with HeliFlite[4] to offer flights from Manhattan to JFK airport between the hours of 1 PM and 6 PM, Monday through Friday. Uber Copter can be booked on demand or up to five days before the flight (Matthews, 2019). The helicopter option appears on the Uber app and the one-way cost ranges from $200 to $225 per person and includes one piece of luggage up to 50 lb (Ballentine, 2019; Uber, 2020). In 2016, Airbus started Voom, an on-demand booking platform that connected travelers to helicopter service providers in São Paulo, Brazil, and later expanded service to Mexico City and the San Francisco Bay Area before permanently ceasing operations due to COVID-19 in April of 2020 (Airbus, 2020b). Flights in Mexico City were bookable within 60 min of departure of the flight or could be reserved up to seven days in advance (Airbus, 2018).

These modern-day on-demand helicopter services have been important to UAM researchers, as they provided information about customer preferences (booking patterns, willingness to pay, most popular routes) and “operational challenges related to a lack of infrastructure, public acceptance, [and] on-demand versus scheduled routes” (Airbus, 2020b). They help set the context for how the UAM community is envisioning the possibilities for stimulating demand through lower per-passenger mile (pax-mile) operating costs with new eVTOL aircraft.

BLADE and Uber Copter charge about $30 per pax-mile in Manhattan, whereas Voom charged about $10 per pax-mile (Booz Allen Hamilton, 2018; Reiche et al., 2018). Uber Elevate estimates the cost of a passenger helicopter service at about $8.93 per pax-mile (Holden, 2018), and McKinsey and Company estimates the cost between $6 and $8 per seat-mile[5] (Johnson, Riedel, and Sahdev, 2020). Uber Elevate has reported that they anticipate at the launch of their on-demand air taxi that service costs will be $5.73 per pax-mile but will decrease in the near term to $1.84 by increasing utilization through ride-hailing (Holden, 2018). In later conferences, Uber Elevate noted that at $2.00 per pax-mile, the flight operating cost would be $662/hr as compared to $1,253/hr that is more common among helicopters operating today (Uber Elevate, 2019). On an hourly basis, longer-term, Uber Elevate anticipates that advancements in manufacturing and autonomy will decrease both fixed and variable costs, resulting in $0.44 per pax-mile cost; in comparison, in 2017, the American Automobile Association (AAA) estimated the full cost of auto ownership in the U.S. to be between $0.46 and $0.61 per mile (Holden, 2018; AAA 2017). The McKinsey report estimates near-term costs between $2.50 and $4.50 per seat-mile and long-term costs between $0.50 and $2.50 (Johnson, Riedel, and Sahdev, 2020). The UAM cost estimates provided by Uber Elevate and McKinsey and Company are optimistic compared to other reports, such as one conducted for the National Aeronautics and Space Administration (NASA) that forecasts the costs of a five-seat eVTOL at $6.25/pax-mile in the near term but “in the long term,

[3] On-demand service was temporarily suspended during the COVID-19 pandemic (BLADE, 2020).

[4] Uber Copter service was temporarily suspended during the COVID-19 pandemic (Uber, 2020).

[5] Within the airline industry, RPM and ASM are more common definitions used. Revenue passenger miles (RPM) refer to miles flown by paying customers, and available seat-miles (ASM) refer to actual seats available for sale. From the reports we reviewed, we assumed pax-miles are similar in spirit to RPM and seat-miles are similar to ASM.

operational efficiency, autonomy, technology improvements may decrease costs by 60%" (i.e., $3.75/pax-mile) (Booz Allen Hamilton, 2018; Reiche et al., 2018). Although the cost estimates of providing UAM service vary, near-term and long-term eVTOL operations will likely operate at lower costs compared to current helicopter service, resulting in more demand for UAM service. In comparison, costs for shared autonomous vehicles in the 2030s to 2040s have been estimated by multiple studies to range from $0.29 to $0.49 per-seat-mile (Johnson, 2015; Albright et al., 2015; Chen et al., 2016; Corwin et al., 2016), with lower cost estimates corresponding to purpose-built SAVs. These costs range from five times to ten times lower than the UAM cost estimates noted above in the mid-term to near-parity with UAM in the long-term; however, direct comparisons are challenging at present because of the uncertainty in the technologies and development timelines for both SAVs and UAM.

Despite these differences, what is notable is the extent that research in the eVTOL area has grown in the last five years, and how quickly some manufacturers are moving toward certifying their aircraft. Part of the interest in designing eVTOL aircraft is due to the value many believe is present for passenger UAM markets. Table 1 summarizes these valuation estimates for different geographies. For U.S. markets, these estimates range from $500B to $1B in the near term to $1B–$3.6B in 2025 to $17.7B in 2040. Globally, these estimates range from $0.3B to $3B in the short-term (2018 to 2025 time frame) to $32B by 2035. Many of the valuations of the UAM markets distinguish between intracity markets and intercity or regional markets, reflecting that as battery technologies advance, eVTOL aircraft will be able to fly longer missions. Looking ahead, Roland Berger and Porsche forecast larger UAM valuations for intracity taxis and airport shuttles than for regional intercity flights (Roland Berger, 2018; Porsche Consulting, 2018, as quoted in Volocopter, 2018).

2.2. Overview of eVTOL aircraft designs

Worldwide, there are multiple efforts focused on designing eVTOL aircraft, and more than $2B has been invested in this industry (Sherman, 2020). Collectively, these designs represent fundamentally different design concepts. Multiple publications provide overviews of the different technical specifications and characteristics associated with eVTOL aircraft (e.g., see Roland Berger, 2018; Porsche Consulting, 2018). The Vertical Flight Society (VFS) provides one of the more thorough overviews of the different types of eVTOL aircraft and maintains a database of known eVTOL designs (Electric VTOL News™, 2020). According to VFS, as of March 5, 2020, there were a total of 260 aircraft[6] that included 99 vectored thrust, 39 lift + cruise, 26 wingless multicopters, 46 hover bikes/flying devices[7] and 20 eHelos and eGyros (Sherman, 2020). Across these designs, there are large variations in the number of seats, speed, and range.

Vectored thrust aircraft can use any of their thrusters[8] for both lift and cruise; representative examples include the Lilium Jet (2 to 5 seats; 186 mph; 186-mile range), Airbus A[3] Vahana (1 seat; 118 mph; 31-mile range), Bell Nexus 4EX (5 seats; 150 mph; 150-mile range), and Joby S4 (5 seats; 200 mph; 150-mile range) (Lilium, 2020; Hawkins, 2019; Airbus, 2020a; Bell Flight, 2020; Pope, 2019; Goldstein, 2019; Bogaisky, 2020). According to Sherman, vectored thrust designs—the most common among potential eVTOL designs—will likely be the most efficient eVTOL aircraft but also likely the most difficult to bring to market due to the complexity of designing the aircraft to safety transition between vertical flight and forward flight.

The lift + cruise is another popular aircraft category under development that has two sets of independent thrusters—one set that is used only for cruise and a second set that is used only for vertical lift. Lift during cruise flight is provided by one or several wings. Representative examples include the Aurora Flight Sciences Pegasus (2 seats; 112 mph; 50-mile range; Aurora Flight Sciences, 2020), EmbraerX Eve[9] (5 seats; speed and range not public), and Wisk Cora (2 seats; 100 mph; 25-mile range) (Electric VTOL News™, n.d. 1, n.d. 2; EmbraerX, 2020; Wisk, 2020).

Wingless multicopters are another common design that use their thrusters to produce lift not only for takeoff and vertical flight but for cruise, as well. Representative examples of these aircraft include the Volocopter VC200 (2 seats; 50–62 mph; 19-mile range), the eHang 216 (1 seat; 81 mph; 22-mile range), and the LIFT Aircraft Hexa (1 seat; 60 mph; 12–15 mile range) (Volocopter, 2018, 2020; eHang, 2020a; LIFT Aircraft, 2020). The LIFT Aircraft Hexa is an ultralight passenger air vehicle that seats one passenger who controls the aircraft. Ultralight aircraft will be restricted to recreational use and speeds of under 60 mph but will likely be some of the first eVTOL aircraft to enter the market, as they do not require aircraft and pilot certification under Federal Aviation Regulations Part 103 (FAA, 1982, as noted by Sherman, 2020).

Rotorcraft designs are another area being considered for UAM applications. These concepts include both electric helicopters and novel autogyros (i.e., helicopter-like aircraft in which the rotor rotates not by shaft power from the engine but by the force of air flowing through it; propulsion in forward flight is provided by a separate propeller). Representative examples include the Jaunt Air Mobility gyrocopter (5 seats; 175 mph; range unknown) and the Pal-V Pioneer flying car (2 seats; 99–112 mph; 250–300-mile range) (Jaunt Air Mobility, 2020; Blain, 2020; Pal-V, 2020). Although the popular press often refers to UAM/eVTOL aircraft as "flying cars," these aircraft typically do not meet the historical definition of a "roadable aircraft" that can be both driven on the ground as a car and flown as an airplane. However, the Pal-V is a roadable aircraft. The Pal-V is not an electric aircraft (hence not an eVTOL) and is intended for personal use and not necessarily UAM; however, it is representative of the novel rotorcraft configurations being explored

[6] Not all of these aircraft are serious designs, but the momentum building in this area is clear.

[7] Hover bikes and similar flying devices are outside the scope of our analysis.

[8] VFS uses the word "thruster" as a way to generalize different thrust-producing devices including propellers, rotors, and ducted fans. We maintain their use of the word here for generality.

[9] The EmbraerX DreamMaker was renamed to the EmbraerX Eve in August of 2020 (Alcock, 2020).

Table 1
Valuation estimates for passenger UAM markets.

Report	Market	Geography	Valuation
Booz Allen Hamilton[1]	Airport shuttle and intracity air taxi	U.S.	\$500B unconstrained market 0.5% captured near term at \$2.5B
Deloitte[2]	Intracity and regional markets	U.S.	\$1B in 2025 for intracity \$13.8B in 2040 for intracity \$2.6B in 2025 for regional \$3.9B in 2040 for regional
Frost and Sullivan[3]	Passenger service	Global	\$0.3 M in 2018 to \$3B in 2023
KPMG[4]	Intracity and regional service	Global	12 M enplanements per year by 2040 400 M enplanements by 2050
Porsche Consulting[5]	Passenger service (intracity and regional)	Global	\$1B by 2025 \$21B intracity by 2035 \$11B regional by 2035

References: [1]Booz Allen Hamilton (2018) and Reiche et al. (2018); [2]Lineberger et al. (2019); [3]as quoted in eHang (2020b); [4]Mayor and Anderson (2019); [5]Porsche Consulting (2018).

in the UAM field. Fig. 2 provides examples of each of the aircraft designs discussed above.

What is clear from the discussion above is that there is currently a lack of convergence in designs and underlying business models envisioned by the eVTOL community. The non-convergence of design concepts reflects the novelty of these new battery and electric propulsion technologies and uncertainties regarding how these new technologies will impact aircraft performance. It also reflects a lack of consensus on which missions (or market segments) these aircraft can profitably serve, and whether the aircraft should be flown by the passenger, an onboard pilot, a remote pilot, or autonomously.

3. Meta-Analysis of research in UAM, EV, and AV

3.1. Methodology and scope of review

To identify relevant publications in UAM, we conducted a keyword search of “urban air mobility,” “air taxi,” and “UAM” in the AIAA publication database. A similar search was conducted on Scopus using the same keywords but adding exclusion terms for “drone” and “UAV.” The searches were initially conducted in the spring of 2020 and were updated in mid-July 2020.

The search results included journal and conference publications relevant to UAM that were published from January 1, 2015, to June 30, 2020, in which the aforementioned keywords appeared in the title or abstract. A total of 251 publications were identified from the AIAA database and an additional 61 from the Scopus search.

To identify relevant EV and AV articles, we reviewed the table of contents of key journals from the transportation field from January 2015 to June 2020[10] and identified articles that were relevant based on their titles and abstracts. We explicitly decided not to use a keyword search for this part of the analysis, so that we could go through the titles and identify publications that were relevant to UAM research, such as ride-hailing or carsharing, that may not directly fall into searches returned using EV and AV keywords. EV, AV, carsharing, and ride-hailing are synergistic areas within the ground transportation field, given interest in using future AVs as an electric fleet that operates as a carsharing or ride-hailing service. However, a simple search of “ridesharing” on Scopus of publications published since 2015 conducted in September 2020 returned over 2500 publications. Thus, we opted to use a more directed approach by carefully reviewing titles and abstracts from selected journals to identify papers in the ground transportation literature that showed potential for having ideas, concepts, methods, or results that could inform UAM research.

Given our overarching objective in comparing the EV/AV and UAM fields is to glean insights from the EV/AV areas that may be applicable to the UAM area, we excluded some papers in the EV/AV areas that were not directly applicable to the UAM field. For example, papers that discuss strategies for safely merging AV ground vehicles into traffic are not applicable to UAM given UAM has another dimension for conflict avoidance and different traffic management rules than ground transportation modes. Similarly, when doing a detailed analysis of a particular area (such as demand segmentation), we tagged all articles that fit into the category, but then focused our in-depth discussion on the subset of articles most relevant to UAM (e.g., we exclude a discussion of how EV vehicle characteristics like acceleration influence EV purchases).

We reviewed articles from the following journals—the number of articles in total and those we included in our analysis are shown in parentheses: *Transportation Research Part A* (1392 published; 125 inventoried); *Transportation Research Part B* (970 published; 62 inventoried); *Transportation Research Part C* (1971 published; 100 inventoried); *Transportation Research Part D* (1281 published; 124 inventoried), *Transportation* (545 published; 51 inventoried); and *Transportation Science* (444 published; 16 inventoried).

The final number of articles we identified includes 312 for UAM and 478 for EV/AV research. For each of the 790 articles, we identified research themes by associating up to six keywords based on a review of the abstracts (or where unclear, a review of the

[10] In 2019, David Hensher, a transportation professor at the University of Sydney, identified and ranked the quality of transportation journals. We used this list to select the transportation journals that were ranked in the top two (of four) tiers that had published a non-trivial number of AV- and EV-related research over the past five years (Hensher, 2019).

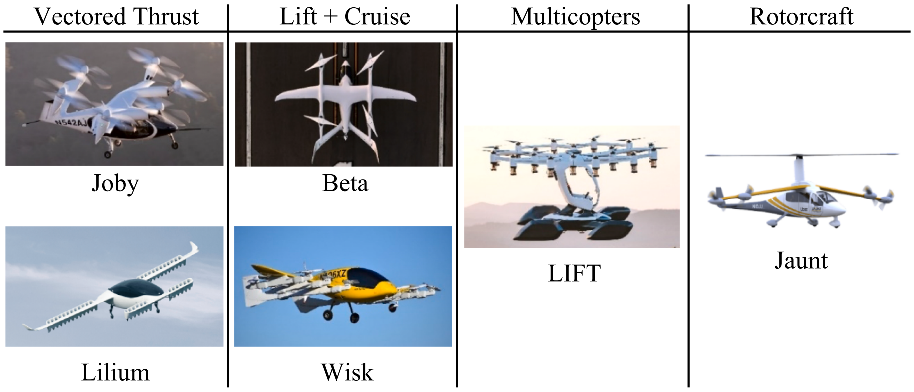

Fig. 2. Examples of different UAM aircraft designs.
Image credits: Joby Aviation (2021), Lilium (2021), Beta (2021), Wisk Aero (2021), LIFT (2021), Jaunt Air Mobility (2021).

articles). For each publication, we recorded author and publication information. Information for each of these 790 articles, including DOI links, are included in an Excel sheet as a supplemental document to this paper. Co-author Garrow, an expert in travel behavior modeling from civil engineering, tagged the articles related to EVs and AVs, and co-author German, an expert in aircraft design from aerospace engineering, tagged the articles related to UAM. While the subject classifications are arguably subjective, they nonetheless enable us to identify high-level trends across the fields.

3.2. UAM publications

Based on our review of UAM-related articles, we conducted a *meta*-analysis focused on two overarching themes: (1) categorization of the technical content of the articles, and (2) analysis of the affiliations of the authors. The former theme provides insights into the breadth and depth of the topics addressed in UAM research, and the latter provides insights into what nations, organizations, and individuals are actively focused on UAM research.

To categorize the content in the UAM-related articles, we first identified low-level topic categories that were present in multiple articles, and we created corresponding content tags. In defining these categories, we were guided in part by our knowledge of new technical topic areas related to eVTOL aircraft that are being actively addressed within the UAM community, e.g. “Distributed Electric Propulsion” and “Aero-Propulsive Interactions.” We then grouped related low-level tags hierarchically under higher-level categories associated with traditional research disciplines related to aircraft technology and operations, e.g. “Propulsion,” “Aerodynamics,” and “Simulation.” Finally, we grouped these higher-level categories into two overarching categories: “Aircraft Technology” and “Market and Operations.” The resulting categorization reflects our attempt to identify and group common themes in UAM research cogently; however, we do not claim that the categorization is mutually exclusive, collectively exhaustive, or unequivocal.

The hierarchical categories are shown in Fig. 3. The numbers in parentheses indicate the number of articles with lower-level tags assigned to the corresponding category. The number of articles indicated for each higher-level parent category are summative of all children tags for the category. Note that any one article is likely to have been assigned more than one tag based on the breadth of topics covered in the article. The individual low-level content tags corresponding to the overall categories are not shown in Fig. 3 to limit the size of the figure; however, these tags are provided in the spreadsheet provided as supplemental material to this article.

The first observation from this analysis is that current articles on UAM have a nearly even split of content related to “Aircraft Technology” (295 papers) and “Market and Operations” (248 papers). This thematic balance likely reflects an understanding within the community of the “chicken-and-egg” issue associated with the emergence of UAM, i.e., aircraft must be technically capable of serving the missions required for profitable large-scale UAM operations, and a market must exist for the types of missions and operations that can be supported given the technological limitations of emerging aircraft. A concrete example of this interplay is related to eVTOL aircraft with battery electric propulsion. These aircraft have the capability of being much quieter and more economical than current generation helicopters, potentially allowing widespread operations in urban environments at low ticket prices. However, battery electric eVTOL aircraft have very limited range and speed capability because of the low specific energy of current and near-term batteries, potentially limiting the potential for the aircraft to serve an adequate network of origins and destinations and to offer adequate travel time savings compared to other modes when trip times are dominated by ingress and egress on short-ranged flights.

Within the “Aircraft Technology” category, the majority of papers had content related to “Propulsion” (82 papers) and “Aircraft Design and Performance” (92 papers). The “Propulsion” category includes papers with content related to new propulsion architectures relevant for UAM, including “Electric Propulsion” (battery powered propulsion; 29 papers), “Distributed Electric Propulsion” (multiple electric motors powering rotors or fans located in multiple locations on the aircraft; 9 papers), and “Hybrid Propulsion” (propulsion powered by both batteries and a combustion engine; 18 papers) as well as papers with a focus on associated propulsion component technologies such as “Battery” (12 papers) and “Fuel Cell” (4 papers). The majority of the papers in the “Aircraft Design and Performance” category is related to “Design Methods” (30 papers) or present a “Concept Study” of the design and performance of a novel UAM aircraft configuration (41 papers). The “Aircraft Technology” category has a significant number of papers related to

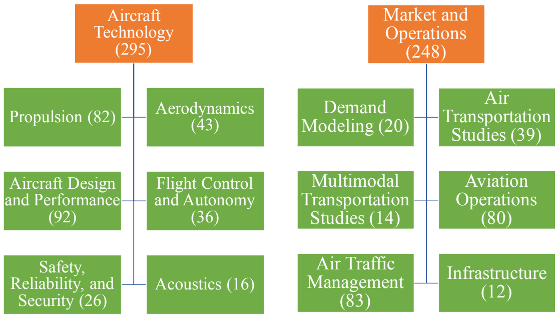

Fig. 3. UAM themes from AIAA and Scopus search, January 2015 to June 2020.

"Aerodynamics" (43 papers), as well, with many papers focused specifically on the aerodynamics associated with eVTOL aircraft and other distributed propulsion configurations, i.e. "Propeller, Rotor, Ducted Fan" (16 papers) and "Aero-Propulsive Interaction" (7 papers).

The large number of papers focused on novel propulsion—especially electric propulsion—and ways to design novel aircraft with new propulsion technology is not surprising. Indeed, electric propulsion is widely recognized as one of the underpinning technical enablers of aircraft capable of serving the UAM market. What is more surprising is that other key technical disciplines for enabling UAM aircraft such as "Autonomy" (11 papers), "Acoustics" (16 papers), and "Safety" (18 papers) have relatively few papers and are arguably underrepresented relative to their importance to the field. The relatively few papers focused on autonomy is likely a result of the very broad character of autonomy research, which focuses on technical fundamentals, as well as a myriad of application domains, including ground AVs. This breadth has likely resulted in few researchers focusing on autonomy research specifically for the emerging field of UAM. Additionally, aviation is a highly-regulated industry with inherent skepticism about the potential of autonomy for replacing pilots in the near future; this viewpoint has led to research in *simplified vehicle operations (SVO)* focused on enabling piloted aircraft with increasingly *automated* but not *autonomous* systems for flight control and navigation (Goodrich and Moore, 2015). The relatively few papers in the "Acoustics" category may result from the ramp-up of the research community to develop fundamentally new foundational computational tools and appropriate metrics for UAM aircraft noise, which differ substantively from traditional aviation noise metrics (Josephson, 2017). The few papers in the "Safety" category may be a result of the need to make initial research progress to address the novelty of UAM aircraft, which require envisioning entirely new paradigms for achieving safety. For example, the simple rotor systems in eVTOL aircraft do not typically offer the potential for "autorotation" for safe descents after an engine failure that is available to helicopters; instead eVTOL aircraft are designed with multiply-redundant powertrain components to prevent a complete propulsion failure in flight (Fredericks, 2016). The few papers in these categories may represent an opportunity for researchers to have impact by engaging in UAM research in these critically important research fields.

Within the "Market and Operations" category, the majority of papers had content related to "Air Traffic Management" (83 papers) and "Aviation Operations" (80 papers). The "Air Traffic Management" category includes papers focused on topics such as exploring paradigms for integrating large volumes of UAM air traffic within the existing NAS (Mueller, Kopardekar, and Goodrich, 2017; Thipphavong et al., 2018), constraints on UAM operations based on current operations at major airports (Vascik and Hansman, 2017; Vascik et al. 2018), and assessing and increasing airspace density and throughput for UAM operations (Goodrich and Barmore, 2018; Lowry, 2018). The "Aviation Operations" category includes papers with a focus on topics of economic and practical interest to UAM air carriers, including flight planning (Stouffer and Kostiuk, 2020) flight scheduling and dispatch (Roy et al., 2020; Shihab et al., 2019; Shihab et al., 2020), concepts of operations (Nneji et al., 2017; Kotwicz et al., 2019), and issues associated with electric aircraft recharging for flight operations (Hamilton and German, 2019; Shihab et al., 2020).

A significant number of papers in the "Market and Operations" category was focused on transportation studies and research to assess the potential of UAM for providing an effective and scalable means of reducing travel time in cities, assessments which lend to understanding the market potential of UAM and its value to society. Papers in the "Air Transportation Studies" category (39 papers) assessed specific types of novel UAM aircraft in on-demand or scheduled service, typically through the lens of one or several operational case studies in example cities, and papers in the "Multimodal Transportation Studies" category (14 papers) assessed connections between UAM and other transportation modes such as cars or public transport or at least discussed differences between UAM and other transportation modes. Examples of applied transportation studies include a series of papers on "suburban air mobility" with electric short takeoff and landing (eSTOL) in the south Florida region (Wei et al., 2018; Robinson et al., 2018; Justin and Mavris, 2019; Somers et al., 2019). Papers in the "Demand" category (20 papers) focused on topics such as assessing the potential market size for UAM and other forms of on-demand air mobility based on census data and choice models (Kreimeier et al., 2018; Roy et al., 2020; Ploetner et al., 2020), stated preference surveys to assess UAM demand (Binder et al., 2018; Garrow, Roy, and Newman, 2020; Fu et al., 2019), and agent-based demand simulation (Rothfeld et al., 2018; Fu et al., 2019 Ploetner et al., 2020). Finally, the "Infrastructure" category (12 papers) includes papers focused on optimization-based site selection of new vertiports (Daskilewicz et al., 2018) and STOLports (Wei et al., 2020) to serve the maximum demand, as well as papers that assess capacity constraints of vertiports (Vascik and Hansman, 2019; Maheshwari et al., 2020).

In our *meta*-analysis of author affiliations, the 251 UAM-related articles from AIAA consisted of a total of 862 listed authors, many of whom were listed on multiple papers, resulting in 554 unique authors. Among the 554 unique authors, 44 percent are affiliated with an academic institution, and 31 percent are associated with NASA. The remaining 25 percent of authors are associated with U.S.-based and international companies and research agencies. The majority of authors in the AIAA database (83 percent) are affiliated with institutions in the U.S., and the country with the second-highest representation (7 percent) is Germany. As these statistics reveal, the majority of UAM research has been conducted by the U.S., and NASA has played a critical role in this research.

A similar *meta*-analysis was conducted with UAM articles returned from the Scopus search with AIAA publications excluded. The 61 UAM-related articles from the Scopus search consisted of a total of 175 listed authors and 141 unique authors. Of all 141 unique authors, 66 percent are affiliated with an academic institution, and 16 percent are affiliated with NASA. The remaining 18 percent of authors are affiliated with U.S.-based and international companies and research agencies. Similar to the results seen in the AIAA database, the majority of authors (52 percent) are affiliated with institutions in the U.S., and the country with the second-most representation in the Scopus search is Germany (20 percent). The country with the third-most representation is the Republic of Korea (4 percent). These statistics confirm the trends seen in the AIAA search—UAM research has been concentrated primarily among U.S.- and German-based researchers, and NASA has played a critical role.

3.3. Ground transportation publications

To categorize the content of ground-transportation articles, we first identified broad topics. Many of these topics are overlapping and represent envisioned synergies across new technologies. For example, papers that discuss a future in which a fleet of AVs operate on batteries would be classified under the high-level categories of "Electric Vehicles" and "Autonomous Vehicles." Once we identified broad topics, we tagged themes within each topic area that were potentially relevant for UAM research. The content tags are shown in Fig. 4. Later sections present our review of these lower-level tags in depth, so we restrict our discussion here to one key observation: within the top-tier transportation journals identified on Hensher's list (2019), there were only four articles published on UAM. This highlights the opportunity for the transportation planning community to take a more active role in research related to the design and operations of UAM systems and apply insights they have gained through related research in the EV and AV fields to UAM.

The 478 ground transportation articles from the journals *Transportation Research Part A (TR–A), TR–B, TR–C, TR–D, Transportation Science*, and *Transportation* consisted of a total of 1,594 listed authors, many of whom were listed on multiple papers, resulting in 1,154 unique authors. Among the 1,154 unique authors, 84 percent are affiliated with an academic institution. The remaining 16 percent of authors are associated with U.S.-based and international companies and research agencies. Among authors associated with academic institutions, 26 percent are affiliated with institutions in the U.S. The country with the second-highest representation (13 percent) in the ground transportation journal database is China, closely followed by Germany (9 percent). As these statistics reveal, the majority of ground transportation research has been conducted by the U.S., but the authors are much more diverse in their affiliated countries than the UAM authors. Ground transportation authors are also much more commonly affiliated with academic institutions compared to UAM authors.

4. Demand modeling

To date, the UAM and ground transportation communities have taken different approaches with respect to modeling demand. The UAM community is currently focused on conducting high-level assessments to understand if there are viable markets for UAM and how mission requirements for these markets (which tie directly to aircraft design specifications) vary across different cities. Identifying where UAM could offer door-to-door travel time savings compared to other modes is a key part of these high-level assessments. To this end, macro-level data of economic activity, aggregate data of commuter flows, and census and other government data are often used to estimate UAM market demand.

In contrast, the ground transportation community often conducts surveys to predict how individuals will respond to different operational, pricing, and policy measures. These surveys enable researchers to understand how opinions and intentions to adopt a new technology vary as a function of socioeconomic and sociodemographic (SED) characteristics, as well as attitudes and perceptions (e.g., is the individual tech-savvy?). Insights from these surveys can be helpful for identifying potential early adopters and designing marketing campaigns. Surveys also allow researchers to focus on specific questions, such as the willingness to travel with strangers in ride-hailing situations or the value of times across different modes as a function of trip purpose. These and other questions will be relevant to the UAM community as they start conducting detailed assessments of which particular consumers will use UAM and how much they are willing to pay.

This section provides an overview of demand studies from the UAM and EV/AV literatures, and summarizes key insights from the EV/AV literatures that can help inform future UAM research.

4.1. Review of UAM demand studies

This section reviews three types of demand studies that have been conducted by UAM researchers: global market studies that have ranked cities worldwide for their potential to offer UAM services, studies that have compared potential travel times savings with UAM against other modes, and survey-based research.

4.1.1. Global market studies

Multiple studies, including those of Becker et al. (2018), Robinson et al. (2018), Booz Allen Hamilton (2018), KPMG (Mayor and

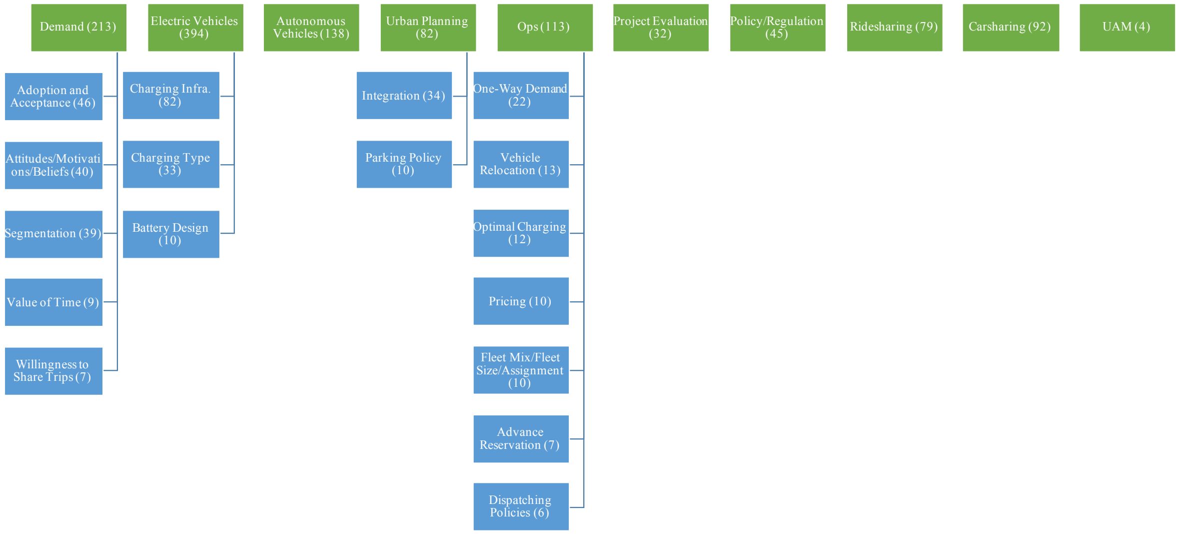

Fig. 4. Themes from transportation journals' table of contents search, January 2015 to June 2020.

Anderson, 2019), and NEXA Advisors (2019), have examined the potential for on-demand mobility for UAM across different cities. These studies used various qualitative and quantitative methodologies to measure the demand potential. For example, Becker et al. (2018) used a gravity model to forecast interurban air passenger demand for 2042 based on socioeconomic factors and generated a list of potential UAM markets. NEXA Advisors (2019) modeled demand for UAM for different use cases including an airport shuttle, a corporate campus shuttle, an on-demand air taxi service, medical and emergency operations and service, and regional air transport service. Various inputs were used including population and density, gross domestic product (GDP) per capita, age distribution, current commercial and business aviation activity, and presence of Fortune 1000 companies (NEXA Advisors, 2019).

KPMG modeled UAM demand using inputs that included city GDP and GDP growth, city population and population growth, city population density, city change in income distribution through 2050, wealth concentration, and information about existing ground services (Mayor and Anderson, 2019). Mayakonda et al. (2020) estimated the UAM share of total passenger kilometers traveled for the cities identified in the KPMG report as a function of UAM ticket cost, travel time savings, and vertiport density. For UAM service offered at $1.50/km, they found UAM shares of 0.18–0.4 percent across different vertiport densities, but for UAM service offered at $0.30/km, these shares increased to 3.2–8.5 percent.

The study by Booz Allen Hamilton selected 10 cities from a possible pool of 40 cities based on population and population density as case studies for a UAM analysis. The final 10 cities were selected based on qualitative criteria including ground transportation

Table 2
U.S. cities identified in the literature as having potential for UAM service.

	Studies	Rank among U.S. cities in KPMG report in 2040
Atlanta	Robinson, KPMG, NEXA	8
Baltimore	NEXA	
Boston	Robinson, KPMG, NEXA	12
Chicago	Robinson, KPMG, NEXA	3
Dallas–Ft. Worth	Robinson, BAH, KPMG, NEXA	4
Denver	BAH, NEXA	
Detroit	NEXA	
Honolulu	BAH	
Houston	Robinson, BAH, KPMG, NEXA	5
Los Angeles	BAH, KPMG, NEXA	2
Miami	Robinson, BAH, KPMG, NEXA	6
New York City	Robinson, BAH, KPMG, NEXA	1
Philadelphia	KPMG, NEXA	9
Phoenix	BAH, KPMG, NEXA	11
San Diego	NEXA	
Seattle	NEXA	
Silicon Valley	Robinson, BAH, KPMG, NEXA	7
Washington, D.C.	BAH, KPMG, NEXA	10

Note: Additional cities included by NEXA are San Jose, Charlotte, Tampa, Nashville, Las Vegas, Salt Lake City, Raleigh–Durham–Chapel Hill, and Syracuse.
Reference Key: Robinson = Robinson et al. (2018); BAH = Booz Allen Hamilton (2018) and Reiche et al. (2018); KPMG = Mayor and Anderson (2019); NEXA = NEXA Advisors (2019).

congestion, weather, and existing infrastructure and ground transportation patterns (Booz Allen Hamilton, 2018; Reiche et al., 2018).

Robinson et al. (2018) identified potential cities for UAM based on qualitative criteria such as the city's level of sprawl, density, presence of water bodies (that could be used to construct barges for potential vertiports), number of airports currently in the city, population wealth, presence of high-tech industries, ground transportation congestion, ground transportation patterns, and weather. The U.S. cities identified as potential candidates for UAM for the reports discussed above are summarized in Table 2 and show that there is a large degree of overlap in the candidates identified in the previous literature, with the NEXA Advisors including more cities in their analysis, and thus having more smaller cities than the other studies.

4.1.2. Door-to-Door travel time studies across modes

Numerous studies have compared door-to-door travel times between UAM and conventional modes and examined the sensitivity of these door-to-door times to different parameters, such as access and egress times, and aircraft cruise speeds. Wei et al. (2018) conducted a door-to-door travel time comparison between personal cars and short takeoff and landing (STOL) aircraft. They found potential demand for STOL operations that have cruising speeds of 160 knots for individuals who have commutes in excess of 45 min based on a case study of the South Florida region, which includes Miami. As range decreases, access and egress times to and from the port become increasingly important (and the travel times savings associated with the air taxi decrease compared to auto) (Wei et al., 2018). Roland Berger (2018) found that air taxi trips need to be at least 15 to 25 km (about 9 to 16 miles) to provide travel time savings over existing modes.

Swadesir and Bil (2019) compare travel times, costs, and general convenience of using an air taxi service, bike, auto, and public transport for Melbourne, Australia. Consistent with the results from the South Florida study, Swadesir and Bil (2019) found that demand for an air taxi service is sensitive to access and egress times to the vertiport, as well as the times to board and disembark the aircraft. Based on an analysis of UAM service in Sioux Falls, South Dakota, USA, Rothfeld et al. (2018) found that UAM processing times have a larger influence on UAM adoption than the UAM vehicle cruising speed and that "the current focus on UAM vehicle capacity and speeds should be extended with UAM accessibility and shorter processing times."

Antcliff, Moore, and Goodrich (2016) compared travel times for urban and suburban commutes between ground and air taxis in the Silicon Valley and found travel times that were three to six times lower for some commutes in the area. They also found that a key factor in improving door-to-door travel times for air taxis is to minimize preboarding times (e.g., waiting times and security clearance times) as well as the times to board and disembark the aircraft. Kreimeier, Strumpf, and Gottschalk (2016) assessed the viability of a UAM service in Germany for intercity travel and found that UAM market shares are highly sensitive to UAM prices as well as access and egress times.

Other studies that have compared costs and travel times across modes include those by Roy, Maheshwari, et al. (2018); Akhter et al. (2020); and Vascik, Hansman, and Dunn (2018). The latter compare door-to-door travel times for 32 reference missions in the Boston, Dallas, and Los Angeles areas to identify operational constraints. Their analysis focused on high-income commuter neighborhoods, which they defined as those with annual household incomes of at least $200K or as neighborhoods with average home valuations of at least $1M in Los Angeles and Dallas and at least $900K in Boston (Vascik, Hansman, and Dunn, 2018).

4.1.3. Survey-Based UAM demand studies

Several survey-based studies of UAM have been conducted by consulting firms, aircraft manufacturers, and academics. For example, Booz Allen Hamilton (2018) conducted a survey that explored the potential for intercity and intracity UAM service. They sampled approximately 300 individuals in each of the following five cities: Houston, San Francisco, Los Angeles, New York City, and Washington, D.C. Airbus conducted a survey of 1540 individuals that compared public perceptions of UAM service among residents of Los Angeles, Mexico City, New Zealand, and Switzerland. Overall, 45 percent of respondents' initial reactions to UAM were positive, with 42 percent believing UAM was safe or very safe. Interest in UAM was higher among males, those with higher educational attainment levels, those who frequently use ride-hailing services or public transportation, and those from Los Angeles or Mexico City (Yedavalli and Mooberry, n.d.). Deloitte conducted a survey of approximately 10,000 individuals representing the regions of the U.S., Canada, the U.K., France, China, Japan, and Australia and similarly found that nearly half of the respondents viewed autonomous UAM vehicles as a potentially viable solution to roadway congestion, but 80 percent had safety concerns (Lineberger, Hussain, and Rutgers, 2019).

On the academic side, Fu, Rothfeld, and Antoniou (2019) modeled the choice among private car, public transportation, autonomous ground taxi, and autonomous air taxi using multinomial logit, nested logit, and mixed logit models based on a stated preference survey of 248 respondents from the Munich metropolitan area. Two trip purposes were considered and combined into a single estimation dataset: daily commuting and a non-commuting private trip. The authors estimated values of times for these four modes as 27.55, 27.47, 32.57, and 44.68 €/hour respectively, which correspond to[11] 33.89, 33.79, 40.06 and 54.96 USD/hour, respectively.

Based on a survey conducted by Uber of 2607 residents from Dallas–Ft. Worth (DFW) and Los Angeles (many of whom were drawn from the Uber customer database), Song, Hess, and Decker (2019) estimated a latent class model and found values of time ranging from $11.15 to $36.78 for different travel time components. On average, across two latent classes the access time, egress time, flight time, and in-vehicle travel time in $/hour were found to be 26.03, 34.43, 20.75, and 13.94, respectively.

Binder et al. (2018) and Garrow et al. (2019) conducted two surveys of high-income commuters residing in Atlanta, Boston, DFW,

[11] An exchange rate of 1€= 1.23 USD was used based on the average exchange rate in February to April of 2018, when the survey data were collected (Pound Sterling Live, 2020c).

San Francisco, and Los Angeles. The first survey, which contained 2499 responses, examined competition with current modes, and the second survey, which contained 1405 responses, was expanded to include competition with autonomous ground vehicles. Results from the first survey showed that individuals who were male, tech-savvy, and frequent users of ride-hailing services were more likely to take an air taxi for commuting. (Boddupalli, Garrow, and German, 2020). Results from the second survey were consistent with the first survey in that males, tech-savvy, and frequent users of ride-hailing services were more likely to take an air taxi. In addition, those who had positive attitudes toward collective modes (i.e., transit, ride-hailing, etc.) and those who felt time pressured were more likely to take an air taxi (Garrow, Roy, and Newman, 2020). In both surveys, the authors found significant heterogeneity in individuals' value of time (VOT), and in the second survey that included AVs, the authors found that compared to the VOT for a conventional auto, the median VOTs for an AV and air taxi were 15 percent lower and 9 percent higher, respectively.

Based on a survey of 221 individuals, the majority of which resided in Europe, Al Haddad et al. (2020) estimated multinomial and ordered logit models, where the ordering corresponds to the time of adoption, and interpreted the results in the context of the Technology Acceptance Model. Among the 221 respondents, 22 percent stated they would adopt UAM in the first year, 37 percent in the second or third year of implementation, 14 percent during the fourth and fifth year, and 3 percent during the sixth year; 3 percent stated they would never adopt the service and 22 percent indicated they were unsure on their adoption time horizon of UAM. Based on a survey of 4700 individuals conducted in 2019, Ljungholm and Olah (2020) found that 14 percent of respondents would be "ready and comfortable to ride in a flying taxi" right now, 18 percent within the next year, 21 percent within the next five years, 20 percent in more than 10 years' time, and 14 percent would never be comfortable. While the timing of adoption across these studies varies, what is clear is that UAM adoption by all consumers will not be instantaneous.

Finally, Han, Yu, and Kim (2019) examined customers' decision-making processes for adopting electric airplanes for traditional commercial flights. Based on a survey of 321 airline customers in the U.S. who had used an airline for traveling within the last year, they found that reducing consumers' perceived risk and increasing new product knowledge was critical to increasing trust and positive attitudes toward electric airplanes and their willingness to pay.

4.2. Review of EV and AV demand studies

Within the ground transportation literature, there have been more than 200 studies over the past five years that have focused on demand. Some of these studies focus on understanding how demand for EV, AV, carsharing, and/or ride-hailing services varies as a function of sociodemographic and socioeconomic (SED) characteristics, as well as different attitudes, beliefs, and personality factors. About 50 studies within the ground transportation literature have focused on how adoption of new EV and AV technologies will increase over time. These studies include an assessment of barriers to adoption, analysis of the differences between early adopters and late adopters, and extension and application of different theoretical frameworks used to predict the timing of adoption across a population. Finally, there are two topics that have been explored in the ground transportation literature that are particularly relevant for UAM: studies that have examined individuals' value of time, defined as the amount of money individuals are willing to spend for travel time savings, and studies that have examined individuals' willingness to ride in vehicles with individuals they know or strangers. This section reviews these demand-related topics in depth.

4.2.1. SED characteristics and segmentation

Within the ground transportation literature, there are many publications that focus on understanding how SED characteristics influence transportation choices. Segmentation studies that compare the travel behavior of different populations defined by sociodemographic, socioeconomic, and/or geographic characteristics are common. Examining how travel behavior varies across different populations is important from a public policy perspective, as it helps better target limited resources to meet demand, helps ensure that the travel needs of mobility-restricted individuals are met, and helps ensure that policies are equitable across different population segments and geographical areas.

Here, we loosely use the term segmentation to identify studies that examined how consumer preferences for AVs, EVs, and/or sharing programs vary across demographic, socioeconomic and/or geographic segments. Several studies have found that interest in AVs, EVs, and sharing technologies is associated more with individuals who are younger, more educated, have higher incomes, and are male (e.g., see Dong, DiScenna, and Guerra, 2019; Hudson et al., 2019; Kopp et al., 2015; Liu, Guo, et al., 2019; Potoglou et al., 2020; Shabanpour, Golshani et al., 2018; Spurlock et al., 2019; Vij et al., 2020; Wang and Zhao, 2019).

There are subtle differences across studies related to gender and income. For example, while many studies have found that women are more risk-adverse and less likely to adopt AVs (Wang and Zhao, 2019; Kaltenhäuser et al., 2020), Spurlock et al. (2019) found that women are less likely to adopt new transportation technologies except for ride-hailing. While Young and Farber (2019) found that ride-hailing is generally a wealthier, younger phenomena, Spurlock et al. (2019) found that higher-income individuals are disproportionately represented among current adopters of new ground vehicle technologies and that low- to middle-income individuals are just as likely to have adopted pooled ride-hailing. Kim (2015) found that carsharing in low-income and high-income areas of NYC were similar.

Several studies focused on the travel behaviors of those with disabilities or older adults, who are two populations for which AVs and sharing services could potentially help increase mobility. For example, Bennett, Vijaygopal, and Kottasz (2019) investigated how attitudes toward AVs differ for those with physical disabilities and those without physical disabilities in the U.K. Harper et al. (2016) used the U.S. National Household Travel Survey to predict potential trip increases for older adults and individuals with travel-related medical conditions. Faber and van Lierop (2020) examined preferences for AVs among older adults in Utrecht, the Netherlands. Other studies focused on better understanding particular (and often narrow) market segments. For example, Lee and Mirman (2018) explored parents' perspectives on using AVs to transport their children. Ghasri, Ardeshiri, and Rashidi (2019) compared how perceptions toward EVs vary among younger adults, i.e., Gen X, Gen Y (Millennials) and Gen Z, in New South Wales, Australia, and found that the Millennials showed interest in adopting EVs. Alemi et al. (2019) used a survey of Millennials from California and found that those who frequently use smartphone apps to manage other aspects of their travel (e.g., checking traffic) or who frequently travel by plane for leisure purposes were more likely to use a ride-hailing service.

Several studies investigated geographic differences. Huang and Qian (2018) explored how preferences for EVs differ across cities with different population sizes in China. They found that consumers in smaller cities are more sensitive to EV purchase price and subsidies. Illgen and Höck (2018) explored the potential for carsharing services in rural regions of Switzerland, and Rotaris and Danielis (2018) explored the potential for ride-hailing services in the Friuli Venezia Giulia region, Italy, "a region characterized by small-sized towns and less-densely populated rural areas." Based on a comparison of individuals in Germany, India, Japan, Sweden, the U.K., and the U.S., Potoglou et al. (2020) found that Japanese consumers are generally willing to pay for AVs, whereas European consumers need to be compensated for automation. Finally, Liu, Khattak, et al. (2019) used the U.S. National Household Travel survey to investigate geographic differences in the ownership of alternative-fueled vehicles and found higher ownership rates among high-income households in states in the southeast or northwest, and higher ownership rates among seniors in states in the northeast and northwest.

4.2.2. Attitudes, Beliefs, and personality factors

Within the ground transportation literature, a wide body of literature focused on understanding how individuals' attitudes, beliefs, personality, and similar factors influence travel behavior choices, including the adoption of new technologies. Table 3 in the appendix

Table 3
Ground transportation studies that have examined the influence of customer attitudes towards EVs, AVs, or sharing programs.

Study	Location	Sample Size	Key Findings
Axsen, Goldberg and Bailey (2016)	Canada	94 plug-in EV owners and 1754 conventional auto owners	Early adopters of EVs have higher levels of environmental concerns and higher engagement in environment- and technology-oriented lifestyles.
Bansal and Kockelman (2018)	Texas, USA	1088	About 50% of respondents will likely time their AV adoption in conjunction with their friends. Environmental friendliness and cost savings were factors in current carsharing users.
Bennett, Vijaygopal, and Kottasz (2019)	UK	444 physically disabled; 353 with no physical disability	Higher levels of interest in new technology associated with intention to use AVs.
Biresselioglu et al. (2018)	Review article with focus on Europe	N/A	Motivation to purchase EVs are influenced by environmental, economic, and technical benefit.
Cherchi (2017)	Denmark	2363	Social conformity effects (e.g., word of mouth) were just as important as vehicle characteristics on intention to purchase EV.
Degirmenci and Breitner (2017)	Germany	40 interviews	Environmental performance of EVs is a stronger predictor of EV purchase intention than price value and range confidence.
Hohenberger et al. (2016)	Germany	1603	Anxiety associated with AVs can be mitigated through providing safety-related information.
Huang and Qian (2018)	South Jiangsu region, China	348	Social conformity effects (word of mouth, peer influence) positively influenced consumer preference for EVs; risk-aversion negatively influenced EV preference.
Kim et al. (2019)	Georgia, USA	2890	Respondents who would select air over AV tended to be more tech-savvy.
Kim et al. (2015)	Seoul, Korea	533 participants in an EV carsharing program	Individuals with higher environmental concerns and higher concern for what others think are more likely to purchase an EV.
Lane et al. (2018)	United States	1080	Respondents preferring a battery EV over a plug-in EV were drawn to its environmental and technical appeal.
Li and Kamargianni (2019)	Taiyuan, China	3486	Pro-environmental attitudes are positively associated with an intention to use bike-sharing.
Liu, Ma, and Zuo (2019)	China	213 college students	Highlighting the environmental advantages of AVs and increasing public trust in AVs may increase societal acceptance of AVs.
Potoglou et al. (2020)	Germany, India, Japan, Sweden, U.K., and U.S.	6033	Individuals self-identifying as having a pro-environmental identity and as being innovators were more in favor of automation and AVs.
Smith et al. (2017)	Perth, Australia	440	Individuals who always selected EVs as preferred choice among six trade-off questions were more concerned with the environment.
Sovacool et al. (2019)	Denmark, Finland, Iceland, Norway, Sweden	5067 online surveys and 257 interviews	Pro-environmental and safety attitudes are positively associated with women's preferences for EV vehicles.
Sweet and Laidlaw (2019)	Toronto and Hamilton, Canada	3201	Individuals who are first to try out a new product and live a hectic life are positively associated with interest in using AVs.
Tsouros and Polydoropoulou (2020)	Greek Islands of Lesvos and Chios	550	Tech-savvy individuals are more likely to purchase vehicles with higher levels of automation, and pro-environmental individuals are more likely to purchase hybrids.
Wang et al. (2020)	China	426, primarily university students	Early adopter of new technology, environmental awareness, and perceived usefulness is positively associated with intention to use ridesharing.

summarizes 19 ground transportation studies that have examined the influence of individuals' attitudes toward EVs, AVs, or sharing programs. Sixteen of the studies used surveys, two used interviews, and one reviewed the literature. The studies were conducted across a range of nations including Australia, Canada, China, Europe, the U.S., and South Korea.

Three key themes emerge from these studies. First, individuals with pro-environmental attitudes are more likely to prefer (and by extension adopt, use, or purchase) EVs and/or AVs over conventional vehicles (Axsen et al., 2016; Biresselioglu et al., 2018; Kim, Ko, and Park, 2015; Potoglou et al., 2020; Smith et al., 2017; Sovacool et al., 2019; Tsouros and Polydoropoulou, 2020). Environmental performance of EVs was a stronger predictor of EV purchase intention than price and range confidence in a study by Degirmenci and Breitner (2017). Given a choice between a hybrid and battery-EV, respondents preferring a battery-EV were drawn to its environmental appeal (Lane et al., 2018). Pro-environmental attitudes were also positively associated with intention to use bike-sharing (Li and Kamargianni, 2019), ride-hailing (Wang et al., 2020), and carsharing (Bansal and Kockelman, 2018; Kim, Ko, and Park, 2015). Liu, Ma, and Zuo (2019) found that highlighting the environmental advantages may increase social acceptance of AVs.

Second, tech-savvy individuals who have higher levels of interest in new technology, a technology-oriented lifestyle, and/or are individuals who are the first to try out a new product were found to be early adopters of EVs (Axsen et al., 2016; Biresselioglu et al., 2018), have higher intentions of using AVs (Bennett et al., 2019; Potoglou et al., 2020; Sweet and Laidlaw, 2019), and were more likely to purchase AVs with higher levels of automation (Tsouros and Polydoropoulou, 2020). Individuals from the U.S. who preferred battery-EVs over plug-in EVs were also drawn to its technological appeal (Lane et al., 2018). Early adopters of new technology were positively associated with the intention to use ride-hailing services (Wang et al., 2020). In a study that included both AV and commercial air, respondents who selected air over AV tended to be more tech-savvy (Kim et al., 2019). For individuals who are anxious about using new AV technologies, one study found that this anxiety could be mitigated through providing safety-related information (Hohenberger, Spörrle, and Welpe, 2016). Sovacool et al. (2019) found that safety attitudes were positively associated with women's preferences for EV vehicles.

Third, multiple studies have found that social effects are important to AV and EV adoption. Bansal and Kockelman (2018) found that about 50 percent of respondents would time their adoption of AVs in conjunction with their friends. Huang and Qian (2018) and Kim, Ko, and Park (2015) found that social conformity effects (such as word-of-mouth and peer influence) positively influenced consumer preference for EVs. Cherchi (2017) found that word-of-mouth effects were just as important as vehicle characteristics on the intention to purchase EVs.

4.2.3. Acceptance and adoption

Numerous papers in the ground transportation field have examined general barriers to EV adoption (e.g., see Berkeley et al., 2017, 2018; Kim et al., 2018) and applied or extended theoretical models used to predict the timing of adoption for EVs, AVs, and sharing services. Several review papers have been written, including one by Becker and Axhausen (2017) who reviewed surveys regarding AVs with a focus on methodologies and results as they pertain to acceptance of AVs, and a second by Rezvani et al. (2015) who reviewed the drivers for and barriers against adoption of plug-in EVs and provided an overview of the theoretical perspectives that have been used. In this section, we present an overview of papers that provided general overviews of barriers toward adoption of new ground technologies and papers that modeled the timing of adoption of new ground technologies.

Cunningham et al. (2019) conducted a survey to gauge public acceptability and opinions of AVs within Australia and found that the majority of Australians are currently not willing to pay more for a fully autonomous vehicle than a conventional car. Raj et al. (2020) examined the barriers to AV adoption and found that the lack of customer acceptance is the most prominent barrier.

Multiple authors have applied or extended Davis' Technology Acceptance Model (TAM) to show that perceived usefulness and perceived ease of use are use predictors or behavioral intentions to have or use new ground technologies (Davis, 1989). These include studies by Globisch et al. (2018) and Wolff and Madlener (2019) that examined acceptance of EVs in commercial fleets, and studies by Panagiotopoulos and Dimitrakopoulos (2018) and Lee et al. (2019) that examined acceptance of AVs and found that perceived usefulness, perceived ease to use, perceived trust and social influence helped predict behavioral intentions to have or use AVs. Zhang, Tao, et al. (2020) extended the TAM to show that at the beginning of AV commercialization, perceived ease of use and perceived usefulness help describe intention to use, but social influence and initial trust contributed most to explain whether users would accept AVs or not. Zhang et al. (2019) showed that initial trust could be enhanced by improving perceived usefulness and reducing perceived safety risk. Adnan, Nordin, bin Bahruddin, and Ali (2018); Khastgir et al. (2018); and Xu, Zhang, et al. (2018) also found that trust is important to AV acceptance and that experience with AVs could increase trust (Xu, Zhang, et al., 2018), as well as providing knowledge about the AV system's true capabilities and limitations (Khastgir et al., 2018). Du et al. (2019) found that information about AVs provided to respondents before they participated in a driving simulator experiment helped increase trust in and preference for AVs. Wang et al. (2018) used an extended TAM to show that consumers' lack of knowledge and risk perceptions could be barriers to the acceptance of EVs, and Wang et al. (2020) used an extended TAM to show that personal innovativeness, environmental awareness, and perceived usefulness are positively associated with the intention to use ride-hailing services, whereas perceived risk is negatively associated with intention to use and perceived usefulness.

Other theoretical frameworks have been used to model adoption and timing of new ground vehicle technologies. For example, Adnan, Nordin, Amini, and Langove (2018) used the Theory of Planed Behavior (Ajzen, 1985) to examine the adoption of plug-in hybrid vehicles in Malaysia, and Wang et al. (2016) used this theory to examine adoption of hybrid EVs in China. Roger's Diffusion of Innovations Theory (Rogers, 2003) has been used in multiple studies. Kröger et al. (2019) examined potential AV market penetration in the U.S. and Germany; Prieto et al. (2017) examined diffusion of carsharing services in London, Madrid, Paris, and Tokyo; and Zhang, Schmöcker, et al. (2020) examined diffusion of a one-way carsharing system in Tokyo. Shabanpour, Shamshiripour, and Mohammadian (2018) modeled the timing of AVs that considers individuals' desires to innovate and need to imitate the rest of society, and Talebian and Mishra (2018) predicted the adoption of connected AVs and found that information individuals receive from peers was a key influence of adoption.

Two studies have extended discrete choice models to incorporate timing effects associated with adoption. El Zarwi et al. (2017) integrated discrete choice and TAM models to predict the adoption timing of a one-way carsharing service. They found that adoption is influenced by social influences, network effects (e.g., placement of stations), level of service attributes, and sociodemographics and that placing a carsharing location outside a major technology firm induced the highest expected increase in the monthly number of adopters. Liu and Cirillo (2018) used a generalized dynamic discrete choice model to predict the initial and repeat purchases of alternative fuel vehicles that accounts for technology improvements and changes in prices over time.

In summary, studies based on TAM have confirmed that that perceived usefulness and perceived ease of use, perceived trust, and social influence help explain the adoption of EVs, AVs, and ride-hailing services, whereas perceived risk is a barrier to adoption. Providing safety information and general information about the technical capabilities and limitations of new transportation technologies are strategies that authors have identified for increasing comfort in the new technologies. Within the UAM, only one study has applied the TAM framework. Al Haddad et al. (2020) extended the TAM framework and confirmed the importance of safety and trust and affinity to automation in the timing of the adoption of UAM.

4.2.4. Value of time

UAM offers the potential for travel time savings. Several studies within the ground transportation literature have focused on evaluating the value of time for AVs. As air taxis enter the market, they may be competing with AVs, thus the findings from these studies are particularly relevant for UAM demand and pricing studies.

Multiple studies have noted that VOT is related to productivity and two theoretical papers have shown that the VOT for AVs will be less than the VOT in a conventional ground vehicle. Correia et al. (2019) presented a theoretical model for VOT, noting that "full automation will enable passengers to perform other, non-driving, related tasks while traveling to their destination. This may substantially change the way in which passengers experience traveling by car, and, in turn, may lead to considerable changes in [VOT]." Pudāne and Correia (2020) adapted this model, showing that "if automated vehicles provide identical work or leisure experience to out-of-vehicle locations, then the opportunity costs of travel time are erased and the (VOT) equals the intrinsic costs of travel, which is strictly smaller than the VOT in a conventional vehicle."

Several empirical studies have confirmed this theoretical result. Based on a survey of approximately 500 individuals from the Netherlands, Correia et al. (2019) found that the average VOT for an AV with an office interior[12] (5.50€/hr; $6.16/hr USD) was lower than the VOT for a conventional car (7.47€/hr; $8.37/hr USD); no significant differences in VOT were found between the AV that contained a leisure interior and a conventional car. Based on a survey of approximately 500 individuals from Germany, Kolarova et al. (2019) found an average value of travel time savings (VTTS) reduction of 41 percent for the AV compared to a conventional car for commuting trips; no significant changes in the average VTTS were found for leisure or shopping trips. Gao et al. (2019) found that VOT was 13 percent lower when being driven in a ride-hailing service than a personal car and, further, that mentioning the ability to multitask explicitly led to a much lower VOT, approximately half that of driving oneself. However, noting that the ride-hailing service was driverless led to a 15 percent higher VOT compared to driving a personal car, "which may reflect a lack of familiarity and comfort with driverless technology at present" (Gao et al., 2019).

These findings are important, as they suggest that the UAM community should not use an average VOT, but rather incorporate a distribution of VOTs across the population that accounts for "non-adopters."

4.2.5. Willingness to share rides with strangers

As noted by Kolarova et al. (2019), prior results in the literature have shown that using a shared autonomous vehicle alone and sharing the journey are perceived as two distinct mobility options (Krueger et al., 2016), which may be due to psychological barriers or discriminatory attitudes associated with sharing a ride with a stranger (Correia and Viegas 2011; Middleton and Zhao, 2019). For example, based on focus groups of older adults in the province of Utrecht, the Netherlands, Faber and van Lierop (2020) found that participants had a strong interest in using AVs in their daily life and that the option to travel with friends was an important factor in having a positive attitude toward AV adoption. Lavieri and Bhat (2019) noted that an important obstacle to ride-hailing adoption is the user's willingness to share rides with strangers and "recent studies indicate that travelers are hesitant about being in an automobile environment with unfamiliar faces, due to a desire for personal space, an aversion to social situations, distrust, and concerns about security and privacy (see, for example, Tahmasseby et al., 2016; Morales et al., 2017; Amirkiaee and Evangelopoulos, 2018)." Based on a 2017 survey of 1607 commuters in the Dallas–Ft. Worth–Arlington Metropolitan area, Lavieri and Bhat (2019) examined individuals' willingness to share trips with strangers in an AV. They found that privacy is a main deterrent to pooled ride-hailing service, with non-Hispanic whites being more privacy sensitive than individuals of other ethnicities. However, they found that respondents are less sensitive to the presence of strangers when in a commute trip compared to a leisure-activity trip and found evidence that the travel time added to the trip to serve other passengers may be a greater barrier to the use of shared services compared to the presence of a stranger.

Conversely, a study of Australians found that riding with strangers was more onerous than the added trip time. Based on a survey conducted in 2018 of 3985 Australians that asked for their preferences for a ground on-demand transportation system, Vij et al. (2020)

[12] We used an exchange rate of 1€=1.12USD based on the average exchange rate in 2019 (Pound Sterling Live, 2020c).

found that consumers are willing to pay[13], on average, AUD $0.28/km (USD $0.33/mi) more to avoid sharing a vehicle with other passengers, AUD $0.17/km (USD $0.20/mi) more for door-to-door service, and AUD $0.10/km (USD $0.12/mi) to be able to book the service in real time as opposed to having to book the service several hours in advance. All trip purposes were included in their analysis.

The willingness to travel with strangers may be related to ride-hail usage and whether individuals in general like to interact with other people. Based on a database of 6.3 million Lyft trips taken in Los Angeles County in 2016, Brown (2020) found higher rates of ride-hailing usage among frequent Lyft users compared to moderate and less-frequent users, which "suggests either that repeat users seek more economical service options and/or repeated ride-hail use increases or is associated with peoples' comfort in sharing cars with strangers." Based on focus groups of individuals from Denmark, Nielsen et al. (2015) found that some Danish negatively perceive ride-hailing with strangers due to "social awkwardness," whereas other Danish positively perceive ride-hailing with strangers due to the ability to "socialize" with others.

The willingness to travel with strangers may also be related to modes, given individuals are more used to traveling with strangers by air than in an automobile. In the UAM context, Garrow, Roy, and Newman (2020) found that the willingness to ride with strangers varied across the AV and air taxi modes, with those ages 18–24 less willing to travel with strangers in an AV than those ages 25–64 in an AV and that the willingness to travel with strangers was about the same for the air taxi (across all ages) as for those ages 25–64 in an AV. Finally, it is important to note that while many studies point to the willingness to pay to travel with strangers, the result is not consistent across all studies. Based on a survey of approximately 500 individuals from Germany, Kolarova et al. (2019) did not find any differences between using a shared AV alone or with others.

4.3. Bringing it all together—Demand modeling insights and research directions for UAM

As seen from the literature review, demand modeling within the UAM and EV/AV domains have focused on different objectives. Within the UAM field, the primary focus has been on determining if UAM is a viable concept—e.g., will enough people be willing to fly in these new air taxis and can the service be supported across different cities? Within the ground transportation field, EVs, AVs with lower levels of automation, and sharing services have already been implemented, allowing researchers to focus on understanding SED characteristics of early adopters or how individuals respond to different policy incentives and operational policies.

To the extent that individuals who are interested in EV, AV, and/or sharing modes will also be interested in air taxis, we would expect that early adopters of air taxis will be more likely to be male, have higher incomes, have pro-environmental attitudes and/or be tech-savvy, technology-oriented lifestyles and be the first to try out new products. These expectations have been confirmed in surveys of U.S. commuters by Boddupalli et al. (2020) and Garrow, Roy, and Newman (2020).

The EV and AV literature have several findings that are relevant for the UAM community. To date, there has been a significant amount of research in the EV and AV literature that has looked at the timing of when adoption occurs, but only one paper in the UAM area, by Al Haddad et al. (2020). These technology adoption models can provide valuable information on the role of trust, safety, and perceived usefulness on the adoption of UAM. The literature across both the air and ground transportation areas show mixed reactions in the population with respect to autonomy. Finding ways to increase individuals' trust in autonomy would be a valuable direction for future research. For example, we may find that it is important to provide demonstrations of what it would be like to fly in a UAM using virtual reality and/or to provide safety information to increase individuals' comfort levels with the new technology. The role of social effects (like trusting perceptions of friends and family) has been shown to play a role in adoption of ground vehicle technologies and could be investigated in the context of UAM.

Unlike with ground transportation modes, individuals are more likely to expect to travel with strangers in an aircraft. It is, thus, unclear whether the same effects seen for ride-hailing services will apply to UAM. One study, by Garrow, Roy, and Newman (2020) did find that younger commuters were less likely to take a UAM with strangers compared to older commuters. However, there is a research need to understand if the willingness to travel with strangers in a UAM aircraft varies across nations and trip purposes.

Perhaps one of the most interesting findings from the AV literature is that the VOT for commuters will decrease when ground AVs enter the market due to the ability for commuters to use their time more productively. From the UAM perspective, this is important as it suggests that AVs will compete more heavily with air taxis than with conventional autos and that additional travel time savings will be required for the air taxi mode relative to the AV. Potential productivity gains in an AV compared to an air taxi have not been explored in the literature, and there is a need to determine what levels of productivity would be achievable in a UAM vehicle and how productivity varies as a function of ride quality, trip duration, and other factors. Given the VOT decreases seen for AV ground research, better understanding of VOT decreases for UAM vehicles—particularly as they relate to commute trips—is an important area of future research.

Another interesting avenue for future research would be to explore how AVs and air taxis will compete across different trip purposes as an air taxi system evolves and adoption rates increase across both new modes.

5. Integration with existing modes and infrastructure

UAM has the potential to transform urban travel by providing faster connections among residential, business, sports, medical, and other facilities. To achieve this goal, air taxis will need to fly close to and/or over high-density population areas and integrate with

[13] An exchange rate of 1 AUD = 0.7407 USD was used based on the average exchange rate in 2018, when the survey data were collected (Pound Sterling Live, 2020a).

existing city infrastructure—including other modes of transportation, the electric grid, and the NAS. As such, there will be many questions that the aviation community will need to address with respect to how we can safely integrate UAM into existing infrastructure while ensuring equitable access. This section reviews infrastructure-related topics that have been investigated by the UAM and EV/AV areas.

5.1. Review of UAM infrastructure studies

Several UAM researchers have focused on infrastructure-related issues, mostly in the context of UAM operations. This section highlights the tight couplings researchers have observed among vertiport placement, operations, demand, and energy requirements.

5.1.1. Vertiport Placement, Design, and airspace integration

Multiple terms have been used for vertiports, including vertipads, vertistops, and skyparks (Vascik and Hansman, 2017). In this paper we will refer to vertiports for eVTOL operations and STOLports for operations that involve short takeoff and landing flights. Multiple types of locations have been suggested as possible infrastructure that could be used to integrate vertiports into cities, including rooftops with parking lots and/or parking decks (Kreimeier et al., 2018; Robinson et al., 2018; Uber Elevate, 2016), vacant land, floating barges, pre-existing airports and helipads (Robinson et al., 2018), the land adjacent to highways and/or in cloverleaf interchanges, parking lots at places of worship that may be used only on weekends, large stadiums or concert venues that are unused for large portions of the year, the corner of a parking lot in large superstores or malls, and technology campuses (Uber Elevate, 2016).

Several studies have examined optimal locations for vertiports to serve different types of demand. Most of these studies are focused on finding which census tracts and/or larger geographic area would be ideal locations, instead of actual siting. For example, Lim and Hwang (2019) investigated how competitive eVTOL would be for commuters in the Seoul metro area by increasing the number of vertiports from 2 to 36; Daskilewicz et al. (2018) found vertiport locations that maximize population-cumulative potential travel time savings compared to driving in San Francisco and Los Angeles; and German et al. (2018) formulated an optimization problem to find vertiport locations for a cargo demand application in the San Francisco Bay area. As part of a broader study that identified eight operational constraints that could limit or prohibit UAM service, Vascik, Hansman, and Dunn (2018) found that the three most stringent constraints concerned community acceptance of aircraft noise, vertiport availability, and air traffic control scalability.

In terms of vertiport designs, several architectural firms have presented visions (Uber Elevate, 2020b). For example, Vascik and Hansman (2019) considered how different vertiport designs (defined by the number of touchdown and liftoff pads, number of aircraft gates, and number of aircraft staging areas/parking spaces) and the layout of these designs (which include linear, satellite, pier, and remote apron topologies) impact vertiport capacity envelopes. They found that the ratio of gates to touchdown and liftoff pads is a key design parameter, that aircraft staging areas can provide significant benefits, and that vertiports with multiple touchdown and liftoff pads can greatly increase throughput.

Several studies have examined how constraints on the paths aircraft use to take off and land from a vertiport restrict the number of locations that can be used for siting vertiports. Conceptually, even though eVTOL aircraft can hover, they typically climb from and approach a vertiport at an angle to conserve energy reserves and to operate in safe areas of their flight envelopes (e.g., see Yilmaz et al., 2019). The same design criteria and guidance used for helipads can be used as a starting point for siting of vertiports, e.g., the departure and approach paths must be free of obstacles and consider historic wind patterns. Two FAA documents that are particularly relevant in this context include *FAA Advisory Circular AC-150/5390-2C Heliport Design* (FAA, 2012) and *FAA Instrument Procedures Handbook FAA-H-8083-16B* (FAA, 2017).

To date, we could find no published studies that explicitly examined the optimal placement of vertiports for eVTOL operations that considered port design criteria; however, work is in progress by Tarafdar et al. (2020) that uses Zillow's Assessor and Real Estate Database (ZTRAX) to identify parcel-level characteristics important for siting (Zillow, 2020). Several studies have examined the optimal placement of STOLports for short takeoff and landing operations in urban and suburban areas of South Florida, which includes the Miami metro area (Robinson et al., 2018; Justin and Mavris, 2019; Somers et al., 2019; Wei et al., 2020). Robinson et al. (2018) found that an average density of 1.66 STOLports per square mile can be achieved with 300-ft-long runways. Subsequent studies by Justin and Mavris (2019), Somers et al. (2019) and Wei et al. (2020) built on this initial analysis by accounting for obstacles and historic wind patterns and formulating an optimal facility location problem among potential sites.

Finally, several authors have pointed out how the placement of vertiports needs to integrate with airspace restrictions. Verma et al. (2019) looked at near-term routes for UAM based on current-day helicopters routes in DFW, and Vascik and Hansman (2017) used radar trajectory data recorded by the FAA Airport Surface Detection Equipment Model X (ASDE-X) from LAX to identify areas where it may be feasible to route future UAM operations due to the low volume of conventional operations. Air taxi trips into a major commercial airport pose particular challenges due to the need to coordinate trajectories with existing commercial operations. Vitalle et al. (2020) looked at route design for eVTOL aircraft transporting passengers into Tampa International Airport (TPA). They consider three possible vertiport locations at or near the airport: a helipad located two miles from the airport, the rooftop of the economy parking lot in the main terminal area, and the rooftop of the rental parking garage. The rooftop of the economy parking lot is ideal from the passengers' point of view in that it reduces the time to reach their commercial gates and remains inside a secure area; however, this location presents greater challenges with designing trajectories, as aircraft would need to land between two parallel runways.

Vascik and Hansman (2020) developed an approach to analytically identify terminal airspace that is procedurally segregated from large aircraft operations and may be appropriate for new airspace cutouts for eVTOL operations. They applied the methodology to the 34 largest metro areas in the U.S. and found that, on average, 65 percent of a city's population was accessible to vertiports operating under visual flight rules and without air traffic control (ATC) limitations. However, on average, only 34 percent of long-duration commuter workplace locations could be accessed by UAM. Further, a very large variation in accessibility measures existed across the metro areas. The authors found that providing access to special-use airspace, and especially temporary flight restrictions for sporting events, increased commuter workplace access to 54 percent for the median U.S. city.

5.1.2. Battery and electric grid considerations

There is a fundamental trade-off between battery size and mission length. On one hand, bigger batteries have more energy, which can translate into longer missions. However, with the increase in battery size comes additional aircraft weight, which can translate to increased acquisition cost. Based on current battery technology, eVTOL aircraft will likely need to be partially or fully recharged after each mission. Given current battery-charging technologies, the time to perform this charging is likely to deter high aircraft utilization, particularly during peak demand periods. The amount of electricity required to power an electric fleet of aircraft is not trivial and will likely have significant impacts on the electric grid, which may not be able to be supported by the current electric grid.

The issues are described by Kohlman and Patterson (2018) as follows:

> *"if UAM vehicles are to be all-electric, as many are proposing, there will be new demands placed on the electrical grid infrastructure that must be understood. Additionally, vehicle-level characteristics such as the recharge time or energy used for a flight will have direct impacts on the efficiency, cost, and ultimate viability of UAM networks. For example, if vehicles must be charged for long periods of times between missions, a very large number of charging stations will be required at vertiports and many vehicles may be required to meet demand for UAM services."*

Further, the cost of grid upgrades to support UAM operations is not trivial. A recent report by Black & Veatch estimates the cost to extend an existing service line to support 31 MW chargers to be between $75K and $100K; the cost for a new feeder line to support up to 83 MW chargers to be between $2.6K and $1.3M per mile; a new transformer bank over 10 MW to support over 15 chargers to be between $3M and $11M; and a new substation bank over 20 MW to support 30 chargers to be between $40M and $80M (Stith, 2020).

The impact of charging on operations and the number of required charging stations has been noted by other authors. In a study of cargo operations in the San Francisco Bay Area, German et al. (2018) found that for a lift + cruise eVTOL concept model and a tiltrotor aircraft model, charging times with a 300 kW charger ranged from 12.5 to 19.1 min and 16.0 to 23.1 min, respectively. When the charger was increased to 400 kW, these charge times decreased to 9.5 to 14.4 min and 12.1 to 17.4 min, respectively.

The impacts of UAM operations on the electric grid were clearly demonstrated in a study by Justin et al. (2017). Based on an examination of electric aircraft for regional distances, they generated power profiles for stations where Cape Air and Mokulele Airlines operate. Cape Air's network included 525 daily flights to 43 airports primarily in the New England area using mostly twin-engine piston-powered Cessna 402s. Mokulele's network included 120 daily flights to airports primarily in the Hawaiian Islands using 11 single-engine turboprop Cessna 208s. They found very high peak powers at the airlines' busiest airports, i.e., for Cape Air the peak power exceeded 1 MW in Nantucket Memorial (ACK) airport and in Boston Logan International (BOS) airport, which is the order of magnitude of the demand of approximately 1,000 households. For Mokulele, the peak-power at Molokai airport (MKK) was 517 kW, which is about 1/20th of the total generation capability for the entire island of Molokai (Justin et al., 2017). The authors explored various operational strategies to reduce peak-power demands and the cost of electricity, and found that a strategy that includes optimizing battery recharging with battery swaps can achieve reductions on the order of 20 percent compared to a power-as-needed strategy.

What is clear from these and other publications is that the power requirements on the electric grid are not trivial, and significant opportunities exist to optimize the deployment of charging and fast-charging stations. Furthermore, given that electricity prices vary across cities and providers, the optimal battery recharging solution will likely be city-dependent.

5.2. Review of EV and AV infrastructure studies

This section provides an overview of the types of questions that researchers and policy makers have investigated when integrating a new mode into the existing ground transportation network, and the role of parking availability on mode choice. This discussion is followed by a detailed review of a topic that is particularly relevant to UAM: integration with the electric grid.

5.2.1. Integration with existing modes and the ground transportation network

As new technologies and transportation modes enter the market, transportation planners need to understand whether these modes will complement or compete with existing modes. For example, is ride-hailing complementary with public transit in providing first-mile and/or last-mile access, or does ride-hailing replace public transit trips? Transportation planners are also interested in longer-term impacts, such as whether carsharing reduces car ownership or influences households' residential location choices. Finally, transportation planners often model "rebound effects," which occur when new technologies result in increased travel that can have negative environmental impacts, e.g., through the generation of more trips or longer trips. For example, will AVs reduce the need for parking but generate longer trips due to the fact they can drop passengers off and travel back home and/or travel to a less expensive and more remote location to park?[14] As shown in Fig. 3, more than 30 studies exist within the ground transportation literature that look at how EV, AV, and/or ride-hailing services will integrate or compete with existing infrastructure. In addition, the U.S. Department of Transportation has funded studies that have developed planning tools for on-demand mobility that consider UAM

[14] This is of particular concern for airports, which could lose significant parking revenues if AVs simply drop off passengers.

(Shaheen et al., 2020).

From a UAM perspective, what is most relevant about these studies is not necessarily the results, but rather the underlying motivations for *why* transportation planners are asking these questions. Within the U.S., urbanized areas that have a population of greater than 50K are required to have a metropolitan planning organization (MPO) that is responsible for establishing a long-term transportation improvement plan (TIP) that sets transportation investment priorities in the area (FTA, 2019). Major federal transportation authorization bills, such as the Moving Ahead for Progress in the 21st Century Act (MAP-21) and the Fixing America's Surface Transportation (FAST) Act, establish regulations that MPOs must follow in order to receive transportation-related funding. These regulations require that the selection of projects be based on performance metrics, equity considerations, and other criteria (e.g., see US DOT, 2013). In the case of congestion management plans, the regulations state that an MPO's TIP "must include regional goals for reducing peak-hour vehicle miles and improving transportation connections and must identify existing services and programs that support access to jobs in the region … [23 U.S.S. 134(k)(3)]" (FHWA, 2016). Other federal legislation is critical to transportation planning and funding priorities, including the Clean Air Act (CAA), Clean Water Act (CWA), National Environmental Policy Act (NEPA), National Historic Preservation Act (NHPA), and Americans with Disabilities Act (ADA) (EPA, 2020a, 2020b; NPS, n.d.; US DOJ, 2020). From a UAM perspective, it is important to note that as we integrate this new mode into our cities, government funding for infrastructure improvements will likely be tied to these or similar regulations.

Given the focus (not only in the U.S., but in many countries throughout the world) on transitioning to clean energy and reducing the negative impacts of the transportation sector on carbon emissions, many studies that look at integration of new ground technologies with existing modes and infrastructure consider metrics that tie to these goals, including total vehicle miles traveled (VMT) and greenhouse gas emissions. For example, Jones and Leibowicz (2019) examined these issues in the context of shared AVs, and Shen et al. (2018) examined these issues in the context of an integrated AV and public transit system for Singapore. Bansal et al. (2016) examined long-term adoption of shared AVs in Austin, Texas, and simulated long-term adoption under different scenarios to help assess sustainability impacts. Ai et al. (2018) found through siting EV charging stations near public transit in Chicago, Illinois, that commuters can reduce up to 87 percent of personal VMT and 52 percent of carbon emissions, and Muñoz-Villamizar et al. (2017) evaluated environmental impact and delivery cost implications of using an all-electric fleet of delivery vehicles in Bogotá, Colombia.

One of the key findings from the ground transportation literature that is directly applicable to UAM research is the role of parking availability on mode choice. Within the ground transportation field, several researchers have explored the relationships among mode choice, work departure time, ground transportation congestion, and availability of parking at the work destination (e.g., see Tian, Sheu, and Huang, 2019; Wang et al., 2019). Intuitively, we expect that individuals are more likely to take a ride-hailing service and/or transit modes compared to a conventional auto if there is limited parking availability at their destination. This has important implications for UAM. First, if parking in business centers is expensive and/or limited, using an air taxi for commuting will be more competitive with auto. Similarly, if on-site parking at airports[15] reaches capacity at certain times of the day and/or days of the week, then using an air taxi to travel to and from the airport will be more competitive with auto (although maybe not as competitive with ride-hailing services).

It is also important to note that UAM may interact with other modes in both positive and negative ways, and the ultimate impacts on energy usage and sustainability have yet to be determined (ARPA-E, 2021). Congestion in the ground transportation systems at the network level may improve as the air system provides additional capacity for transporting individuals and could reduce the number of long-distance ground vehicle trips. This is particularly relevant if UAM is able to replace single-occupancy ground transportation trips with shared-occupancy air trips, thereby leading to improvements in energy use and reductions in greenhouse gas emissions. In the context of SAVs, multiple authors have evaluated the energy and environmental impacts of automated vehicles (e.g., see Greenblatt and Shaheen, 2015; Lee and Kockelman, 2019; Fleming and Singer, 2019; Brown and Dodder, 2019). Shaheen and Bouzaghrane (2019) note that "while the literature on potential SAV impacts on travel behavior and the environment is still developing… [researchers] speculate that SAVs would result in a 55% reduction in energy use and [about a] 90% reduction in greenhouse gas (GHG) emissions." In the context of UAM, multiple strategies for reducing energy usage and GHG emissions are being investigated that include vehicle improvements (e.g., through the design of electric propulsion systems and batteries) as well as connectivity and automation strategies (e.g., through trajectory optimization or optimized network coordination strategies with air and ground traffic systems). Representative studies include Pradeep and Wei (2019), Shihab et al. (2019) and Kasliwal et al. (2019).

5.2.2. Integration with the electric grid

Within the ground transportation literature, multiple studies have examined how and where to place recharging infrastructure, how plug-in EVs (PEVs) and consumers' charging behaviors will impact the electric grid, and how policy strategies can be used to help reduce peak loads on the electric grid. In the area of charging infrastructure site selection, optimization-based and activity-based approaches for selecting recharge sites have been developed (Dong et al., 2014; Yang et al., 2017; Li et al., 2020; Lin and Greene, 2011). These approaches are typically formulated to maximize the feasibility of daily use of EVs within a community. Additional work has focused on site selection for intercity trips (Xie et al., 2018, Xie et al., 2021).

Significant research has also focused on the impact of charging on the electric grid and how this impact is affected by driver behavior relating to charging. Hardman et al. (2018) reviewed the literature as it pertains to infrastructure requirements for PEVs and

[15] A simple Google search of "how often does airport parking reach capacity" conducted on September 14, 2020, returned multiple results to airport webpages and/or news articles that issued warnings about their parking lots "routinely" reaching capacity. These included airports in Las Vegas, Salt Lake City, Sacramento, San Jose, Honolulu, Denver, Atlanta, Spokane, and many others.

found that PEV charging will not impact electric grids in the short term but may need to be managed long term. Marmaras et al. (2017) modeled the impact of EV driver charging behavior on the transportation and electric grid networks. They found that EV driver behavior has “direct and indirect impacts on both the road transport network and the electricity grid.” They examined consumer charging preferences (e.g., normal charging at home, normal or fast charging at a public charging station) and offered operational strategies to help shift peak loads at public charging stations. Additional studies focused on the impact of driver behavior on EV demand, charging infrastructure usage, and corresponding impacts on the electric grid include Tal et al. (2014), Chakraborty et al. (2019), and Lee et al. (2020). Considering the importance of recharging costs on driver behavior, multiple studies have also investigated the economics of recharging based on the cost of electricity for fast charging and associated infrastructure costs (Muratori, Elgqvist, et al., 2019; Muratori, Kontou, et al., 2019; Borlaug et al., 2020).

Significant research has also been conducted related to policies and strategies to manage the impact of charging on the electric grid. These studies have shown that controlled charging of EVs, including time-of-day pricing, can better balance loads on the electric grid and impact power grid loads, voltage, frequency, and power losses (Bailey and Axsen, 2015; Daina et al., 2017; Latinopoulos et al., 2017; Xu et al., 2017). Luo et al. (2020) went one step further by jointly designing charging station and solar power plants with time-dependent charging fees to improve management of transportation and power systems.

Some studies have analyzed interactions between the electric grid and e-mobility and how these interactions are dependent on policy choices. These studies are difficult to conduct in some countries due to limited information that is publicly available about the electric grid (e.g., capacity and loads as a function of different times of the day); therefore, it is common to produce EV charging profiles and examine how these profiles are affected by different policies (such as changing time of day pricing), e.g., see Delgado et al. (2018) for a study in Portugal. A notable exception is a study by Kannan and Hirschberg (2016) who used a detailed energy model developed for Switzerland and found that the cost effectiveness of e-mobility depends on policy decisions in the electric sector.

Within the ground transportation literature, there has been considerable interest in vehicle-to-grid technologies and policies in which energy is stored in EVs and returned to the grid when it is needed, generating revenues for the EV owner (e.g., see Kester et al., 2019; Nourinejad et al., 2016; Sovacool et al., 2019). Within a UAM context, vehicle-to-grid approaches are likely not a viable option, given the high costs of aerospace-grade battery packs and the battery degradation that would occur through the charging and discharging cycles. Additionally, this use case would likely further add to the challenge of certificating UAM battery packs with national aviation regulatory agencies. However, the concept could be adapted to UAM applications by using batteries that are no longer viable for use onboard the aircraft to store energy on the ground at or near vertiports, e.g., by charging these ground batteries during less-expensive off-peak hours and then using them to charge the flight batteries in the UAM aircraft during peak-period operations.

Given the high cost of batteries, several studies have examined how different recharging strategies, including battery swapping and fast charging, can be optimized to help regulate the charge profile and enhance battery life (e.g., Amjad et al., 2018; Sweda et al., 2017; Pelletier et al., 2018; Keskin and Çatay, 2016; Liao et al., 2016; Qin et al., 2016; Wu and Sioshansi, 2017; Widrick et al., 2018). The study by Pelletier and colleagues offers one of the more comprehensive optimization models and incorporates realistic charging processes, time-dependent energy costs, battery degradation, grid restrictions, and facility-related demand charges for a fleet of electric freight vehicles. They found that fast chargers may be required for vehicle operation flexibility when longer routes are performed.

Optimal charging strategies for carsharing and fleet vehicles have received a lot of attention in ground literature in part because EV charging has a significant impact on EV downtime. For example, in a study by Roni et al. (2019) they noted that in free-floating EV carsharing fleets “downtime due to charging, including time spent traveling to and waiting in queues at charging stations in a sparse charging infrastructure network is a major barrier to sustainable operations.” The authors found that fleet vehicle charging time comprises 72–75 percent of the total downtime spent on charging trips and that adding new charging stations reduced total charging trip travel time but did not significantly reduce total downtime. These results are relevant for UAM because they show that a significant operational bottleneck is related not only to battery recharging but to queuing for battery charging. Shen et al. (2019) and Amjad et al. (2018) provided review articles that cover EV charging operations and optimization approaches.

5.3. Bringing it all together—Infrastructure insights and research directions for UAM

Across both the UAM and EV/AV literature, station placement has been shown to be a critical factor influencing overall system performance. The sheer volume of publications in the EV area that have focused on charging infrastructure or charging type is noteworthy—about one out of every five EV papers we inventoried addressed these topics, as indicated in Fig. 3. Within the EV community, significant attention has been placed on understanding individuals’ charging behavior and strategies for shifting charging patterns to reduce the peak period load on the electric grid. This is relevant from a UAM perspective, as it suggests that the transportation community is already experiencing challenges associated with charging a ground EV fleet. Some EV research has suggested that current electric grids won’t be able to support future EV ground vehicle charging needs. Needless to say, if we are not in a position to handle charging of a ground EV fleet, how are we going to handle charging a UAM fleet that will likely require even faster charge times? There is a clear research need to better understand the power profiles of UAM fleets and develop strategies for how to optimally charge UAM fleets without overwhelming the electric grid. Another interesting topic would be to jointly examine the power profiles for UAM fleets and EV ground fleets, as both technologies will be competing for a limited amount of electricity.

As will become more evident in the next section that focuses on operations, the placement of vertiports is closely coupled with operations and other factors. All of this points to the need to develop high-fidelity simulation models for UAM operations that capture interactions among vertiport locations, vertiport topology, demand, pricing, dispatching, and airspace restrictions.

In comparing the UAM and AV/EV literatures, we could find no mention of the role of parking availability on air taxi mode choice, and we suggest this could be an interesting factor to include in future air taxi mode choice studies, particularly studies that included ride-hailing, air taxis, and traditional autos as potential modes. As we integrate UAM into our cities, it will be important to work with local planning organizations to ensure that any infrastructure investments that require public funding align with regulations these organizations need to follow.

6. Operations

This section reviews operations-related topics explored by the UAM and EV/AV research communities and identifies results from the EV/AV areas that can help inform future UAM research.

6.1. Review of UAM operations studies

As the UAM community designs an air taxi system capable of high-volume throughput integrated in urban areas, many operations-related questions arise. One of the first steps in the analysis process is to design a concept of operations (ConOps), which is essentially a plan for how UAM operations can be safely integrated into the national airspace system. In June 2020, NASA released its ConOps vision, which includes UAM corridors in the sky in which aircraft could operate without the direct involvement of air traffic control (ATC) (Bradford, 2020). Given the importance of ensuring safe operations within the existing NAS, it is not surprising that the UAM community has focused significant attention on ATC-related issues (as shown in the *meta*-analysis, Fig. 2).

Given a concept of operations, researchers can assess whether a particular aircraft design can successfully and economically perform a given mission, and if it cannot, make modifications to the aircraft design (e.g., see Clarke et al. 2019). To determine whether a mission can be performed successfully for an electric-powered aircraft, researchers need to model the mission's power and energy requirements, which imply the peak current and total capacity required by the battery. For example, Kulkarni et al. (2018) developed an on-board battery monitoring and prognostic architecture for batteries on electric-propulsion aircraft. Alnaqeb et al. (2018) and Prabhakar et al. (2020) developed models to predict mission-based energy and performance metrics; Donateo and Ficarella (2020) proposed a modeling approach for the degradation of the battery performance during its aging; and Pradeep and Wei (2019) developed energy-efficient trajectory plans for a multirotor eVTOL. Hamilton and German (2017, 2019) optimized airspeeds for electric aircraft operations to maximize energy feasibility in the schedule by balancing energy expended during cruise and energy replenished during recharge.

Several researchers have investigated the relationships among aircraft design parameters and operational requirements such as cruise speed and hover time. For example, using the Uber eCRM-001 eVTOL common reference model (Uber Elevate, 2020a), Ha et al. (2020) jointly optimized aircraft design parameters in addition to operational parameters to achieve a 9.66 percent decrease in required hover power. Other researchers have examined the potential for retrofitting existing aircraft with an electric propulsion system to determine if such aircraft could profitably operate for pilot-training applications (Olson, 2015) or short-haul UAM intracity commuter trips in U.S. cities (Kotwicz et al., 2019).

UAM clearly will not be successful without a ConOps that safely integrates aircraft into the NAS and aircraft that can complete the required missions. Thus, it is not surprising that much of the research by the UAM community has been focused on mission performance and related areas, such as battery design and battery modeling. However, as the vision for UAM ConOps and aircraft designs has become clearer, the UAM community is starting to focus on more complex operational issues that include dispatching algorithms and pricing approaches, which are similar topics explored by the EV and AV communities. For example, Roy et al. (2019) examined how existing infrastructure, resources, and operational strategies could be leveraged with improvements in battery and autonomy for regional air mobility. Roy, Crossley, et al. (2018) jointly optimized aircraft designs, operations, and revenue management, and Roy et al. (2020) developed a dispatch model to optimally schedule UAM flights for a shuttle service to an airport that has both scheduled and on-demand customers. Shihab et al. (2019) developed a model to decide whether to offer on-demand or scheduled flights, and how to dispatch the fleet and schedule operations based on simulated market demand. Munari and Alvarez (2019) assigned aircraft to on-demand requests while accounting for maintenance events, allowing flight upgrades in order to reduce operational and repositioning costs. Narkus-Kramer et al. (2016) examined trade-offs associated with battery-powered, remotely piloted semi-autonomous personal aircraft, and found that profitability is closely tied to high network utilizations (which result in fewer deadhead and repositioning flights) and high daily utilization (or higher average hours flown). Finally, Stouffer and Kostiuk (2020) designed a dispatching tool for UAM operations that enables a dispatcher to plan a UAM flight and check for issues before filing a flight plan.

The majority of the papers to date focused on dispatching and scheduling algorithms have presumed a deterministic framework, but two important consideration in UAM applications are that scheduling and dispatching algorithms may need to be done in real time or using a rolling horizon framework to account for delays and uncertainties, and these algorithms may need to be applied at a network level. As Thipphavong et al. (2018) noted, "due to limited energy reserves, UAM aircraft must have assurances prior to takeoff that their destination landing site will be available when they arrive. The tight coupling between arrivals and departures across the vertiports in a UAM network points to the possible need for continuous network-wide scheduling as a first-order control method for real-time, on-demand resource management."

6.2. Review of EV and AV operations studies

EVs have been integrated into many communities throughout the world. As a result, researchers have been able to both develop and validate models using case studies. In the process, researchers have gained many insights regarding how system performance and profitability are affected by fleet size, demand, pricing, and reservation and dispatching strategies. Many of these insights are relevant to the UAM community, particularly given similarities in the directional demand patterns that both ground and UAM communities seek to serve.

From an operations perspective, developing strategies to serve one-way demand while maintaining profitability has been a particularly vexing problem for vehicle-sharing companies. Many travel patterns exhibit strong uni-directional flows, especially during peak periods. For example, in many cities morning rush hour traffic is created by commuters traveling from the suburbs into the city centers to work. Before COVID-19, airports that served predominately business travelers would see peaks of passengers traveling to the airport for Monday morning flights and peaks of passengers leaving the airport Thursday evening and/or Friday to return home. One-way demand patterns result in the need to increase the number of vehicles available to serve peak directional demand (e.g., see Hörl et al., 2019) and/or increase the need to reposition empty vehicles. Staging vehicles to serve peak demand and/or attempting to temporally or spatially shift demand to nearby pick-up and drop-off locations are some strategies that have been explored to serve one-way demand profitably (e.g., see Ströhle et al., 2019).

Within the ground transportation literature, many researchers have focused on the vehicle relocation problem, often in the context of one-way demand systems. Illgen and Höck (2018) provide a review of methods used to relocate vehicles in carsharing networks. Representative studies include those by Wang, Liu, and Ma (2019) and Wang, Yang, and Zhu (2018), who examined one-way electric carsharing systems; Warrington and Ruchti (2019), who studied Philadelphia's public bike-sharing program; and Vasconcelos et al. (2017), who studied a carsharing service in Lisbon, Portugal, and found that relocating vehicles generated an additional 19–24 percent in profits for operators.

Given that "the cost associated with vehicle relocation operations represents a significant proportion of the total operating cost" (Boyacı and Zografos, 2019), many researchers have developed methods for better predicting demand and for tailoring operational strategies to minimize relocation costs while maintaining high service levels. Wen et al. (2019) examined dispatching polices with different types of demand information for an AV shared system and found that individual demand information from in-advance requests improves performance, but the degree of performance depends on the spatial disparity of requests. Boyacı and Zografos (2019) examined temporal and spatial flexibility regarding pick-up and drop-off of vehicles in a one-way electric carsharing system and found that spatial flexibility has a stronger effect than temporal flexibility, but both temporal and spatial flexibility can increase profitably of the system by serving more customers with fewer relocation needs. Hyland and Mahmassani (2018) compared different dispatching policies for an AV service and found that the optimal dispatching policy is a function of demand, with more sophisticated dispatching polices generating higher revenues during the peak demand period and simple dispatching policies (i.e., assigning passengers sequentially to nearest idle AV) working well in low demand periods. This result is consistent with the findings based on a case study of Zurich, Switzerland, that investigated different operational policies for an AV shared mobility system and found that operational policies had a significant impact on vehicle assignment and repositioning, heavily influencing system performance of wait times and cost (Hörl et al., 2019). Both Hyland and Mahmassani (2018) and Hörl et al. (2019) found that the utilization of intelligent demand forecasts and dispatching and rebalancing algorithms were crucial elements of profitability. In addition, Hyland and Mahmassani (2020) found that increases in the mean curbside pick-up time for a shared AV system significantly degrades operational performance in terms of user in-vehicle travel time and user wait time.

The role of advance reservations in the profitability of sharing services is nuanced. On one hand, advance reservations provide more certainty with respect to future demand and allow the operator to position vehicles in advance to the locations where customers have requested service. However, if operators take vehicles out of service too far in advance to guarantee availability for reservations, then vehicle utilization and the ability to serve on-demand requests may decrease, resulting in a less profitable system. As Molnar and Correia (2019) pointed out "while it is convenient for customers to be able to do one-way trips and drop off vehicles anywhere in a service area, this makes it difficult to offer reservations in advance" and there is a need to explore ways to increase advance reservation times by relocating vehicles to shortly before reservation pick-up times.

Several researchers have explicitly focused on the issue of advance reservations and traveler flexibility. Wu et al. (2019) examined the role of guaranteed advance reservations for a free-floating carsharing service in London and found that individuals are willing to pay £0.54 per journey ($0.75 USD)[16] for a guaranteed advance reservation. Duan et al. (2020) examined a system in which individuals can either request immediate rides or reserve an AV taxi service in advance, and optimized a model that considers vehicle-to-passenger assignment with empty vehicle rebalancing. They found that when the number of vehicles is adequate and reservations are made further ahead of time, the completion rate of requests and revenue improve. Allahviranloo and Chow (2019) examined a system in which individuals can buy future time slots for AV and are guaranteed service. They found the spatial temporal distribution of demand impacts the solution to the fleet sizing problems.

Several researchers have jointly optimized fleet size and trip pricing for sharing systems. Xu, Meng, and Liu (2018) jointly optimized EV fleet size and trip pricing for a one-way carsharing service that considers vehicle relocation and personnel assignment based on a case study of Singapore. Jorge et al. (2015) used a theoretical case study network of 75 carsharing stations in Lisbon, Portugal, and found that trip pricing can increase profits through more balanced systems; optimal profits are on average 23 percent higher than base prices and serve 18 percent less demand.

Finally, several researchers have noted that the optimal operational policies and/or deployment of charging stations will evolve over time as demand increases. Ghamami, Zockaie, and Nie (2016) found that ignoring delay induced by charging congestion led to

[16] An exchange rate of 1 GBP = 1.383 USD was used based on the average exchange rate in January 2018, when the survey data were collected (Pound Sterling Live, 2020b).

suboptimal configuration of charging infrastructure, with effects potentially more prominent as demand increased over time for PEVs. Wu and Sioshansi (2017) found challenges in planning placement of public fast-charging stations for EV due to uncertainty in future demand with initial expansion concentrated around the urban core. Dong, Ma, et al. (2019) found that as additional charging stations are built, the optimal locations start in central London and gradually expand out to suburban areas of London. Zhang, Schmöcker, et al. (2020) found when expanding one-way carsharing stations, demand growth is higher around transit hubs and public facilities than in residential areas.

6.3. Bringing it all Together—Operations insights and research directions for UAM

Based on prior research from the ground transportation literature, it is clear that system performance and profitability is driven by multiple factors, including the spatial and temporal distribution of demand, fleet size, pricing, and operational policies, and that there are strong couplings across these factors. As Repoux et al. (2019) eloquently stated, "The interaction between all parameters and settings in carsharing is complex and highly non-linear. It re-emphasizes the importance for any practitioner to identify the most effective elements (namely fleet size, station capacities, rental rules) as well as the ones specific to the system's environment and demand." From a UAM perspective, this highlights a critical need to jointly optimize interactions among fleet, demand, pricing, and dispatching policies. The fact that many use cases for UAM (such as commuting and trips to the airport) exhibit strong directional or one-way demand patterns will likely put further pressure on the profitability of UAM networks. One key difference between the UAM and EV/AV communities relates to the need for real-time optimization and dispatching algorithms. The penalty for running out of battery energy is much more severe in air applications than ground applications; simply stated, an eVTOL aircraft cannot run out of battery power for safety reasons. Consequently, approaches that synchronize takeoffs and landings at a vertiport in real time or under a rolling horizon framework will likely be much more critical (e.g., see Kleinbekman et al., 2020).

The experiences from the ground transportation literature with respect to the potential reduction in utilization caused by guaranteeing advance reservations is particularly relevant for the UAM community, given many customers may expect a high level of availability for their flights. Results from the ground transportation literature that find profitability can be significantly increased by rejecting demand requests is similarly problematic for UAM applications, given customer retention and wide-scale adoption will likely be strongly tied to reliability and availability of air taxis. Some strategies to increase reliability used in public transportation, such as a guaranteed ride home, may be valuable for UAM applications, e.g., if the UAM service cannot fly, the passengers would be given priority and guaranteed a ride via a ground transportation mode (like ride-hailing) for a similar or reduced price as UAM. Based on a survey of 2500 commuters in the U.S., Boddupalli et al. (2020) found that individuals were 1.8 times more likely to take an air taxi if a guaranteed ride home were provided.

All of these factors point to the trade-off between system performance and system cost—that is, we can over-design a system by ensuring extra aircraft in the fleet are available to serve peak periods and most customer demand requests, but serving all customer demand requests will likely be prohibitively costly. For example, the former CEO of NetJets, a private business jet company with fractional ownership, noted that in order to be profitable, he needed to cover 98 percent of all requested trips, and that serving 100 percent of all requested trips eliminated profits (Berger, 2001, as quoted in Mane and Crossley, 2007). Findings related to intelligent operational strategies and pricing policies that have been able to improve performance in ground transportation offer promising directions for the UAM community.

Optimizing over different time horizons will be important, particularly given the higher costs of establishing vertiports and charging stations for UAM applications than for EV applications. In addition, planning the deployment of vertiports and charging stations in ways that provide equitable access to citizens will be important if public funding is used for this infrastructure.

7. Conclusions

Research and interest in UAM have grown exponentially over the past five years, but significant questions remain with respect to whether UAM will become the next disruptive technology in urban transportation. As seen in the *meta*-analysis of UAM publications, much of the emphasis to date has been focused on fundamental questions. How do we design an eVTOL aircraft? How can we create more energy-dense batteries to support eVTOL missions? How do we design the airspace so that high-volume eVTOL operations can occur simultaneously with commercial and drone operations? Will there be demand for an eVTOL air taxi service and, if so, which business cases make the most sense—commuting, business shuttles to an airport, or other trip purposes? In contrast, research in EV/AV and sharing technologies for ground transportation is further along, and researchers and communities have experiences in designing and implementing EV fleets, some of which are part of ride-hailing or carsharing applications.

This paper conducted a *meta*-analysis of UAM, EV, and AV research published over the past five years (i.e., 2015 to 2020) to compare and contrast their research thrusts. By conducting an in-depth review of articles related to demand modeling, operations, and integration with existing infrastructure, we gleaned insights that can inform future UAM research directions.

From a demand perspective, if UAM follows trends seen in EV adoption, we would expect early adopters of UAM to more likely be male, have higher incomes, and have tech-savvy and pro-environmental attitudes; however, differences in adoption across countries is expected, with Asian countries having greater pro-technology inclinations. Importantly, the EV/AV literature has consistently found that individual preferences vary greatly and a polarization often occurs in which some individuals are enthusiastic about the new technology and willing to pay for automation and other technology features, while other individuals are negative about the new technology and state they will never adopt it. One of the reasons the EV community has focused so much research in the technology adoption area is because EV use and adoption rates have not been as high as researchers expected. The UAM community should pay particular attention to this phenomenon, as it suggests that modeling when individuals will adopt UAM will be important for demand estimations and that there is a research need to better understand how to help potential consumers feel more comfortable with the technology. Applying insights from the EV/AV area, this could include designing messages and information campaigns about the safety and limitations of UAM vehicles, and it may involve marketing campaigns that focus on recommendations from trusted family and friends. From a technology adoption perspective, it will be important to model how adoption rates for UAM evolve as AVs enter the market. Based on the theoretical and empirical results reported in the EV/AV literatures that find values of time decrease (and potentially significantly) for commute trips due to the fact individuals can be more productive in an AV compared to a conventional car, we expect that the introduction of AVs into the market will erode demand for commuter air taxis.

Our review of articles focused on infrastructure- and operations-related topics revealed strong couplings among multiple factors, including the spatial and temporal distribution of demand, fleet size, pricing, vertiport placement, vertiport topology, airspace restrictions, and operational policies. Further, many of the articles focused on one or more of these topics showed significant impacts on system performance. An important direction for the UAM research community is to develop high-fidelity simulation models that take these and potentially other factors into account. Given demand profiles today will not be reflective of demand profiles in the future (due to different adoption rates, spatial changes in populations, the introduction of competing technologies such as AVs), it will be important to conduct these simulations over different time periods to ensure results are robust over time.

It will be important for the UAM community to understand how UAM operations will impact the electric grid (and if the grid can even support UAM operations). Given insights from the EV literature that suggest the electric grid will already be stressed handling ground EV charging requirements, jointly considering EV and UAM power profiles may be important to ensure the electric grid can support both EV and UAM charging needs.

As with any analysis, there are limitations to be noted. The classification of keywords we associated with each article is arguably subjective; however, the classification enabled us to identify high-level trends across the fields. Given that researchers may be interested in identifying themes that we did not cover in this paper, we compiled a supplemental spreadsheet file, which is available online as a compendium to this paper. Our intention for this spreadsheet is to help facilitate the ability of other researchers to quickly identify keywords and/or to use the DOI links provided to more quickly identify to find papers relevant to their own research areas. Additionally, it is important to note that the publications in the AIAA database include both peer-reviewed journal publications as well as non–peer-reviewed conference proceedings.

It is important to note that our review was conducted pre-COVID-19 and that the future of transportation is at this time unclear. Some trends suggest that demand for UAM may actually increase. For example, as individuals move out of cities and into suburbs and work from home multiple days per week, they may be more interested in using an air taxi to commute to work on the days they need to travel to the office. Other trends suggest that demand for UAM may decrease. For example, if business travel decreases, the overall demand for business trips to commercial airports will decrease and fewer individuals would likely take an air taxi to the airport. It is also important to recognize that the momentum we have seen on UAM development may stall as the effects of COVID-19 continue to ripple through the industry. For example, on September 18, 2020, Boeing announced that it was suspending work at its NeXt innovation unit, which is the business division that was responsible for its UAM efforts (Gates, 2020).

In conclusion, it is our hope that both the air and ground transportation communities will find this article to be a valuable resource document, generate discussions as to potential research directions in UAM, and encourage interdisciplinary research in UAM. Never before have we attempted to fly so many air vehicles in our cities—and achieving this goal will not be a problem solved in isolation by the aerospace community.

CRediT authorship contribution statement

Laurie A. Garrow: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. **Brian J. German:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. **Caroline E. Leonard:** Conceptualization, Data curation, Formal analysis, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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