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Assessing automated air-taxis for urban mobility

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Abstract

This paper explores the feasibility and potential implications of automated air-taxis as a new mode of urban transport. By applying flight simulation and operations research, we investigate different questions regarding travel time, travel costs, and transport sustainability. As practical application, we consider the transportation service between the city and the airport, as well as on-demand air-taxi services within the city of Vienna. We compare the air-taxis with gasoline taxis and e-taxis, as they serve analogous transportation needs and cater to a similar clientele. In our effort to assess the feasibility of air-taxis, we aim to answer crucial questions that will influence the future of urban transportation. Our study examines how efficient air-taxis are in reducing travel time and explores their cost dynamics, addressing the affordability for passengers and their value of travel time savings. Additionally, we investigate their environmental impact by looking into energy consumption and CO_2 emissions. Through a rigorous analysis of empirical data and simulation outcomes, we aim to provide a comprehensive perspective that informs policy decisions and guides the evolution of urban transportation networks in the years to come.

Keywords Urban air mobility, Air-taxi

1 Introduction

With increasing population, urbanization and time fragmentation, the search for new transport solutions commences that can cover the expected demand. Especially transport measures in the air are increasingly being brought into focus. With the progress in automation in road traffic, urban air mobility (UAM) and automated air-taxis become within reach. However, with these new possibilities, the resulting impacts and viable business models need to be investigated.

In recent years, the concept of air-taxis has gained significant attention and regulatory focus. Notably, the European Union Aviation Safety Agency (EASA) took a pioneering step by publishing the world's first rules for the operation of air-taxis within urban environments. These proposed regulations encompass various technical domains, including airworthiness, air operations, flight crew licensing, and rules of the air. EASA has also provided guidance on vertiport design, further emphasizing their commitment to fostering safe and efficient UAM. EASA's efforts extend to defining design specifications for vertical take-off and landing aircraft intended for passenger transport as air-taxis, as outlined in an article published on their website [5]. Bauhaus Luftfahrt published a white paper that shares valuable insights into the core aspects of passenger UAM research [17]. Their work delves into vehicle design, vertiport infrastructure, and transport system considerations. They conclude that UAM will show a potential time benefit compared to car travel only in heavily congested cities if short ground access and egress to vertiports is ensured, and that with a predicted market share in the range of 1%, UAM will

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not have a noticeable positive impact on existing modes of transport while resulting in a significant amount of flights. The UAM market study [11], commissioned by NASA evaluates market size and potential obstacles for UAM based on application areas. They project that air-taxi is the third milestone in UAM, after air-delivery and air-metro are successfully implemented. They foresee that the resources for the required infrastructure to truly allow a door-to-door transport operation will be extensive. Another market study by ARK Invest describes the development of air-taxis in terms of range through battery improvements and resulting lower prices. A flight from Manhattan to JFK is used as a comparison route. They conclude that the air-taxi will be only 10% to 20% more expensive than taxis in the long run. From the studies above, we gain the impression that air-taxis will be affordable, but not a mainstream transport mode, technologically feasible, not be implemented in the near future. Scientifically, there are works that assess the impact of air-taxis as a complement to public transport. For the Munich metropolitan region [18], use an agent-based transport model and an incremental logit model to simulate different scenarios and sensitivity studies for UAM. Rothfeld et al. [19] also considered the Munich region and estimated the potential travel time savings of urban air mobility (UAM) for different trip types and distances by using geographic information system (GIS) and a network analysis. These works are particularly relevant since the culture and the mobility behavior of people in Munich and Vienna are comparable.

In this paper, we want to analyze the potential impacts of air-taxis in Vienna and examine the viability of air-taxis as a new urban transportation mode. The novelty is a data-based approach that compares air-taxis with regular taxis using real-world trip data. Besides environmental dimensions such as energy consumption and CO_2 emissions, the focus is on travel efficiency and costs. Based on calculating the value of travel time savings for leisure trips and business trips in Austria, we estimate the number of trips that can be replaced by air-taxis. This is an alternative, data-based approach compared to the simulations in the literature. It has the advantage of being easier to apply and easier to transfer to other regions.

2 Methodology

We use a set of different methodologies to assess the different impacts of air-taxis. We use flight simulation to realistically calculate the performance of each flight, and operations research for the evaluation of the air-taxi operation in the final results. In this section, we first describe the air-taxi use case and its cost models, followed by the different methodologies.

2.1 Air-taxi use case

Based on the current market situation and the technological potentials of unmanned air vehicles, we consider air-taxis to be battery-powered and mainly operating for airport transfer and on-demand transport services in this paper. The demand data is based on the national wide survey “Österreich Unterwegs” [21] where people and their daily trips are recorded as activity chains, and a dataset of 50.000 real taxi trips within Vienna and to/from the airport. For the air-taxis as a new transport mode, we use flight simulation for unmanned aerial vehicles with approximated parameters to calculate the flight trajectories and to obtain the key values such as flight duration and energy consumption. The resulting assessment framework is comprehensive so that all essential parts, such as mesoscopic simulation, realistic flight trajectories, and overall traffic are considered in a coherent approach.

The on-demand transport offers door-to-door travel just like regular taxis on the road, but the air-taxi is not tied to a road network. There are no fixed departure and arrival points or timetables for the flight service. The air-taxi is requested by a user on demand to one of the predetermined hub locations. For the sake of simplicity, we assume takeoff and landing from predetermined designated areas for VTOL operations that were created as 68 clusters (k-means clustering) from observed locations of demand (i.e., 50.000 real taxi trips). Preliminary considerations of requirements give rise to the assumption of the basic technical feasibility of these locations, without necessarily specifying the exact positioning. We assume that the air-taxis are very small (to accommodate one or two passengers) and require only little space for takeoff and landing (e.g., the size of three cars parked side by side). While there is no demand, the air-taxis remain stationary at hubs, which serve as air-taxi stands and can also be used for recharging the battery. After a request is made, the air-taxi heads to the passengers to pick them up. Ride pooling to bundle ride requests is not envisioned, but only a single-use 50.000 concept. The technological as well as legal feasibility for flexible take-off and landing areas is assumed to be given.

For the airport transfer, trips between the airport and the city are carried out as an alternative to conventional means of transport. It has the advantages of being independent of a static route network with its associated traffic loads or capacity limits and the resulting congestion during peak hours. Benefiting a more direct flight path, the air-taxis benefit from travel time savings compared to the other transportation systems. The transport mode can be individual on-demand, or carried out as hub-to-hub where hubs at key locations can be used as take-off and landing points. By moving traffic through hubs, passengers can be better bundled, and air-taxis take on the character of airport shuttles with room for multiple passengers. Reasonable locations are large companies, high-end hotels, and public transport hubs.

2.2 Cost models and comparison

A widely used approach in determining and comparing the operating costs of air-taxi is quantifying them per passenger and per kilometer. Estimates in this regard vary in the literature and existing studies, with a corresponding analysis showing that the following cost items are particularly considered:

- Depreciation costs for the air-taxi (capital costs)
- Battery and energy costs
- Crew costs
- Infrastructure costs
- Maintenance costs for air-taxi and infrastructure
- Insurance costs for operation

Based on a study by Hamilton [10], the maintenance costs, capital costs, and personnel costs take a major part and account for approximately 60–70% of the total operating costs. Patterson [16] collected data from different air-taxi providers to compare the indicated operating costs: Archer Aviation, Eve Urban Air Mobility, Lilium, and Nasa. The projected costs were stated between USD 2.25 and USD 11.00 per person per mile. Unfortunately, these numbers do not include the "first and last mile," which would be necessary to include potential transports to "vertiports" and thus make the overall travel costs comparable. Goyal R. et al. [9] investigated the average costs per passenger mile using different types of aircrafts and number of seats. Intuitively, the average operating costs per passenger mile decrease with increasing aircraft seating capacity, as economies of scale emerge. Median costs per passenger mile range from USD 4.75 for a five-seater to USD 9.50 for two-seaters.

On the demand side, the Bauhaus Luftfahrt study [17] considered four fare models for the passengers, each including a basic fare and a factor depending on the trip length:

- *Fare 1: EUR 5 base fare + EUR 1 per km*
- *Fare 2: EUR 5 base fare + EUR 2 per km*
- *Fare 5: EUR 5 base fare + EUR 5 per km*
- *Fare 10: EUR 5 base fare + EUR 10 per km*

Note that following the literature on operating costs on the supply side (i.e., for air-taxi operators), only Fare 5 and Fare 10 are economically viable. However, we further consider all four fare models to obtain a comprehensive view on the demand side.

2.3 Flight simulation

A two-stage simulation pipeline is created for flight performance indicator estimation between a starting point and a landing point. Firstly, a trajectory generation algorithm, that takes into consideration terrain elevation [8] and legal constraints [1]), creates legal and feasible path-length-optimal flight routes for all required source-target-relationships. The algorithm is based on a variation of rapidly exploring random trees [13] with iterative re-connection and a customized sampling heuristic (i.e., empowering sampling close to existing trajectories) with multi-goal search, followed by gradient descent optimization [7]. In a subsequent step, the trajectories are flown in a microscopic flight simulation. The vehicle resembles a realistic assumption in terms of size, flight performance (i.e., thrust to weight ration ~ 2:1), mass (MTOW 1600 kg) inertia and energy consumption, based on available review literature [20]. The assumed parameters are chosen to cover a UAM vehicle that can carry up to 4 passengers. All simulations are performed fully seated, so that the energy consumption is at the unfavorable limit of the possible spectrum. Within the idealized simulation, technical feasibility of the required endurance is assumed.

For the microscopic flight simulation, a physical simulation of the flight (six degrees of freedom rigid body equations following first principles of motion) is implemented as a Matlab©/Simulink© model and the differential equations of motion are integrated numerically with commonly available ODE solvers [15]. The simulation represents the flight performance with a state-of-the-art flight controller (cascaded flight controller with a carrot-chasing guidance law, rate controller, attitude controller, thrust allocation) for trajectory following in in three dimensions and attitude tracking as well as state-flow based flight phase dependent control gain scheduling. A reference speed of 36 m/s is set for cruise flight and a target climb rate of 4 m/s is set for climb/descent phase, whereas the finally achieved ground speed strongly depends on prevailing wind regime and flight direction. A realistic yearly averaged wind-field [14] and a low altitude turbulence regime [4], is implemented. The simulation yields a complete time history of the required propulsion speed of the six separate propulsion units to achieve the desired attitude and velocities to follow the trajectory. The commanded thrust values serve as a base for power consumption calculation through momentum theory [2]. The simulation yields total energy consumption and the travel time for each direction for each connection. With the current emission values (CO2 per kWh) for Austria's electrical power generation, the emission KPI is calculated.

2.4 Operations research

Operations research (OR) is a method class that uses mathematical models, statistical analysis, and optimization techniques to solve complex problems in decision-making. It is used to analyze and improve the performance of systems, processes, and organizations. In the context of urban air mobility, operations research can be used to optimize the planning and operation of air-taxis, as well as to develop efficient traffic management systems. For example, it can be used to model passenger demand and optimize flight schedules to minimize waiting times and maximize passenger throughput.

For our use case, we collected 50.000 real taxi trips within Vienna and to/from the airport. They are compared to the simulated performance of air-taxis (Sec. 2.2). All taxi trips are between 5 and 35 km since shorter trips do not make sense for air-taxis. The start and end points of the taxi trips are shown in Fig. 1. As described in Sec. 1.2, we assume that the air-taxis are stationed at hubs and fly to the start point of the trip one a request is placed. This is like the taxi system in Vienna, where taxis are also stationary and are summoned upon request. Therefore, we do not compare the deadhead, but only the net trip when the customers enter the vehicles.

The considered key performance indicators (KPIs) are:

-Travel time.
-Trip fare.
-Energy consumption.
-CO_2 emission.
-Value of travel time savings (VTTS).

For air taxis, travel time directly comes from the flight simulation, and trip fare uses the four different fare models in Sec. 2.2. and the current fare model for regular taxis according to Wiener Taxitarif [24]:

$$\text{EUR}\,5.80\,(\mathit{base\,fare}) + 4.75\,(\mathit{first\,5\,km}) + 0.58\,\mathit{per\,km}\,(\mathit{above\,5\,km}) + 0.58\,\mathit{per\,min}$$

For energy consumption, we assume that regular taxis use gasoline and have a consumption of 10 L/100 km in urban environment [23]. E-Taxis are assumed to be Tesla Model 3 and have a consumption of around 14 kWh/100 km [6]. For the air-taxis, the consumption is obtained via flight simulation for each trip, that considers the ascend and descent phases, the difference in altitude, and the average wind direction in Vienna. CO_2 emission calculation is straightforward. For gasoline, it is 2.3 kg CO_2 per liter and for e-taxis and air-taxis, the energy mix in Austria translates to 159 g CO_2 per kWh [22].

The VTTS is a calculated value that composes of travel time, cost, and the value of time in Austria. For this, we assume that the on-demand air-taxis and taxis are mainly used for leisure trips and business trips. For leisure trips, VTTS is calculated as.

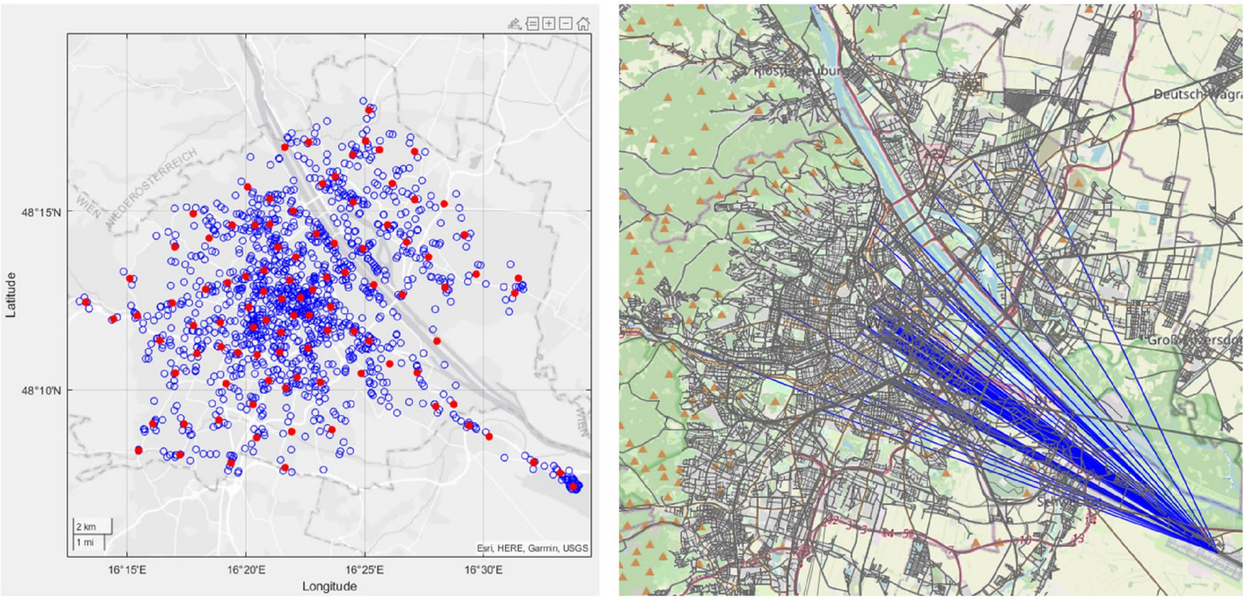

Fig. 1 In the left picture, start and end points (blue circles) of considered taxi trips in Vienna and their cluster centers (red points). The right picture shows the trips from/to the Vienna airport in the south-ern-east part (blue lines)

$$VTTS = VoL - VTAT$$

Where VoL is the value of leisure and VTAT is the value of time assigned to travel [3]. For the sake of simplicity, we assume that VTAT is equal for air-taxis and taxis since both travel modes are private, direct, and the customers do not need to drive. In a recent paper, VoL is estimated as EUR 8.17 per hour or EUR 0.14 per minute as Austrian average [12]. For business trips, we assume that the trip fare is paid by the employer, therefore VTTS is the actual personnel cost. We assume that only the top 10% paid jobs in Austria will allow air-taxis for business trips, so the salary for this group is above EUR 4800. The costs on the employer side, including labor costs, is EUR 46.13 per hour or EUR 0.77 per minute. Based on these values, we can say that the customer is likely to prefer the air-taxi if the additional cost divided by the travel time saving is lower than the VTTS.

3 Results and discussion

Table 1 shows the average values of the 50.000 trips. In the columns we compare the performance between taxi, e-taxi and air-taxi on short trips, medium trips, and long trips. The rows show the different KPIs: duration of the trip, trip costs where for the air-taxi where we considered four fare models (see Sec. 2.2: EUR 5 basic fare + EUR 1, 2, 5, or 10 per km).

The results offer several interesting insights. The significantly reduced duration of air-taxi trips is expected. First, air-taxis use direct distance compared to taxis and secondly, they are not delayed by traffic jams and traffic lights. The latter are the main cause for taxi trips being slow. Whether air-taxis can fly via direct distances or must follow certain air-routes in the future will change this indicator but is not considered in this paper.

For the trip fare, there are some surprises. Using the models Fare 1 and Fare 2, the air-taxi is cheaper in most cases, even without considering VTTS. This is due to the shorter trip length and the shorter duration of the air-taxi trips. In these cases, unless customers feel uncomfortable or reluctant to air-taxis, air-taxis are always favored over regular taxis. From these numbers, the basic fare of EUR 5 seems to be too low for Vienna if regular taxis already start at EUR 5.80.

The substantial high energy consumption for air-taxis is to be expected. It is obvious that flying is not a low-energy transport mode. This trend continues when looking at the CO_2 emissions. Air-taxis have a significantly higher emissions, even compared to taxis using gasoline, and even with the relatively environmentally friendly power plants in Austria. For short trips, air-taxis emit more than 3 times the CO_2 than taxis and for long trips, it is still a factor of around 2.5.

Figure 2 shows a relative comparison between air-taxis and taxis on all trips (short, medium, and long trips together) on four KPIs as histograms. For travel time and fare cost, we calculate for each of the 50.000 trips the ratio.

$$taxi\_kpi/air - taxi\_kpi$$

These ratios are inserted into a frequency table with 200 intervals. The y-axis shows the frequency where a ratio is within the corresponding interval. The bottom diagrams for energy consumption and CO2 use the inverted ratio.

$$air - taxi\_kpi/taxi\_kpi$$

We observe that travel time of taxi is mostly 4× to 6× higher, trip fare of taxi is mostly 30% to 40% cheaper when considering the model Fare 5, energy consumption of air-taxi is mostly 5× to 7× higher, and CO_2 emissions of air-taxi is mostly 3× to 4× higher.

For VTTS, we focus on the model Fare 5 which is EUR 5 base fare + EUR 5 per km. The reason is that for Fare 1 and Fare 2, the air-taxi is always cheaper. Also as discussed in Sect. 2.2, Fare 1 and Fare 1 are not viable from perspective of air-taxi operators. For Fare 10, the air-taxi is almost always too expensive. Therefore,

Table 1 Average KPI values for the taxi, e-taxi and air-taxi trips, grouped by short trips, medium trips, and long trips

	Short trips (5–8 km)			**Medium trips (8–14 km)**			**Long trips (14–35 km)**		
KPI	**Taxi**	**E-taxi**	**Air-taxi**	**Taxi**	**E-Taxi**	**Air-taxi**	**Taxi**	**E-taxi**	**Air-taxi**
Duration (min)	16.7		2.6	22.9		3.9	28.4		7.6
Fare 1 (EUR)	21.0		9.1	27.1		11.9	36.2		19.7
Fare 2 (EUR)	21.0		13.3	27.1		18.9	36.2		34.5
Fare 5 (EUR)	21.0		25.7	27.1		39.7	36.2		78.7
Fare 10 (EUR)	21.0		46.4	27.1		74.5	36.2		152.5
Energy (kWh)	5.6	0.9	34.2	9.5	1.5	48.5	18.6	2.9	88.5
CO_2 (kg)	1.7	0.1	5.4	2.9	0.2	7.7	5.7	0.5	14.1

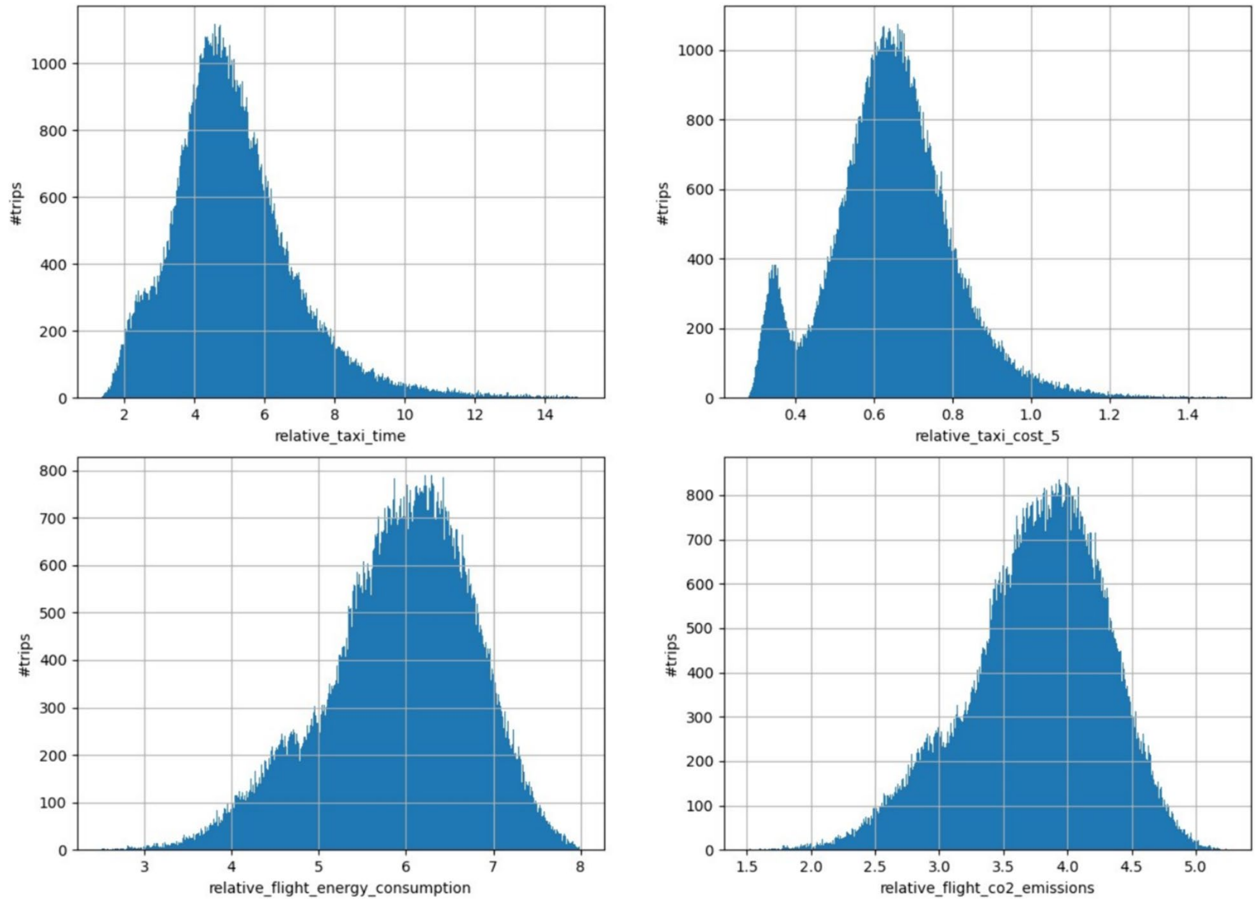

Fig. 2 Histogram over the trips for the relative comparison between air-taxi and taxi for all trips: travel time (top left), fare cost (top right), energy consumption (bottom left), and CO_2 emissions (bottom right)

these models are not useful for comparison. For the Fare 5 model, Fig. 3 shows a histogram for the additional fare cost of using the air-taxi (in Euro) divided by the travel time saving (in minutes) for short trips, medium trips, long trips, and all trips. The ratio for each trip is (air-taxi_cost—taxi_cost) / (taxi_duration – air-taxi_duration).

These ratios are inserted into frequency tables and displayed as histograms.

The green bar is the VTTS for leisure activities at EUR 0.14 per minute, and the red bar is the VTTS for business trips at EUR 0.77 per minute. As explained in Sec. 2.4, if we do not take other factors into account, if the cost per time saved is less than the VTTS (i.e., the left side of the bars), air-taxi would be favored. Since the VTTS for leisure is so low, the air-taxi is only attractive for a small number of these trips. For business trips, more than half of the short trips and medium trips are attractive for the air-taxi. For long trips, since the trip fare gets quite expensive with increasing distance, only a small number of trips are attractive. Considering that most business trips are from/to the airport and the direct distance from the center of Vienna to the airport is around 17 km, we conclude that around half of the airport trips are attractive for the air-taxi.

4 Conclusions and future work

This paper explored the emerging field of urban air mobility (UAM) with a specific focus on air-taxis. The integration of automated air-taxis into urban transport systems represents a significant advancement, offering the promise of reduced travel times, increased convenience, and more direct routes for passengers.

Our simulation framework composes of different methods to address different factors such as flight trajectories and overall traffic considerations. Through this comprehensive approach, we were able to evaluate the potential impacts of air-taxis on the transportation system. First of all, air-taxis offer substantial reductions in travel duration, a consequence of their ability

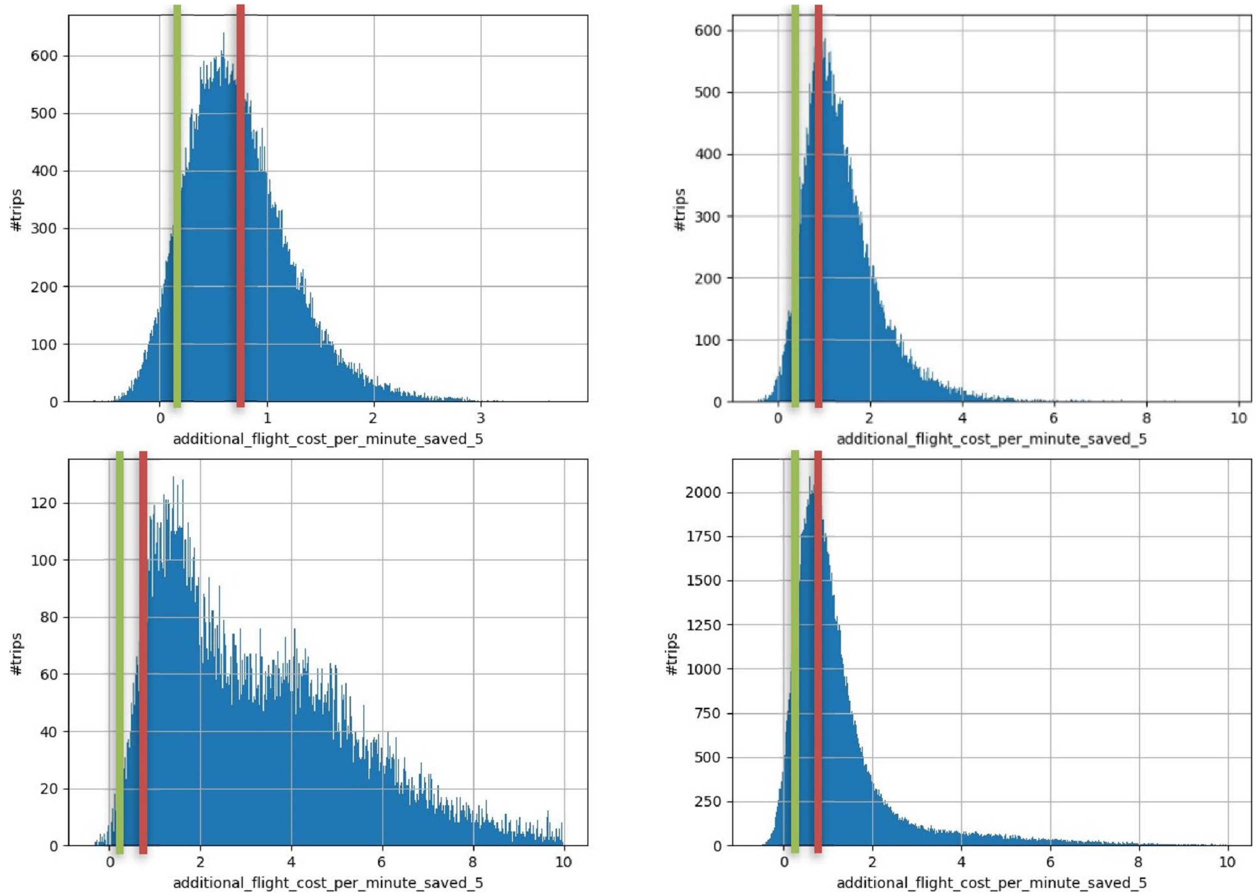

Fig. 3 Histogram over the trips for the additional fare costs of air-taxis divided by the travel time saved for short trips (top left), medium trips (top right), long trips (bottom left), and all trips (bottom right). The green bar is the VTTS for leisure activities, and the red bar is the VTTS for business trips

to navigate direct routes unburdened by traffic congestion or traffic lights. In terms of costs, the considered fare models show that air-taxis can often provide cost-effective alternatives to taxis. This affordability can make air-taxis an attractive choice for passengers, particularly on shorter routes. One of the key findings from our research is the substantial energy consumption linked to air-taxis. As anticipated it exceeds that of conventional ground-based transportation modes. Consequently, depending on the energy composition of the country, air-taxis may contribute significantly to CO2 emissions. If electricity generation relies on fossil energy, air-taxis can prove to be even more environmentally detrimental than gasoline-powered taxis. This highlights the environmental challenges associated with urban air mobility and the need for sustainable solutions. In the context of value of travel time savings (VTTS), the results indicate that air-taxis become particularly appealing for business trips, where the cost per minute saved is lower than the VTTS. This makes air-taxis particularly attractive for time-critical trips. For leisure activities, the attractiveness of air-taxis is limited due to the lower VTTS in Austria. This suggests that the appeal of air-taxis is closely tied to specific trip purposes and economic considerations.

In summary, the findings underscore the importance of tailored pricing strategies to ensure the sustainability of air-taxi services. As urban air mobility continues to evolve, further studies and ongoing evaluation will be essential to guide its integration into future transportation systems, ultimately shaping the way we move within our cities.

For the future work, we want to extend the methodology framework by the following aspects. While we've focused on point-to-point air-taxi services, assessing hub-based operations offers unique benefits like optimized routing and increased passenger pooling. This is an important aspect for improving the environmental impacts. Then, incorporating mode choice models can help us comprehend how air-taxis influence traveler decisions. Analyzing factors such as pricing, travel time, and environmental concerns will unveil potential shifts in transportation preferences. Finally, investigating passenger experiences, safety concerns, and societal acceptance will be crucial for fostering trust and confidence in air-taxis, promoting their successful integration into urban mobility.

Authors' contributions

AIT members were responsible for the overall paper structure, the operations research part, and the results part. PLANUM members were responsible for the transport model, FH JOANNEUM members were responsible for flight simulation, and BRIMATECH for the KPIs and acceptance. All authors then contributed equally to the creation of this final article version.

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Availability of data and materials

Two datasets were used in this paper:

The "Österreich Unterwegs" datasets is public available on https://www.bmk.gv.at/themen/verkehrsplanung/statistik/oesterreich_unterwegs/berichte.html.

The taxi trips dataset with 50.000 trips is a private data collection by the taxi platforms in Vienna. They are not publicly available.

Declarations

Ethics approval and consent to participate

All authors have approved the manuscript for submission.

Consent for publication

We confirm that the manuscript has not been published, or submitted for publication elsewhere.

Competing interests

We declare that we have no competing interests with the journal and its editorial board. The funding agency had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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