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An overview of current research and developments in urban air mobility – Setting the scene for UAM introduction

Anna Straubinger [a,*], Raoul Rothfeld [b], Michael Shamiyeh [a], Kai-Daniel Büchter [a], Jochen Kaiser [a], Kay Olaf Plötner [a]

[a] Bauhaus Luftfahrt e.V., Willy-Messerschmitt-Str. 1, 82024, Taufkirchen, Germany
[b] Technical University of Munich, Arcisstraße 21, 80333, Munich, Germany

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ABSTRACT

Recent technological advances provide the means for potentially realizing urban air mobility (UAM) as a passenger transport mode for intra- and inter-urban transport. However, questions regarding regulations, infrastructure requirements, and economic constraints remain to be answered. Therefore, this review aims at giving an overview on different research areas in the emerging topic of UAM. To this end, findings from several fields within the UAM research community were gathered and are presented here to provide a landscape of relevant questions surrounding the implementation of UAM. This overview considers vehicle-related aspects, such as aircraft requirements and aircraft classification for intra- and inter-city passenger transport, and discusses potential hurdles to their introduction. The exploration of challenges includes questions on certification and policy, as well as challenges in the area of traffic management and ground infrastructure requirements. Besides that, literature on operational concepts, possible market structures and the interaction with existing transport systems will be reviewed. The discussion of hurdles will conclude with a summary of current literature on public acceptance of UAM. An overview of methods for modelling and simulation of UAM will wrap up the prior discussion and provide insights on first modelling results.

1. Introduction

Urban air mobility (UAM) is an emerging topic that is currently gaining a lot of attention from both industry and research. In this overview, we consider inter- and intra-city air passenger transport services, with a special focus on services enabled by novel aircraft types with the capability for vertical take-off and landing (VTOL). The operational concept which utilizes these VTOL-enabling aircraft is also often referred to as flying taxis or flying autonomous vehicles. Following Gartner's Hype Cycle (Panetta, 2019) flying autonomous vehicles are still in the so-called innovation trigger phase, but are expected to reach the peak of inflated expectations soon. The plateau of productivity that follows the trough of disillusionment and slope of enlightenment is said to be reached within the next five to ten years.

This article aims at giving an overview on the different relevant fields in UAM research. With UAM being a rather novel and hyped topic, we want to give the reader insights into the entire field and guide her along different lines of argumentation. So far, no exhaustive overview of the several fields within UAM has been provided, and this paper aims at closing this gap. Fig. 1 provides a first overview over the various fields of research.

Understanding the historical development of urban air mobility and its predecessors – especially helicopter services – helps to understand potential developments and required next steps to enable a transformation from helicopter services to UAM. Thus, a brief overview will be given in the following.

The idea of flying vehicles within urban areas started in the 1940s, with the advent of helicopters which provided vertical take-off and landing (VTOL) capability. Low technology maturation led to several accidents, which - together with high noise levels and high operating costs - forced most of the operators in the US and Europe to cease their operations in late 1960s to mid-1970s. Today, helicopter-based passenger transportation exists as a small niche on a charter basis in various cities, e.g. New York, Sao Paulo, Mexico City or Monaco. Besides passenger transport, UAM covers a broad variety of operational concepts like medical emergency missions, logistics, or surveillance as a non-

* Corresponding author.
E-mail address: anna.straubinger@bauhaus-luftfahrt.net (A. Straubinger).

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transport service example. While this paper focusses on passenger transport applications, the operational concepts mentioned above might provide market entry opportunities for manufacturers and service providers to gain higher public acceptance.

Progress in power electronics, communications, sensors and data analytics, combined with large cost reductions due to the availability of high performing commercial of the shelf components, have opened up completely new opportunities especially for small unmanned aerial vehicles (Shamiyeh et al., 2017). Currently, various stakeholders with backgrounds in aeronautics, technology, ground transportation, as well as start-ups financed by equity investments, are active in the field (Shamiyeh et al., 2018). As the development of new mobility technologies is being spurred by the increasing strain of traffic congestion in large cities, it is not surprising that more and more start-ups and established companies from the aviation and automotive industries are active in the field of UAM, with the goal of providing competitive solutions to an emerging market.

Technology is often discussed as one of the main reasons for the hype surrounding UAM. During the last decade, significant technological progress, especially regarding distributed electric propulsion and battery storage (Kuhn et al., 2011; Rezende et al., 2018), have led to a large number of flying vehicle concepts and demonstrators for personal air transport. An overview of research discussing vehicle concepts and aircraft requirements will be covered in chapter two.

It is essential to have appropriate regulation in place to enable safe UAM operation. In this context, this overview focusses on aircraft certification, discussing current approaches pursued by, e.g., EASA, as well as possible policies and market regulation. Especially in view of market regulation aspects, chapter three tries to find analogies to existing urban transport modes in order to, wherever possible, draw from this knowledge.

As most transport systems, UAM also requires infrastructure. This infrastructure does not only encompass physical ground infrastructure for the vehicles itself (vertiports), but requires the means for traffic management based on digital technology and telecommunications. Chapter four thus provides a discussion of ground infrastructure, mainly focusing on vertiport location. Besides that, a brief introduction into the field of UAM traffic management (UTM) will be given, also touching on the need for appropriate digital infrastructure. As UTM is a topic that currently receives a lot of attention, this overview is far from giving a holistic review but rather gives a brief introduction. The interested reader is invited to gain additional information from the broad range of research projects currently founded, e.g. under the umbrella of U-Space (SESAR Joint Undertaking) in Europe.

A broad range of topics related to UAM operation is discussed within chapter five. One section refers to concepts of operation, giving insight into various application cases and target segments identified by research. Besides providing an overview of different market actors, the level of integration over different market levels is discussed and insight into required partnerships is provided. The chapter closes by discussing the need for an efficient integration of UAM into existing transportation systems, based on considerations of sustainability and allocation of resources.

Industry representatives (Yedavalli and Mooberry, 2019) have identified public acceptance and user adoption as main hurdles for successful UAM introduction. Chapter six gives insight into relevant research in this field and draws analogies to other autonomous modes of transport.

The last field of research discussed within this paper is UAM transport modelling and simulation. First attempts have been made to model urban aerial transport in different levels of granularity. Chapter seven introduces the reader into this field and guides her along different publications.

This review closes by highlighting fields not yet sufficiently covered by research and derives key contributions.

2. Vehicle design and technological requirements

Design and development of suitable VTOL aircraft is an important element in the successful implementation of an UAM transport system. At the same time, it appears to be a promising and lucrative opportunity for prospective manufacturers and the aviation industry in general. Various market forecasts predict high production volumes, which would be exceptional for the aerospace industry. A market study commissioned by NASA predicts a near-term demand in the U.S. of 55,000 daily trips for air taxis and airport shuttles, served by 4100 aircraft. Here, restrictions due to weather, time of day, capacity restrictions by infrastructure and the willingness to pay of potential customers were taken into account. In less constrained scenarios, several hundreds of thousands of aircraft would serve a predicted demand of up to eleven million daily trips across the U.S. (Booz-Allen and Hamilton Inc., 2018). Considering the number of units sold, this market may therefore be

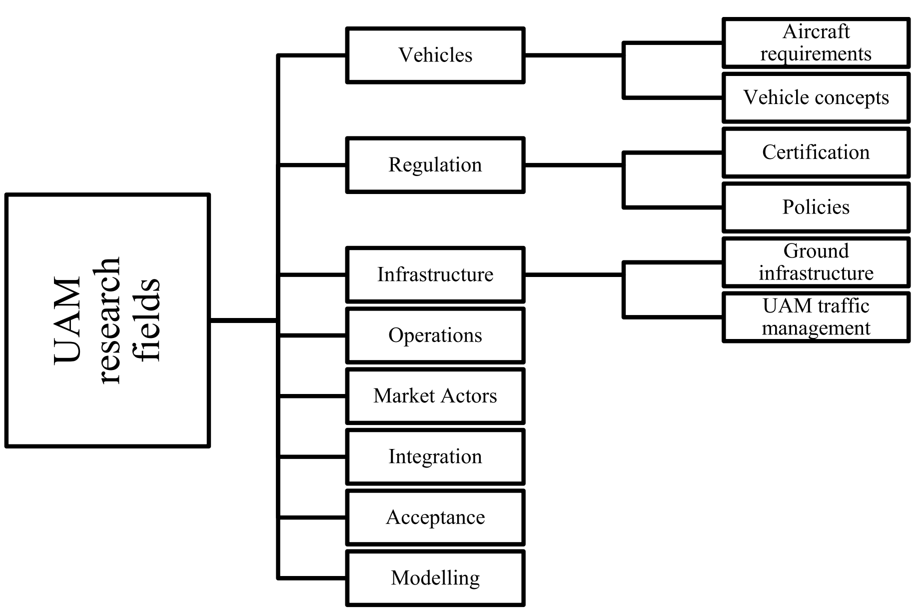

Fig. 1. UAM research fields.

many times larger than that for commercially operated helicopters today. To serve this market, new aircraft have to be developed to meet new requirements regarding performance, operation and production.

2.1. Towards aircraft requirements for UAM

The requirements and boundary conditions on aircraft design for UAM are manifold and in some cases novel, regarding their impact in comparison to classical aircraft design. The diagram depicted in Fig. 2 shows the main design drivers affecting the choice of specific aircraft type and the subsequent detailed design. Although the idea of UAM has been around for some time and is becoming more and more concrete in some respects, the views on detailed aircraft requirements differ considerably. The latter already applies to the top-level aircraft requirements (TLARs) of design range, seat capacity and cruise speed.

Probably the most comprehensive compilation of consistent soft and hard requirements for air taxis is sketched by the transport service provider UBER, with the Elevate Whitepaper (Holden and Goel, 2016) and a follow-up document containing further technical requirements (UBER Elevate). The documents are intended to provide a framework for prospective aircraft manufacturers to meet the requirements of a planned on-demand air-taxi service. UBER stipulates a design mission range of about 95 km and a reserve range of almost 10 km at a minimum cruise speed of 240 km/h. Cruise altitude is set to 300 m above ground level (AGL). A required payload of 500 kg is specified for four passengers.

NASA suggests a two-leg mission without intermediate recharging for VTOL UAM-vehicles (Patterson et al., 2018). Both flights are of 70-km distance at a cruise altitude of 1200 m AGL. The cruise speed varies between 150 km/h and 200 km/h for six vehicle concepts, each designed for carrying 545 kg or up to six passengers. A 20-minute reserve at cruise power must be available.

Both examples for design missions address the same UAM-market, considering regions within the U.S., but differ significantly with regard to the top-level requirements on range, cruise speed and seat capacity. The composition of the mission(s) is of crucial importance in this regard, since it has a major impact on the design trade-off made concerning hover/vertical flight efficiency and cruise efficiency. The relative share of take-off, climb and landing maneuvers in the overall mission shifts the optimum design point and may lead to an entirely different, optimal aircraft type.

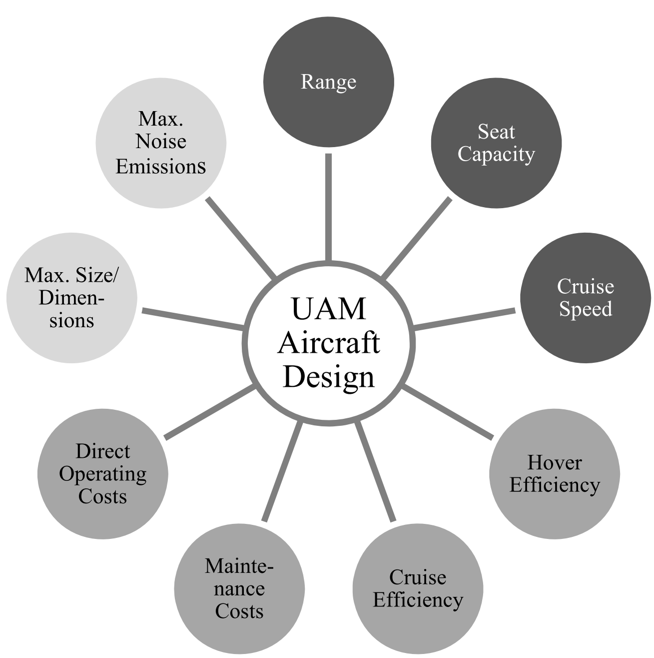

Fig. 2. Requirements (dark grey), external boundary conditions (light grey) and further important design drivers (grey) affecting the aircraft design for UAM significantly.

Furthermore, the demand for low noise emissions will also have a significant impact on success or failure of an UAM vehicle concept, since public acceptance strongly depends on it. Studies on public perception of UAM indicate that not only the loudness itself but also the type of noise is a major concern of the persons interviewed (Yedavalli and Mooberry, 2019). To ensure community acceptance, UAM noise signatures should, as far as possible, blend into the existing urban background soundscape. Expressed in numbers, this corresponds to noise level 15 dB below that of a conventional light helicopter (UBER Elevate). This is a major challenge that requires early consideration in the design process. A key design parameter is the blade tip speed, which needs to be reduced as much as possible. Potential approaches are the distribution of thrust production to multiple rotors, minimizing take-off weight and/or increasing the rotor area. The latter contradicts the demand for air taxis to be as compact as possible to cope with the limited space in the cities. Considering the limited available space, this means that aircraft size could become the restricting factor for throughput of UAM stations in urban areas.

2.2. UAM vehicle concepts and classification

Driven by the predicted potential of distributed electric propulsion (DEP) and recent advancements in required electric technologies, numerous aircraft design projects for UAM have been initiated. Typically, autonomous vehicles are designed for one to five passengers. The large design space opened up by DEP in combination with strongly diverging, underlying operational requirements lead to fundamentally different aircraft types. A two-step classification scheme depicted in Fig. 3 clusters the concepts according to lift production during cruise and the mechanism enabling VTOL. The aim is to obtain aircraft clusters with comparable performance data and characteristics.

Aircraft configurations that generate lift exclusively with rotating wings during cruise flight (left branch) are typically limited in cruise speed, are typically less efficient during cruise flight and therefore have range disadvantages compared to other concepts. However, they naturally have very good hover and VTOL characteristics. The rotary-wing group includes all kinds of multi-copter configurations (exemplarily illustrated in Fig. 4a) as well as conventional helicopters. To counteract the tendency towards a very large footprint due to large rotor areas, the rotors are often placed in a stacked configuration, at the cost of aerodynamic efficiency. Compact dimensions are also provided by the so-called Lift-Fan concepts (Fig. 4b). Although significantly less efficient than rotors under hover conditions, they allow configurations close to the size of an automobile. While the encased fans offer advantages in terms of safety during ground handling, achieving sufficiently low noise levels is probably an even greater challenge. Due to their small cross-section the fans produce high downwash velocities to provide sufficient thrust. This is typically associated with considerable noise emissions.

The possibilities of DEP seem to enable the implementation of aircraft concepts capable of, both, VTOL and a fixed-wing based cruise flight, while keeping system complexity and weight at an acceptable level. Concepts of this group (right branch, Fig. 3) are significantly more efficient and faster during cruise flight compared to rotary-wing cruise configurations. While this also increases the attainable ranges, the characteristics in hovering flight and during VTOL are subject to compromise. Integration aspects and the intention to avoid reducing cruise efficiency too much limit the implementation of large rotor areas required for efficient hovering flight.

Lift + cruise aircraft (Fig. 4c) have two separate power trains for VTOL and cruise. All thrust generating components are mounted such that they produce thrust in the required direction, so that no tilting mechanisms are needed. This reduces system complexity and allows for

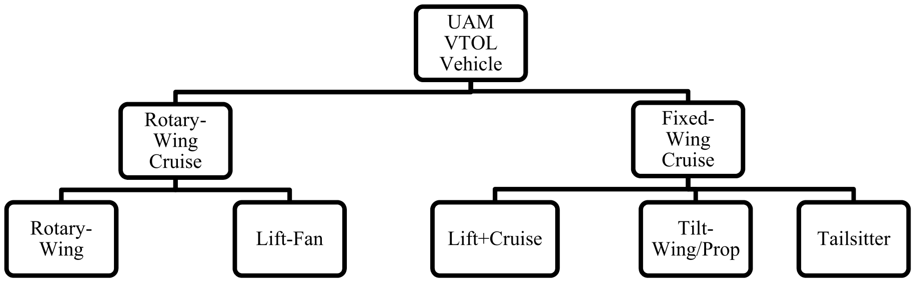

Fig. 3. A two-step classification scheme for UAM VTOL aircraft (Shamiyeh et al., 2017).

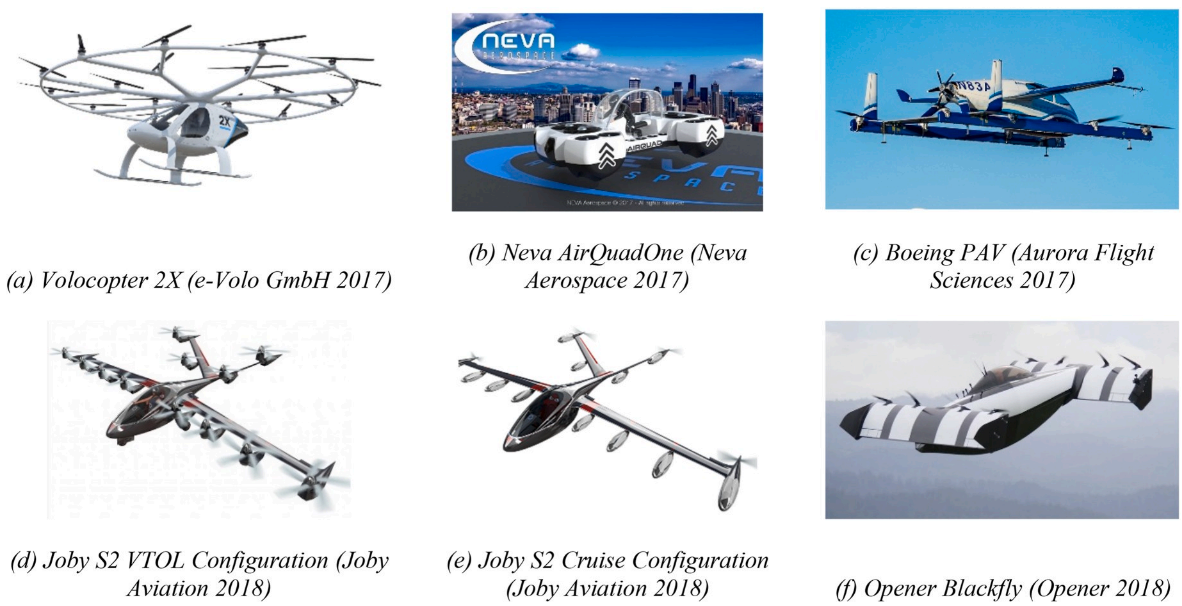

Fig. 4. Examples of representatives from all UAM VTOL aircraft classes.

an optimum design of all rotors/propellers. Tilt-wing/tilt-prop aircraft (Fig. 4d and e) and tail-sitters (Fig. 4f) use the same propulsion system during all flight phases, which requires a compromise in the design of the propulsion system. In contrast, by optimization of dedicated propellers for cruise conditions and by switching off VTOL propellers during cruise, efficiency losses can be reduced. Shrouding or folding of unneeded propulsors enables aerodynamically clean and thus very efficient cruise flight configurations. The necessary tilting mechanisms mean additional weight and increased system complexity. Tail-sitter configurations enable VTOL in combination with efficient fixed-wing cruise by performing a ninety-degree transition of the full vehicle. At take-off, the aircraft stands in an upright position, the front aligned to the sky. After lift-off, the configuration gradually tilts toward horizontal flight, until attitude for cruise flight is reached. While this doesn't require tilting mechanisms, passenger comfort is a critical aspect of tail-sitters. The complete tilt-over requires reasonable solutions to ensure convenience and well-being of the passengers (Shamiyeh et al., 2017).

To enable a holistic assessment of UAM vehicle types in general and detailed concepts in particular, their impact within the whole urban air transportation system has to be understood. To investigate the interaction between detailed characteristics of the aircraft and the transport system, the simulation of a complete city transportation system, as described in chapter VII, is required. First investigations regarding greenhouse gas emissions indicate that under certain boundary conditions, VTOL aircraft for three or more passengers produce fewer emissions than combustion engine powered automobiles and even battery-powered cars. Considering a 100-km mission and assuming an average occupancy of 1.54 passengers for ground based vehicles, the emissions per passenger kilometer of a fully loaded VTOL aircraft are stated to be 52% lower than the combustion engine powered car (1.54 seat-load factor), and 6% lower than the battery-powered car (1.54 seat-load factor) with additional benefits in terms of travel time (Kasliwal et al., 2019). These numbers only hold for the stated parameters, where occupancy of cars and VTOL vehicles strongly differ. However, if central requirements such as low noise emissions or significantly reduced operating costs compared to helicopters cannot be met, this will hamper the outlook on success of UAM. The newly developed aircraft will then most probably remain in niche markets such as those currently served by conventional helicopters.

3. Regulatory aspects

One of the main challenges for successful UAM introduction is appropriate regulation, which includes defined standards for certification but also policies regulating the UAM market itself. Both will be discussed in the following.

3.1. Certification

A major hurdle for commercial flight operations in urban areas will be the safety requirements and certification criteria. Corresponding regulations for certification are currently being considered in particular by the European Aviation Safety Agency (EASA) and the US Federal Aviation Administration (FAA). The first proposal of EASA in the Special Condition Vertical Take-Off and Landing Aircraft (SC-VTOL-01) from July 2019 (SC-VTOL-01/02.07.2019), based on the CS-23 construction and certification regulations, refers to safety standards comparable to those applicable to smaller commercial aircraft. The number of persons on board is limited to five and the maximum take-off mass is set to 2000 kg. In addition, for use over densely populated areas or in commercial passenger transportation, the design must ensure that the aircraft can continue to fly and land safely even after a critical malfunction in the propulsion system. This increases the requirements for the overall technical design and contradicts, for example, parachutes as risk minimization within the scope of certification. This classification of the "Enhanced VTOL" category in terms of safety requirements is comparable to that of helicopters used for commercial flight operations.

Since April 2019, there is a separate department within EASA for eVTOL (electric VTOL) and Special Concepts. The revised Special Condition for eVTOL has been published in July 2019 (Special Condition, 2019). The corresponding AMC (Acceptable Means of Compliance) and additional Guidance Material will follow in September of the same year. However, the timeframe until which European approval regulations for autonomous and pilotless UAMs are available is still open and may probably take several years. It is expected that there will be a step-by-step procedure in which pilots will first have to be on board for passenger transport before any kind of autonomous flight operation can be introduced into daily use. For the certification authorities, the difference to traditional helicopters and aircraft lies primarily in the innovative control systems (e.g. position control via engine speed) and the planned degree of autonomy in the aircraft.

EASA is also dealing with the regulations for airspace and plans to publish a first step for a future structure in mid-2020. This will define the airspace types and modalities as well as access to airspace. The airspace types and modalities should be based on the planned regulations for unmanned aerial vehicles (drones) and access to airspace should be based on the U-Space concept (SESAR Joint Undertaking, 2018). U-space provides an enabling framework to support routine unmanned aerial system (UAS)/UAM operations, as well as an interface to manned aviation, air traffic management (ATM) and air navigation service (ANS) providers and authorities. U-space is therefore not to be considered as a defined volume of airspace, which is segregated and designated for the sole use of drones. U-space shall be capable of ensuring the smooth operation of unmanned air vehicles in different operating environments and in all types of airspace, in particular to very low-level airspace below 150 m.

In addition to the certification of aircraft, there are other aspects, which still need to be organised in accordance with the relevant regulations. These points are mostly in the hands of national authorities and are not yet being considered intensively:

- Flight crew licencing and training: requirements for pilots' and later operators' training, licensing and task performance have to be defined.
- Landing areas: Establishment and operation of UAM pads as well as the use of infrastructure on existing airfields close to cities that are not necessarily set up or licensed for commercial flight operations today.
- Maintenance regulations for the operation and the related personnel need to be set up.
- Requirements on operating organisations and their certification - most probably based on the regulations for today's commercial air transport operators-have to be defined.
- ATM and ANS especially for low altitudes anticipated for urban air mobility needs to be established. Additional ATM solutions allowing for a high level of autonomy have to found (keyword UTM).
- Databases for obstacles and terrain are needed in high quality. Updates on obstacles (e.g. a temporary construction crane) need to be submitted to UAM vehicles in that area immediately.
- Security regulations for passengers and personnel have to be set up.

3.2. Policies and market regulation

Like all modes of transport, UAM will create externalities. Besides noise, air pollution and visual impact, congestion and harm to third parties will occur. In addition to that, induced demand could arise and changes in land-use, especially urban sprawl might be an issue if a sufficiently large share of transport demand shifts to UAM. Thus, besides strict regulation on the vehicle and surrounding technologies, the UAM market in general might also face regulatory interventions aiming to minimize externalities.

Looking into other modes of transport, one can see that the transport system as a whole often faces severe regulation. Especially modes with strong infrastructure dependencies, and therefore a high risk of natural monopolies, face strict policies. This, for example, is the case in the German rail sector where, operation and infrastructure are clearly separated and the infrastructure provider is strongly regulated in pricing (Bundesnetzagentur, 2008), even though deregulation tendencies are strong since the 1990s (Cantos and Maudos, 2001). Local public transport is also regulated in Germany. It is mostly unprofitable and the local government initiates competition for the market by calling for tender (Weiβ, 2003). The taxi market in contrast faces quality and quantity regulation by concessions, nowadays mainly justified through information asymmetries in the market (Baake & Schlippenbach). Private car usage mainly stays unconstrained, even though approaches like peak-load pricing (Bailey, 1973) or congestion pricing (Palma and Lindsey, 2004) are being discussed. Transferring these findings from other modes of transport shows that UAM might as well face market regulatory interventions. Yet, it is hard to predict regulatory responses to the introduction of a novel mode of transport. Often regulation is not yet in place, when new services enter the market, as it was the case for UBER or Lyft. While some countries did not introduce policies to regulate the novel services, countries like Germany or Spain massively regulated them (Rabadjieva, 2016).

Three main points justify market regulating policies: natural monopolies, externalities and information asymmetry (Schulz, 2003). All three could be relevant for the UAM market. Thus, price, quality or quantity regulation (Sheshinski, 1976), as we see it for other modes of transport, might be introduced for UAM as well.

4. Infrastructure requirements

As indicated by Straubinger and Rothfeld (2018), a need for take-off and landing infrastructure that also enables intermodal connectivity is related to UAM introduction. Yet, UAM does not only require ground infrastructure but also relies on ATM and appropriate communication infrastructure enabling UTM.

4.1. Ground infrastructure

With regard to the architectures and designs of most UAM vehicles currently developed, dedicated VTOL infrastructure is assumed to be required for potential UAM operation. So-called vertiports, or vertistops (Fadhil, 2018), represent the required ground infrastructure for take-off and landing operations of UAM vehicles. Yet, there is only little research on UAM ground infrastructure, despite its relevance for the highest-risk flight phases, namely take-off and landing, and in terms of vehicle throughput and accessibility.

Vascik and Hansman (2017) outline various options for UAM ground infrastructure placement, as summarized by Fadhil these can include (2018): (1) rooftops, (2) barges over water, (3) inside highway cloverleafs, and (4) on top of existing ground-transport infrastructure. Further, Vascik and Hansman (2019) discuss various layout options for vertiports, while using existing heliports as their research foundation, such as linear, satellite, and pier topologies. So far, while research is being conducted on the potential space requirements of UAM ground infrastructure, the authors (Fadhil, 2018; Vascik and Hansman, 2019) orientate themselves on existing infrastructure regulations for helicopters and re-size the derived minimum space requirements based on the various wingspans, lengths, and heights of different UAM designs that are in development. Whether or not eVTOL vehicles, using exclusively electrical propulsion and energy storage, may be considered for deviations from the current safety regulations has yet to be evaluated.

In contrast to ground-based transportation, UAM is believed to require little to no en-route infrastructure. Still, space requirements for VTOL infrastructure may become a highly limiting factor in terms of vehicle throughput. In one of the few analyses of potential vertiport capacity, Vascik and Hansman (2019) outline the factors that determine the number of UAM vehicle departures and landings, such as the number of gates and vehicle taxi times. They conclude that there might be a balance between take-off and landing pads and passenger gates at vertiports that "will maximize throughput for a given set of operational parameters". This would result in vertistops with multiple VTOL pads and gates with substantial space requirement and rule out many UAM station placement options, such as rooftops. Further, Vascik and Hansman (2019) propose providing staging stands at vertiports to increase station throughput, yet also requiring additional space. Lastly, they underline the importance of VTOL pads that allow independent take-off and landing operations for high station throughput.

Regarding UAM station placement, no empirical placement method has yet been presented in current research. While some studies, e.g. (Vascik and Hansman, 2017), propose deriving suitable positions from a supply-side view, subtracting closed airspace from the available station placement options, other studies try to combine demand- and supply-side factors (Fadhil, 2018) in trying to identify the most suitable positions for UAM stations. Regarded factors include population density, job density, median income, existing noise, and ground-based transport accessibility. While Fadhil (2018) presents a methodical approach for station placement, using factors weighted by experts' judgements, the results clearly indicate a lack of consensus among UAM researchers and experts in terms of the importance of the various factors. One factor, though, was ranked the highest by Fadhil's interviewees: access/closeness to major transport hubs, such as airports or major train stations.

Rath and Chow (2019) assess the location of vertiports for UAM serving mainly as an access mode for airports. In this contribution, vertiport placement is optimized based on airport traveler data, adapting methods used for hub location problems. Taking into account ground transportation to the airport as well as to the vertiport itself, they do not account for other possible influencing factors.

While the importance of UAM station accessibility, especially with existing ground-based transportation modes, has already been identified, there is a lack of analytical research on mode choice regarding UAM station access and egress – the so-called first or last mile. Thus, it is still unclear which requirements and facilities UAM stations must provide in terms of, e.g., parking space or connection times to public transport. The main advantage of UAM over conventional ground-based transportation is the promise of shorter total travel times. Thus, short access and egress legs as well as short process times within potential UAM stations might become crucial factors in the overall attractiveness of such a new mode.

4.2. UAM traffic management

The current drone market shows strong growth potentials, especially considering larger and more capable flight vehicles and prospective beyond visual line of sight (BVLOS) operations, but existing ATM systems are not well suited to address the expected growth in air vehicle densities. As of 2019, operations of remotely piloted aircraft systems in conventional airspace typically require airspace segregation. Efforts to establish UTM systems aim to change this, and ultimately shall ensure "operation of drones in all operating environments" according to the European U-Space framework (SESAR Joint Undertaking, 2018). FAA describes how a "distributed network of highly automated systems via application programming interfaces, and not between pilots and air traffic controllers via voice" enables the management of BVLOS operations (Federal Aviation Administration, 2019). This approach is described as separate from, but complementary to, ATM. In both frameworks, however, the focus is currently on very low level flight operations of unmanned aircraft below the traditional airspaces. With regard to UAM, Kleinbekman et al. (2018) were among of the first to discuss efficient trajectories. Using a mixed-integer linear program, they even created a basis for determining separation requirements in UTM. Their work focusses especially on the airspace surrounding vertiports and gives first insight into trip scheduling for determined arrival times.

Urban air mobility requires full airspace integration, and represents high-risk operation according to the FAA (2019) especially as passenger operations are implied. Mueller et al. (2017) have put forward an assessment framework discussing possible starting points to enable on-demand mobility in an evolutionary approach, and defined the following airspace integration principles:

1. Does not require additional ATC infrastructure
2. Does not impose additional workload on ATC
3. Does not restrict operations of traditional airspace users
4. Will meet appropriate safety thresholds and requirements
5. Will prioritize operational scalability
6. Will allow flexibility where possible and structure where necessary

According to the analysis in (Mueller et al., 2017), starting from increasingly automated, VFR-type operations does not limit vehicle density explicitly by ATC-imposed capacity constraints ("well clear" requirement), but would require adequate sense-and-avoid technology to mimic or surpass abilities of qualified human pilots. The aircraft would require a method to determine safe separation distance by itself in this case. To this end, Geister et al. (2017) suggested that each air vehicle could be assigned an aircraft safety bound that takes up a volume of airspace, taking into account for example maneuverability, speed, and situational awareness abilities of individual air vehicles. Alternatively, starting airspace integration efforts from IFR-type operation offers technologies and rules that are well suited for high grades of automation. However, growth potentials are restricted considering strict separation minima, and potentials of evolutionary upscaling of existing systems (e.g. ADS-B), that were designed for traditional aircraft, are limited. Existing UTM-frameworks as a starting point for UAM operations is a third option. Either of the mentioned approaches by itself would restrict operations to certain airspace classes. Therefore, the authors argue that a practical way of moving forward considers the gradual increase in air traffic density and technological evolution in a successive approach to integration, starting from procedures, over increasing levels of autonomy, toward a fully cooperative ATM system.

Regarding drones as cyber-physical systems (CPS) that ultimately integrate sensing ability, on-board computing and connectivity to other drones, ground networks and infrastructure, the prospect for future drone operation is that of a CPS of systems of fully networked, highly automated, connected air vehicles. Future airspace scenarios will thus benefit from the convergence of technologies, integrating data from on-board and ground sensors, using on- and off-board intelligence for safe navigation, robust telecommunications for operations and cooperative flight routing, and real-time database-representation of airspace information for ultimate situational awareness. Several technological challenges remain and include the development of reliable and robust technologies for sense-and-avoid and flight control, contingency management procedures, cooperative route planning, weather consideration, high-precision localization systems for low-level, automated flight (Krishnakumar et al., 2017) as well as development of required infrastructure. As for providing telecommunications, cellular networks are feasible candidates due to ubiquitous availability and high capacity especially in urban areas. Ensuring cyber-security and considering the quality-of-service limitations of commercial networks are related challenges. The 5G standard introduces services such as ultra-low latency reliable communications and vehicle-to-X communication, which are capabilities that provide interesting building blocks for cellular-based drone operation (5G Americas, 2018; Ullah et al., 2019). Finally, regulation and implementation need to especially consider the co-existence of different airspace users with differing capabilities and scalable infrastructure architectures supporting integration of UAM with ATM.

5. Operational concepts, market structure and integration to the existing transport system

The selection of an operational concept and business model approach has already been identified as key driver for a successful UAM introduction by a number of researchers (Hansman and Vascik, 2016; Holden and Goel, 2016; Kopardekar, 2017; Liu et al., 2017; Nneji et al., 2017; Schuchardt et al., 2015; Vascik, 2017), as this determines the service characteristics. Moore (2010) identified the following service characteristics as essential to foster attractiveness for users: ease of use (autonomy/little pilot training required), safe/reliable, community friendly (minimize negative impact on other travelers), environmentally friendly, affordable, door-to-door, on-demand mobility. Possible operational concepts, market structures, business models and options for an efficient integration between the existing transport system and UAM will be discussed in the following.

5.1. Operational concepts

UAM includes intra-as well as inter-city concepts. Hansman and Vascik (2016) identified the relevant system characteristics to enable intra- and inter-city service offers. For the intra-city case, they see vertical take-off and landing capabilities as essential, whereas for inter-city applications, short take-off and landing (STOL) capabilities are seen as sufficient. Besides that, the need for less noise emitting propulsion and autonomy are higher for the intra-city case.

While Schuchardt et al. (2015) see commuting as the main trip purpose, Hansman and Vascik (2016) name non-commute, point-to-point and non-transportation missions as application scenarios, besides daily or weekly commute trips. Nneji et al. (2017) differentiate the different possible operational concepts by the way they are operated (private, personal or commercial) and by whether the service is on-demand or scheduled.

5.2. Market actors

The UAM market consists of different sub-markets and market actors. Nneji et al. (2017) as well as Hansman and Vascik (2016) already identify two, namely the service operator and the vehicle owner when discussing different possible ownership structures. Yet, there are more UAM sub-markets. In the following each of them will be discussed, giving insight also on possible market power of each actor and potential collaboration and vertical integration between different market levels, where the latter is mostly speculation.

- Platform provider: The platform provider directly interacts with the end customer and offers the UAM service to the customer. The platform provider can either be a company that organizes services of different service providers and then sells them, or it can be a company that only offers a digital platform for service offers of one or several service providers. Due to network effects, a smaller number of platform providers appear to be more efficient but might lead to strong market power of one or a few players, which again might lead to inefficiencies.
- Service provider: The service provider is the company providing the UAM transport service. This is done by scheduling trips, managing the vehicle fleet (including charging/fueling, scheduling maintenance, repair and overhaul (MRO), cleaning). Depending on the business model, this company can either directly interact with the end customer or offer its transport service via an external platform. In cases with direct customer contact, the service provider can also operate the platform either encompassing other service providers' offers, or only its own transport services. Looking into markets of other urban transportation modes, we see a large number of service providers on a global level, while locally certain providers might have market power.
- Vehicle owner: The company owning the UAM vehicles can either be the company also providing the service, or a separate leasing company whose sole business it is to lease UAM vehicle to service operators. This could either happen via long-term leasing contract or via short-term and flexible contracts. The number of companies active in this field is expected to pretty much depend on the overall and local UAM market size.
- Vehicle manufacturer: Currently, the number of companies developing UAM vehicles is pretty large compared to, e.g., the number of car manufacturers, train manufacturers or aircraft manufacturers. This is expected to decrease over time to converge towards an oligopoly. Vehicle manufacturers are discussing being active in offering services themselves.
- Maintenance, repair and overhaul (MRO) company: Provision of MRO service can either be offered by independent companies, by the vehicle manufacturer, by the vehicle owner or the service provider. As aerial transport faces high safety and security standards the MRO company will face high certification criteria and has to ensure high quality levels.
- Insurance company: Another market relevant in the scope of UAM is the market for insurances. Depending on the level of autonomy, liability for aircraft failure will either be with the service provider, the vehicle owner or the vehicle manufacturer. Yet, insurances are not only required in case of aircraft failure but might also need to cover losses from vehicles being grounded due to weather, or losses arising from inappropriate passenger behavior.
- Ground infrastructure provider: Provision and operation of ground infrastructure is essential for successful UAM introduction. Ground infrastructure could either be supplied by public authorities, public private partnerships or private companies. Due to the high investment costs a natural monopoly might arise. For other modes of transport this issue is often solved by either putting infrastructure under a public body's responsibility, or by strongly regulating the infrastructure provider. It is important to enable equal access to infrastructure to all service providers. This could especially be at risk in case of service providers integrating infrastructure provision, or in the case of real estate developers, limiting passenger access to the building.
- Communication infrastructure provider: Communication infrastructure is a necessary prerequisite for UAM, especially when expecting high levels of autonomy. Similar to communication infrastructure provision in general, we expect the market to be dominated by one or a few suppliers due to the high fix costs. Players are likely to be current telecommunication providers.
- UTM provider: The discussion on UTM provision is currently still at the very beginning. Depending on the level of autonomy and the general system set-up (central organization by a UTM provider versus decentral organization on a vehicle level, where every vehicle ensures de-confliction). One way or the other, a general body is expected to oversee and maybe organize air travel. Therefore, market power of one supplier can be expected in case the service is not offered by a public entity.

Currently, little research is taking place in this field. A lot of research is still needed to identify who is going to be active in which fields and how this translates into different competition levels on the different market levels, and into suitable business models.

5.3. Integration to existing transport system

Yet, as energy consumption of UAM is assumed to be significantly higher than for ground transportation (Condon and Dow, 2009) and vertiports are assumed to be the capacity restricting component (Ploetner et al., 2019), UAM is not expected to be a mass transport service. Thus, an efficient integration with existing modes of transport especially public transport (PT) is essential. When considering the funding structure of most transport offers, policy makers' aim should be to enable UAM systems that complete and not compete with PT. Cannibalizing efficient mass transport systems is likely to decrease transport efficiency within cities and is not in line with general sustainability strategies.

A similar discussion is currently taking place in the field of autonomous ground vehicles, where negative effects on other modes of transport - especially PT - are likely. Scholars (Huwer, 2004; Kamargianni et al., 2016; Kamargianni and Matyas, 2017; Li and Voege, 2017) have identified physical, fare, service and platform integration as well as data exchange as necessary prerequisites for a successful integration of autonomous ground vehicles and PT. Besides that, empirics show that an efficient integration of various transport modes promotes usage of each of the modes as Akin (2006) and Parkhurst (1995) show.

A possible option for successful integration could be the introduction of feeder concepts in which people from rural regions are transported to the PT service area of the city. This could especially be beneficial in geographically unique regions such as islands, mountains or regions separated by lakes and rivers, where ground connectivity is limited. Another option is to offer service on routes where PT either is not available or inconvenient. The overall level of integration can vary from integrated ticketing to only enabling physical transfer from one mode to the other.

6. Potential users and public acceptance

Public acceptance is seen as one of the prevailing factors in discussions regarding UAM introduction. A market study on public acceptance (Yedavalli and Mooberry, 2019) showed that the public's top five concerns are safety of the people on the ground, type and level of noise emitted by the vehicles, time of day during which the vehicles travel and the altitude at which they fly. Thus, the lower the impact on the non-users is, the higher is their willingness to accept UAM.

Yet, aiming at a successful market introduction it is also essential to understand the reservations not only of the public but also of potential users (Vascik, 2017). As the field of UAM is rather new, there until now is little research on acceptance drivers for UAM. While some factors like the perceived reliability of automation (Nees, 2016), the perceived vehicle's safety (Silvia Gaggi, 2017) or affinity towards automation (Clements and Kockelman, 2017) can be transferred from existing literature on autonomous vehicles (AV), others are very specific to the service offer and thus are hard to transfer from AV literature.

While the civil usage of drones has already been studied in terms of acceptance, the assessment was until now limited to certain fields, e.g. noise (Hansman and Vascik, 2016) or privacy issues (Lidynia et al., 2017) and did not only consider passenger services but also cargo delivery. Al Haddad et al. (2020) applied a broader approach and studied the impact of acceptance drivers of other modes of transport on the stated time of UAM adoption in a survey. The authors were able to show that the potential user's affinity to automation, online services, social media and sharing positively influence stated adoption, while data concerns, environmental concerns and safety concerns negatively influence stated UAM adoption.

In addition to the factors affecting user acceptance, general demand drivers of urban mobility need to be considered. As Straubinger et al. (2020) show in a meta-analysis of mode choice studies, travel time and cost are the dominant factors affecting modal choice in cities. Socio-demographic attributes like income, gender, age and household composition also are significant mode choice factors. Especially regarding travel time, UAM is expected to have a strong positive impact, in particular on long routes, where the fixed time demand for boarding and deboarding loses relevance. Again, little research has been performed on mode choice including UAM.

Garrow et al. (2017) emphasize that passenger behavior for UAM is not comparable to passenger behavior for commercial aviation. Garrow et al. (2019) even see AVs as main competitor for UAM. Due to the services' similarities – especially due to their on-demand service offer - AV studies can serve as a proxy for mode choice decisions including UAM. Fagnant and Kockelmann (2018) as well as Krueger et al. (2016) show that waiting time is an important factor for people regarding AV use. They also indicate that people currently using cars have higher likelihood of shifting to AVs. Besides that, socio-demographic factors also influence AV mode choice. Kyriakidis et al. (2015) e.g. find a positive correlation between openness towards automation and income.

These findings support the assumption that AVs and UAM can be treated as closely related, as these results go in line with the study of Fu et al. (2019). They also identify travel time (including access, egress and waiting time) and travel cost as dominant factors. The study also showed that people currently using soft modes or public transport are less likely to shift to UAM. So far, only little research has been conducted in the field of mode choice including UAM. Garrow et al. (2017, 2019) conducted surveys in the US to understand UAM adoption. The recent work (Garrow et al., 2019) extends the earlier survey (Garrow et al., 2017) by introducing autonomous vehicles as a competing mode. Yet, no model results have been published so far.

Summarizing the above, travel time, including access, egress and waiting time together with travel costs also are the prevailing mode choice factors for UAM. An efficient system design that minimizes transfer time, thus, is essential. Travel costs that during early system deployment will be rather high (Holden and Goel, 2016) could be a show stopper if the operator fails to address the right target segments. In addition to that it is essential for user and public acceptance to have a transparent service and technology and informing people about measures to ensure (data) privacy, as well as safety and security for third parties not using the system as well as system users' (Al Haddad et al., 2020). Early campaigns to raise automation awareness could be one way to proceed.

First studies on UAM market shares assume very different prices and thus find massive variations in possible adoption rates. Looking at numbers for UAM prices at taxi price levels, which goes in line with potential service provider statements (Holden and Goel, 2016), estimated modal share estimations converge towards 4% (Decker et al., 2013; Kreimeier and Stumpf, 2017; Syed et al., 2017).

7. UAM modelling approaches

Currently, research is ongoing on modelling and simulating UAM, even though said research is still in an early stage. As Rothfeld et al. (2019) outline, some studies have been performed concerning topics such as infrastructure requirements or operational constraints (Antcliff et al., 2016; Holden and Goel, 2016; Kleinbekman et al., 2018; Vascik and Hansman, 2017). With regards to the simulation of UAM, Balac et al. (2018) set the foundation for the integration of UAM within transport simulation frameworks, in this instance, MATSim (Horni et al., 2016), "an open-source framework to implement large-scale agent-based transport simulations" (Rothfeld et al., 2019).

The properties of MATSim of being readily extensible and agent-based, which – according to Balac et al. (2018) – are features that facilitate the integration of UAM in transport models and enable user-centric result analyses, are of particular importance for individualistic transportation modes. Thus, first studies have emerged outlining the development and use of an UAM extension for MATSim as summarized by Rothfeld et al. (2019) with an initial study for Zurich (Balac et al., 2018) and Sioux Falls (Rothfeld et al., 2018a).

Balac et al. (2018), simulating transportation in Zurich, provided the simulation's agents with the following modes as transport options: car, public transport, bicycle, walking, and UAM – named personal air vehicle (PAV) within the study. Based on a preliminary multi-nominal logit (MNL) model – as, according to Balac et al. (2019), mode choice models including UAM do not yet exist – agent's would probabilistically select a mode and route combination in order to maximize their utility, more specifically to minimize their disutility from traveling in-between their scheduled daily activities.

With that, Balac et al. (2019) already demonstrated the ability to incorporate on-demand UAM as a novel transport mode with conventional transportation simulation frameworks. Further, as illustrated in Fig. 5 and Fig. 6, they showed the impact of first operational parameters of UAM, i.e. UAM access time, UAM lift-off time, and UAM cruise speed on demand generation within the transport simulation. Fig. 5 illustrates the impact of the before-mentioned operational UAM properties on the overall number of trips, while Fig. 6 shows the average travel times for agents using UAM for the same variations in UAM properties. Combined, both figures highlight the inverse relation between decreasing demand for a transport mode with increasing travel times for said mode – given that other factors, such as price, remain constant – which is also commonly observed with existing ground-based transportation modes.

Balac et al. (2018) assumed various UAM access times, which prolong a potential UAM user's travel time by said fixed amount of time, yet allowed them to use UAM directly from that agent's origin and destination locations. Rothfeld et al. (2018b, 2018a) built on these simulation capabilities and advanced them by allowing the definition of UAM flight networks and stations, i.e. dedicated infrastructure for VTOL operations which require access and egress legs from potential UAM passengers. Fig. 7, by Rothfeld et al. (2018b), depicts the network model for a UAM station for MATSim, connecting the ground-transport network (car) with the flight network (uam), next to a rough illustration of a possible physical UAM station:

Using the depicted methodology of including UAM stations within transport simulation, access times ranged from less than 1 min up to 30 min (Rothfeld et al., 2018b), contrasting Balac et al.'s (2018) earlier assumptions. Still, both studies observed a high time sensitivity of simulated agents despite optimistic price assumptions based on pricing expectations set forth by (Holden and Goel, 2016). Again, both studies (Balac et al., 2018; Rothfeld et al., 2018b) identified the relative higher importance of fast process and access times over fast UAM vehicle cruising speeds.

Currently, though, the introduction of UAM stations within transport simulation requires pre-defined locations for VTOL operations. Vascik and Hansman (2017) and Fadhil (2018), as mentioned by Rothfeld et al. (2019), provide first suggestion for an approach for identifying suitable locations for UAM stations, so-called vertiports or vertistops (depending on their size). Both studies use similar factors for locating UAM stations, such as existing helicopter pads, restricted flights zones, and population density. Also, both studies apply their methodology on the use case of Los Angeles, United States. However, while Vascik and Hansman (2017) focus on the operational constraints for UAM missions, including different UAM flight phases, Fadhil (2018) increases the number of factors included for station placement by, e.g., median income distribution, office rent prices, major transport nodes, and job density. Despite the utilization of pair-wise factor comparison in an expert-involving Delphi workshop, Fadhil (2018) could not derive a universal approach for UAM station placement suitable for UAM in general.

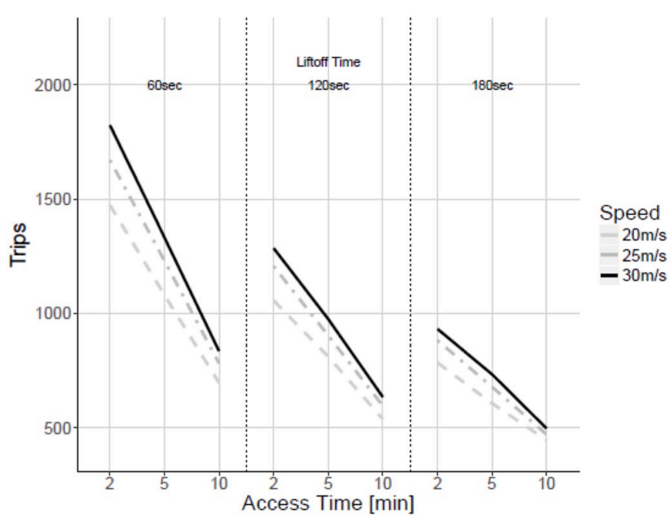

Fig. 5. Number of UAM trips based on variations in access time, vehicle speed, and lift-off time by Balac et al. (2019).

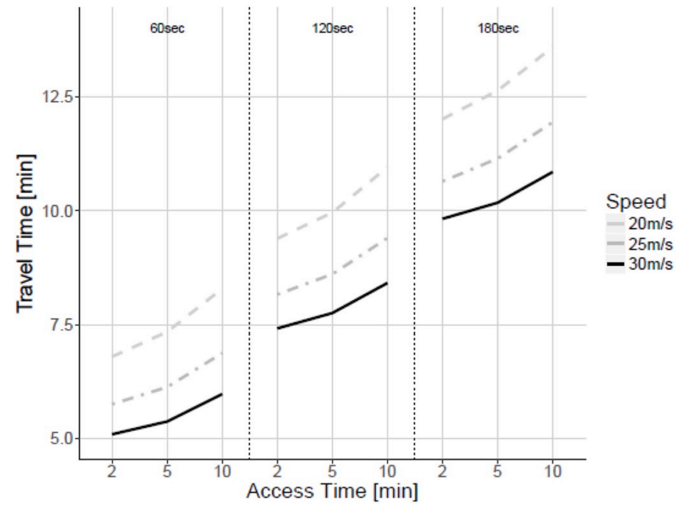

Fig. 6. Average UAM travel time based on variations in access time, vehicle speed, and lift-off time by Balac et al.(2019)).

The importance of short access times, as Rothfeld et al. (2019) have summarized, requires the integration of systematic, optimized UAM station placement into transport simulation frameworks. Bosson and Lauderdale (2018), for example, present an algorithm for identifying UAM station locations that could, potentially, be incorporated in future UAM-enabled transport simulations. Other topics, however, require modelling advances as well, such as intelligent passenger pooling and vehicle dispatching algorithms. Additionally, most transport simulation frameworks have rudimentary vehicle properties with little to no differences between vehicles of the same transportation mode. For UAM, with varying energy capacities, flight efficiencies, and in-flight separation requirements, a greater vehicle modelling detail than for existing ground-based vehicles might be required to fully understand that mode's impact and transport performance. Finally, while first studies on the environmental impact of UAM emerge, see Pukhova (2019), their findings have yet to be incorporated into UAM transport simulation in order to gauge the potential balance between UAM's transport performance and its emissions.

8. Potential influence and open research questions

The overview and discussion given above on current developments, vehicle concepts and challenges regarding the introduction of UAM, highlight that a number of companies currently focus on the development and prototyping of air vehicles to mature UAM technologies, while the research communities, in collaboration with regulatory bodies, are focusing on realizing airspace integration. Fewer activities can be seen on infrastructure developments, detailed city integration studies and economic assessments. Challenges regarding regulatory aspects,

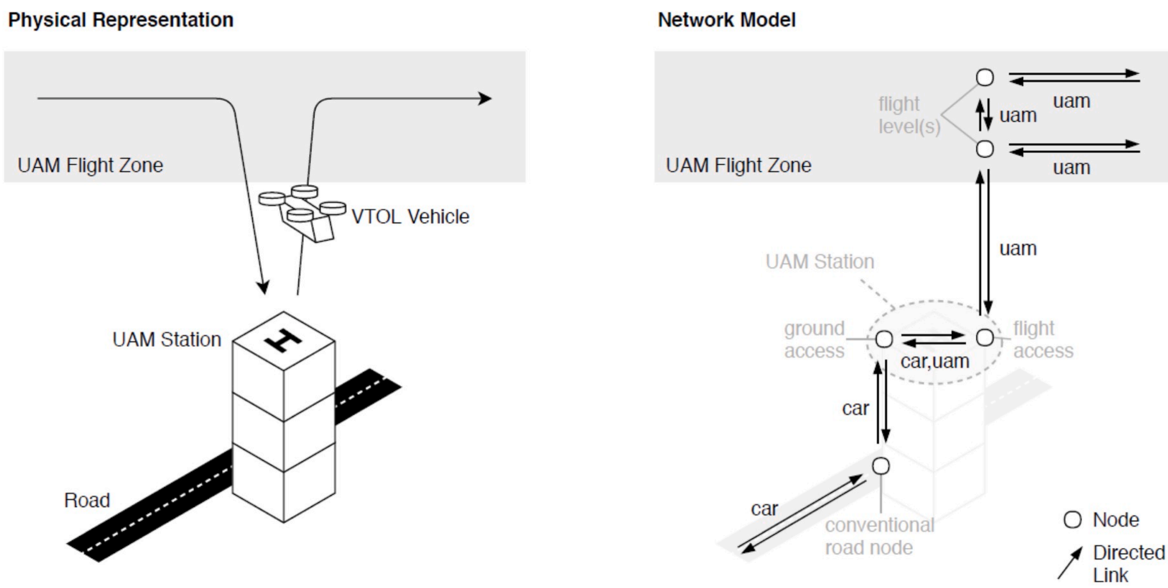

Fig. 7. Illustration of current UAM network encoding by Rothfeld et al. (2018b).

infrastructure development as well as operational concepts have to be met before first services can be launched. User and public acceptance are currently being discussed as main hurdles that have to be overcome. In addition to that, this research also gives insight on how to model UAM introduction.

Successful UAM introduction relies on a broad variety of factors that have to be considered and still a large number of questions stay unaddressed in existing literature. Literature on possible impacts of UAM is very limited. Assessments of changes of accessibility of rural regions, discussions on equity - Who benefits from the service? Who loses? – As well as discussions on inclusiveness of the system especially regarding people with special needs do not take place. First discussion on modal shifts and complementing instead of competing public transport have just recently started.

Summarizing existing research, several findings can be derived:

- If process times are sufficiently short, and travel distances long enough, UAM offers travel time savings, but these time savings might come with an energy consumption penalty.
- Due to a need for physical infrastructure solely at vertiports, network flexibility and scalability is high.
- Large scale vertiports offering high vehicle throughput capacities come with a relevant space requirement or large ground handling complexity, which opens up the question of land availability and of the relevance of infrastructure costs.
- UAM might complement existing mobility system, but due to probable capacity constraints at vertiports, UAM will likely not fully substitute them.
- With a limited number of vertiports, UAM still relies on ground transportation systems due to required access and egress modes.
- The potential to drastically impact the congestion problem is rather low due to possible induced demand and the modal split that current studies see for UAM

Thus, further research could focus on market entry strategies, business models for the different sub-markets, relevant steps in certification, the competitive situation on the various sub-markets and potential regulatory answers, technological requirements for vehicle design, sensor developments, implications on the operational concept or the impact on third parties and the city.

CRediT authorship contribution statement

Anna Straubinger: Conceptualization, Writing - original draft, Writing - review & editing. **Raoul Rothfeld:** Writing - original draft, Writing - review & editing. **Michael Shamiyeh:** Writing - original draft, Writing - review & editing. **Kai-Daniel Büchter:** Writing - original draft, Writing - review & editing. **Jochen Kaiser:** Writing - original draft. **Kay Olaf Plötner:** Conceptualization.

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