PIONEERING THE URBAN AIR TAXI REVOLUTION

1.0

VOLOCOPTER

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THE CASE FOR URBAN AIR TRANSPORTATION

The next decade is forecast to be the greatest period of urban migration in human history. By 2030, more than 60 % of the world's population will live in cities. Ground infrastructure, which is already operating at full capacity in many areas, is struggling to keep up with this urban growth. We believe that one answer to the challenges of urbanization is to take to the sky and unleash air travel in urban environments as a viable alternative to ground transportation.

In this article we will make a case for why we at Volocopter believe that we are on the cusp of a technological revolution enabling urban air mobility (UAM) at scale. We will focus on the requirements for the urban air taxi mission and discuss how we specifically designed the Volocopter, our electric vertical take-off and landing (eVTOL) aircraft, with this mission in mind.

It is important to note that, in this discussion, we will focus on the intra-city transportation use case: flying passengers within cities, where the greatest pain points will be alleviated. We will not be addressing the requirements for high-speed regional shuttles, which will ferry passengers between metropolitan regions.

THE RENAISSANCE OF ELECTRIC FLIGHT

Before diving in, we want to reflect on the renaissance underway in electric propulsion, the technology that will unlock urban air mobility.

The concept of electric propulsion in aviation is nearly as old as aviation itself. The first electric-powered aircraft debuted in 1917 (the tethered PKZ-1) and electric aviation has been a hobbyist's alternative in the interim years. Now, with the advancements in multirotor distributed electric propulsion systems and the sophisticated controls to manage them, electric propulsion has finally become a viable alternative to hydrocarbon-based systems.

THE URBAN AIR TAXI MISSION

The mission of the urban air taxi is to transport passengers and luggage from point A to B within a defined urban metropolitan area at a price that is competitive with alternative transportation modes.

In order to accomplish this mission, an eVTOL will need to at least address the requirements in the non-exhaustive list below.

1. **Safety & Certification:** Urban air taxis need to be as safe as any other commercial aircraft and consequently be designed to meet equivalent safety standards.

2. **Noise Emissions:** In order to fly in the city and take-off/land in populated areas, the urban air taxi will have to comply with demanding noise restrictions to achieve public acceptance.

3. **Range & Speed:** The air taxi needs to be able to cover the most popular high-traffic routes in major cities, like the airport to city-center route. These trips should be covered at a reasonably high speed in order to save time compared to ground transportation alternatives.

4. **Operating Costs:** To enable a viable and scalable business that addresses a meaningful customer base, air taxi operating costs should be low enough to offer competitively-priced transportation services.

5. **Number of Seats:** The number of passenger seats is a key design driver and needs to match the needs of the urban air taxi mission.

6. **Design for Usability:** Passengers need to be able to embark, travel, and disembark comfortably and safely. This will entail design requirements for cabin noise levels, vibration, climatic conditioning, perceived safety, etc.

We will address each of these requirements in detail below and elaborate on how Volocopter addresses them in its development of a viable urban air taxi product.

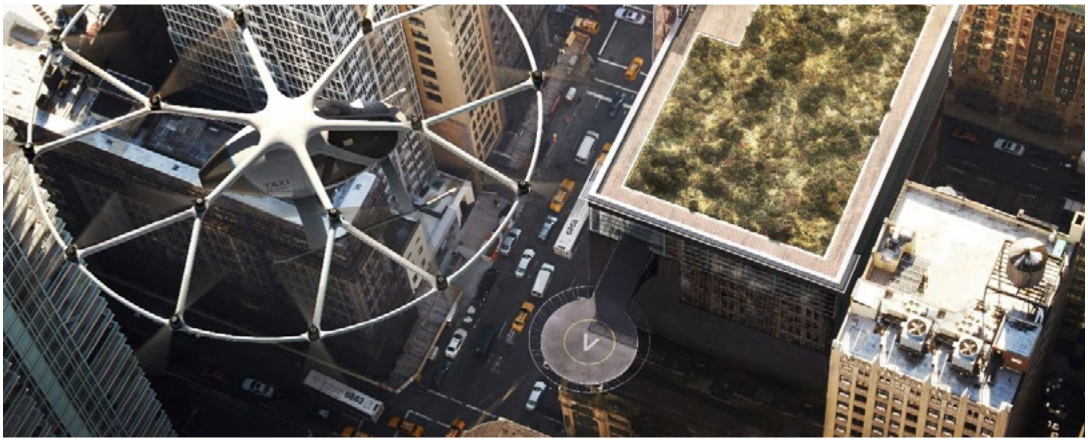


Figure 1 The Volocopter deployed as an urban air taxi

SAFETY & CERTIFICATION

Safety is paramount in designing next-generation eVTOL aircraft for an urban air taxi mission. The service will only achieve public acceptance if it can be shown to operate safely. To this end, the European Union Aviation Safety Agency (EASA) published the SC-VTOL-01 "Proposed Special Condition for small-category VTOL aircraft" in October 2018, which outlines the airworthiness standards for eVTOLs. (The final version is expected to be published by EASA in June 2019. Data shown in Figure 2 reflect updates towards the final version, which have been shared at VTOL special conditions briefing by EASA on Feb. 27, 2019.)
In this document, EASA defines required safety objectives for urban air taxis, which are basically equivalent to those for other commercial aircraft. Details can be found in Figure 2, where "Category Enhanced" applies to urban air taxis. We applaud EASA for proposing explicit regulations for this new market and for recognizing that upholding the highest safety standards is key to market success.

	Maximum Passenger Seating Configuration	FAILURE CONDITION CLASSIFICATION			
		Minor	**Major**	**Hazardous**	**Catastrophic**
Category Enhanced	**0 to 9**	$\leq 10^{-3}$ FDAL D	$\leq 10^{-5}$ FDAL C	$\leq 10^{-7}$ FDAL B	$\leq 10^{-9}$ FDAL A
Category Basic	**7 to 9**	$\leq 10^{-3}$ FDAL D	$\leq 10^{-5}$ FDAL C	$\leq 10^{-7}$ FDAL B	$\leq 10^{-9}$ FDAL A
	2 to 6	$\leq 10^{-3}$ FDAL D	$\leq 10^{-5}$ FDAL C	$\leq 10^{-7}$ FDAL C	$\leq 10^{-8}$ FDAL B
	0 to 1	$\leq 10^{-3}$ FDAL D	$\leq 10^{-5}$ FDAL C	$\leq 10^{-6}$ FDAL C	$\leq 10^{-7}$ FDAL C

Quantitative safety objectives are expressed per flight hour

Figure 2 Safety objectives for eVTOL aircraft (EASA) according to VTOL Special Condition Briefing 27-Feb-2019

Practically speaking, when designing a new aircraft to these standards, we must take into account all aspects of the system, including (but not limited to) product design, crew training, maintenance aspects, manufacturing, air traffic management deployment, etc. In this white paper, we will limit the discussion to the safety of the vehicle itself.

In principle, the minimum safety requirements for air taxis will be standardized, and thus should be identical for each vehicle. These standards are set and enforced by international aviation agencies like EASA and the FAA. Any vehicle that fails to meet the safety requirements will not be permitted to fly in commercial operations. We would therefore expect that safety, while being an entry-barrier, is not going to be a differentiating factor. However, if we look into the details, there can be substantial differences. This is because historically, mission-specific requirements are not outlined in the type certification requirements. Instead, they are specified in additional operational requirements that need to be met by the operator in order to receive approval for a specific mission.

EASA has defined this in the SC-VTOL certification basis. Simply put, the SC-VTOL foresees different levels of safety requirements depending on the intended mission of the aircraft. An aircraft used only for sports and leisure activity outside of the city is required to meet safety levels that are up to 100 times lower than an aircraft used for commercial air taxi services within a city (i.e. compare “basic” and “enhanced” requirements in Figure 2).

Therefore, when we compare different eVTOL concepts, we need to look at them within the context of their intended mission. Many of the eVTOLs marketed as “air taxis” today, are actually more likely intended to be “sports & leisure” type aircraft. By design they are unlikely to meet the strict safety requirements for urban air taxis. Both, the FAA and EASA, offer ways to operate such aircraft non-commercially outside urban areas (e.g. when classified as “ultralight” aircraft).

In developing the Volocopter we take safety into account for every aspect of the design. We believe that safety and simplicity are closely correlated. Thus, the simpler the architecture, the more likely that the aircraft will gain certification. Specifically, the Volocopter has 18 motors fitted with fixed-pitch rotors, which have only one degree of freedom: the rpm (revolutions per minute) at which they operate. There are no tilting components in this highly-redundant propulsion system, which is extremely robust vis-à-vis individual motor failure. In other words, the Volocopter can safely end its mission even after multiple motor failures. This essentially enables the vehicle to meet the safety standards specified by EASA. Similar levels of redundancy are designed into the Volocopter flight control system and its onboard data networks. The Volocopter is one of the few eVTOLs actually designed to meet all the safety requirements for operating in urban air taxi missions.

Figure 3 Volocopter undergoing flight trials in an urban environment

Many different eVTOL architectures have been proposed. In our view, the more complex a system becomes, the more difficult and expensive it will be to show that the system will have the required low failure probability required for certification, i.e. a failure probability of one in a billion flight hours for critical systems functions. There are some interesting architectures with tilting wings, tilting rotors and variable pitch propellers. These can all be made to work and are as such amazing technologies. However, designing them in a way that demonstrates the required low failure probability is likely to be difficult.

As an example, imagine how difficult it would be to show continued safe flight operations if a tilt rotor were to become jammed halfway through a tilt. Even something as basic as a retractable landing gear or an electric wheel brake can be extremely hard to certify, because malfunction can typically lead to a loss of the aircraft.

To summarize our position: simplicity = safety = certifiability.

NOISE EMISSIONS

The next key design driver for any urban air taxi is the noise signature. One of the reasons that helicopter flights over many cities are strictly limited today is because of the "noise pollution" that they cause. If air taxis are to be accepted by the people living and working in the cities they fly in, they will need to be designed and operated in a way that strictly limits the noise level audible on the ground. Plus, the generated noise should be subjectively non-disturbing. Certain frequencies are perceived as more disturbing than others, regardless of the actual decibel levels of the noise. Consider the high-pitch sound of a legacy helicopter tail rotor as an example.

In Uber's Elevate white paper[1], noise is identified as one of the major differentiators and vehicle design drivers. Further studies by Porsche Consulting[2], Roland Berger[3], and McKinsey[4] support this analysis. Due to the laws of physics, air taxis with low disc loading and low rotor tip speed produce less noise than those with higher disc loading and faster rotor tip speeds. The rotor tip speed and number of rotor blades defines the frequency signature and in combination with the disc loading defines the overall noise level of the rotor.

In simplified terms, this means that an air taxi that has a small rotor surface relative to its weight is likely to be very loud. This is because the weight of the aircraft will need to be carried by accelerating air up to very high speeds using a very small rotor surface. On the other hand, an air taxi with a rather large rotor surface relative to its weight will have a better noise signature, as it can deliver the required lift by accelerating the air with less speed over a larger surface. In addition, keeping rotor tip speeds low is another key to improving the noise signature.

1 Uber Elevate; "Fast-Forwarding to a Future of On-Demand Urban Air Transportation"; October 2016
2 Porsche Consulting; "The Future of Vertical Mobility"; March 2018
3 Roland Berger GmbH; "Urban air mobility: The rise of a new mode of transportation"; November 2018
4 McKinsey Company for Future Mobility; "Taxiing for take-off: The flying cab in your future"; January 2019

Human Powered Multicopter

Jet Pack

Human Powered Multicopter		Jet Pack
like a glider	**Noise**	like a racing car
balanced	**Noise spectrum**	very disturbing
0.7 kW	**Power required**	150 kW

Figure 4 Difference in noise lifting the same payload (Source: Aerovelo, Martin Jet Pack)

To visualize this relationship between disc loading, tip speed and noise, consider the following two applications for lifting the weight of one person. The slow-moving large rotors of the human powered multicopter can hardly be heard, while the "jet pack" solution with its small, fast-spinning rotors generates a lot of noise (compare to Figure 4).

The above holds true in the critical vertical take-off and landing phase, where the distance to people on the ground is smallest. In cruise flight at sufficient speed, generating lift using wings may be an efficient way to reduce noise signature, although vertical noise emissions by conventional propellers may negate part of this advantage.

When looking at the urban air taxi mission, the most critical phases in terms of noise emission are take-off and landing. It is in these phases that the aircraft has the greatest impact on the surrounding area and people. Aircraft like the Volocopter with a large rotor area and low disc loading will be more likely to comply with strict noise regulations and be granted access to densely populated areas. It is important to note that a large rotor disc area can be achieved by using a few large rotors or numerous smaller rotors. Slower tip speeds can be achieved by using a large number of small rotors, which in turn reduces noise coming from the rotor tips. In addition, a large number of smaller rotors is perceived to be quieter than one larger rotor. This is because various weak noise sources spread noise over a broad frequency spectrum, which is less disturbing to the human ear than one prominent noise source.

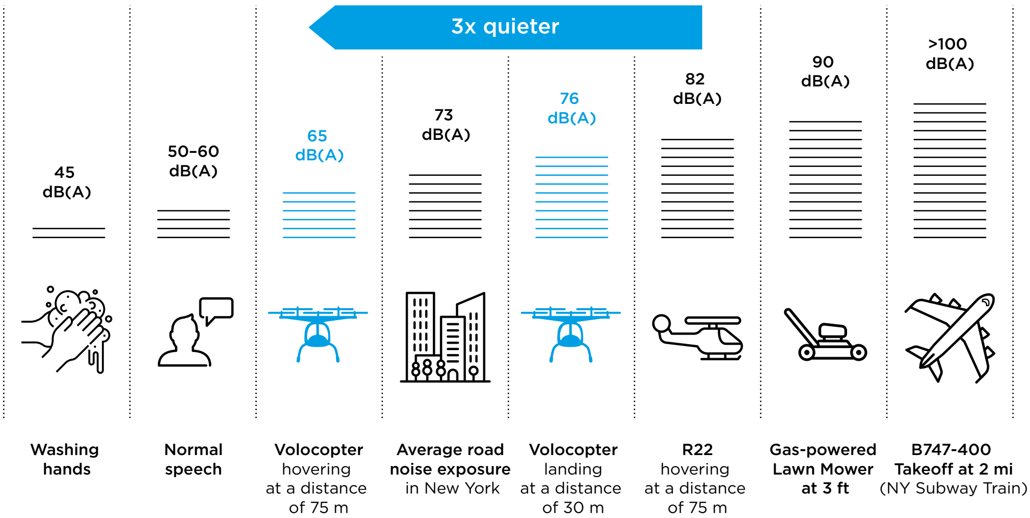


Figure 5 The Volocopter can be integrated into the city without adding significantly more noise pollution

Volocopter has taken all of the above factors into account in the design of its air taxi. As a result, Volocopter has emerged as the air taxi with the lowest noise signature that is best suited to fly into the populated centers of megacities without adding to the present noise pollution.

RANGE & SPEED

One of the most hotly-debated questions about urban air taxis focuses on the required range of an eVTOL for the urban air taxi mission. Compared to conventional aircraft, urban air taxis fly very short distances and thus only require a limited range to offer useful capabilities.

Uber's Elevate paper suggests that urban air taxis will mainly be useful to so-called "mega commuters," people who commute more than 160 km per day, therefore making a minimum useful range for these commuters half of that distance (80 km). The paper also suggests that there would be no opportunity to recharge the batteries between flights, which means that the air taxi would have to fly the return trip (160 km) without recharging. The authors assert that for shorter range commutes, the ground infrastructure requirements would be too cumbersome for practical purposes.

Figure 6 Thanks to its low noise signature, the Volocopter can fly into densely populated areas

Volocopter takes a different view. The Elevate paper focuses on a very specific use case (mega commuters) in a limited number of geographic areas. However, there are a multitude of urban air taxi use cases that exist globally. In our view, many timesaving routes can be operated efficiently and economically with limited infrastructure at a much shorter range. Examples include connecting key geographic locations, like airports, shopping malls, business districts, train stations and hotels. Consequently, urban air taxis can be used for purposes other than the daily commute use case, e.g. to shuttle passengers between a business district and an airport, or between a shopping mall and a major hotel, etc. In fact, studies suggest that the inner-city air taxi mission represents the highest demand and thus business potential.

Volocopter's in-house analysis found that most megacities have an urban area spanning less than 30 km around the geographic center, while most of the major airports serving these cities are within 30 km of the city center. More specifically, 70 % of the analyzed megacities have a major airport within 20 km of the city center (e.g. Melbourne or Mumbai), while 93 % have a major airport within 30 km of the city center (e.g. Houston or Guangzhou).

Examples illustrating this point are outlined below.

GIS population density of selected cities of our top 100 city list

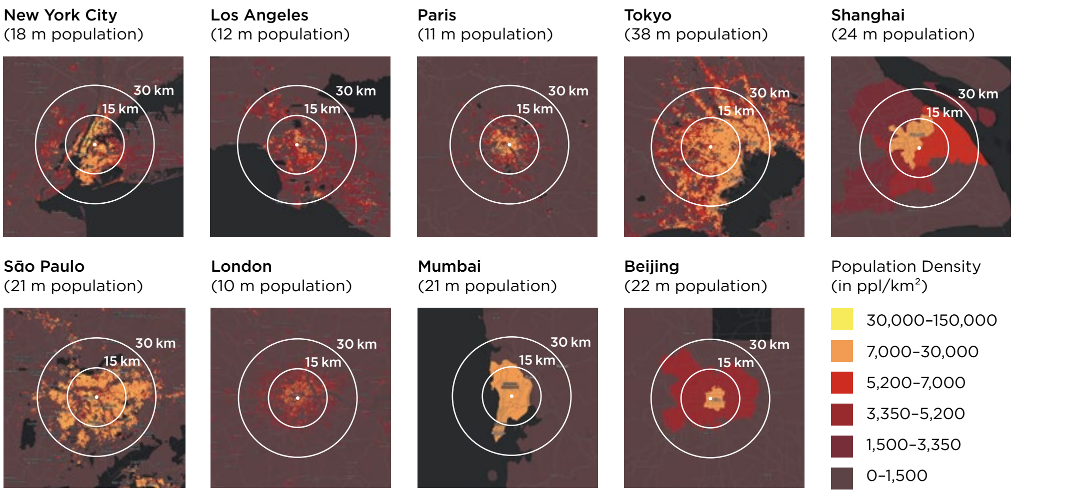
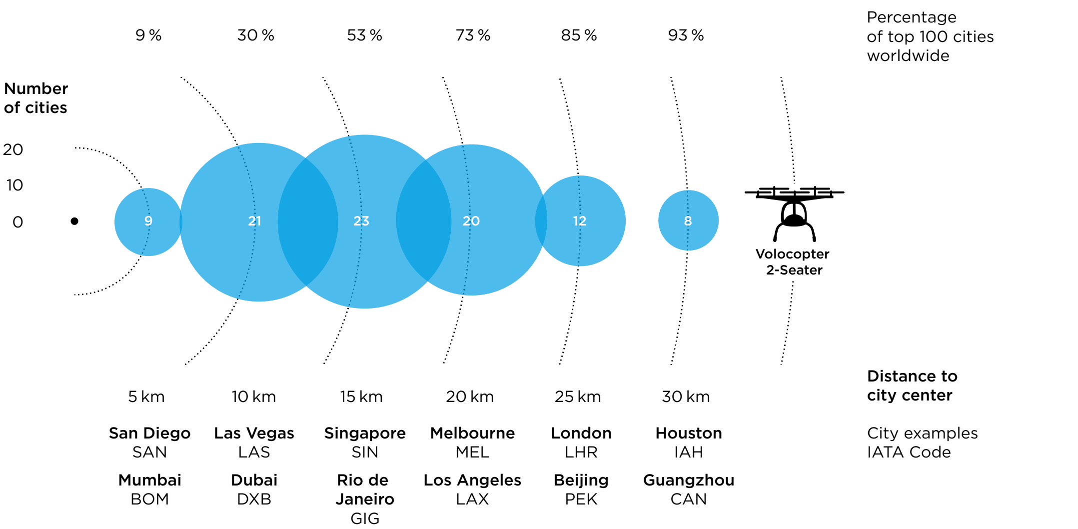


Figure 7 Most major cities have an urban area spanning less than 30 km around the geographic center (Source: ARCGIS)

With its initial range the Volocopter serves 93 % of all airport to city center routes of our top 100 city list[1]



1) 7 of the 100 cities are not accessible because of a respective airport to city center distances of up to 48 km.

Figure 8 With the Volocopter's initial range, most key airport – city center routes can be served

This view is generally supported by studies from Roland Berger[5] and Porsche Consulting[6] that forecast a larger UAM market share for intra-city air taxis and airport shuttles than for intercity flights.

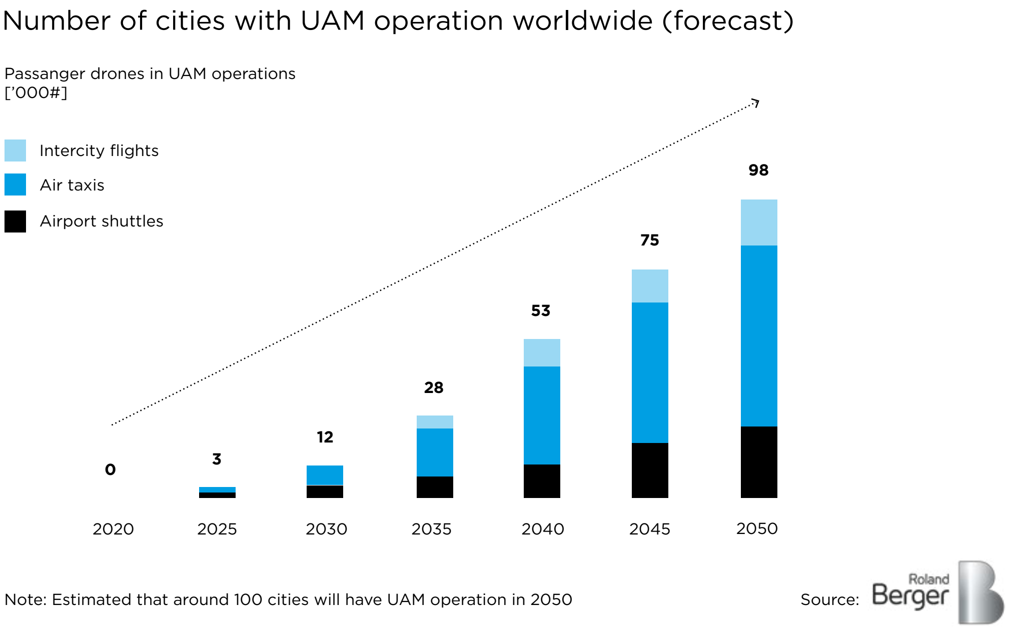


Figure 9 Forecasted number of cities with UAM operations worldwide (Source: Roland Berger)

Looking at a practical example, we could imagine implementing an airport shuttle between John F. Kennedy International Airport (JFK) and Midtown Manhattan, which is a notoriously cumbersome route to travel by road or by rail. The distance through the air is less than 30 km and can be covered by an air taxi in 20–25 minutes, whereas according to cellphone data[7] 90 % of ground trips take longer than 60 minutes and roughly 50 % of trips take longer than 90 minutes. This represents a huge potential for time saving! In addition, this trip could already be implemented under current regulations utilizing existing helicopter routes.

5 Roland Berger GmbH; "Urban air mobility: The rise of a new mode of transportation"; November 2018
6 Porsche Consulting; "The Future of Vertical Mobility"; March 2018
7 www.streetlightdata.com Analytics tool

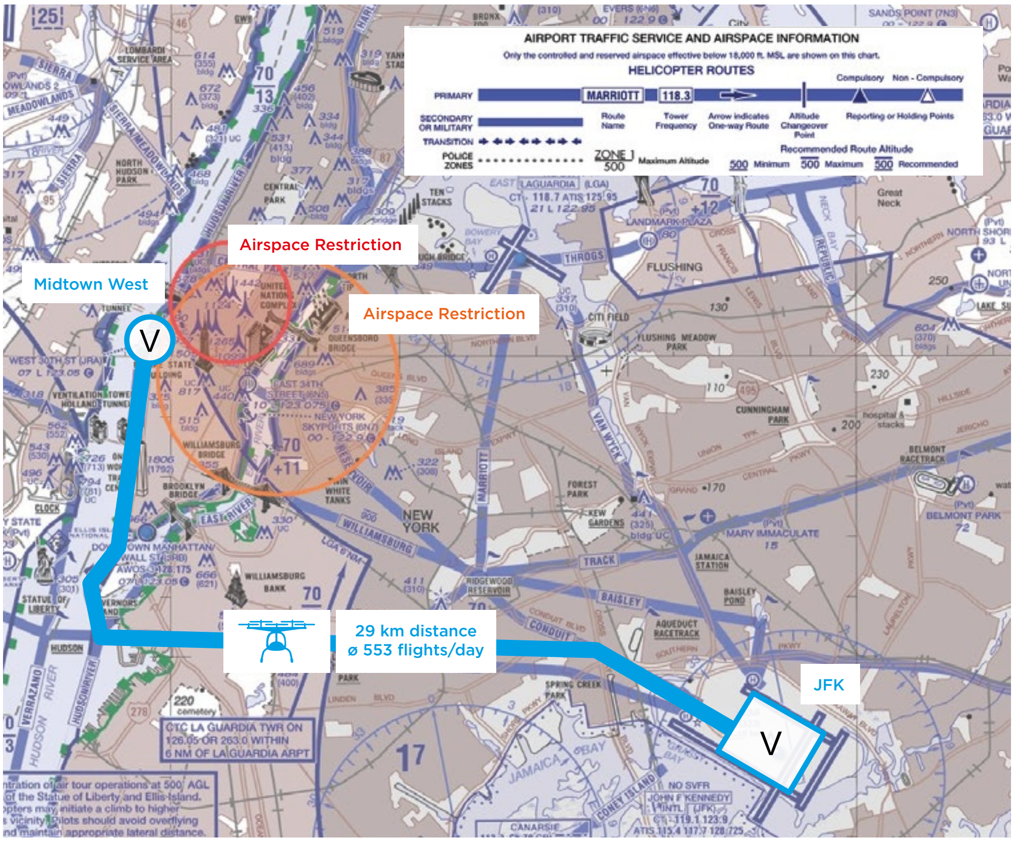


Figure 10 Example of an urban air taxi route for New York (JFK-Manhatten)
(Source: streetlight data)

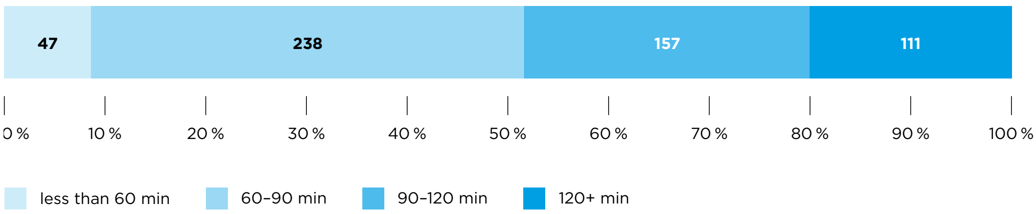


Figure 11 Statistics on trip times from JFK Airport to Midtown Manhattan (Source: streetlight data)

From the above analysis, we at Volocopter have determined the range requirement for our Volocopter air taxi to be somewhere between 30 and 35 km. This will enable the Volocopter to offer inner-city taxi and airport shuttle services in more than 90 % of megacities.

The corollary consideration to range is time saving. Ultimately, in order to serve as a viable mass-market transportation solution, air taxis must save customers time compared to a road trip. In short, speed is important. Even without traffic jams, it is rare to travel within megacities at an average speed of more than 50 km/h. It is even rarer to find a direct straight-line connection between two major locations inside such a city. This means that using ground transport, a 30 km trip will take from 35 minutes to more than 120 minutes if there are traffic jams or no efficient routing.

With a Volocopter traveling at an average speed of 80 to 100 km/h, a 35 km trip would take 18 to 22 minutes. This represents a time saving of at least 50 %! Faster speeds may further reduce travel times. However, when air taxis are operating at low altitudes over densely populated areas there will be limitations on the speed for the following reasons:

- **Noise:** This issue is addressed in detail above. Faster aircraft will generate more noise.

- **Collision-avoidance:** It is reasonable to assume that other aircraft and drones will be operating in the same airspace (e.g. camera drones, parcel delivery drones, helicopters providing emergency medical services, etc.). It is paramount to ensure these aircraft share the airspace safely. Detecting and avoiding other aircraft will be more difficult with increasing speed. This is because the required detection range increases linearly with higher speed (e.g. imagine spotting a parcel drone that is only 1 km away).

- **Bird strike damage:** Flying birds are an important consideration in low-altitude airspace. Lower speeds will be necessary to enable timely detection and avoid collisions. In addition, potential damage caused by birds striking an aircraft increases quadratically with the aircraft speed. Hence, limiting speed will be one way of avoiding “armoring” air taxis (which comes at a high weight expense).

Flight time at different cruise speed scenarios

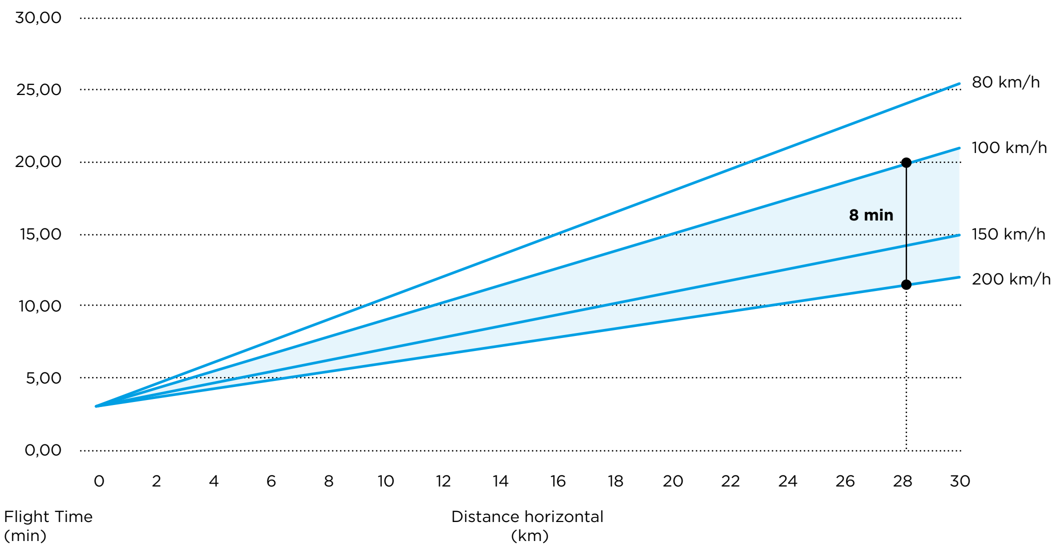


Figure 12 Travel time savings relative to speed of travel

In practice, when designing an air taxi, tradeoffs need to be made between range, speed, noise, weight, and other factors. At Volocopter, we have found that with a cruise speed in the range of 80 to 100 km/h, we can offer a service that saves significant trip time while enabling low-cost, safe operation at low altitudes and offering a design that is the benchmark for low noise signature.

OPERATING COSTS

The viability of urban air taxis as a complementary mode of transportation will depend largely on the level of pricing that can be offered to the end customer. The high operating cost of legacy helicopters is one of the reasons they are not widely used for airborne taxi services today.

What can we do to ensure low operating costs for air taxi services? For simplicity, this white paper will focus on technical, design-related issues. However, it is clear that there are additional factors, like landing fees, that also contribute to the equation.

COST OF ENERGY

The most obvious cost component of an electrically powered air taxi is the cost of electrical energy consumed to carry out the flight. While the actual cost of electrical energy may vary from one geographic region to another, it is safe to say that a more energy-efficient design will lead to lower operating costs. If we take the need for vertical take-off and landing as a prerequisite, a large part of the energy will be consumed during these energy-intensive phases in which the air taxi needs to hover and maneuver at low air speed. During this phase, all lift needs to be generated by the propulsion system. These flight phases will be especially challenging for air taxis that are optimized for larger passenger capacity and range. A larger number of passengers will contribute to a higher take-off weight, while the bigger battery for longer range will also add considerable weight. The high weight will require a large amount of thrust, and power, to maintain flight. Unfortunately, the level of required power in vertical take-off increases more than linearly with the take-off weight (momentum theory), while a smaller rotor area also leads to a significant increase in power requirements.

The following example illustrates how significant this is. A typical transformative eVTOL design may have a power requirement ranging from 500 to 1000 kW for take-off and landing. If we assume just three minutes for take-off and landing per flight, this results in energy consumption of 25 to 50 kWh – just for take-off and landing! This is equivalent to the full battery charge of an electric car (e. g. Tesla Model 3 SR with 50 kWh battery) consumed in just three minutes. Most available battery technologies cannot reliably deliver this level of power within the weight and size limits of the aircraft design (i.e. it would require a very large, heavy battery). To illustrate once more, the 50 kWh required for an eVTOL would require more than 200 kg of battery chemistry. This does not include the cruise phase of the flight nor does it take into account the package weight of the battery (assuming an optimistic 250 Wh/kg on cell-level).

The Volocopter, on the other hand, can complete a full 30 km urban air taxi mission including take-off, landing and cruise phase with a similar amount of energy thanks to its very high energy efficiency in the low-speed phases of flight. As a result, the energy and battery contribution to the overall operating costs will be relatively low for the Volocopter.

The conclusion that multicopter concepts are preferable for short- to mid-range missions is generally supported by the NASA study "Observation from Exploration of VTOL Urban Air Mobility Designs" published by Wayne Johnson and Christopher Silva[8].

8 NASA Ames Research Center; "Observation from Exploration of VTOL Urban Air Mobility Designs"; October 2018

Hover vertical lift efficiency as a function of disc loading

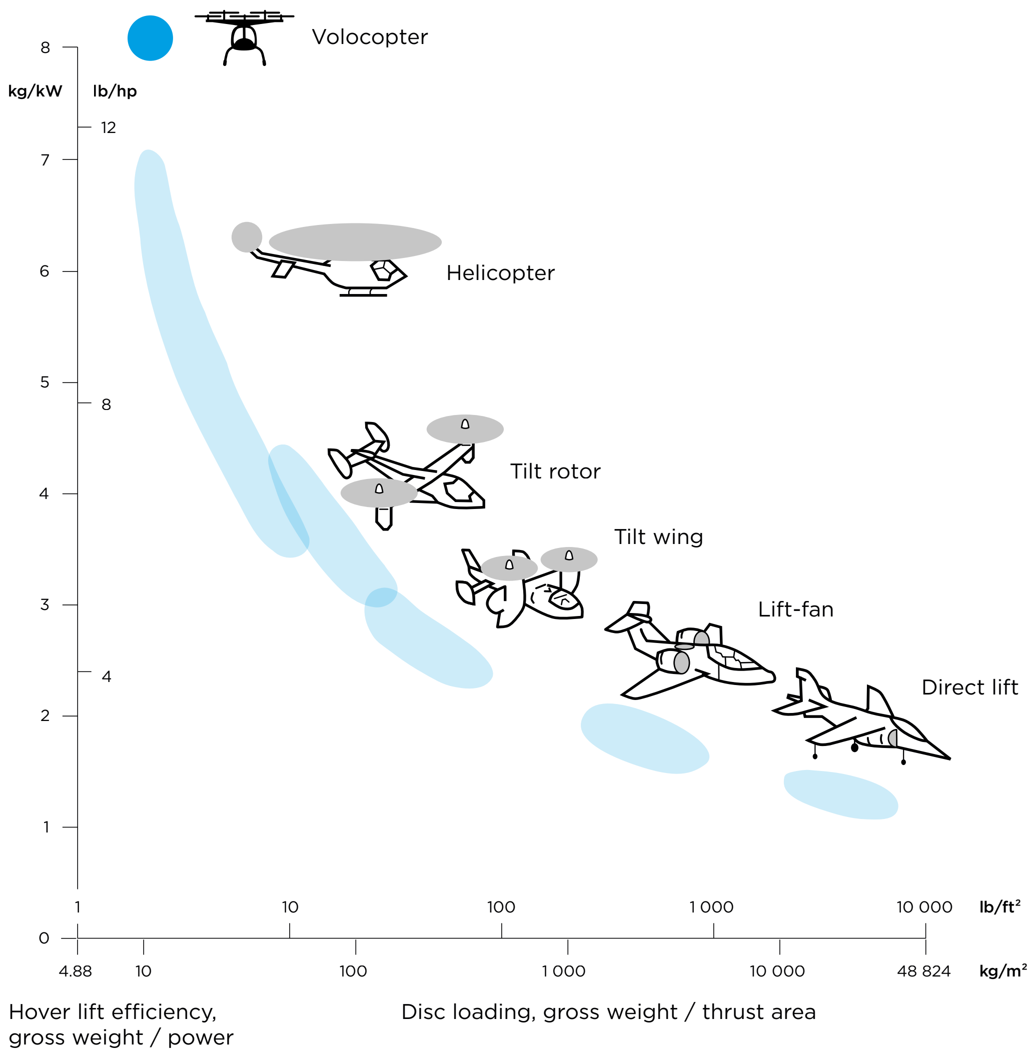


Figure 13 Lift efficiency in vertical take-off and landing (Source: NASA, edited by Volocopter)

COST OF BATTERIES

Directly related to energy consumption is the cost attributable to the battery depreciation per flight. Although automotive applications have become very good at designing batteries that are optimized for long life, the severe weight constraints of air taxi applications mean that trade-offs need to be made. These often favor battery systems with a lower lifetime that are capable of delivering higher power and energy densities (i.e. capable of supplying high continuous power). More specifically, common techniques to extend battery life in EVs include reducing thermal stress using a sophisticated liquid-based battery cooling system and reducing load on individual battery cells by over-sizing the battery.

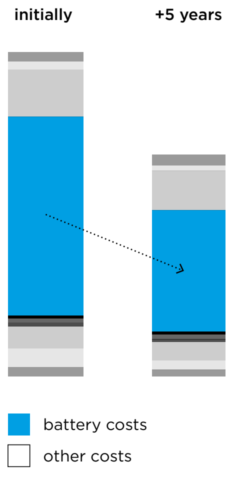
Moreover, an EV battery may be designed for a car that primarily operates in the middle of the charge spectrum, never completely charging or discharging the battery (full charge/discharge cycles lead to reduced lifetime). These techniques are difficult to implement in air taxis because they inevitably lead to additional weight.

For the above reasons, it is fair to assume that battery lifetime in an air taxi (counted in charge/discharge cycles before 80 % of the original capacity is reached) will be far lower than in a typical EV. Current commercial battery cells for air taxi applications typically offer between 600 and 800 cycles, although this number may be lower in poorly designed battery systems or under unfavorable operating conditions. This is assuming that the batteries are charged and cooled between flights (e.g. swapped). The battery life will suffer further if fast charging is applied in between flights. This means that the cost of the battery pack needs to be amortized in 600 to 800 flights, which makes it a major contributor to operating costs even if EV costing levels are reached (imagine 20–30 or more flights per day to visualize what this means for battery lifetime).

Main drivers for operating cost

Preliminary city transport economics per seat

PRELIMINARY COST BREAKDOWN



VOLOCOPTER BATTERY COSTS

Low capacity = low amortization

- High mission efficiency
- Capacity similar to Tesla Model 3 SR

Increased lifetime

- No fast charging
- Operating at moderate discharge rates
- Low thermal stress

Figure 14 The battery is one of the main drivers for operating costs. The Volocopter and its infrastructure are designed to minimize the cost impact

OTHER COST DRIVERS

Additional factors contributing to high operating costs include inspection, maintenance, and overhaul. With legacy helicopters, there are many items that require frequent inspection, maintenance and overhaul (including turbine engines, gear boxes, hydraulic systems, complex main rotor systems, etc.). Consequently, hybrid-propulsion eVTOLs relying on turbine engines (or turbo-generators) will suffer from some of the same high cost issues as legacy helicopters. The same may well apply to complicated tilting mechanisms, where actuators are typically safety-critical components designed for a limited number of tilting cycles and requiring frequent inspection/overhaul. One might argue that in the digital age, sophisticated, data-driven health monitoring systems will make the need for inspections obsolete. Looking at practical examples however, proving that such systems will detect failures before disaster strikes is far from trivial and requires operational experience to obtain certification. Hence, the more mechanical components with limited operating life that are implemented in a particular air taxi design, the higher the costs attributed to performing inspections, maintenance and overhaul (this does not include the indirect cost of aircraft downtime during maintenance).

Finally, the cost of developing and producing an air taxi will need to be amortized over its useful lifetime. This issue is especially tricky for short-range air taxis for the following reason: Aircraft lifetime is typically calculated in duty cycles. For an airliner, a cycle may consist of one multi-hour flight between two airports, whereas take-off and landing are the penalizing phases for aircraft. For the sake of argument, let's assume a typical short-haul airliner may see 4–5 cycles per day. By contrast, an air taxi operating just 12 hours per day on 20–30 km routes may experience as many as 20–40 duty cycles per day. This means that when we assume identical design standards, air taxis will reach their service life limits one order of magnitude faster than typical airliners. Therefore, their costs will have to be amortized over a much shorter period of calendar time.

Generally speaking, air taxi designs that include many high-cost components or are difficult to manufacture at scale will incur significant amortization cost. Typical examples of expensive components with limited life include gear boxes, overly-complicated electric motors, retractable landing gears, and sophisticated sensor suites (e.g. high-end lidar systems).

Moreover, it is worth noting that most air taxi designs proposed today, including the Volocopter, make use of carbon composite materials. Building a prototype aircraft in a manual process may be feasible, but many companies have historically failed in the economic upscaling of their composite production processes. This could quickly lead to the airframe becoming an expensive contributor in the overall cost equation.

Figure 15 The Volocopter uses a battery swapping technique to maximize battery lifetime, and minimize turnaround time

VOLOCOPTER ON COSTS

Finally, let us conclude with an explanation of how the Volocopter design leads to best-in-class, low operating costs. As previously mentioned, the Volocopter is specifically designed for short-haul missions in which the vertical take-off and landing phases contribute heavily to the overall energy consumed and wing-born flight does not pay off. The Volocopter can fly a complete mission with less than 50 kWh of energy. Battery cost is managed by maximizing useful battery life. A direct consequence is that Volocopter does not apply fast-charging to its batteries. Instead, it swaps the batteries after every flight. This allows the batteries to be charged at optimal (low) C-rates, while being properly balanced and reducing thermal stress by using efficient, ground-based cooling systems.

In addition, the Volocopter was specifically designed to exclude high-maintenance systems that drive the maintenance cost of legacy helicopters. Direct-drive electric motors and fixed pitch rotors were chosen and high-maintenance tilting mechanisms were avoided. For the same reason, a skid-based landing gear system was chosen over a wheeled solution with active brakes. The carbon composite air frame was designed to enable high-volume production using established aerospace manufacturing techniques. All of this helps keep periodic inspection and maintenance to an absolute minimum.

NUMBER OF SEATS

The number of seats an air taxi offers is one of the key design drivers. A larger number of seats offers the potential to transport more paying passengers and spread operating costs over more seats. But at the same time, more seats have a significantly negative impact on the overall weight of the air taxi and the power required for vertical take-off and landing. As explained in a previous section, this higher power requirement will likely translate into a higher noise profile during take-off and landing. In our view, these circumstances favor smaller air taxis with fewer seats for missions in a densely populated urban area where low noise emissions are paramount.

Another aspect is that having more seats is only economical if a high passenger load factor is achieved. Therefore, the key question is how many people can be transported on a typical air taxi trip. Even though air taxis are not commonplace today, we have some good data to use as a basis for our analysis.

NASA published a paper in 2016[9] called “Silicon Valley as an Early Adopter for On-Demand Civil VTOL Operations.” This paper references data from the American Travel Survey, which shows that 70 % of all road trips under 160 km involved one single person, while the average load factor is 1.3 people. The data referenced in this paper also shows that load factors are very similar for conventional take-off and landing (CTOL) air taxis. Anecdotal evidence from the few helicopter air taxis in service today confirm these load factors.

There is no indication that load factors for a typical trip by air taxi will differ significantly from ground taxis. For this reason, the Volocopter has been designed to have two seats. Initially, one will be occupied by a pilot, which enables 70 % of typical short distance trips to be serviced. In a second step, as autonomy-enabled solutions become viable, two passenger seats will become available, enabling the Volocopter to perform the vast majority of the urban air taxi missions.

DESIGN FOR USABILITY

In order to become a common everyday mode of transport, eVTOLs must be practical in their design. Most general aviation aircraft are cumbersome when it comes to passenger entry and exit. Unfortunately, this factor has left its mark on many of the current designs being presented as air taxis. In our view, nobody ordering an air taxi ride would expect to have to climb into the cockpit like a jet fighter pilot or step around rotors installed at knee height.

9 NASA Langley Research Center; “Silicon Valley as an Early Adopter for On-Demand Civil VTOL Operations”; June 2016

Figure 16 The Volocopter is designed to provide practicability and comfort for passengers

So, what makes an air taxi design practical? Embarking and disembarking need to be convenient, safe, and comfortable for people of any age. This should be as convenient for elderly passengers as it is for younger ones and equally comfortable for people dressed in business or casual clothing.

Safe embarking and disembarking imply that the passenger does not move through the rotor or propeller area (regarded as a crucial safety issue for passengers and aircraft), even when the blades are not turning. Next, the passenger should have sufficient space inside the cabin along with comfortable seating. Some of the “air taxis” demonstrated thus far show two persons crammed side by side into a small capsule. While we do not believe that paying customers will accept this lack of comfort for very long, this also constitutes a safety issue, since the passenger could easily interfere with the pilot’s flight controls. Passengers should also be able to bring a reasonable amount of luggage onboard. There would also need to be a practical way to stow the bags to avoid becoming a safety hazard for the pilot, passengers, or aircraft.

Another issue that seems to have attracted little attention in air taxi designs is the fact that many of the powerful propulsion systems produce extensive cabin noise due to high disc loading and tip speed. It is questionable whether high noise will be acceptable to travelers expecting to use their cell phones and make conference calls while in transit. The powerful motors required for vertical take-off also tend to cause heavy vibrations in the cabin. In legacy helicopters, this is often extremely uncomfortable and is partially compensated by active or passive anti-vibration systems that come with a weight penalty. Travelers in an air taxi will find it difficult to check e-mails or a news feed if they are being constantly shaken by excessive vibrations.

Figure 17 A practical design for urban air taxis

Another issue involves air conditioning systems, which are not very common in small general aviation aircraft but may well be expected by passengers that are accustomed to commuting with a ride hailing service. Unfortunately, these environmental control systems (ECS) consume large amounts of energy and are generally heavy, which can have an impact on the maximum range of an air taxi.

We at Volocopter consider all these aspects to be key factors for a comfortable and safe use of this new transport technology. The Volocopter specifically improves embarking and disembarking without interference by the rotor disc area. Rotors are mounted overhead to avoid direct contact. Boarding a Volocopter is similar to getting in and out of a car. The Volocopter is designed with an integrated luggage compartment so that passengers can comfortably stow their carry-on luggage when embarking. An air conditioning system is integrated into the design and the Volocopter noise signature is intrinsically low.

CONCLUSION

Urban air taxis need to meet clearly delineated design and certification requirements to be effectively used for their intended purpose. The Volocopter is specifically designed for urban air taxi missions and offers a great combination of characteristics needed to fulfill all key air taxi requirements, in our humble opinion.

The Volocopter is designed to comply with the specific airworthiness requirements for intra-city commercial air transport and serves as an industry benchmark for low noise emissions. Hence, it may go where other, more noisy aircraft, cannot go. With a range of more than 30 km, it can service the all-important airport route in 93 % of the world's largest cities. A cruise speed of 80–100 km/h enables the Volocopter to offer significant time savings compared to ground transport, without the practical drawbacks of higher-speed aircraft. With its two-seat configuration, the Volocopter will be able to service the vast majority of urban air taxi missions. The Volocopter design allows for comfortable, safe embarking and disembarking along with a comfortable environment for passengers. Its design simplicity and efficient use of batteries enable the Volocopter to be operated at a low operating cost. This allows the air taxi service to be deployed at scale within competitive price levels. The Volocopter is thus destined to pioneer the emerging Urban Air Mobility revolution, offering an additional mode of transport to people in cities around the world.

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REFERENCES

McKinsey Center for Future Mobility	Taxiing for take-off: The flying cab in your future, January 2019
Roland Berger GmbH	Urban air mobility: The rise of a new mode of transportation, November 2018
Porsche Consulting	The Future of Vertical Mobility, March 2018
NASA Langley Research Center	Silicon Valley as an Early Adopter for On-Demand Civil VTOL Operations, June 2016
Uber Elevate	Fast-Forwarding to a Future of On-Demand Urban Air Transportation, October 2016
NASA Ames Research Center	Observation from Exploration of VTOL Urban Air Mobility Designs, October 2018

ABOUT THE AUTHOR

Jan-Hendrik is Chief Technology Officer and a Managing Director at Volocopter GmbH, a start-up that is pioneering urban air mobility solutions. Jan-Hendrik leads the engineering, production and airworthiness organization at Volocopter. He has managed the rapid growth of the company from around 10 employees to well over 100 within one year.

Prior to joining Volocopter, Jan-Hendrik held several management positions with Airbus Helicopters (previously Eurocopter). He headed the international engineering department tasked with electrical systems engineering and electric drive systems, leading electrical systems development on the H160, H175 and City Airbus projects.

In addition, Jan-Hendrik was a chief engineer for the H135 helicopter, led an avionics systems engineering team, and was an active member of the RTCA/EUROCAE working group that developed the DO-178C industry standard for software in aviation.

ABOUT VOLOCOPTER GMBH

Volocopter is a global leader in the development of electrical vertical take-off and landing aircrafts (eVTOL) deployed as air taxis to safely transport passengers to their destinations. The aircraft's technical platform is extremely versatile and permits piloted, or fully autonomous flight. Its unique design offers unprecedented degrees of safety based on the high level of redundancy in all critical components. In 2011, the company earned its position in aviation history with a manned flight in the world's first fully-electric multicopter. Since then, the young enterprise has continued to mark new milestones. In 2016, Volocopter obtained provisional licensing for a two-seat Volocopter from Germany's aviation authorities. And in 2017, the aviation start-up showcased the first autonomous flight of an urban air taxi in cooperation with RTA Dubai. In the meantime, company founders Stephan Wolf and Alexander Zosel have formed an effective team of experienced managers including CEO Florian Reuter, CTO Jan-Hendrik Boelens, and CFO Rene Griemens. This has paved the way for further expansion of the company. Volocopter investors include Daimler and Intel.

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