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Flying taxis revived: Can Urban air mobility reduce road congestion?

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ABSTRACT

Many metropolitan regions are investigating Urban Air Mobility (UAM) as a new transport mode for medium distance intra-regional trips. In this paper, an agent-based travel demand model was developed to simulate UAM demand for the region surrounding Munich, Germany. Special attention was given to mode choice, vertiport access and egress, airport trips, and UAM vehicle capacity constraints. Under base conditions, the model predicts a rather small mode share for UAM of 0.61%. The results show that in a metropolitan area with well-developed road and transit networks, traveling by UAM does not save much time. This is particularly true if access and egress trips to and from vertiports are included, as well as wait times, security checks and boarding times. The model shows that there is no reduction in vehicle kilometers traveled by car due to the modal shift to UAM. In fact, if access and egress trips to the vertiports are included, the total vehicle-kilometers traveled by car increases by 0.3%. Therefore, UAM is not found to alleviate congestion, but at most may serve selected markets, such as emergency vehicles or longer trips between remote areas where other transport networks are not as well developed.

Keywords

uam, Transport modelling, Mobility, Mode choice model

Introduction

Growing congestion around the world has renewed interest in flying taxis. While envisioned as a mode of transport in the 1930s (Wright & Walker, 1932), recent advances in technology suggest that flying taxis will become reality within a few decades. The current concept, called Urban Air Mobility (or UAM), is envisioned to provide an affordable alternative to ground transport in congested urban areas (Ploetner et al., 2020). It could operate an on-demand service or use a fixed schedule. UAM vehicles are abbreviated as eVTOL (electric vertical take-off and landing).

At present, there are substantial operational and technical hurdles to overcome with UAM. The eVTOL vehicles would require time and infrastructure for battery charging or swapping, impacting the operational frequency of UAM service. User acceptance is another challenge. The eVTOL vehicles could be autonomous or piloted. Flying autonomously allows for an extra passenger seat, but it negatively influences the perceived safety for users. In a stated preference (SP) survey on UAM, only 21% of respondents said they would feel safe travelling alone in an autonomous eVTOL vehicle. However, 38% said they would feel safe with another passenger they do not know (Booz Allen, 2018). The space required to accommodate a single eVTOL vehicle is around 400 m^2 (Ploetner et al., 2019), making them challenging to accommodate in urban areas. Despite these challenges, some studies suggest that introducing UAM operating at defined vertiports, routes and schedules could be feasible by 2030 (Berger, 2018; Crown Consulting Inc, 2018; Lineberger, Hussain & Rutgers, 2019; Michelmann et al., 2020). It is important to keep in mind that these predictions are based on the state-of-the-art and this timeline may change.

Technological challenges aside, the impact of UAM on the ground transportation system in terms of accessibility, congestion, and emissions is of particular interest. UAM does not yet exist, so there are no observed data. Alternative approaches to study UAM include heuristic studies (in particular, in-depth interviews with UAM experts and sketch-planning scenario analysis), analysis of comparable modes (such as helicopters) and simulations. While each approach has its value, this study applies a simulation approach to quantify the impacts of UAM. Particular challenges include developing a mode choice model that includes a mode for which no observed data exist, modeling access and egress to UAM vertiports, accounting for points of interest that are likely to attract lots of UAM traffic (such as airports, train stations, congress centers or touristic destinations) and simulating traffic flows for a mode that is highly restricted in capacity.

Given the exploratory nature of such a simulation study, several assumptions need to be defined, tested and acknowledged. To avoid the dependence on static assumptions, a series of sensitivity analyses are necessary to assess the plausibility of model results. This paper makes a fair attempt to assess the likely demand for UAM and to simulate the impact on the existing ground transportation system.

Literature review

UAM literature can be classified into studies focusing on the technical side of eVTOL vehicles (see (Zhou, Zhao & Liu, 2020) for a literature review), studies investigating how to incorporate it into air

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Table 1
Key differences among previous studies on potential UAM demand.

Author, year	Study area	Modeling tool	Mode Choice Estimation	Assumptions	Key findings
Rothfeld et al., 2018	Sioux Falls, the USA	Agent-based framework MATSim	Mode choice relies solely on agent's value of time	Station-based operation	Travel time reduction is the most crucial element in UAM adoption
Balac et al., 2019	Zurich, Switzerland	Agent-based framework MATSim	Multinomial logit model based on a stated preference study	Station-based operation	Demand for UAM in low population areas is rather small
Balac et al., 2018	Zurich, Switzerland	Agent-based framework MATSim	Multinominal logit model with auto, transit, walking, cycling and personal aerial vehicle (PAV)	Landing platforms within the city	Low PAV demand due to the low level of automation
Pu et al., 2014	Seven metropolitan areas, the USA	SAS 9.3 software	Multinominal logit model with auto, transit, and Zip aircrafts (automated electric propulsion aircraft)	ZIP on-demand aircrafts operating from airports and heliports	Travel cost and time, out of vehicle travel time are the attributes for consumers' willingness to select ZIP aircraft
Postorino and Sarné, 2020	No study area, inter- and intra-city travel, grid network	Agent-based model with ground and flying modes		Flying car operation from dedicated locations	Increase in UAM demand increases the ground traffic flows
Syed et al., 2017	Two large metropolitan areas, the USA		Conditional logit model with auto, transit and on-demand eVTOL	eVTOL aircraft operating from existing airports and heliports	The on-demand eVTOL cost should be below 1$ per passenger mile to be competitive with other modes
Kreimer and Stumpf, 2017	Germany		Mode choice based on opportunity costs for auto, air transport and on-demand air mobility	On-demand air mobility operates from existing airfields	On-demand air mobility cost should not be more that 0.15–0.2€/km more expensive than car cost

traffic management (Bosson & Lauderdale, 2018; Chan et al., 2018; Thipphavong et al., 2018), and studies investigating users' perception of UAM (Al Haddad, Chaniotakis, Straubinger, Plötner & Antoniou, 2020; Dunn, 2018; Eker, Fountas, Anastasopoulos & Still, 2020; Fu, Rothfeld & Antoniou, 2019), and studies investigating potential demand. Trips to and from the airport have been identified as largest potential market for UAM (Becker, Terekhov & Gollnick, 2018; Pu, Trani & Hinze, 2014; Syed et al., 2017; Uber, 2016).

Potential UAM demand has been investigated for commuters in some cities in the US (Pu et al., 2014; R. Rothfeld, Balac, Ploetner & Antoniou, 2018; Syed et al., 2017); in Zurich (Balac, Rothfeld & Horl, 2019; Balac, Vetrella & Rothfeld, 2018); for long-distance private and business trips in Germany (Kreimeier & Stumpf, Jun., 2017) or for daily mobility in the metropolitan region of Munich (Pukhova, Llorca, Moreno, Zhang & Moeckel, 2019). The predicted modal share of UAM generally varied between 0.01% and 4% (Balac et al., 2018; Pu et al., 2014; Pukhova et al., 2019; R. Rothfeld et al., 2018; Syed et al., 2017); but was as high as 19% for inter-city trips in Germany (Kreimeier & Stumpf, 2017). The differences can be explained by the choice set of the existing mode choice model, the way UAM was incorporated into the existing mode choice model, and the assumptions about UAM supply, costs, and waiting times.

The mode choice model estimation is crucial to assess the expected market share of UAM. While Pu et al. (2014) estimated a multinomial logit model with auto, transit and aircrafts based on travel cost, in-vehicle travel time and egress time, Syed et al. (2017) estimated a conditional logit model with auto, transit and on-demand eVTOL using total travel time and travel cost. Three studies used the agent-based transport simulation framework MATSim and expand its multinomial logit model to consider auto, transit, walk, bicycle and UAM (Balac et al., 2018; Balac et al., 2019; R. Rothfeld et al., 2018). These three studies assumed that the value of time for UAM was similar to that for public transport. These studies included walk access time and cost as independent variables. Kreimeier and Stumpf, (2017) modeled auto, air transportation and on-demand air mobility for trips between German cities. Their modal preference model used opportunity costs for each OD-pair, which depended on trip purpose (private vs. business) and household income levels. Finally, Pukhova et al. (2019) incorporated UAM into a nested logit model using an incremental logit approach. Access and egress travel times to and from the vertiports were assumed to be by auto.

UAM networks were designed using different criteria. They varied from allowing UAM operations only at already existing airfields (Kreimeier & Stumpf, 2017; Pu et al., 2014; Syed et al., 2017) to assuming that aircrafts could land at any point (Balac et al., 2018). In at least three studies, new vertiports were defined near airports, points of interest and common tourist destinations (10 stations in Sioux Falls (R. Rothfeld et al., 2018), 16 stations in the Munich metropolitan area (Pukhova et al., 2019) and 10 stations in Zurich (Balac et al., 2019)).

Assumptions about UAM costs varied widely. Pu et al. (2014) assumed costs between \$0.50 and \$1.50 per passenger per mile, while Syed et al. (2017) proposed several fare structures, which could include a base fare of \$15, a landing fare of \$6.70, and different prices per passenger per mile (from \$0.75 to \$1.63). For auto costs per mile, \$0.54 was used by Pu et al. (2014) and Syed et al. (2017). Balac et al. (2018) assumed UAM costs to be the same as Uber Black prices in Zurich (4 CHF + 4 CHF/km), and also tested a scenario with 4 CHF + 2 CHF/km. These costs were smaller in Balac et al. (2019), varying from 0.6 CHF/km to 1.8 CHF/km. R. Rothfeld et al. (2018) set the UAM cost at three times the auto cost. Kreimeier & Stumpf, 2017) tested scenarios with UAM costs of 0.40 €/km and 0.6 €/km. As a reference, Uber estimated that UAM would initially cost between \$0.84/mile and \$1.19/mile, but could decrease to \$0.50/mile in the long-term (Uber 2016). Pukhova et al. (2019) performed a sensitivity analysis with costs ranging from 1 €/km to 5 €/km.

Waiting times at vertiports were usually not considered (Balac et al., 2018; Kreimeier & Stumpf, Jun., 2017; Pu et al., 2014; R. Rothfeld et al., 2018; Syed et al., 2017). Where they were considered, they were assumed to be static and did not depend on the current balance between demand and supply at each vertiport (Balac et al., 2019; Pukhova et al., 2019). Under constrained supply conditions, waiting times would depend on how busy the vertiports are at each point in time and whether the passengers need to wait until a vehicle is available for the trip. The summary of the previous studies on UAM demand are presented in the Table 1.

Predicted mode shares of UAM highly depend on its cost, the alternatives modes in the choice set and the UAM supply. Most previous studies used limited choice sets or considered less realistic locations for vertiports. Furthermore, not all studies have estimated specific trips to and from the airport; or included access and egress travel to and from the vertiport. Given that the share of UAM trips depends on travel time, considering dynamic waiting times is likely to be significant. To the best of the authors' knowledge, this explicit feedback between travel demand and traffic assignment has not been modelled for UAM yet. The current research tries to fill this gap by providing a comprehensive mode choice model, which includes an access/egress mode choice model, and a feedback loop between travel demand and traffic assignment to consider dynamic, demand-dependent waiting times.

Methodology

In this study, a simulation model was developed to assess the demand for UAM and the impact on the ground transportation system. As no observed data are available for UAM choice behavior, an incremental mode choice model was coupled with a SP survey. Special attention was given to access and egress travel to and from UAM vertiports. UAM trips to and from the city's international airport are distinguished because of the unique attributes of airport travel demand. Given the strict constraint of capacity (depending on the configuration, two to four passengers can fly in a single UAM vehicle), capacity constraints were modeled explicitly.

The model applied for this study is the agent-based travel demand model MITO (Moeckel, Kuehnel, Llorca, Moreno & Rayaprolu, 2020) coupled with the agent-based transport simulation framework MATSim (Axhausen, Nagel & Horni, 2016). MITO is a trip-based model, but it microscopically simulates travel behavior for individual agents. The model incorporates travel time budgets (Zahavi, 1974), which influences destination choice: people who spent a lot of time commuting may perform less discretionary travel, while people who telecommute may have additional discretionary travel. The mode choice model is nested logit, which allows for larger cross-elasticities between modes in the same nest compared to other nests. The time-of-day model samples from empirical distributions using 1-minute intervals.

After travel demand is generated, agents' plans are sent to MATSim for assignment. MATSim is a dynamic traffic assignment (DTA) model that simulates individual vehicles on the road network. MATSim has been extended with a dedicated UAM extension that accounts for a capacity-constraint assignment of passengers to UAM (R. Rothfeld, Balac, Ploetner & Antoniou, 2018).

New, faster modes of transport commonly induce additional travel demand (Kitamura, 2009). Previous research included estimation demand induced by UAM (Pukhova et al., 2019); this research also included an analysis of demand that is potentially induced by UAM. Results, however, showed very small impacts of UAM service on travel demand. Given the strict capacity constraints of UAM, gains in travel time and accessibility are limited. Therefore, the induced travel demand was found to be negligible (Moreno, Llorca, Moeckel & Antoniou, 2019). To avoid this added level of uncertainty, induced demand was assumed to not exist in this paper.

Survey-based incremental logit model

Two strategies are commonly used to estimate the mode share for a mode not yet in operation: SP surveys results can be used to estimate a mode choice model that includes the new mode, or an incremental logit model as proposed by Koppelman (1983) can be used. SP surveys have a tendency to overestimate the demand of new alternatives. Incremental logit models require the selection of a base mode, and the new mode is assumed to be very similar to the base mode. By combining these two

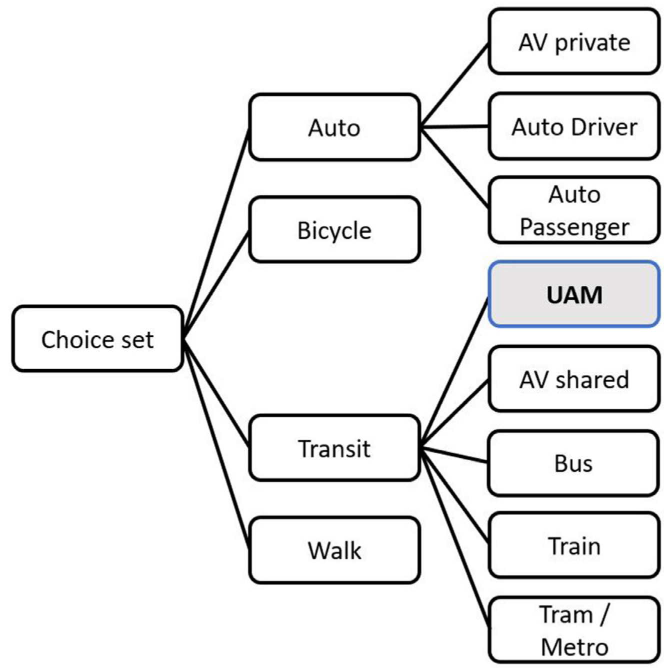

Fig. 1. The extended mode choice nesting structure with UAM.

methods, the uncertainty to predict the demand for a mode that does not exist yet can be reduced.

The principle of an incremental logit model is to select a reference mode for the new mode and to define the changes in utility provided by the new mode. This study applies an incremental approach from the existing nested logit mode choice model in MITO. In the first step, a nest for the new mode is selected. Given the similarity of unobserved attributes, UAM was added to the transit nest alongside bus, train, tram/metro, and shared autonomous vehicle (AV). Similar to other transit modes, UAM vehicles are not owned by the traveler, the ride is shared with other riders, operation depends on service providers, and there are waiting times at stations. In the next step, a reference mode is selected that is believed to be most similar to UAM. We assume that UAM is an improvement on Train. Like trains, eVTOL vehicles travel quickly and serve fewer stops than other transit modes because they require substantial station infrastructure. Fig. 1 shows the structure of the extended nested mode choice model including UAM.

In the existing mode choice model, utilities for each mode are assessed in terms of person attributes, household attributes and trip related attributes. For example, utilities for home-based other trips (HBO) are calculated using Eq. (1).

$$\begin{aligned} u_{m,HBO} = {} & c_{m,HBO} + \beta_{1,m,HBO} \cdot s + \beta_{2,m,HBO} \cdot l \\ & + \beta_{3,m,HBO} \cdot a + \beta_{4,m,HBO} \cdot h + \beta_{5,m,HBO} \cdot d \\ & + \beta_{6,m,HBO} \cdot \left(tt_m + \frac{tc_m}{VOT_{m,HBO,i}} \right) \end{aligned} \quad (1)$$

Utility equation for HBO trips where:

$u_{m,HBO}$: Utility of mode m for HBO purpose

$c_{m,HBO}$: Mode specific constant representing unobserved attributes

$\beta_{\_,m,HBO}$: Evaluation parameters, estimated with the German household travel survey MiD[1] s: Dummy variable for sex of traveler (0 – female, 1 - male)

l: Dummy variable for driver's license availability for a traveler (0 – no license, 1 - license)

[1] German household travel survey, available at http://www.mobilitaet-in-deutschland.de/

a: Number of cars owned by the household

h: Household size

d: Distance to the next transit stop, m

tt_m: Travel time in minutes by mode, min

tc_m: Travel costs in Euros by mode min

$VOT_{m,HBO,i}$: Value of time for HBO purpose for mode m for household income i

Results from the SP survey by Fu et al. (2019) are used to adapt the train utility to UAM. We assume the generalized costs (which convert travel time, travel cost and value of time into a utility value) are different for train and UAM. Fu et al. (2019) estimated the travel cost parameter to be −0.51 for UAM and −1.12 for transit. These parameters cannot be transferred directly to the mode choice model because the other parts of the utility equation and the choice set are different. Instead, the ratio between these two parameters is assumed to reflect the difference in the evaluation of travel cost for UAM versus transit (Eq. (2)). This ratio was also calculated for the travel time parameters (Eq. (3)).

$$\gamma_{tc} = \frac{-0.51}{-1.12} = 0.45 \tag{2}$$

Adjustment coefficient for travel costs

$$\gamma_{tt} = \frac{-1.00}{-0.68} = 1.48 \tag{3}$$

Adjustment coefficient for travel time

These adjustment factors were used to calculate generalized costs for UAM based on the existing generalized costs for train (Eq. (4)).

$$u_{UAM,p} = \ldots + \beta_{6,train,p} \cdot \left(\gamma_{tt} \cdot tt_{UAM} + \gamma_{tc} \cdot \frac{tc_{UAM}}{VOT_{UAM,p,i}} \right) \tag{4}$$

Adjusted utility calculation for UAM

These SP survey results suggest that UAM costs are perceived to be smaller than train costs. This suggests that travelers are willing to pay a higher fare for UAM given the higher speed and added comfort. Travel time for UAM, however, is evaluated more sensitively than for train. This finding appears to reflect that travelers would expect shorter travel times on UAM.

Finally, the value of time for UAM travelers was adjusted. Value of time cannot be measured, but is commonly derived using SP surveys (e.g., Would you be willing to pay 10% more for this trip if the travel time was 20% faster?), or by calculating the ratio between estimated time and cost parameters of a mode choice model. Given that value-of-time surveys are challenging enough for existing modes (Tseng & Verhoef, 2008), they seem unreasonable for non-existing modes. It would be extremely difficult for respondents to assess how much more they are willing to pay to save time on a faster UAM trip if they are not familiar with the UAM at all. Following this, we calculated the average between the value of time for auto passenger and transit (Moeckel, 2020) and applied this average value of time to convert UAM costs to equivalent minutes (Llorca, Ji, Molloy & Moeckel, 2018).

Access and egress mode choice

In the context of UAM, the access trip is the segment between the origin and first vertiport, while the egress trip is the segment between the final vertiport and the destination. High infrastructure requirements suggest that UAM vertiports would be sparse. Therefore, access and egress could be a substantial portion of UAM journey time and cover a larger distance than access and egress for existing transit modes. UAM users are likely to be time-sensitive (similar to air travelers (Gayle & Yimga, 2018)), preferring access and egress modes like car or taxi that minimize overall travel time. The access and egress mode chosen by UAM users could have important effects on network congestion, especially in the areas surrounding the vertiports. Therefore, this study incorporates additional models to estimate access and egress modes for UAM journeys before they are simulated on the network.

The UAM access and egress models were based on the existing main mode choice model (without UAM). However, access and egress mode choices are made in a different context compared to the main mode choice. Therefore, the following modifications were made to adapt the model for access and egress:

1) *Trip-related attributes*
   It was assumed that access or egress mode choice is based on the characteristics of only the access or egress portion of the trip instead of the whole trip. To account for this, the access model assumed a trip between the origin and first vertiport, while the egress model assumed a trip between the final vertiport and the destination.
2) *Trip purpose*
   For home-based purposes, the access trip is always on the home end and the egress trip is on the non-home end. For non-home-based purposes, both the access and egress trips are on a non-home end. Therefore, UAM access trips kept the same purpose as the main trip purpose, while UAM egress trips were always modelled using non-home-based purposes.
3) *Household location*
   Since egress trips are always on the non-home end, the egress model replaced household location attributes with destination location attributes.
4) *Household automobiles*
   It was assumed that UAM users would not have access to their automobiles unless they were on the home (access) end of a home-based trip. To account for this, the coefficient for household automobiles was fixed at zero for all egress trips and non-home-based trips.

Airport access

Some authors propose access trips to the airport as one of the most relevant markets for UAM (Al Haddad et al., 2020; Booz Allen, 2018), despite potential conflicts with air traffic (Thipphavong et al., 2018). Therefore, an airport travel demand model was built into MITO for this study. This model is based on passenger counts at Munich airport by mode and origin for the year 2016, and applies the following steps:

1) *Generation of the total number of passengers (includes departing and arriving passengers)*
   The number is based on the observed (for current years) or forecasted (for future years) number of passengers, defined as an exogenous assumption.
2) *Origin/destination choice*
   For each arriving (or departing) passenger, the model selects a location for the non-airport trip end. This is based on mode choice logsums (an aggregation of cost and time by all modes from the airport to every alternative destination), and population and employment densities. For each outgoing trip, the model picks up a traveler from the synthetic population of residents.
3) *Mode choice*
   For each trip to/from the airport, a mode is selected based on travel time and cost.
4) *Departure and arrival time*
   For each trip, an arrival time to the airport (or departure time from it) is chosen based on the distribution of takeoffs (or landings) plus check-in (or baggage claim) times.

Airport trips are not included in the travel time budget module, which only considers local travel. The traffic assignment is performed jointly with the rest of the demand; therefore, the airport travel demand is fully integrated with the rest of MITO.

Feedback MATSim-MITO

The classical four-step approach selects a mode in the third step based on certain travel time and congestion conditions. However, these conditions are unknown before running the fourth step (traffic assignment). This may result in too many trips made by UAM initially, as

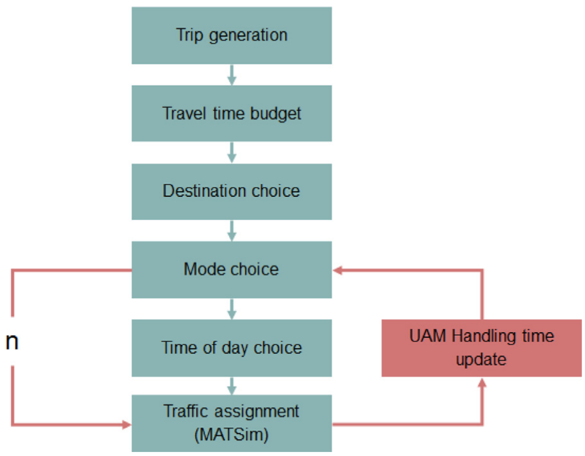

Fig. 2. MITO extended 4-step model (green) and feedback loop (red), n - number of iterations.

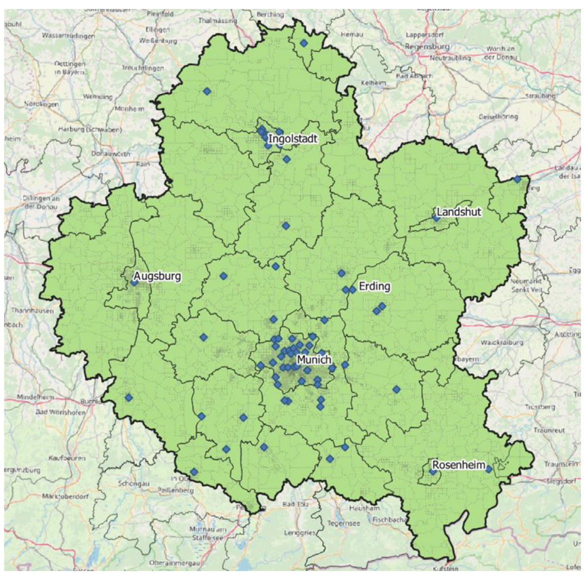

Fig. 3. Study area in Upper Bavaria, Germany, with a network of 74 vertiports.

the travel time savings are significant when waiting times due to limited capacity are not reflected. Therefore, we ran several iterations of mode choice and traffic assignment (Fig. 2). Every time traffic assignment (route and vehicle choice) is executed, the travel times by UAM (including demand-dependent waiting times) are updated, affecting the mode choice decisions in the next iteration. None of the other MITO components are executed again (i.e. the agents do not change the number of trips, their destination or the time of the day). This process runs until an equilibrium between demand and supply is achieved. We set the number of agents that can change mode in successive iterations to 30% after checking different shares. That share was able to fulfill a convergence criterion defined as a change in less than 5% of the number of UAM trips with respect to the previous iteration. At maximum, we ran 20 iterations of the mode choice model.

Results

A test scenario was developed for the Munich region for the year 2030 with a medium-density UAM network of 74 vertiports, as shown in Fig. 3 (Ploetner et al., 2020). This network includes UAM vertiports in densely populated areas, employment centers and transportation hubs of the study area. It is assumed that by 2030 AV's current drawbacks will be solved and AVs will be integrated into ground transportation. In the test scenario, the UAM fleet was constrained to 50 vehicles per station and the UAM boarding time was fixed at 10 min. The model assumes a UAM cruise speed of 100 km / h and a capacity of one passenger per vehicle. The cost of a UAM journey in this scenario comprised of a 5 € base fare plus 2 € for each kilometer travelled. The assumptions regarding travel cost, boarding time, and fleet size are tested in the sensitivity analysis. Following the results of the proposed scenario, it was found that the highest number of take-offs and landings at one vertiport is 11,300 and 11,500 respectively, which corresponds to 8 take-offs and 8 landings per minute if the service operates 24 h a day. That is why an unlimited capacity for the number of take-offs and landings at vertiports is assumed in this scenario.

Mode choice

The UAM test scenario was compared to a base scenario that does not include UAM. Fig. 4 presents a comparison of main mode choice and the UAM access and egress modes.

Fig. 4 shows that UAM had the greatest relative impact on transit modes (train, tram/metro, bus) and shared AV. This is a result of the nested structure described earlier, in which UAM is in the same nest as these modes (recall Fig. 1). The model forecast that 49% of all UAM users would have otherwise chosen transit if UAM were not available.

Regarding access and egress, it was estimated that 52% of UAM access and egress trips would be made by either automobile or AV. This is similar to the results of the main mode choice model, in which 59% of all trips were made by these modes.

Impact on road congestion

To determine the impacts of UAM on road traffic, the total vehicle kilometers travelled (VKT) in the region was estimated for the base scenario and the UAM test scenario. These calculations assumed that only automobile drivers, private AVs, and shared AVs contributed to road traffic. The results are given in Fig. 5

The main mode choice resulted in 49.39 million VKT for the base scenario and 48.94 million VKT for the UAM scenario. However, UAM access and egress trips created an additional 0.59 million VKT, leading to a grand total of 49.53 million VKT for the UAM scenario. This means the UAM scenario generated approximately 0.14 million more vehicle-kilometers than the base scenario, an increase of 0.27%.

The increase in VKT for the UAM scenario is counterintuitive at first sight. After all, UAM was expected to reduce auto travel. However, the nesting structure of the mode choice model drew more UAM trips from transit than from auto. Also, access and egress trips were done by car more often than by transit or non-motorized modes. While the net impact on VKT is very small, UAM could not be shown to reduce auto travel.

Sensitivity to UAM cost and boarding time

Most of the UAM mode choice utility coefficients were copied from the reference mode (train), with the exception of travel time and travel cost. The SP survey results showed that train and UAM users have different perception of time and cost. The UAM time and cost coefficients in MITO were adapted using the findings from the SP survey. This enables MITO to simulate how train and UAM users react differently to changes in time and cost.

Sensitivity testing was performed to understand how the total number of UAM trips changes with boarding time and cost per kilometer. For the test scenarios, the UAM fleet was unconstrained, meaning there is always a UAM vehicle available at each vertiport at any point of time. The tests use the same UAM network of 74 vertiports (see Fig. 3), a UAM cruise speed of 100 km/h, and a capacity of 1 passenger per vehicle. When testing sensitivity to boarding time, the cost per kilometer was fixed to 2 €. When testing sensitivity to cost per kilometer, the boarding

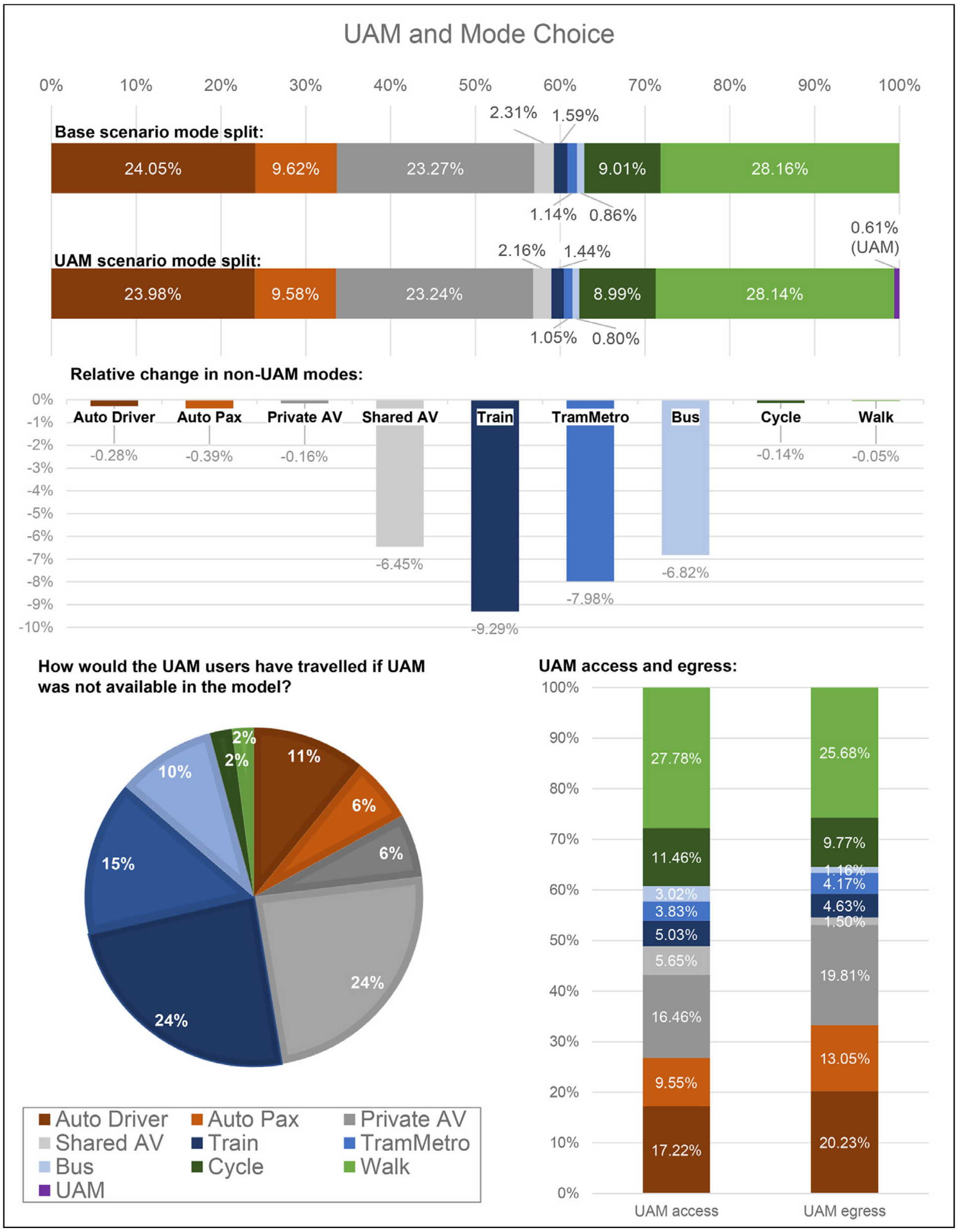

Fig. 4. Comparison of mode choice in the base scenario and UAM scenarios, mode choice for UAM users if UAM was not available, and UAM access and egress.

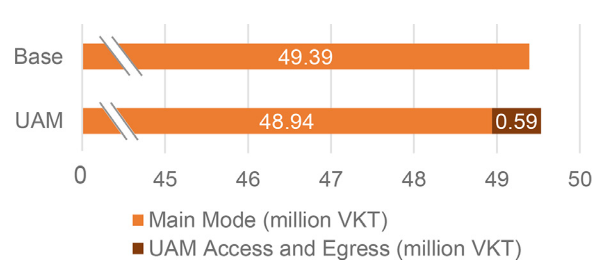

Fig. 5. Comparison of vehicle-kilometers travelled on the road network.

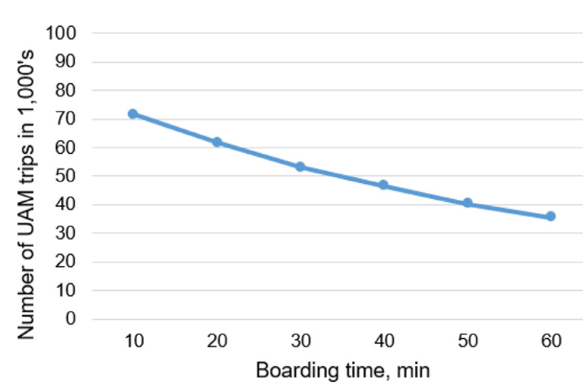

Fig. 6. Model sensitivity with respect to boarding time.

time was fixed to 10 min. For both tests, the base fare of 5 € remained constant.

Fig. 6 shows the model sensitivity regarding the changes in boarding time due to possible delays of assigned vehicles, organizational purposes, security checks, etc. When the boarding time increases from 10 min to 60 min, the UAM demand is reduced by 50%. Regarding the changes in UAM cost per km, Fig. 7 shows that increasing UAM cost from 1 € to 7 € per km reduces UAM demand by 70%.

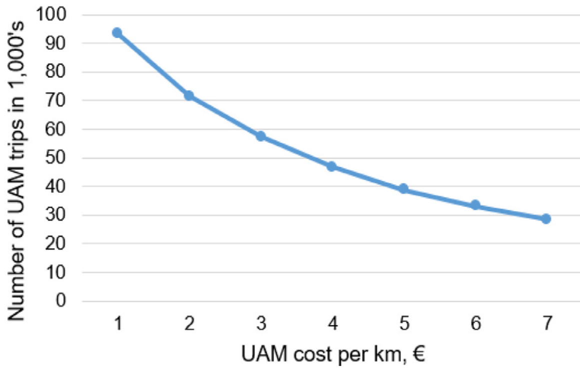

Fig. 7. Model sensitivity with respect to UAM travel cost.

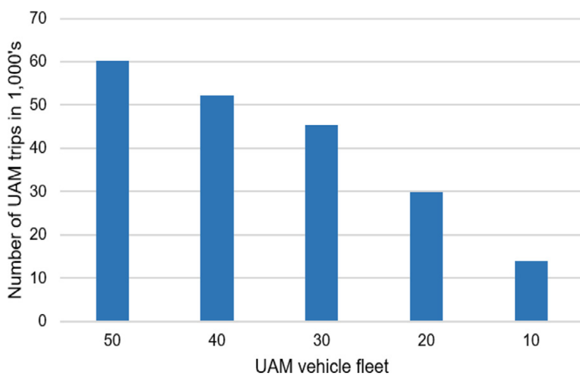

Fig. 8. Model sensitivity with respect to UAM vehicle fleet size (UAM vehicle fleet per station).

Sensitivity to constraints on the UAM vehicle fleet

To fulfill UAM demand, a high number of air vehicles would need to be available at vertiports. However, there is insufficient free space available in cities to allocate vertiports large enough to accommodate all demand for UAM. The dimensions of an eVTOL multicopter are 9.15 m by 9.15 m (Hermiyanty, 2017). Adding necessary safety areas, one eVTOL vehicle requires an area of 20 m by 20 m. Considering UAM operation, vertiports for 10 eVTOL vehicles would require an area of 4,160 m^2 (Ploetner et al., 2019). It will be challenging to provide this much space in dense urban areas.

Several scenarios with a limited vehicle fleet were executed to assess more realistically UAM operations in an urban agglomeration. The MATSim-MITO feedback loop updates waiting times based on current demand. Agents may select a different mode if waiting times make UAM less attractive. Fig. 8 shows that a UAM fleet of 10 vehicles per station at the beginning of the day and the UAM network of 74 vertiports can accommodate 14,000 trips. This corresponds to UAM share of 0.14%. UAM demand increases with the availability of eVTOL vehicles and accounts for 0.61% if 50 eVTOL vehicles are available at every station. The (unrealistic) scenario of unlimited vehicles per station resulted in 69,223 trips or a mode share of 0.70%.

Limitations

The methodology used for modeling this non-existent mode has many limitations. One of these was the incremental logit approach used to adapt the mode choice model. In this process, the utility of UAM was adapted from the base mode of train. Without doubt, there are substantial differences between UAM and train. The challenge for a model is to quantify this difference. There is no urban mode that would be closer to UAM than train. The incremental logit model requires a reference mode, and considering all urban travel modes available, UAM's characteristics have more similarities with train than with other urban travel modes. Given this limitation, we did not rely entirely on the incremental mode choice model, but rather combined it with a stated preference survey. The results of the stated preference survey were used to adjust the UAM sensitivities to time and costs. Thereby, UAM is not treated identically as train, but merely train serves as a basis to further refine the calculation of utilities of UAM. Nevertheless, it is readily admitted that train is at best a poor proxy for the base to model UAM demand.

The chosen nesting structure is another exogenous assumption that affected the model results. While the nesting structure in this research assumed that more passengers shift from other transit modes to UAM, one could also argue that the UAM mode would be more prestigious and similar to taxi, which would imply that UAM should be nested with the auto modes. Here, it was decided that the unincluded attributes (such as shared vehicle, waiting times, fare structure) would be more similar to transit than auto, but there are other nesting structures that could be justified.

Finally, the assumptions on costs, travel times and frequencies are – while based on yearlong exchange with aviation experts who work on UAM – arbitrary to some degree. Given the lack of existing UAM travel, the assumed values are based on plausible UAM development scenario but not confirmed by operational UAM systems.

Conclusions

The potential of UAM to improve travel conditions is limited in urban areas like Munich that have an extensive road infrastructure and public transport network. For the majority of origin-destination pairs, UAM does not provide a reduction in travel times when travel time for access and egress, boarding time and potential waiting time are included. As a consequence, the share of UAM trips is relatively low with 0.14% to 0.61% of the total number of trips depending on the fleet size. UAM vehicles are expected to be less noisy than helicopters, but they will still increase noise pollution and create additional visual pollution if operated extensively. Substantial energy is need for vertical take-off and landing, so UAM cannot preserve energy consumption in comparison to ground transportation (Pukhova, 2019).

Given the very limited capacity of UAM vehicles and the time required to process boarding, take-off, vertical ascent and descent, alighting and recharging, travel time savings within an urban area will be negligible. UAM would reduce travel times only for a limited selection of origin-destination pairs (mainly between remote areas where other transport infrastructure is limited). Therefore, UAM is likely to remain a niche mode of transportation for special purposes. Current helicopter flights for medical emergencies and VIPs are expected to be replaced by UAM because eVTOL vehicles are likely to generate less noise and fewer greenhouse gas emissions than traditional helicopters.

UAM could potentially offer more benefits in rural areas such as mountainous regions. Some valleys are difficult to reach because the topography requires large detours for ground transportation. In such cases, UAM could reduce travel times substantially. Remote areas could be connected with airports, high-speed rail stations and other services provided only in core cities. Whether UAM flights across sensitive mountainous areas are desirable is another research question that requires attention. Another potential task for UAM could be to provide connectivity for islands. If demand to travel to and from an island or between multiple islands is relatively low, ferry service will be inefficient or require detours and transfers. UAM potentially could become an alternative mode that provides easy access to regions with limited ground transportation infrastructure.

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