UBER Elevate

Fast-Forwarding to a Future of On-Demand Urban Air Transportation

October 27, 2016

Introduction

Imagine traveling from San Francisco's Marina to work in downtown San Jose—a drive that would normally occupy the better part of two hours—in only 15 minutes. What if you could save nearly four hours round-trip between São Paulo's city center and the suburbs in Campinas? Or imagine reducing your 90-plus minute stop-and-go commute from Gurgaon to your office in central New Delhi to a mere six minutes.

Every day, millions of hours are wasted on the road worldwide. Last year, the average San Francisco resident spent 230 hours commuting between work and home[1]—that's half a million hours of productivity lost every single day. In Los Angeles and Sydney, residents spend seven[1] whole working weeks each year commuting, two of which are wasted unproductively stuck in gridlock[2]. In many global megacities, the problem is more severe: the average commute in Mumbai[3] exceeds a staggering 90 minutes. For all of us, that's less time with family, less time at work growing our economies, more money spent on fuel—and a marked increase in our stress levels: a study in the *American Journal of Preventative Medicine*, for example, found that those who commute more than 10 miles were at increased odds of elevated blood pressure[4].

On-demand aviation, has the potential to radically improve urban mobility, giving people back time lost in their daily commutes. Uber is close to the commute pain that citizens in cities around the world feel. We view helping to solve this problem as core to our mission and our commitment to our rider base. Just as skyscrapers allowed cities to use limited land more efficiently, urban air transportation will use three-dimensional airspace to alleviate transportation congestion on the ground. A network of small, electric aircraft that take off and land vertically (called VTOL aircraft for *Vertical Take-off and Landing*, and pronounced *vee-tol*), will enable rapid, reliable transportation between suburbs and cities and, ultimately, within cities.

The development of infrastructure to support an urban VTOL network will likely have significant cost advantages over heavy-infrastructure approaches such as roads, rail, bridges and tunnels. It has been proposed that the repurposed tops of parking garages, existing helipads, and even unused land surrounding highway interchanges could form the basis of an extensive, distributed network of "vertiports" (VTOL hubs with multiple takeoff and landing pads, as well as charging infrastructure) or single-aircraft "vertistops" (a single VTOL pad with minimal infrastructure). As costs for traditional infrastructure options continue to increase[5], the lower cost and increased flexibility provided by these new approaches may provide compelling options for cities and states around the world.

Furthermore, VTOLs do not need to follow fixed routes. Trains, buses, and cars all funnel people from A to B along a limited number of dedicated routes, exposing travelers to serious delays in the event of a single interruption. VTOLs, by contrast, can travel toward their destination independently of any specific path, making route-based congestion less prevalent.

[1] Average one-way commute time of 27.6 minutes in SF zip code 94109, 33.0 in LA zip code 90017 (https://project.wnyc.org/commute-times-us/embed.html#12.00/37.7964/-122.4222), 35 in Sydney (https://www.allianz.com.au/car-insurance/news/the-daily-battle-metropolitan-commutes). 50 work weeks per year
[2] Time only stuck in traffic congestion (http://inrix.com/scorecard/), does not include all in-car time
[3] Times of India
[4] Cooper Center Longitudinal Study, 2012. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3360418/
[5] For example, the UK's proposed High Speed 2 railway would cost taxpayers £27B ($33B) over nine years for a single straight-line route between London and Birmingham—that's nearly $280M/mile, a projection that continues to increase. See http://www.bbc.com/news/business-36376837. This is just one example project; our point is that new technology can create options for transportation infrastructure that are far lower cost.

Recently, technology advances have made it practical to build this new class of VTOL aircraft. Over a dozen companies, with as many different design approaches, are passionately working to make VTOLs a reality. The closest equivalent technology in use today is the helicopter, but helicopters are too noisy, inefficient, polluting, and expensive for mass-scale use. VTOL aircraft will make use of electric propulsion so they have zero operational emissions[6] and will likely be quiet enough to operate in cities without disturbing the neighbors. At flying altitude, noise from advanced electric vehicles will be barely audible. Even during take-off and landing, the noise will be comparable to existing background noise. These VTOL designs will also be markedly safer than today's helicopters because VTOLs will not need to be dependent on any single part to stay airborne and will ultimately use autonomy technology to significantly reduce operator error.

We expect that daily long-distance commutes in heavily congested urban and suburban areas and routes under-served by existing infrastructure will be the first use cases for urban VTOLs. This is due to two factors. First, the amount of time and money saved increases with the trip length, so VTOLs will have greatest appeal for those traveling longer distances and durations. Second, even though building a high density of landing site infrastructure in urban cores (e.g. on rooftops and parking structures) will take some time, a small number of vertiports could absorb a large share of demand from long-distance commuters since the "last mile" ground transportation component will be small relative to the much longer commute distance.

We also believe that in the long-term, VTOLs will be an *affordable* form of daily transportation for the masses, even less expensive than owning a car. Normally, people think of flying as an expensive and infrequent form of travel, but that is largely due to the low production volume manufacturing of today's aircraft[7]. Even though small aircraft and helicopters are of similar size, weight, and complexity to a car, they cost about 20 times more[8].

Ultimately, if VTOLs can serve the on-demand urban transit case well—quiet, fast, clean, efficient, and safe—there is a path to high production volume manufacturing (at least thousands of a specific model type built per year) which will enable VTOLs to achieve a dramatically lower per-vehicle cost. The economics of manufacturing VTOLs will become more akin to automobiles than aircraft. Initially, of course, VTOL vehicles are likely to be very expensive, but because the ridesharing model amortizes the vehicle cost efficiently over paid trips, the high cost should not end up being prohibitive to *getting started*. And once the

[6] "Operational emissions" refers to the emissions from the vehicle during operation, which is only a portion of the full life-cycle emissions. There is great value in achieving zero operational emissions: see the Vehicle: Emissions section for a deeper discussion on this topic.

[7] High-volume production of aircraft was was achieved during World War II and for a few years afterward. Also during the 1970's General Aviation sales reached ~20,000 units/year, but since the early 1980's have experienced sales of only a few thousand units per year.

[8] Not only are aircraft and helicopters dramatically more expensive than cars, but also the components going into the vehicles. The 430-horsepower Corvette LS3 6.2 liter crate complete engine has a MSRP of $7911 from GM (http://www.chevrolet.com/performance/crate-engines/ls3.html) yet is far more complex than an aircraft engine, such as the Continental IO-550C 300 hp engine which has a MSRP of $46,585 (http://www.continentalmotors.aero/Engine_Details/Stock_Engines/). See the Economics section for more details

ridesharing service commences, a positive feedback loop should ensue that ultimately reduces costs and thus prices for all users, i.e. as the total number of users increases, the utilization of the aircraft increases. Logically, this continues with the pooling of trips to achieve higher load factors, and the lower price feeds back to drive more demand. This increases the volume of aircraft required, which in turn drives manufacturing costs down. Except for the manufacturing learning curve improvements (which aren't relevant to ridesharing being applied to automobiles), this is very much the pattern exhibited during Uber's growth in ground transportation, fueled by the transition from the higher-cost UberBLACK product to the lower-cost and therefore more utilized uberX and uberPOOL products.

Market Feasibility Barriers

The vision portrayed above is ambitious, but we believe it is achievable in the coming decade if all the key actors in the VTOL ecosystem—regulators, vehicle designers, communities, cities, and network operators—collaborate effectively. The following are what we perceive as the most critical challenges to address in order to bring on-demand urban air transportation to market.

- **The Certification Process.** Before VTOLs can operate in any country, they will need to comply with regulations from aviation authorities—namely the US Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) who regulate 50% and 30% of the world's aviation activity, respectively—charged with assuring aviation safety. VTOL aircraft are new from a certification standpoint, and progress with certification of new aircraft concepts has historically been very slow, though the process is changing in a way that could accelerate things significantly. We explore this topic in depth in the *Vehicle: Certification* section.

- **Battery Technology.** Electric propulsion has many desirable characteristics that make it the preferable propulsion choice for the VTOL aircraft contemplated in this document, and electric batteries are the obvious energy source. That said, the *specific energy* (the amount of energy per unit weight provided by the battery, which ultimately determines the gross weight of the vehicle) of batteries today is insufficient for long-range commutes. Additionally, the *charge rate* (how quickly the battery can be brought back to a nearly full charge, which determines operational idle time) of batteries today is also too slow to support high-frequency ridesharing operations. *Cycle life* (the number of charge/discharge cycles the cell can sustain before its capacity is less than 80% of the original, which determines how often the battery must be replaced) and *cost per kilowatt-hour* (which determines the overall battery cost) are also important to the economic viability of electric aircraft. We discuss the current state of the art battery developments, as well as promising (required) advances that are likely to occur in the coming several years in the *Vehicle Performance: Speed and Range* section.

- **Vehicle Efficiency.** Helicopters are the closest current-day proxy for the VTOLs discussed in this paper, but they are far too energy inefficient to be economically viable for large-scale operations. Helicopters are designed for highly flexible operations requiring vertical flight. With a more constrained use case focused on ridesharing, a more mission-optimized vehicle is possible, e.g utilizing distributed electric propulsion (DEP) technology[9]. Large efficiency improvements are possible because DEP enables *fixed-wing* VTOL aircraft that avoid the fundamental limitations of helicopter edgewise rotor flight, and wings provide lift with far greater efficiency than rotors. But no vehicle manufacturer to date has yet demonstrated a commercially viable aircraft featuring DEP, so there is real risk here. We cover this topic in the *Economics: Vehicle Efficiency/Energy Use* section.

- **Vehicle Performance and Reliability.** Saving time is a key aspect of the VTOL value proposition. In the ridesharing use case, we measure and minimize the comprehensive time elapsed between request and drop-off. This is affected by both *vehicle performance*, particularly cruise speed and take-off and landing time, and *system reliability*, which can be measured as time from request until pick-up. In this context, key problems to solve are vehicle designs for 150-200 mph cruise speeds and maximum one-minute take-offs and landings[10], as well as issues like robustness in varied weather conditions, which can otherwise ground a large percentage of a fleet in an area at arbitrary times. The *Infrastructure and Operations* section and the *Operations: Trip Reliability* and *Weather* sections address the challenges and compelling technology advances in these areas.

- **Air Traffic Control (ATC).** Urban airspace is actually open for business today, and with ATC systems exactly as they are, a VTOL service could be launched and even scaled to possibly hundreds of vehicles. São Paulo, for example, already flies hundreds of helicopters per day. Under visual flight rules (VFR), pilots can fly independent of the ATC and when necessary, they can fly under instrument flight rules (IFR) leveraging existing ATC systems. A successful, optimized on-demand urban VTOL operation, however, will necessitate a significantly higher frequency and airspace density of vehicles operating over metropolitan areas simultaneously. In order to handle this exponential increase in complexity, new ATC systems will be needed. We envision low-altitude operations being managed through a server request-like system that can deconflict the global traffic, while allowing UAVs and VTOLs to self-separate any potential local conflicts with VFR-like rules, even in inclement weather. There are promising initiatives underway, but they will play out over many years and their pace may ultimately bottleneck growth. The *Operations: Air Traffic* section expands on the issues here and summarizes current ATC initiatives.

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[9] http://arc.aiaa.org/doi/abs/10.2514/6.2016-3920

[10] Our economic modeling shows that these performance numbers are necessary for feasible long distance commuteVTOL service. Shorter trip distances could utilize slower vehicles, with a penalty of having lower vehicle productivity.

- **Cost and Affordability.** As mentioned above, helicopters are the closest proxy to the VTOLs contemplated in this paper, but they are prohibitively expensive to operate as part of a large-scale transportation service. They are energy-inefficient and very expensive to maintain, and their high level of noise strongly limits use in urban areas. Demand is accordingly modest for helicopters, and this translates to low manufacturing volumes: current global civil rotorcraft production is only approximately 1,000 units per year, lacking critical economies of scale. Simpler, quieter and more operationally efficient vehicle designs are proposed which leverage digital control rather than mechanical complexity[11]. We expect that this shift can kickstart the virtuous cycle of cost and price reduction described earlier. Our *Vehicle* and *Economic Model* section goes into detail concerning the evolutionary pathway to a mass market through affordable vehicles and operations.

- **Safety.** We believe VTOL aircraft need to be safer than driving a car on a fatalities-per-passenger-mile basis. Federal Aviation Regulation (FAR) Part 135 operations (for commuter and on-demand flights[12]), on average, have twice the fatality rate of privately operated cars, but we believe this rate can be lowered for VTOL aircraft at least to one-fourth of the average Part 135 rate, making VTOLs twice as safe as driving. DEP and partial autonomy (pilot augmentation) are key pieces of the safety equation, discussed in further detail in the *Vehicle: Safety* section.

- **Aircraft Noise.** For urban air transportation to thrive, the vehicles must be acceptable to communities, and vehicle noise plays a significant role. The objective is to achieve low enough noise levels that the vehicles can effectively blend into background noise; ultimately we believe VTOLs should be one-half as loud as a medium-sized truck passing a house. That said, a more sophisticated measure of “noise” is required in order to properly characterize the impact of vehicle sound on a community. Electric propulsion will be critical for this objective, as well: it enables ultra-quiet designs, both in terms of engine noise and propulsor thrust noise. The *Vehicle: Noise* section addresses this issue.

- **Emissions.** VTOLs represent a potential new mass-scale form of urban transportation; as such, they should clearly be ecologically responsible and sustainable. When considering helicopters as the starting point, there is a substantial opportunity to reduce emissions. We consider both the *operational emissions* of the vehicle, i.e. emissions produced by the vehicle during its operation, and *lifecycle emissions*, which accounts for the entire energy lifecycle associated with the transportation method, including (in the case of electric vehicles) the production of electricity to charge VTOL batteries. Among the advantages of electric propulsion designs is that they have zero operational emissions. This leaves energy generation (which today is still largely coal,

[11] Current helicopters have a myriad of parts that are single fault flight critical components which require tight oversight on part production quality as well as frequent maintenance checks of individual components for wear and tolerance due to the harsh, high vibration operating environment.
[12] http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title14/14cfr135_main_02.tpl

natural gas and petroleum-based[13]) with its associated emissions as the primary concern. This topic is covered in the *Vehicle: Emissions* section.

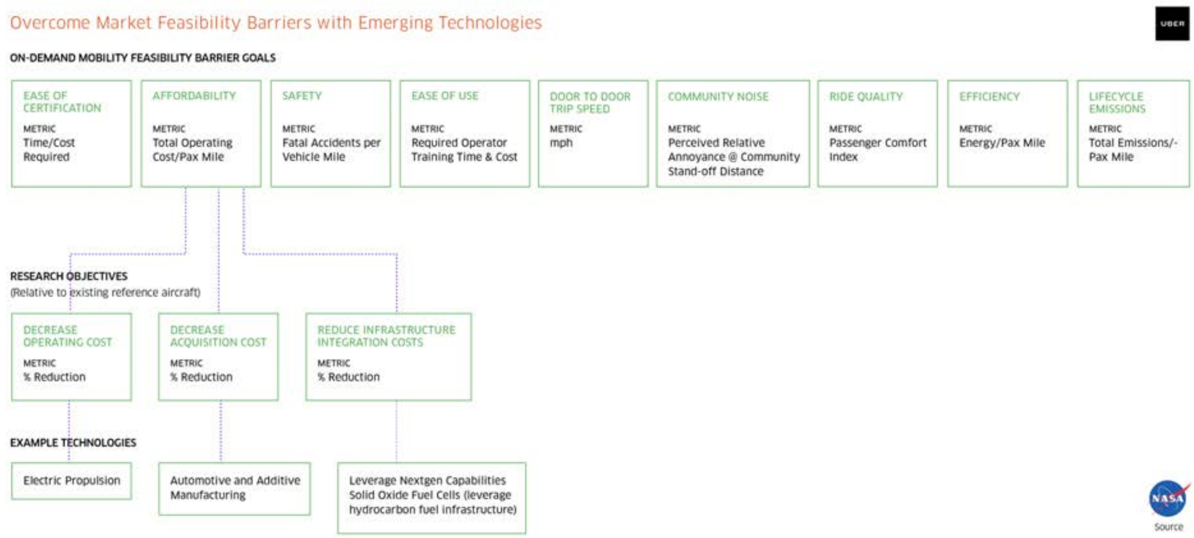
- **Vertiport/Vertistop Infrastructure in Cities.** The greatest operational barrier to deploying a VTOL fleet in cities is a lack of sufficient locations to place landing pads. Even if VTOLs were certified to fly today, cities simply don't have the necessary takeoff and landing sites for the vehicles to operate at fleet scale. A small number of cities already have multiple heliports and might have enough capacity to offer a limited initial VTOL service, provided these are in the right locations, readily accessible from street level, and have space available to add charging stations. But if VTOLs are going to achieve close to their full potential, infrastructure will need to be added. The *Infrastructure and Operations* section goes into this issue more deeply and provides the results of a simulation to determine optimal vertistop/vertiport placement.

- **Pilot Training.** Training to become a commercial pilot under FAR Part 135 is a very time-intensive proposition, requiring 500 hours of pilot-in-command experience for VFR and 1200 hours for IFR. As on-demand VTOL service scales, the need for pilots will rapidly increase, and it's likely that with these training requirements, a shortage in qualified pilots will curtail growth significantly. In theory, pilot augmentation technology will significantly reduce pilot skill requirements, and this could lead to a commensurate reduction in training time. See the *Vehicle: Pilot Training* section for more on this.

Industry Assessment of Market Feasibility Barriers

NASA and the FAA recently spearheaded a series of On-Demand Mobility (ODM) workshops to bring the VTOL ecosystem together—emerging VTOL vehicle manufacturers, federal agencies, private investors, professional societies, universities, and international aviation organizations[14]—to identify barriers to launching an on-demand VTOL service. The barriers identified by the ODM workshops group (in the below diagram) align quite well with the challenges identified in our foregoing assessment.

[13] http://www.tsp-data-portal.org/Breakdown-of-Electricity-Generation-by-Energy-Source#tspQvChart
[14] http://www.nianet.org/ODM/roadmap.htm



The remainder of this paper delves into these challenges for achieving a successful VTOL market, with an eye to surmounting them as quickly as possible, as well as our view on rider experience requirements. Our intent here is to contribute to the nascent but growing VTOL ecosystem and to start to play whatever role is most helpful to accelerate this industry's development. Rather than manufacture VTOL hardware ourselves, we instead look to collaborate with vehicle developers, regulators, city and national governments, and other community stakeholders, while bringing to the table a very fertile market of excited consumers and a clear vehicle and operations use case. At the end of the paper, we introduce an upcoming summit for vehicle developer entrepreneurs, regulators and cities, which we hope will help advance discussions and collaboration to bring on-demand urban air transportation to life.

We welcome all feedback at elevate@uber.com.

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Path to Market for VTOLs

In the subsequent sections, we look at the feasibility of VTOLs and the ecoystem's path to market across four dimensions:

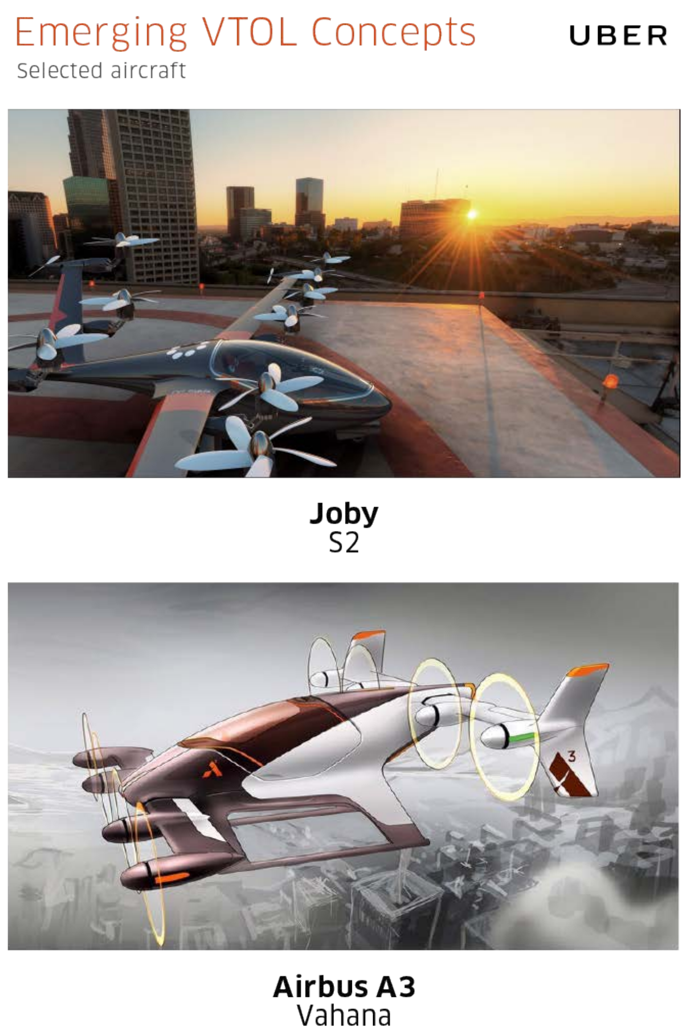
- **Vehicles:** What are the specific requirements of a vehicle to be viable for urban use, particularly for the urban *commute* use case, and what are the technology implications?
- **Infrastructure and Operations:** What are the infrastructure and operational requirements in cities to enable VTOLs to operate at scale?
- **Rider Experience**: How will riders request a VTOL on ridesharing networks (including Uber) and what will their boarding and on-trip experiences entail?
- **Economics:** How much will VTOL service cost for consumers and what are the implications for mass adoption and substitution for other transportation methods, particularly for privately owned cars?

In summary, our analysis concludes that VTOLs with the properties necessary for scaled operation are technically feasible with today's technology and that at scale (i.e., at reasonable manufacturing production levels), VTOL service will be possible at costs sufficiently low to enable mass adoption. The following sections will provide the details of our analysis.

Vehicles

There is a burgeoning VTOL aircraft ecosystem, and a number of companies that are already developing and flying early vehicle prototypes. Jaiwon Shin, NASA Associate Administrator for the Aeronautics Research Mission Directorate, recently discussed NASA's optimism around these VTOLs at a White House workshop on Drones and the Future of Aviation[15]:

> *"Air-taxi[s will] combine electric propulsion, autonomy, vertical lift and many other communication and navigation capabilities. Fully autonomous air-taxi…operations, especially in very populated and heavy traffic…areas, I think it's an exciting possibility. So when we converge all these capabilities… a lot of new chapters in aviation are possible… it's a dawn of a new era in aviation."*



The VTOLs envisioned as serving within a ridesharing network (the aforementioned "air-taxis") will need to address four primary barriers to commercial feasibility: safety, noise, emissions, and vehicle performance. The two most important technologies to overcome these challenges are Distributed Electric Propulsion (DEP) and autonomous operation technologies. Several manufacturers have demonstrated concepts which showcase ways to use DEP technology in order to achieve different advantages (and penalties), depending whether the designer favors cruise efficiency, hover power required, vehicle control, design simplicity, payload, or vehicle cost.

Zee.Aero is the largest of these companies with a focus on advancing the required component technologies (i.e. advanced electric motors, motor controllers, batteries, quiet propulsors, etc.). So far the

[15] Jaiwon Shin, NASA Associate Administrator, Aeronautics Research Mission Directorate. https://www.whitehouse.gov/blog/2016/08/02/harnessing-potential-unmanned-aircraft-systems-technology , at ~1:58:00 timestamp.

vehicle concepts publicly disclosed by Zee[16] utilize a *lift plus cruise* configuration, where the vertical lift and forward thrust are provided by separate, non-articulating propulsors. This type of concept approach results in extra motor weight and aircraft drag since the vertical lift propulsors are ineffective in forward flight. However, the design complexity is low.

Joby Aviation[17] has a different concept approach with their S2 and S4 concepts using a distributed set of tilting prop-rotors (six to twelve depending on the size/capacity of the vehicle) which rotate with the direction of flight so that the propulsors provide both vertical lift and thrust throughout the flight. Since less thrust is required in forward flight than in hover, the inboard prop-rotor blades fold against the nacelle to ensure the highest propulsive and motor efficiency during cruise. This approach has lower motor weight and aircraft drag, but has much higher complexity due to the articulating motor and propulsors.

A³/Airbus has shown its Vahana[18] concept which, instead of articulating the prop-rotors, rotates a forward and aft wing with four prop-rotors on each of the wings. This is a tilt-wing/tilt-tail approach, similar to the recent NASA GL-10 DEP flight demonstrator[19]. This approach reduces the complexity by only requiring two actuators for the wing rotation and avoids prop-rotor download thrust impingement on the wing during hover and transition, while achieving both vectored thrust and lift.

Many additional companies have other approaches, such as the highly redundant 18 prop-rotor eVolo Volocopter[20], or the compact eHang 184 quad/octocopter[21]. These multi-copter approaches will be significantly slower (~60 mph) with shorter range capability, as well as lower efficiency since they aren't using wing-borne flight. Other concepts such as the Lilium push to extremely high levels of distribution while coupling the vertical lift in closely with the wing high-lift system. These jet-lift approaches that have higher disc loading will require substantially higher power for takeoff and landing, with greater challenges operating quietly within cities.

These are only a few of the key VTOL manufacturers within the space, but there is no established set of standards around VTOL. The next challenge beyond the vehicle design is the way in which any designer or the wider ecosystem can push toward satisfying the certification and regulatory procedures required to enable scaled manufacturing.

This section takes a closer look at the vehicle-specific market feasibility barriers detailed in the Introduction, namely safety, noise, emissions, vehicle performance, as well as vehicle certification.

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16 http://www.bloomberg.com/news/articles/2016-06-09/welcome-to-larry-page-s-secret-flying-car-factories
17 http://www.jobyaviation.com/
18 https://vahana.aero/
19 http://www.nasa.gov/langley/ten-engine-electric-plane-completes-successful-flight-test
20 http://www.e-volo.com/index.php/en/
21 http://www.ehang.com/ehang184

Safety

For widespread public adoption of VTOLs as a ridesharing option, riding in a VTOL must be safer than riding in an automobile. In order that VTOLs are accepted by the market, claiming that the vehicles are merely *as safe* as driving, particularly given the active public discourse regarding potential safety improvements from autonomous vehicles, will almost certainly be insufficient. Additionally, the general public is very aware that flying commercial airlines is significantly safer than driving, which puts upward pressure on safety of any aviation offering, especially one intended for daily use.

Establishing a Safety Target

While scheduled airlines operating under Part 121 of the FAA Federal Aviation Regulations (FAR) will almost certainly remain the safest mode of transport, our initial target is to achieve a safety level that is twice that of driving a car based on number of fatalities-per-passenger-mile. Today, using Part 135 helicopter and fixed-wing operations as the closest proxy, the safety level in air-taxi aviation is two times worse than driving, which means we would need to see an improvement of four times (from 1.2 to 0.3 fatalities per 100 million passenger miles) to achieve that target. It's important to note, however, that while we've set this goal, regulators would not necessarily require significantly more stringent VTOL safety targets than automobiles. Additionally, the regulatory discussion will be complex because safety can be measured on a number of dimensions (e.g. injuries, accidents), though we have benchmarked our analysis on fatalities as shown[22].

[22] Ken Goodrich, http://www.nianet.org/ODM/presentations/Overview%20SVO%20Ken%20Goodrich%20and%20Mark%20Moore.pdf Slide 8, Kansas City ODM Workshop, Oct 21-22, 2015.

Transportation Safety

Fatalities by transportation method, normalized against passenger automobiles

VEHICLE TYPES	Annual Fleet Utilization: VEHICLE HOURS (1,000)	VEHICLE MILES (MILLION)	PASSENGER MILES (MILLION)	AVERAGE ANNUAL FATALITIES	Normalized Fatality Rates: PER 100,000 VEHICLE HOURS	PER 100M VEHICLE MILES	PER 100M PASSENGER MILES
PASSENGER CARS	50,300,000	1,510,000	2,340,000	14,701	1X (0.030)	1X (0.997)	1X (0.643)
PART 121 AIRLINES	18,600	7,891	579,000	16	2.9X	0.208X	0.004X
PART 135 AIR TAXI	2,100	375	1,500	18	29.3X	4.9X	1.9X
MOTORCYCLE	600,000	18,000	19,800	4,809	27.4X	27.4X	38.7X
GENERAL AVIATION	22,400	3,370	6,740	511	78.1X	15.6X	12.1X

+ Data is US only

UBER

We have chosen Part 135 rather than helicopters or general aviation for our baseline proxy as this section of the FAR includes scheduled and non-scheduled air taxi services, both helicopter and fixed-wing. We believe the operations under this part will be much closer to the actual operations of VTOL aircraft in comparison to the world of general aviation (GA), which includes aircraft operating under Part 91. General aviation accounts for a large number of accidents due to private pilot inexperience and poor maintenance, as well as antique, warbird, and experimental amateur-built aircraft that similarly represent a large portion of accident incidents. VTOLs will be manufactured, flown, and maintained to meet the more stringent levels of control and FAA supervision covered under Part 135. Additionally, VTOL operations, at least until autonomous operations become commonplace, will require commercial pilots who must have a higher level of training, experience, flight review, and medical certification than is the case for private pilots. Even if aircraft had equivalent failure rates, the control inherent in Part 135 operations will result in VTOL accident rates at least as low as operations within this section generally.

Improving VTOL Safety

To understand the path to improving safety for urban air transportation, we need to understand the root causes of historical crashes.[23] Part 135 scheduled and air-taxi operations are especially common in Alaska, and about half of the fatalities were in Alaska due to pilot

[23] http://www.ntsb.gov/investigations/data/Pages/AviationDataStats.aspx#

error described as controlled flight into terrain, mid-air collisions, and loss of control. Radar surveillance is nonexistent over most of the area, air traffic control is not real-time and weather conditions are often not as forecast. Loss of control occurs when a combination of poor planning and judgement, diminished human ability and inclement environmental conditions combine to put the aircraft outside the pilot's ability to keep it on the desired trajectory. These accident types could be prevented through relatively simple forms of vehicle autonomy that provide supplemental vehicle control while interfacing with improved navigational and weather information. The military has already implemented terrain collision avoidance pilot-aids, such as the Automatic Ground Collision Avoidance System which has been confirmed to have saved F-16 pilots[24]. Major improvements[25] have been made in the midair collision rate in Alaska through aggressive adoption of better navigation sensors and aircraft-to-aircraft ADS-B systems, which will be included in all aircraft flying in most dense urban areas by 2020. VTOLs will necessarily make use of digital fly-by-wire systems and adapting these systems to include pilot aids will be the key to significantly reducing failure modes attributable to pilot error. Pilot aids will evolve over time into full autonomy, which will likely have a marked positive impact on flight safety.

Since half of the Part 135 crashes are related essentially to poor weather data and pilots not being where they thought they were, operating only in urban areas with real-time weather and air traffic control brings existing Part 135 operations to par with the safety of driving a car. Improving a further 2x through the adoption of advanced pilot aids and autonomous systems will bring VTOLs the rest of the way toward our initial goal of being twice as safe as driving.

Distributed Electric Propulsion

In order to improve VTOL safety beyond that of cars, we must consider the complexity of controlling multiple propulsion motors. The VTOLs envisaged in this paper will be inherently "optionally piloted vehicles" in which pilot control is unnecessary except for visual avoidance of obstacles and other aircraft. Rather than physically commanding operation of engines and control surfaces, the pilot establishes a desired trajectory which the vehicle follows. Direct mechanical control workload is greatly reduced, leaving more of the pilot's attention for situational awareness, and this eliminates the need for pilot judgement in planning and executing vehicle state maneuvers to achieve a desired trajectory. Expecting a 2x improvement from state-based to trajectory-based pilot inputs is actually a conservative goal, bringing the expected total fatality rate to at least half that of driving.

Beyond loss of situational awareness and control, the next highest accident cause is associated with engine failure, which accounts for 18% of general aviation accidents when combined with fuel management errors. Fortunately both of these causes are also mitigated with implementation of Distributed Electric Propulsion technology (DEP) that forms the basis for

[24] https://theaviationist.com/2016/09/13/watch-an-f-16s-automatic-ground-collision-avoidance-system-save-an-unconscious-pilot-from-certain-death/
[25] http://www.cdc.gov/niosh/topics/aviation/

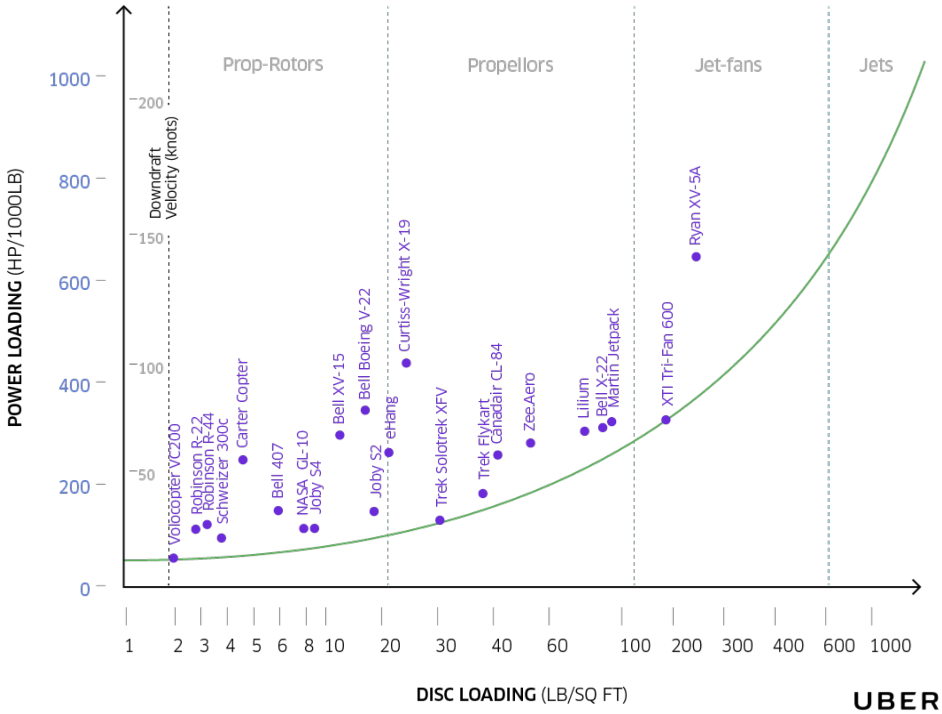
these new vehicle concepts. The use of multiple (typically six or greater) electric motors, controllers, and a redundant battery bus architecture avoids the problems of catastrophic engine failure by having full propulsion system redundancy. An engine failure might result in diminished speed or climb capability, but full control authority within the aircraft's operating envelope can be maintained. Improvements in this area can be expected to reduce accident rates even further than the previously specified goal.

The use of DEP combined with autonomy provides the opportunity for the fully digitally controlled fly-by-wire control system to interact across digital systems without complex analog or mechanical interfaces. Digital data across each element of the propulsion system is managed through redundant master flight controllers, from battery cell voltage state of charge to motor temperatures that permit optimization of the system performance and health.

Distributed propulsion provides not only redundancy, but also the potential for additional control robustness to be designed into the aircraft system such that any component can fail gracefully, enabling a controlled landing. Robust vehicle control provides the ability to deal with uncertainties or disturbances within the vehicle control system. Control robustness is also helpful to deal with high wind or gust conditions, especially when operating in an urban environment that promotes local flow disturbances.

Vertical flight imposes additional operational challenges that conventional takeoff and landing aircraft do not experience. DEP technology already mitigates most of these challenges; DEP VTOLs will likely have a higher downwash velocity that permits a more rapid descent, and when used in combination with multiple propeller-rotors will help to avoid rotor recirculation flow conditions (such as entering a vortex ring state). Downwash is the induced velocity of air deflected downward by the propulsion system prop-rotor to achieve vertical lift. For example, helicopters typically have a rotor downwash of 2 to 10 pounds of thrust per square foot. DEP VTOL configurations typically use 10 to 20 pounds of thrust per square foot.

The figure below illustrates the distribution of disc loadings attempted by past and recent vertical lift vehicles, as well as the increased power required and downdraft velocities that result as disc loading/rotor downwash is increased. Disc loading is defined as the weight of an aerial vehicle divided by the propulsion disc area that produces the vertical lift. The curve in this figure represents the theoretical ideal power required (i.e. with the VTOL achieving a thrust to weight ratio of 1), with a specific VTOL concept being above the line indicating that additional power is present either to provide extra power for increased control, or due to inefficiencies caused by the specific vertical lift approach.



A VTOL will typically have a Thrust/Weight of 1.15 or greater to provide extra power for climb and a control power margin. This Thrust/Weight ratio is typically measured at the continuous power rating. While turbines and piston engines are often able to provide a short time emergency rating that provides a 10-20% increase in power, electric motors are typically able to produce an additional 50%+ power for 1-2 minutes until they overheat. These peak ratings aren't accounted for in the Thrust/Weight, but reserved for emergency operation such as failure of a motor.

For the case of sizing the aircraft to accommodate a single engine (or motor) failure while maintaining the ability to complete the mission and land safely with power, a twin engine helicopter would need to have a Thrust/Weight ratio of greater than 2.0 with the peak rating during the single engine emergency providing an effective Thrust/Weight ratio of 1.1 to 1.2. For a DEP VTOL with 6 prop-rotors, failure of a single motor causes a reduction of thrust of about 17%, with the peak ratings of the electric motors providing greater than this reduction during the single engine inoperative emergency case.

This sizing to account for an engine (motor) inoperative case is one of the significant advantages that DEP offers to reduce the penalties previously associated with vertical lift aircraft. Helicopters are able to auto-rotate and conduct an emergency landing without power, while DEP VTOLs are less likely able to auto-rotate (depending on the specific configuration). In any case, auto-rotation does not work well in dense urban areas from low altitude, because the poor glide slope of helicopters results in landings within a short distance.

The DEP VTOL flight safety value proposition becomes most powerful when combined with increased vehicle autonomy such that the autonomy actually prevents the VTOL from entering potentially hazardous states in the first place. Autonomous flight control will provide improved trajectory flight profiles that are able to minimize the extra power required for control by using the combination of optimal speed, climb angle, angle of attack, and propulsion/wing inclination angles throughout the hover to forward flight transition corridor.

Achieving high perceived safety is also valuable, especially during the initial adoption. Recent GA aircraft have implemented an emergency safety mode that's equivalent to pulling to the side of the road. By avoiding the use of a large rotor, a DEP aircraft is also able to take advantage of Ballistic Recovery Systems (BRS)[26]: whole vehicle parachutes that can be deployed in an emergency to safely bring the vehicle to the ground, and it can avail itself of other evolving safety technologies being tested such as whole aircraft airbags. Multiple companies are developing even more capable BRS solutions that can provide additional safety across nearly all vehicle operating conditions, even if the vehicle is moving slowly and is near the ground.

While there will likely be some variance from the individual contributions of these safety factors, those variances are likely to cancel out enabling the achievement of and likely surpassing the top-level goal of twice as safe as driving a car. Of course, innovation on the safety front will continue after the first VTOLs are in production; full autonomy and large amounts of data from real-world operations fed back into the designs will push VTOL operations toward airline aviation levels of safety.

[26] In fact, BRS systems have already been responsible for saving 358 lifes through deployment on General Aviation aircraft, http://www.brsaerospace.com/brs_aviation_home.aspx

Noise

VTOLs will operate directly overhead, and in close proximity to, densely populated urban areas. It is important that VTOLs do not disrupt communities, and as such it is important that VTOL developers keep noise mitigation firmly in mind. While communities tend to tolerate public safety flights (such as medical helicopters) because the flights are infrequent and have clear community value, they historically oppose other uses due to noise. In this section we look at a set of more restrictive quantitative and qualitative noise goals for VTOLs, analyze the underlying helicopter design features that cause noise, and explore the technological advancements that we believe hold the most promise for delivering quiet VTOL operations.

A Quantitative Goal For VTOL Noise

The FAA and other regulators have set thresholds for community noise around airports for fixed-wing aircraft, as well as thresholds for helicopters and tiltrotors[27]. But to enable widespread commercial use, VTOLs need to meet a stricter noise standard. Use of the current FAA helicopter noise regulations make it challenging to enable high volume, close proximity VTOL urban operations that communities can embrace.

Quantitatively, the emerging VTOL community will benefit from defining and tailoring acceptable operational noise levels—as well as methods to measure them—for vehicles and the vertiports/stops at which they will operate. For communities to accept sizeable fleets of VTOL aircraft, vehicle noise will need to blend into the existing background noise wherever they fly. We analyzed the sources of noise that would emanate from a VTOL aircraft and explored a more nuanced and complete definition of noise than simply sound pressure: some forms of noise are significantly more irritating to humans than their sound pressure measurement would suggest.

We explored existing air- and ground-based transport to understand how noise is measured and perceived, and we build off of these lessons to understand how more restrictive noise goals for future VTOL operations could move beyond regulatory requirements to help unlock consumer acceptance. Our analysis, below, leads us to the following preliminary noise framework and targets:

1. **Noise objectives for the vehicles**: VTOL vehicles operating from vertiports/stops should ultimately approach noise levels (exposure at the front of the nearest residence) half that of a truck traveling on a residential road (75-80 dB(A) at 50 feet): approximately 62 dB L_{Amax} at 500 ft altitude. This is also about one-fourth as loud as the smallest four-seat helicopter currently on the market.

[27] 14CFR36, Subpart H and Subpart K

2. **Long-term annoyance**: VTOL vehicle operations at vertiports and vertistops should not contribute long-term annoyance that exceeds the smallest change in noise background that a person can detect, about 1 dB increase in the day night level indicator (DNL).
3. **Short-term annoyance**: VTOL vehicle operations should not exceed a maximum 5% increase in nighttime awakenings in their surrounding communities.
4. **Site-level analysis and tailoring**: VTOL operations should be measured continuously on an individual site basis to establish actual Day-Evening-Night background sound levels.

1) Noise Objective for the Vehicles

Achieving VTOL noise levels similar to ground transportation is essential for widespread VTOL adoption. Medium-sized trucks traveling through neighborhoods at speeds of 35 to 55 mph[28] generate sound levels of 75-80 dB(A) sound pressure level (SPL) at 50 feet, which are roughly perceived to be acceptable by a listener at an average distance in adjacent buildings. We estimate this figure to be half as loud (10 dB less) as the smallest four-seater helicopter in operation, the Robinson R44, which (*having certificated noise emission levels of 81 dB sound exposure level (SEL[29]) at 500 ft altitude*) is about 87 dB at 250 ft altitude[30].

However, given that a VTOL network would deploy a fleet of potentially hundreds of aircraft, we understand that so many simultaneously operating VTOLs would also not be acceptable at noise levels merely equal to trucks. As such, we feel that a reasonable goal for vehicles is half that of medium-sized trucks today—**67 dB(A) at ground level from a VTOL at 250 ft altitude,** which appears from early analysis to be achievable. For context, this is comparable to a Prius at 25 feet from the listener, driving by at 35 mph.

2) Long-term Annoyance

Sound pressure level alone is necessary but insufficient to specify the noise parameters that should govern VTOLs. This is due to the concept of annoyance, a phenomenon associated with the physiological perception of loudness, duration and repetition. Two different kinds of annoyance responses are triggered in people: (1) some notice individual disturbing events that they remember, and tend to count how many times this disturbing event has happened, and (2) others assess noisiness of an area by averaging noise over the long-term, expressing their assessment as, for example, a “busy or “noisy” neighborhood. “Busy” or “noisy” often equates to lower property values when compared with “quiet” neighborhoods[31]. Short-term noises also create individual alerting events and can awaken people from sleep.

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[28] http://www.fhwa.dot.gov/environment/noise/traffic_noise_model/old_versions/tnm_version_10/tech_manual/tnm10techmanual.pdf
[29] EASA TCDS for R44, Chapter 11 SEL 81 dB at 150 m overflight
[30] We have estimated community SENEL values based on FHWA model data for truck and TCDS SEL values for helicopters and approximated the conversion to L_{Amax} based on our own measurements there is not a direct conversion between any of these metrics.
[31] Schomer, Paul (2001) “Assessment of Noise Annoyance.” Champaign, IL: Schomer and Associates.

Fortunately, there are established methods for measuring annoyance. Since the development of turbofan jet airliners, cities and the FAA have worked on the *long-term* noise issue, which has led to the creation of the Day Night Level (DNL[32]). DNL is the averaged sound pressure level for a 24-hour period, with a sensitivity offset of 10 dB between 10 PM and 7 AM, so a constant sound of 70 dB(A) in the daytime and 60 dB(A) at night would define a neighborhood with 70 dB DNL. The FAA uses a yearlong running average of DNL when reporting the noise impact of airports. Day Night Level guidelines differ by type of neighborhoods. For example, targets in industrial neighborhoods are not as stringent as those for residential or suburban areas[33]. As VTOLs begin operation it will be valuable to characterize the ambient noise of landing sites individually, rather than using arbitrary targets. Doing so would be operationally very powerful as this will enable operations to be sensitive to the characteristics of each take off and landing location and contribute only the amount of additional noise that won't disturb the neighboring community. To achieve more tailored and responsive noise levels at vertiports and vertistops, operators will compute the maximum number of operations of each vehicle that can be conducted at each site while **not increasing the long term average Day-Night Level (DNL) by more than 1 dB, which is the smallest change in loudness that a person can detect.**

3) Short-term Annoyance

While *long-term* annoyance is measured in DNL, *short-term* annoyance is typically measured (around hospital heliports, for instance) with single event noise equivalent level (SEL[34] or SENEL[35]) metrics, which attempt to capture the likelihood that an individual takeoff or landing will disturb everyday activities like speech or sleep. The target for short-term annoyance that has been used in hospital heliport studies is for events not to increase the number of night-time awakenings by more than 10%. This is typically predicted using SEL, which is the A-weighted sound pressure level lasting one second that contains the same energy as an entire aircraft event such as takeoff or overflight. A 70 dB(A) sound lasting for two seconds would produce 73 dB SEL; if it lasted for four seconds it would be 76 dB SEL. For a simple event that rises to a maximum and then drops, the duration is the time from the instant the sound reaches 10 dB less than its maximum, to the time when it drops below that same 10 dB less than maximum value. If VTOL vehicles are able to achieve the absolute noise goals as stated above (67 dB(A) at 250 ft altitude), it will be possible to be more optimistic in reducing the percentage increase of night-time awakenings from operations. Because[36] there is a direct statistical relationship between loudness and awakenings, **decreasing** FICON's guidance for maximum night-time awakenings **(*10%*) to half that—5%—should be achievable.**

[32] Plotkin, Kenneth J, Wyle Labs et al (2011) Updating and Supplementing the Day-Night Average Sound Level (DNL). Wyle Report 11-04, DOT/FAA/AEE/2011-03, June 2011 http://www.faa.gov/about/office_org/headquarters_offices/apl/research/science_integrated_modeling/noise_impacts/media/WR11-04_Updating%26SupplementingDNL_June%25202011.pdf
[33] 14 CFR 150
[34] Sound Exposure Level
[35] Single Event Noise Exposure Level
[36] Federal Interagency Committee on Noise, 1992 Federal Agency Review of Selected Airport Noise Analysis Issues

4) Site-level Analysis and Tailoring

Identifying metrics that are as vehicle platform-agnostic as possible is an important consideration. Several design approaches for electric VTOLs have already been built and tested, at least three with manned flights and many more in scale or static tests. While details are not publicly available, we know that the different design approaches have significantly different acoustic signatures. This variety of designs makes it challenging to define quantitative noise measurements that are strictly neutral. Simple sound level measurements to compare two sounds aren't accurate when the spectral character of the sounds is different.

Due to developments in the field of audio encoding, today there is a much deeper understanding of the physiology of loudness than there was even a decade ago. MP3 coding and other compressed audio formats depend on being able to discard portions of a sound waveform that we don't perceive. Research in this area has put a sharp point on discoveries made by sensorineural researchers decades before, and gives us confidence that our proposed quantitative noise measurement metrics will accurately predict community response to the acoustic component of VTOLs' presence. For instance, we are careful to use metrics that capture the additional annoyance of a prominent tone or whine from some electric motors, which makes the sound louder than a sound level meter would indicate.

VTOL noise measurements will all begin with a calibrated pressure-time history of the sound at a reference location. This information is then processed to yield a time-varying A-weighted sound pressure level L_A (which is the same as a sound level meter would show) and $L_{PN(T)}$ which is a weighted sound level corrected more accurately for human hearing sensitivity. This includes a correction for prominent tones. A-weighting (IEC 61672) is designed to reflect the audibility of single tones at the level of quiet speech, rather than complex noise. It's common for noise measurement because it's simple, but does not capture the annoyance of many sounds and is unsuitable for comparing sounds of different spectral characteristics. Capturing the maximum values from these two metrics identifies the maximum sound pressure level (L_{Amax}) and the weighted maximum level corrected for human hearing sensitivity ($L_{PN(T)max}$). The next step is to measure how long an event lasts and, for the community, how often it's repeated.

Should motors exhibit prominent or annoying whines as some early experiments did, it will be important to be sure that prominent tones are considered if they are present, so we will calculate the tone correction built in to $L_{PN(T)}$[37] in each case. DNL and SEL are defined using A-weighted sound pressure level, which we will use for comparison, but here again we will use physiological loudness metrics, initially $L_{PN(T)}$ in addition to L_A in order to capture annoying characteristics that wouldn't necessarily show up in an L_A measurement. The FAA requires a uniform path to be flown for each vehicle being certificated for noise emissions. In addition to the standardized landing, overflight and takeoff procedures intended for helicopters, innovators should be able to choose whatever flight path, within the approach and departure

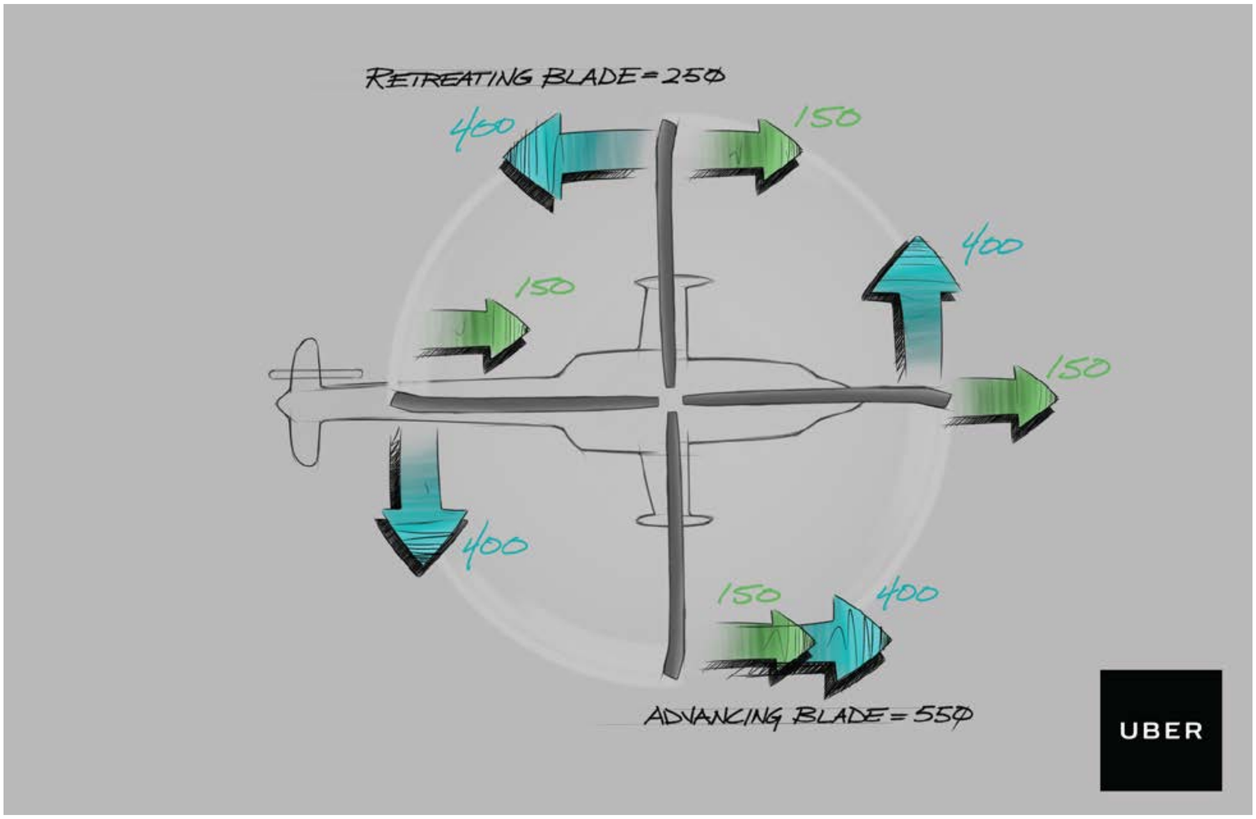
[37] Kryter, Karl D. (1960) "The meaning and measurement of Perceived Noise Level." Noise Control 6, 5

safety zone, will result in the lowest noise dose. We believe that Effective Perceived Noise (EPNdB), which is a measure of the relative loudness of an individual aircraft operation, modified to allow optimum flight path as noted, will be the most appropriate metric for VTOL noise ranking.

Once the noise emissions of each vehicle are characterized, the next activity is to project how many operations at what time of the day or night will result in reaching the 1 dB DNL increase threshold, or the 5% awakening-increase threshold in the community. This requires integrating the *emission* of each vehicle (the sound leaving the vehicle) and its distance from the community (determined by the path loss in the air) so that the *immission* (the sound reaching the listener) of the noise at the closest community point can be predicted. Real-time tracking of site noise will permit documentation that target noise levels are not exceeded, and that thresholds can be adjusted if the noise background changes. A quieter vehicle means more operations are possible at a given site. While computationally difficult a few years ago, this analysis is practical and low-cost today. This approach to site-level analysis will enable operators to measure and tailor noise requirements not only by vertiport/stop, but also enable us to adapt dynamically to operations at the level of specific sites. Doing so would be an efficacious approach to aircraft-related noise measurement and management, which we believe will enhance the capacity for quiet and efficient VTOL network operations in and around communities.

Vehicle Design

As a starting point in understanding vehicle noise, it is instructive to understand noise generated by today's helicopters. They are intrinsically noisy, both because of the rotor tip speeds required to achieve a reasonable cruise speed and because there are at least three spectrally different major noise sources: the main rotor, tail rotor and engine.



Helicopters typically use a single rotor that flies edgewise; while one blade is rotating forward, the air over the blade is traveling at the blade's speed plus the forward speed. Meanwhile on the other side of the helicopter, another blade is rotating backward (called the retreating blade), with the air over the blade traveling at the blade speed minus the forward speed of the helicopter. This means the helicopter rotor must spin much faster than whatever speed it's traveling to still achieve lift on both sides, whether the blade is traveling forward or backward relative to the direction of flight. It is also responsible for the mechanical complexity of a main rotor system that must adjust pitch as the blade rotates around the 360 degree azimuth.

A typical helicopter main rotor blade spins with a tip speed of around 400 mph, with current helicopters flying up to about 150 mph[38]. So what does that mean for noise? The amount of

[38] Compound helicopters have achieved speeds of 300 mph through the use wings to offload the rotor and/or propellers or jets for forward thrust. While able to achieve high speed, the efficiency of this approach is quite poor and results in a complex and expensive solution which doesn't align well with short distance urban flight missions.

noise a rotor blade makes varies as an exponent of tip speed. For example, if the tip speed could be reduced by a third, then the amount of noise energy produced can be reduced by as much as 24 times (the behavior is nonlinear and depends strongly on the initial tip speed and blade geometry). Unfortunately, the rotor tip must always be spinning much faster than the helicopter is traveling, otherwise there will be insufficient lift on the retreating blade side to keep the helicopter level. If you were to slow the rotor tips in the example drawing to 300 mph, the maximum speed the helicopter can travel would drop to about 100 mph because you'd still want to maintain a minimum of 200 mph over the blade to achieve reasonable advancing-retreating blade differential lift and rotor chord size.

In the converse scenario with the helicopter traveling more rapidly and this being additive to the tip speed on the opposite side of the aircraft, the advancing blade tip is traveling near the speed of sound, generating unacceptable levels of community noise. These two cases are some of the fundamental limits that make helicopters inherently noisy—the only way to force them to be substantially quieter is by trading off cruise speed to the point where helicopters are no longer much faster than a car. Adding wings and propellers has been investigated on compound helicopters which are able to travel at higher speeds, however, with much greater complexity while rotor hub drag results in relatively low efficiency compared to fixed-wing VTOL approaches.

Another challenge for helicopters is the size of their rotors. Because helicopters have large rotors turning at low rpm—which lets them hover efficiently—the rate at which the blades pass by a given point is low. This generates a lower frequency sound than a faster rotor. Unfortunately, lower frequencies travel longer distances in the atmosphere. A smaller rotor produces more high frequency noise which is attenuated by the atmosphere, so it would be less loud at a given distance. That sounds like a possible solution, but as human hearing is more sensitive to mid-high frequencies than to low ones[39], shifting the noise pitch higher can present a negative tradeoff. Using more blades in each rotor or using vectored thrust in place of a tail rotor are partial solutions, but the fundamental problems remain. Further, by reducing the size of a helicopter's rotor, there wouldn't be enough disc area to develop the required lift with a single rotor or even two rotors. This is just one example of the multivariate engineering tradeoffs inherent in VTOL design.

By utilizing several small rotors in place of one large one, as contemplated in the previously discussed distributed electric propulsion model, aircraft designers can simultaneously produce sufficient power for vertical take-off and maintain low perceived noise levels.

DEP combined with increasing automation makes it feasible to independently control numerous motors to provide adaptive control of thrust direction (as well as robust adaptation to failures, as discussed in the Safety section) without the need for tail rotors or complex mechanical linkages.

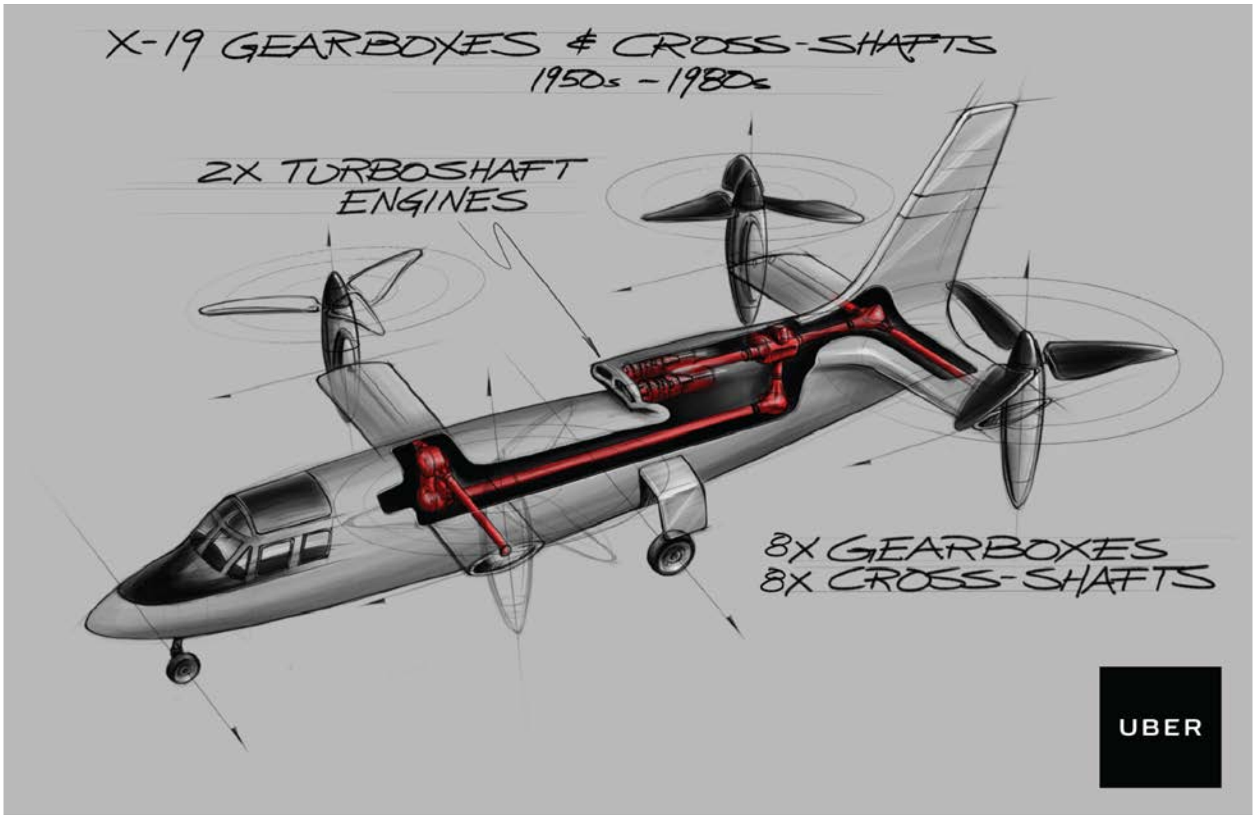
[39] Fletcher and Munson (1933)

Consider the example of an aircraft with 26 rotors, each 5’ in diameter, contrasted with a small helicopter with a 25’ rotor. In each case the total rotor area is roughly 500 square feet. The single rotor at 530 rpm results in a tip speed of 672 fps (about Mach 0.6) while the 26 rotors at 1700 rpm have a tip speed of 445 fps (about Mach 0.4). This seems like a minor change, but it is in the range where noise increases with about the fifth to sixth power of tip speed. In this case 1.5 times the tip speed can be as much as 8 to 12 times the noise energy. Because the 26 rotors are turning at nearly the same speed, the noise is a simple power sum of their individual noises, rather than being perceived as louder due to being discrete noise elements.

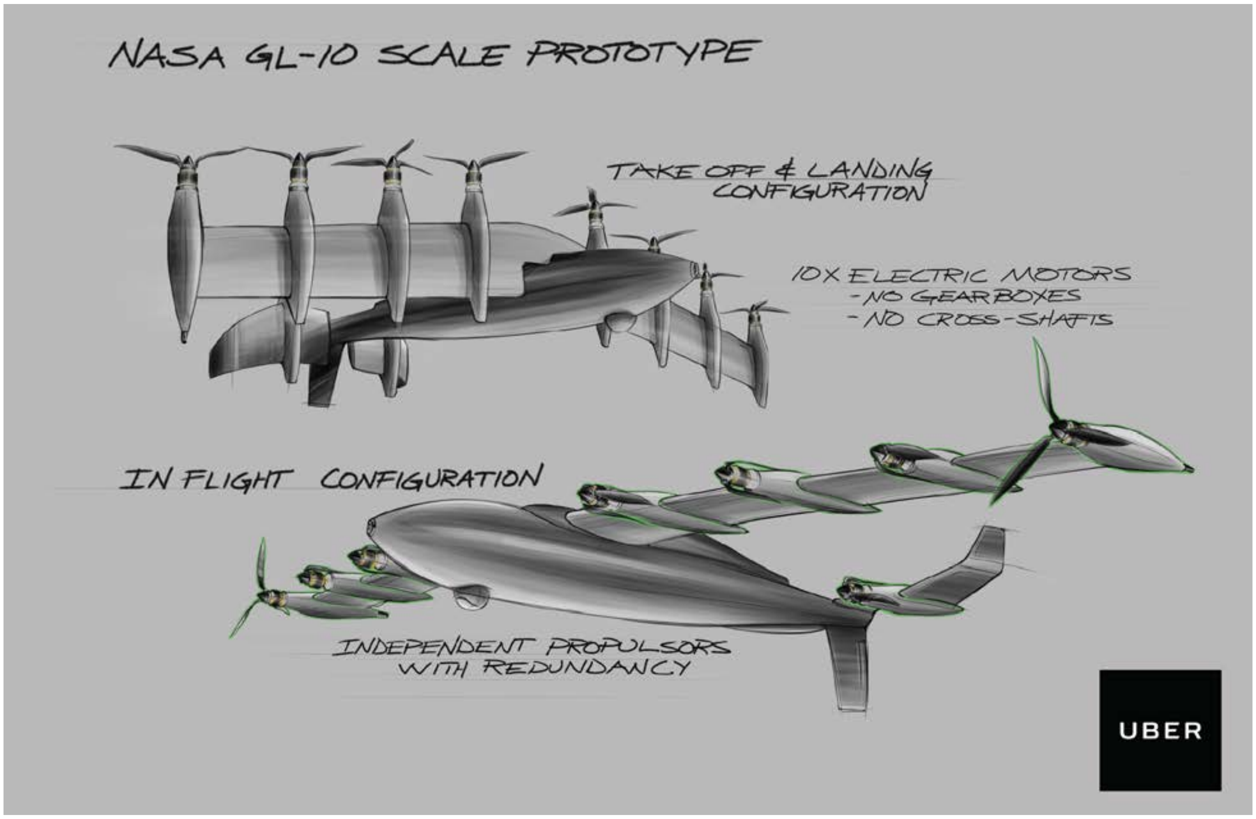
Engines are the next significant noise source, with almost all helicopters using one or two (usually unmuffled) engines. These are either piston or turbine engines, and attempting to have them drive many rotors—suggested to try to reduce noise—would be mechanically complex, requiring gearboxes and cross-shafts which themselves would all generate noise.

Such approaches were attempted by many of the fixed-wing VTOL aircraft developed by NASA, the U.S. military, and numerous countries between 1950-1980 during the golden years of VTOL aircraft development when the U.S. developed many X-planes[40]. The X-19 is an example that showcases the extreme mechanical complexity that was required to achieve fixed-wing VTOL aircraft, which resulted in poor payload carrying capability, high expense and maintenance costs.

[40] https://en.wikipedia.org/wiki/List_of_X-planes



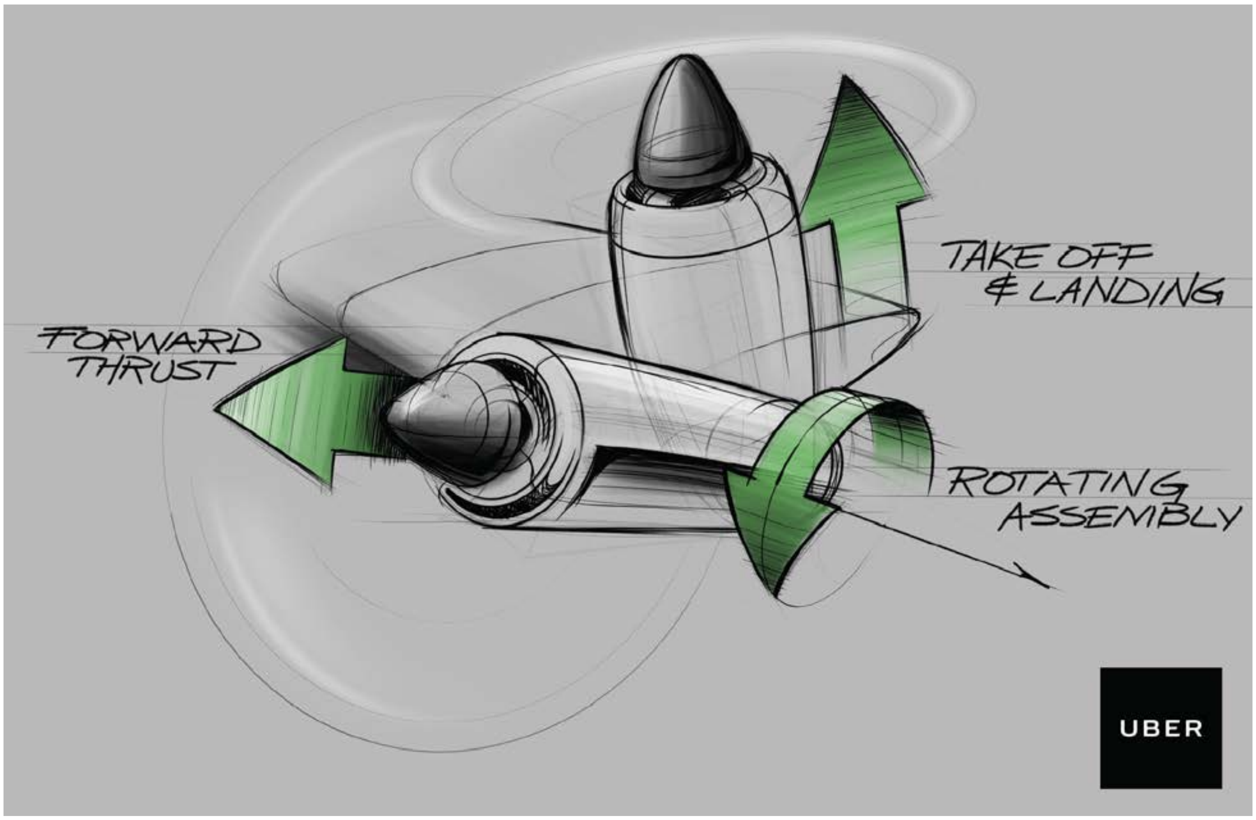
Fortunately DEP is a possible solution here, too. First, removing the engines removes a significant source of noise. Electric motors are far quieter than piston or turbine engines because they don't need to ingest and expel large volumes of air through hydrocarbon combustion. Compared with propeller noise, the noise from an electric motor using a modern sine-wave controller can be inaudible (unlike early prototypes using square-wave controllers), while the noise of a piston or turbine engine is generally about as loud as the noise from the rotor and is heard as a spectrally distinct noise source, further increasing loudness.



Secondly, electric VTOL can take advantage of scale-invariant implementation of DEP. Scale-invariant propulsion technology means designers can, on-demand, allow lift and thrust to be generated. If VTOLs use DEP, they can use many motors with smaller propellers without performance or weight penalties. DEP also allows the design to be optimized for low noise much more easily, because within the scale of VTOLs, the designer has a wide range of choices for speed and torque without needing to add gearboxes. In contrasting the X-19 to the recent NASA GL-10 (which takes advantage of scale-invariant implementation of DEP), the GL-10 design is far less complex without major structures that themselves generate both noise and many possible points of failure. The independent propulsion provides complete redundancy, so a single failure of a propeller or motor has only a minor effect on the vehicle thrust and control.

A further benefit of the flexibility of DEP is it becomes possible to consider designs with rotors that can be quickly turned on or off, and rotors that can be tilted. This approach can be used to avoid edgewise flow in forward flight so it's possible to use tip speeds about half as fast as helicopters without blade stalling, thus achieving radically lower noise.

The overall amount of noise and downwash developed by a VTOL is driven by how much thrust it needs to generate for takeoff and landing. To achieve the lowest possible community noise, a VTOL's passenger capacity needs to be limited so that noise and downwash are not excessive. This capacity is well matched to potential on-demand urban air transportation use cases and similar in nature to cars, which typically only carry one to four people. Downwash scales with weight of the vehicle, because it is directly related to the amount of air the propulsion system must accelerate. Noise likewise scales with power, approximately 3 dB for every doubling of weight, which is reflected in existing helicopter noise rules[41]. But people on the ground are not likely to care whether it is a light or heavy helicopter, only the noise exposure or downwash wind that each event produces.



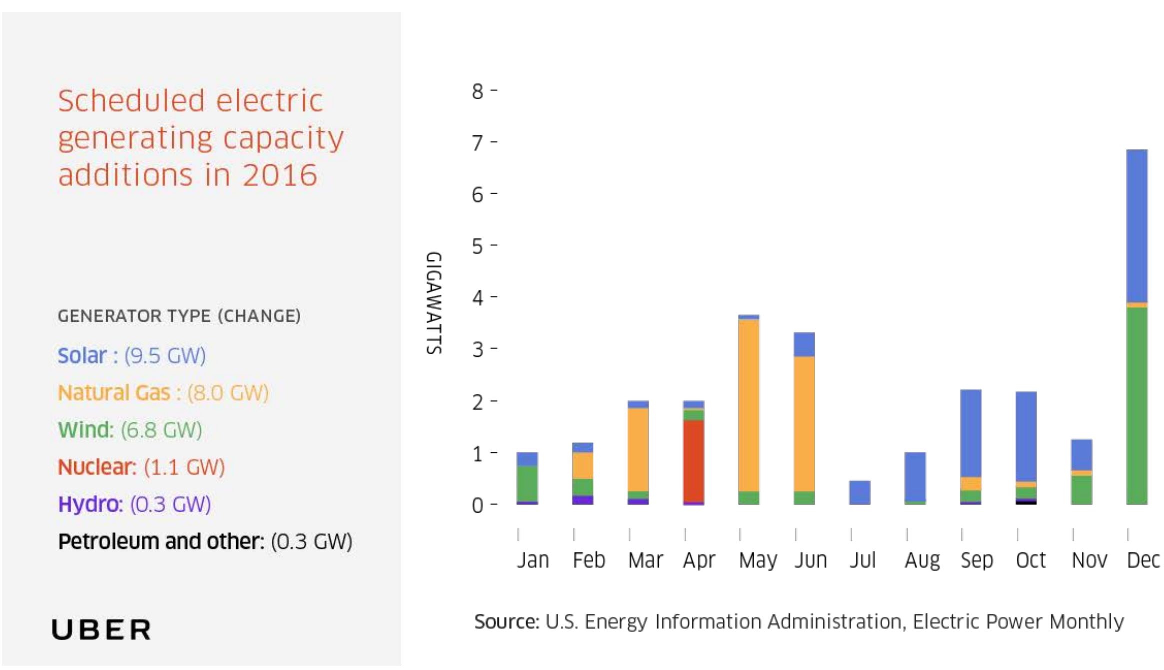
Besides the main rotor, helicopters have several other noise sources: the tail rotor, engine, and the flow interaction between the rotors and their wakes. Because these noises are in different frequency bands, the resulting loudness is higher than if they were clustered together as is the case for DEP. Physiological loudness is significantly greater for widely separated frequencies than for frequencies grouped closely together[42], and wide-bandwidth sounds are perceived as being louder because the ear processes each band of frequencies as a separate noise source. Having this combination of noise sources makes it difficult to develop approaches with traditional helicopters that could drop the noise level to the background level of a freeway or other urban location. Electric DEP VTOLs don't have fuel-burning engines, and use variation of torque across multiple rotors instead of a tail rotor for yaw control.

[41] 14 CFR 36 Subpart H (USA) and ICAO Annex 16 (most of the rest of the world)
[42] Fastl and Zwicker (1990) Psychoacoustics: Facts and Models. Springer

Emissions

Transportation is the single largest source of greenhouse gas emissions in the U.S., accounting for nearly 1.8B metric tons of CO_2[43], which is 26% of total emissions. Urban communities are understandably concerned about pollution from lead in fuel and particulate emissions given the wide range of transport solutions in and above their cities. Any new mass-scale form of urban transportation should clearly be ecologically responsible and sustainable. Fully electric VTOL designs provide a compelling solution; they generate zero in-flight carbon emissions and provide a pathway toward significantly lower carbon emissions as utilities adopt renewable energy solutions such as wind and solar.

First, all-electric vehicles get their energy from the grid, so there is a high degree of centralization of the energy source versus hydrocarbon fuels. This means the true life-cycle vehicle emissions are highly linked to utility emissions (both the legacy electricity as well as the emerging electricity plants). Second, while 90%[44] of all grid electricity generation today is powered by hydrocarbon fuels (petroleum, natural gas, or coal), development of new renewable electricity generation (wind, solar, and hydro) is outpacing development of new petroleum/coal sources by a factor of more than two, based on 2016 data (see chart below). Third, electric vehicles (of all kinds) will increase demand for electricity, which will help create the motivation to move toward renewable grid sources, and the electric utilities becoming more CO_2 responsible.



43 https://www.epa.gov/ghgemissions/overview-greenhouse-gases#carbon-dioxide
44 http://www.eia.gov/tools/faqs/faq.cfm?id=92&t=4

Existing aircraft engines operate either on gasoline (typically 100 Low Lead aviation fuel for piston engines), or jet fuel for turbine engines. 100LL gasoline powering small aircraft is now the single largest source of lead emissions in the US[45], with reciprocating and turboshaft engines adding to the noise, safety and other concerns cited as reasons for closing general aviation airports. Ultrafine particulate matter from turbine engines is predominantly of concern for airline jets[46] but is also contributing to public pressure against helicopter operations, causing one hospital to close its helipad due to exhaust fumes getting into the ventilation system[47]. We know that for communities to welcome urban air transport solutions to their cities, the environmental impact throughout the service—from the vehicles to the ongoing infrastructure and operations—will need to be minimal to zero impact on the local community. Electric VTOLs are an essential and exciting portion of the solution because they provide a zero local emission transportation capability, while helping to move away from hydrocarbon-based approaches.

The factors impacting life-cycle emissions for transportation include not only emissions of the energy source, but also the inherent vehicle energy required per mile per person. Due to electric motors being approximately three to four times more efficient than either internal combustion or small turboshaft engines, the actual vehicle energy used is substantially decreased compared to existing small aircraft and helicopters. The integration freedom of electric motors provides additional energy use reductions of a similar three times magnitude compared to helicopters (i.e. the ability to achieve a high Lift/Drag ratio by using a fixed wing VTOL approach along with synergistic aerodynamic integration benefits). This ten-fold decrease in vehicle energy use is critical for VTOLs to achieve a reasonable and sustainable transportation approach. This efficiency improvement is described in the *Vehicle: Performance: Efficiency* and *Economics: Motion Efficiency* sections.

[45] http://ehp.niehs.nih.gov/121-a54/
[46] http://www.latimes.com/local/la-me-0529-lax-pollution-20140529-story.html
[47] http://articles.latimes.com/2009/feb/07/local/me-county-usc-helipad7

Vehicle Performance

Our consideration of critical customer and community vehicle requirements such as noise and safety suggests that vehicles employing multiple small prop-rotors and using distributed electric propulsion (DEP) will provide the desired path forward. However, it is critical to understand how that design decision impacts the utility and economics of operating the vehicle and whether that limits any desirable use cases.

Cruise versus Hover Efficiency

VTOL operations will involve the ability to take off with a rapid climb at a steep glide path angle to reach a cruising altitude up to a few thousand feet, then decelerate to land vertically at the end of the trip. There will likely be a limited need to hover for durations not exceeding one minute, with most vertical takeoff and landing transitions taking place in approximately 30 seconds.

Helicopters, on the other hand, are designed for military and multi-use roles that require sustained hovering for extended time (search and rescue, powerline inspection, takeoff and landing at unprepared locations, etc.). Hence helicopters are currently designed to optimize for hover efficiency, rather than for cruise. VTOLs will spend far more time in cruise which raises the question of how to optimize such a vehicle across short-term hover power versus long-term cruise energy.

An airplane uses a wing and propeller for efficient cruise flight, while a helicopter uses rotor lift even during cruise with highly inefficient rotor edgewise forward flight. The design tradeoffs determining whether or not to use a wing or rotor depend primarily on speed, range, and hover requirements, as well as design constraints at the landing zone. As DEP VTOL designs mature, there is likely to be a continuum of approaches from fixed multirotor designs, through tilt-rotor to variants of blown-flap airplanes.

Adding wings to enable high aerodynamic cruise efficiency combined with being able to tilt rotors or turn on/off different prop-rotors to provide lift or cruise power is a likely solution when biasing designs for cruise more than hover. These solutions, however, add weight, which increases power requirements for takeoff and landing due to the increased disc loading[48]. This can also increase the noise and downwash in undesirable ways. Downwash concerns focus on the overall mass flow of the air being moved (not merely its velocity), which means that downwash for a small VTOL with disc loading of less than 50 lb/ft^2 that only operate from concrete surfaces is likely not concerning. Few VTOL designs would consider disc loadings higher than this due to the extremely high power required, as shown in the prior downwash and downdraft figure with representative VTOL aircraft.

[48] https://en.wikipedia.org/wiki/Disk_loading

Higher disc loadings can be beneficial, however. In our example commuter scenario—our most likely early use case—we are trading off increased power for a one-minute take-off and landing with acceleration to wing-borne flight for a 50-mile cruise that requires 15 to 20 minutes at significantly lower cruise power. The overall energy savings favorably impacts the economics of the flight and supports a rebalancing of design priorities from hover to cruise efficiency. Future versions of VTOLs may re-bias their designs for different infrastructures as well as primary use cases that may indicate more time needed to loiter, and shorter average distance trips.

While many people associate electric aircraft with low speed, the NASA X-57 and Thin-Haul studies are showing that DEP powered-lift configurations favor high cruise speed solutions greater than 150 mph[49].

Current helicopter designs embody product solutions that capitalize on hover efficiency because their customers are accustomed to this capability. The high degree of operational flexibility that exists with helicopters is invaluable to many missions, but that flexibility comes at a steep price for noise, cost, and especially cruise efficiency.

Speed and Range

VTOL ridesharing networks will eventually need to have a variety of vehicle types, just as automobile ridesharing services offer customers today. VTOLs will likely be developed across a number of different speed and range capabilities. A VTOL optimized for shorter trips (less than 50 miles) won't require as much speed as a VTOL capable of meeting the needs of longer distance commuters, such as those identified in the U.S. Census Mega Commuter and New York University Super Commuter studies with typical travel distances of 100 miles or more daily[50]. Super Commuters are growing at a rapid pace in the U.S., with more than 600,000 commuters matching this description.

As operators consider the parameters impacting the future service, it's obvious that speed will certainly be bounded on the low end by typical ground speeds to be competitive with other modes of transportation through a door-to-door trip speed advantage. This suggests that we need to seek an effective speed—one that accounts for any ground transportation time to get the customer to and from the vertiports— that will provide at least a two times door-to-door trip speed advantage. Based on NASA and MIT Urban VTOL studies[51],[52] a three to four time trip speed multiplier could be achieved in highly congested metropolitan areas during peak travel

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[49] Design Studies of Thin-Haul Commuter Aircraft with Distributed Electric Propulsion, http://www.jobyaviation.com/DesignStudiesOfThinHaulAircraft.pdf

[50] https://www.census.gov/hhes/commuting/files/2012/Paper-Poster_Megacommuting%20in%20the%20US.pdf http://wagner.nyu.edu/files/rudincenter/supercommuter_report.pdf

[51] Silicon Valley as an Early Adopter for On-Demand Civil VTOL Operations, Kevin Antcliff et al, AIAA Paper 2016-3466, June 2016.

[52] Los Angeles Urban VTOL Air-Taxi Study, Parker Vascik, http://vtol.org/what-we-do/transformative-vtol-initiative/transformative-proceedings/transformative-workshop-briefings

times. Since there's a great deal of dependence on the local travel conditions, a specific speed requirement is difficult to lock down. Studies suggest that 150-200 mph is where DEP becomes most efficient[53].

An upper limit (in the US) is the FAA speed limit of 287 mph for flight operations at lower than 10,000 feet. In certain sensitive geographic locations, the FAA has decreased this maximum speed to 230 mph (i.e., Washington D.C). Balancing the higher efficiency of lower speed with the desire to achieve high vehicle productivity to amortize costs across more miles of travel will likely yield a compromise of a desirable VTOL vehicle speed between 150 and 230 mph. Few helicopters are capable of flying at these high speeds and are unable to do so with reasonable efficiency.

According to the US Census Bureau[54], 123M of America's 143M workers (86%) commuted to work in 2013 via private vehicle; 89% of those drove alone. Of these, 18.9M (15.0%) had a commute exceeding 30 miles and 7.9M (6%) longer than 60 minutes - this includes 27.4% of all D.C. workers, the highest of any state.

Although urban commute distances are typically 8.5 miles each way according to the U.S. Census, this is unlikely to be a good early use case due to the dense support infrastructure that would be required. Mega Commuters (within the same metropolitan area) have average daily commutes of 93 miles each way. While these longer trips need much less infrastructure, they would require vehicles that are cruise efficient, or that employ some sort of hydrocarbon-based range extender (to compensate for relatively low battery specific energy), to be able to do more than a single trip on current battery energy storage solutions.

Current commuting practices suggest that a minimal effective VTOL range in the near-term is to conduct two 50 mile trips at maximum speed, with sufficient energy for two takeoffs and landings, while meeting the FAA Instrument Flight Rules (IFR) 30 minute reserves (plus flight to an alternate location). It's likely that by working collaboratively with the FAA and GAMA, vehicle manufacturers could establish the basis for shorter range electric aircraft to have decreased reserve energy requirements, since they have many alternative landing locations and low uncertainty over the short flight time for a change in the weather conditions. Implicit in this range requirement is the need to maintain a minimum of 20% charge in the battery to ensure a high cycle life. This type of mission has a similar energy requirement as performing a single 200 mile trip at the best range flight speed.

Battery Requirements

Our analysis tells us this design mission range can likely be met within the next 5 years—this means embracing VTOL designs that can achieve cruise aerodynamic efficiencies with a Lift/Drag ratio of greater than 10 (with 12 to 17 desirable) and battery cell specific energy of

[53] https://aero.larc.nasa.gov/files/2012/11/Distributed-Electric-Propulsion-Aircraft.pdf
[54] http://www.census.gov/hhes/commuting/

400 Wh/kg[55]. Electric VTOLs will likely use large battery packs, nominally a 140 kWh pack for a 4 person aircraft. Use of a large battery pack ensures the specific power of the batteries is well matched to achieving high specific energy. Nominally, battery packs that can discharge at less than 3C ratings are able to avoid severe penalties to the specific energy. High vehicle utilization requires the ability to perform more than one average trip distance prior to requiring recharge, which further supports the use of a larger battery pack. Essentially this is similar to the way that Tesla designs electric cars versus others, with larger battery packs and improved specific energy due to the limited discharge rates. Trip range is further extended if the VTOL infrastructure supports recharging even for just a few minutes with high voltage rapid rechargers as passengers are loaded and unloaded between trips.

There's no question that battery specific energy will limit the range capability of VTOLs. An important discrimination exists between the battery *cell* specific energy and the resulting effective battery *pack* specific energy. Optimal strategies for packaging batteries together are still being investigated to ensure that even if one battery cell fails, it won't propagate to neighboring battery cells. The weight overhead for this battery casing is quite high with cars (on the order of an additional 100% weight above the battery cell weight). However electric aircraft companies have been making progress in this area due to their weight sensitivity, with aircraft such as the Pipistrel Alpha Electro achieving less than 30% battery packing overhead.

Major investments are being made in batteries since so many products value higher specific energy (i.e., laptops, smart phones, cars, etc.), with many new chemistry approaches being tested. Particularly exciting are recent Department of Energy (DOE) investments which align so well with VTOL priorities. The DOE Battery 500 project is spending $50 million over the next 5 years to develop 500 Wh/kg batteries along with high capacity 350 kW chargers. This collaboration between DOE labs and universities is focusing on lithium-metal batteries, overseen by an industry panel board including Tesla, IBM, and PNNL to ensure manufacturable solutions. While this effort is pursuing a 1,000 cycle life, it's also pursuing a cost target of less than $100 per kWh. If this cost threshold can be achieved, the cycle life would be highly acceptable. Sony is aiming to commercialize 400 Wh/kg Li-S battery packs by 2020[56]. Equally exciting are the high energy chargers which would be capable of recharging in as little as 10 minutes. Additional research into pulse chargers is already showing improved cycle life and maintaining improved maximum charge capacity over time. Achieving rapid charging for large battery packs is as important, if not more important than achieving high specific energy batteries.

Payload

Payload weight, and therefore number of passengers, determines the overall size of the vehicle. Useful payload is reduced by the pilot weight. Over time it's highly likely that VTOLs

[55]The Department of Energy Battery 500 Project, http://www.hybridcars.com/federal-government-aims-to-develop-a-500-whkg-battery-350-kw-charging-system/.

[56] http://techon.nikkeibp.co.jp/atclen/news_en/15mk/121800252/?n_cid=nbptec_tecrs

will become autonomous, though we expect that initial operations will require pilots. Utilizing pilots in the initial period permits a strategy of building up statistical proof for FAA certification while slowly increasing the level of automation. Therefore a 2-seater VTOL would be a minimum, which would allow for just a single passenger.

Larger payloads will require greater power for takeoff and landing, which means more noise. Larger aircraft are more structurally efficient and are able to carry a higher ratio of passengers per pilot, resulting in improved operating costs. Based on prior helicopter noise sensitivity with vehicle size, the greatest probability of meeting the severe community noise limitations exists with smaller VTOL aircraft that are carrying fewer passengers.

The American Travel Survey[57], which tracks statistics relating to automobile transportation usage, provides reasonable guidance concerning typical car-like on-demand passenger trip size. This data shows that for trips less than 100 miles, over 70% of all trips contain a single person with an average load factor of 1.3 people. For trips greater than 100 miles, over 59% of all trips contain a single person with an average load factor of 1.6 people.

Prior conventional air-taxis achieved remarkably similar statistics. Anecdotal evidence of load factors from companies such as SATSAir and DayJet suggest they achieved average passenger loads of 1.3 to 1.7 in four and five seat aircraft. Because of all these factors, the payload capacity that likely best serves urban air-taxi flights would be a 2 to 4 passenger-size aircraft (including the pilot, if there is one). Such a size permits true on-demand operations with a near-term piloted solution, with the larger size enabling pooling to provide the lowest possible trip cost. While increasing to 5 or 6 passenger aircraft will provide improved economics and efficiency, it’s doubtful that such a large size aircraft could meet the severe community noise restrictions.

The amount of lift generated by rotors (for VTOL) and wings (in forward flight) must exceed the total vehicle weight, with occupants, by a sufficient margin to allow for climb and maneuvering. The front-to-back and side-to-side balance is important to keep the center of gravity aligned with the center of lift, again with a sufficient margin to allow safe control in all regimes of flight. The limits are solidly determined during flight test, when the operating envelope is determined. This is where the term ‘push the envelope’ comes from—test pilots push the operating envelope until the aircraft becomes uncontrollable, and then you know you can’t fly it beyond that point. Pilots are required to evaluate loading for every flight to assure that these parameters remain within limits.

For small aircraft, these concerns become more critical because each passenger represents a significant percentage of the total weight. VTOLs will have a maximum payload capacity, which may also vary depending on the trip altitude and the temperature. This raises questions about how the VTOL operator will deal with passenger weights. Initially, the pilot might need to assess the weight of the passenger that is about to come aboard and distribute riders

[57] https://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/subject_areas/national_household_travel_survey/index.html

accordingly (commercial airlines do this today on small planes). As vehicles mature, sensors in the vehicle may be able to do this automatically, especially when paired with ridesharing mobile applications which will maintain user information. DEP represents a partial solution from the outset, in that the center of gravity range will likely be wider than for a similar aircraft with conventional propulsion.

Autonomy

Autonomous VTOLs will improve the safety of their operations, just as self-driving cars have the potential to reduce the number of automobile accidents which cause 1.3 million fatalities per year globally[58]. VTOL autonomy is likely to be implemented over time, as users and regulators become more comfortable with the technology and see statistical proof that autonomy provides greater levels of safety than human pilots. As with other improvements, demonstrating safe operation despite component failures (or operator error) is a direct way to show equivalent or improved level of safety.

To fast-forward to the safest possible operational state for VTOL vehicles, network operators will be interested in the path that realizes full autonomy as quickly as possible. Compared to ground vehicles, the environment in which VTOL aircraft operate is far more open and uncluttered, except during takeoff and landing when operating in close proximity to the ground, buildings, and people. While there may be airspace restrictions and other VTOLs to be aware of, compared to self-driving cars (which need to deal with everything from construction to road obstructions, as well as reacting with only small separation distances), the challenge of automation for VTOLs seems to be less daunting. However, VTOLs do have a higher dependency on the weather as an operating hazard compared to self driving cars[59]. And while there are many ways that VTOLs can be made very safe, it's still not possible to just pull over to the side of the road as a method of dealing with uncertainty or error.

Just as mobility solution providers are experiencing with self-driving cars, there's a nearer-term approach that includes having reversionary modes where the pilot can always overpower the vehicle-recommended control. VTOL pilots will derive substantial benefit from obstacle detection and sense-and-avoid systems that can alert the pilot of concerns and provide operating envelope protection. This approach provides a path to decreased pilot workload (as well as reduced training) in urban environments while potentially achieving a lower certification burden due to the reliability of the combination of pilot along with the autonomy components and software. 'Inward looking' autonomy provides the opportunity for a decreased dependency on pilot skills through active health monitoring of components such as battery systems, active vehicle stabilization, and management of distributed propulsion systems.

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[58] World Health Organization. http://www.who.int/mediacentre/factsheets/fs358/en/

[59] "Transformational Autonomy and Personal Transportation: Synergies and Differences between Cars and Planes", http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160010146.pdf.

Since this level of control system software is new in small aircraft, it raises the question of how these systems will be certified for safety and how long that process will take. This is a significant challenge in time and cost since only large commercial aircraft have been certified previously with fly-by-wire systems. Fortunately, the AgustaWestland AW609 civil tiltrotor and the Bell 525 helicopter are paving the way for GA aircraft to be certified with fly-by-wire systems, with certification of both rotorcraft well underway. Recognizing the potential benefits of automation to the primary causes of accidents in general aviation, we've also seen that the FAA Small Airplane Directorate has initiated efforts to explore more affordable approaches to implementing these type of systems.

Longer-term solutions for autonomy will likely provide distributed avionics and control architectures that can prove a greater system reliability at a lower cost than current approaches. This longer term solution will also likely embrace moving the pilot out of the vehicle and onto the ground to improve the vehicle productivity and economics. "Bunker pilots" are already used in the military to handle the remote control of unmanned drones and it is expected that in the mature state, a pilot on the ground would be able to monitor and manage a number of VTOLs at the same time.

Ground-based operators—just like the pilots who will initially fly these VTOLs—will need to be trained and licensed. As part of certification of a new vehicle, manufacturers will need to define ways an operator can monitor vehicle airworthiness and its ability to make flight safety decisions remotely. This move to remote piloting will likely need close coordination with the FAA Unmanned Aircraft Systems efforts as they address similar issues with large drones in civilian airspace.

The below SAE On-Road Autonomy Taxonomy figure[60] shows the evolution of autonomous capabilities through which automobiles are currently progressing. Uber has begun carrying passengers with Level 3 autonomy in cars equipped with safety drivers to intervene if needed. Tesla has announced[61] that all of their cars will be sold with at least the hardware required for level 5 autonomy, full self-driving capability. While these advancements have excited the self-driving car community, establishing the software[62] to ensure safe operation across all off-nominal conditions will take many more years. Self-flying aircraft will progress across a similar autonomy scale and while autonomous cars won't directly enable autonomous aircraft, their constituent technologies have a strong commonality.

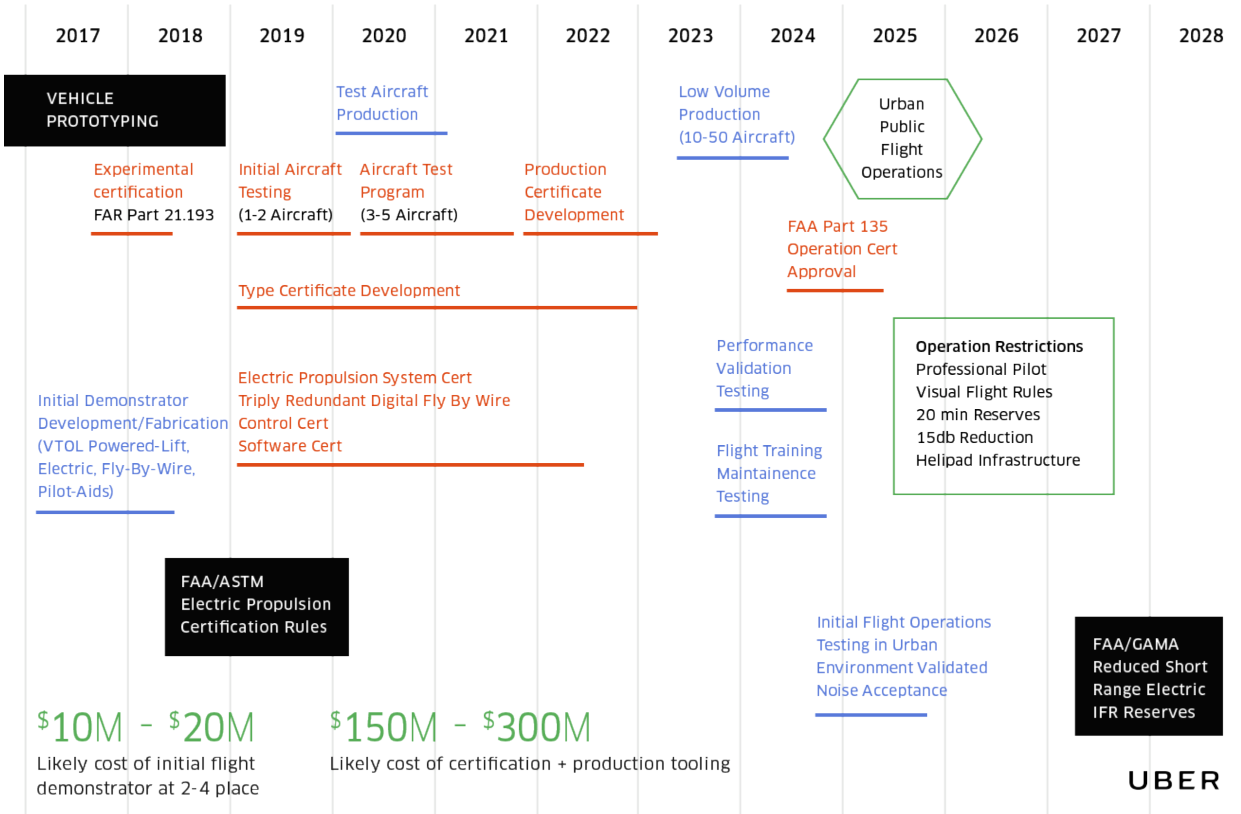
[60] Source: SAE International and J3016.
[61] https://www.wired.com/2016/10/elon-musk-says-every-new-tesla-can-drive/
[62] Tesla includes a disclamer in their level 5 statements that "self-driving functionality is dependent upon extensive software validation and regulatory approval, which may vary widely by jurisdiction. It is not possible to know exactly when each element of the functionality described above will be available, as this is highly dependent on local regulatory approval."

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

The uncertainty and possibility that self-flying aircraft will experience off-nominal conditions that the software and sensors can't resolve during cruise flight is relatively low. The challenge for ensuring self-flying aircraft software can adequately sense and react appropriately across all flight conditions is primarily focused on ensuring safe takeoff and landing autonomous operations. Because the risk can be limited to specific locations, there's the potential that the path to 'level 5' self-flying VTOLs will involve ground-based vehicle autonomy aids that provide a behavioral check of the VTOL sensors and decision making. This type of redundancy couldn't be duplicated with self-driving cars because ground-based autonomy risks can't be isolated to specific locations.

Having an automated ground-based sensor backup that can communicate with the vehicle and verify the autonomous software actions, could also provide a path towards early autonomy adoption. Due to the combination of backup alternatives that exist for VTOLs to ensure safe operation (remote bunker pilots and automated vertiport vehicle flight verification), self-flying VTOLs have the potential to progress at a rapid pace, perhaps even more rapidly than cars or aircraft that aren't operating on a highly structured and standardized vertiport and vertistop infrastructure.

Certification



Before VTOLs can operate in any country, they will need to comply with regulations from aviation authorities charged with assuring aviation safety. These regulations enforce standards for vehicle design, production, pilot licensing, and maintenance and operating requirements. The FAA and EASA function as regulators for 50% and 30% of the world's aviation activity, respectively, which means VTOL developers will ultimately need to secure their approval to achieve mass-scale adoption. Cooperation between the FAA and EASA has resulted in reciprocal arrangements[63] so an aircraft approved in one jurisdiction can be flown in another. Pilot training and commercial operator certification vary by country, but the requirements are similar.

Developing a certification path involves a number of steps. First the regulatory authority and the manufacturer have to agree on the certification basis. This is the set of rules that will apply to the particular aircraft (e.g., in the U.S., Part 23 for general aviation airplanes, Part 27 for small helicopters). Then the regulator and the manufacturer must agree how to determine the compliance of the vehicle with the certification basis. Since this is a new type of aircraft, in the United States it would be certified under Part 21.17(b) with "equivalent level of safety" once it has been proven in an experimental program. Preliminary work has been done by the

[63] https://www.faa.gov/aircraft/repair/media/EASA_EU_roadshows.pdf

FAA for a powered-lift certification basis to accommodate tiltrotors like the AgustaWestland AW609 Tiltrotor[64], but it is not fully defined. Next, the manufacturer demonstrates the compliance of the vehicle to the standards accepted by the regulator to obtain type certification; this is an iterative process. Following type certification, manufacturing can begin[65] while the manufacturer seeks a production certificate to demonstrate the capability of producing many copies of that aircraft to the same standards.

Before an aircraft is produced for commercial sale or use, it is given a special airworthiness certificate in the experimental category for research and development. This is a short part of the development process for piloted aircraft, and involves negotiating operating limitations which allows flight testing away from congested areas. It does not require any special action or new rules from the FAA. Other experimental purposes such as market research are also permitted, but not with paying passengers. Innovators may choose to make kit aircraft available, which can be fabricated and assembled in the manufacturer's facility[66] by an owner-builder in a few weeks to meet the amateur-built requirements. In the U.S., few of the usual airworthiness requirements apply to experimental aircraft. Before the aircraft are built under a type certificate, a broad base of experience can be developed rapidly with experimental aircraft (even though these vehicles cannot be used in revenue service).

Traditionally, the end-to-end certification process (type and production) for a simple case, like a new model of conventional general aviation aircraft, takes about two to three years for a type certificate, plus another year for a new production certificate. The introduction of a new *type* of aircraft, however, requires a new certification basis, developed in parallel with the type certificate, and this could extend the end-to-end certification process to 4 to 8 years (and in the case of the AW609 as long as 20 years). Fortunately, in 1995 the U.S. Congress passed a law to favor industry consensus standards[67] rather than the government's own prescriptive standards, akin to the way automobiles are certified for safety. ASTM International has been an effective forum to facilitate agreement among stakeholders with consensus standards already in place for Light Sport Aircraft (ASTM F37 Committee), as well as emerging consensus about replacing General Aviation Airplanes (U.S. Federal Aviation Regulations - FAR - Part 23) standards with new ASTM F44 consensus standards. This approach offers the potential to radically accelerate the development of new standards (which is required for the certification of new electric VTOLs) because the community takes responsibility for developing the certification basis and then presents it for adoption by the regulator.

ASTM International consensus proceedings are currently finalizing electric propulsion standards (i.e., F39.05 sub-committee standards), which they hope to have adopted by the FAA and EASA. There is less movement to date on vehicle autonomy, but there has been progress recently as the FAA established a streamlined process for approval of pilot aids such as angle-of-attack indicators. The FAA has also been active in new standards for unmanned drones

[64] http://newatlas.com/agustawestland-aw609-tiltrotor/21466/
[65] https://www.faa.gov/aircraft/air_cert/production_approvals/prod_under_tc/
[66] See http://glasairaviation.com for details on "two weeks to taxi"
[67] https://www.whitehouse.gov/omb/circulars_a119

through Part 107 to accommodate initial operations of aircraft less than 55 lb within line of sight.[68] Six unmanned aircraft test locations across the US will allow for rapid testing of new technologies that will transform the current “see and avoid” rules (which are currently in place for manned aircraft) to “sense and avoid” through new sensors and trajectory management systems. This will enable the transition to beyond-line-of-sight autonomous operations.[69] Just as fly-by-wire has been integrated into airliners certificated under Part 25 alongside traditional jet airliners, certification of VTOLs will have to prove an equivalent level of safety to Part 23 (small fixed-wing) or Part 27 (normal category helicopter) aircraft. On the software side, while new airliners typically use RTCA DO-160 environmental and electromagnetic compatibility testing and DO-178 for software validation, less stringent requirements are being defined that offer the potential for more rapid and less costly certification. GAMA has also initiated efforts to support small aircraft fly-by-wire certification through their Electric Propulsion Innovation Committee (EPIC) Simplified Vehicle Operation (SVO) sub-committee efforts that brings manufacturers together to agree on common practices.

Accelerating the Certification Timetable

We see a number of potent ways to accelerate the VTOL certification process and thus time to market for on-demand urban air transportation.

First, flight-based ridesharing is a very specific use case. Uber understands its customers’ needs exceptionally well and we bring an existing large global customer base that very much wishes this vision were a reality today. This is an unusual situation: the demand side of the market is ready to go. The rapid growth of ridesharing has demonstrated a strong desire for on-demand transportation, and the time-savings value proposition of on-demand flight is a natural evolution. To complement the demand pull, we have the interest, resources and relationships to work closely with cities to understand infrastructure and operational requirements. These factors should enable the wider ecosystem to explore the implications of this demand and use cases to constrain the goals and designs of the aircraft. All of this should help accelerate development and testing.

Second, as mentioned above, both the FAA and EASA have adopted consensus-based standards processes as a replacement for their previous very slow internal standards development processes. In relation to VTOL aircraft certification, the FAA and EASA will imminently adopt ASTM’s F44 specification as a replacement for Part 23, which governs small fixed-wing aircraft. Once the adoption of F44 is complete, this opens the door to developing standards for VTOL powered-lift aircraft under this FAA adopted framework.

In order for the standards development process to happen, in this case for powered-lift aircraft, leadership is required to assemble a coalition of stakeholders (e.g. interested vehicle manufacturers) and approach the ASTM to create a committee tasked with creating the set of

[68] https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=20516
[69] https://www.faa.gov/news/updates/?newsId=82947

standards for submission to the FAA and EASA. A consensus standards development gap also applies to defining helipad/vertiport standards. Today, there is no actual standard for helipads; there is only an FAA Advisory Circular of guidelines (that is often treated as if it were a standard by localities). The industry is clamoring for a replacement; there just hasn't been the leadership to assemble the motivated parties and proceed through the consensus standards definition process. This is where Uber can help.

Third, aircraft manufacturers can apply to the FAA to issue an experimental airworthiness certificate for their aircraft before the type certification basis is defined. The approval process is very lightweight, and this enables the vehicle to be flown under constrained circumstances[70] (e.g. only required flight crew, no revenue-earning operation). As more flight time is accumulated, the constraints can be relaxed somewhat to allow demonstration flights[71].This allows demonstration of capabilities and characteristics that can impact operational certification and will likely be essential for the public to hear and accept the substantially lower level of noise these aircraft will produce. Another example is that Part 135 has specific requirements relating to energy reserves that were based on the assumption that the aircraft is flying for long distances where weather could change significantly over the flight time and there are few alternate airports at which to land. For urban electric VTOLs, which are designed to fly over short distances, e.g. 30 minutes, and where there are many potential landing points, a 20-30 minute reserve likely does not make sense. By leveraging Monte Carlo simulations to identify the potential test edge cases, experimental flights can validate the worst cases to provide the proof the FAA requires to modify this critical electric VTOL requirement.

Fourth, the FAA and EASA have traditionally been responsive to the concept of Equivalent Level of Safety (ELOS). As an alternative to complying with a standard requirement directly, evidence can be presented that the same level of safety is achieved through other means. This approach would apply well to full vehicle autonomy, for example. Once piloted operations are in place, autonomous systems can be introduced, enabling large-scale data collection demonstrating with statistical significance that autonomous flight is at least as safe as piloted flight (much like the process occurring today with autonomous cars, beginning with semi-autonomous operations assisted by safety drivers). This could circumvent a very lengthy standard specification process for autonomy, while providing the FAA with the statistical safety proof that the FAA needs to move forward with confidence.

Operator Certification

Commercial air-taxi services in the US are regulated under Part 135 which allows scheduled commuter and non-scheduled air taxi (on-demand) flights. We expect there to be little adaptation of these rules needed for VTOLs once the aircraft is produced under a type

[70] FAA Order 8130.2H

[71] FAA Part 21.191 specifies use of experimental aircraft that includes "Research and development. Testing new aircraft design concepts, new aircraft equipment, new aircraft installations, new aircraft operating techniques, or new uses for aircraft." Further Part 21.195 specifies use of experimental aircraft "for purposes of conducting market surveys, sales demonstrations, and customer crew training."

certificate. An individual can obtain a simplified certificate as a single-pilot operator; or a full Part 135 operation can be developed for a company with many pilots on staff with defined responsibilities for directors of operations and maintenance and chief pilots. Today, approximately 2,100 operators are licensed, flying over 10,000 aircraft in total.[72]

Pilot Training

Part 135 operations in the US today require a commercial pilot's license, minimum pilot-in-command (PIC) experience of 500 hours for visual flight rules (VFR) operation, and 1,200 hours for instrument flight rules (IFR). Typically, new Part 135 pilots log the required time by being flight instructors after obtaining their private pilot license. VTOL pilots will come from both fixed-wing and helicopter backgrounds; the total PIC time requirement may be met using any aircraft. The required commercial license with powered-lift rating[73] will be met by including at least 50 hours PIC time in powered-lift aircraft; the remainder of the time can be in conventional light aircraft.

As described in the safety section, VTOLs with autonomous capabilities will significantly shift pilot skill requirements. Presently, pilots must monitor both the vehicle's trajectory in relation to the desired path and also adjust many vehicle state parameters to force the trajectory to conform to the desired route. Autonomy refers to the ability of the vehicle to make these adjustments itself; pilot inputs are limited to commanding a desired trajectory rather than the means to achieve it.

While we have planned initially for commercial pilots operating under today's Part 135 rules and their equivalents outside the US, we anticipate that demonstrating successful operation with early vehicles will reduce the requirements for pilot experience in conventional aircraft based on reduced pilot task-loading, and more fundamentally, the reduced scope of tasks for which the pilot is responsible. This is similar to what the FAA has done in the definition of the light-sport pilot license which requires roughly half the time that a private pilot license does. Not only must the FAA be convinced, but the insurers who cover the risk of the operation will need to see that pilot skill and experience requirements are reduced.

In pilot training, certification is based on demonstrated competence in handling failure modes, continuing to fly the aircraft safely in a diminished condition. A typical private pilot spends 8 to 10 hours learning to fly the basic maneuvers, and the remainder of the time learning to handle excursions from normal flight (stalls, poor runway conditions, crosswind operations, engine failure, etc.). Commercial and instrument pilots do the same, with more complex aircraft at higher levels of precision, including failures of navigational equipment. Multi-engine pilots spend much of their training dealing with flying with one engine inoperative. Once all these failure modes are addressed by autonomous system design, navigation is suitably redundant and the pilot need not take corrective measures to assure safe flight, it can be demonstrated

[72] http://nata.aero/data/files/gia/4656_001.pdf
[73] 14 CFR 61.129(e)

that a far shorter training period is required to achieve safe operation over all the potential failure modes of the aircraft. There is already precedent for this; a multi-engine rating can be achieved in far less time if it is limited to centerline thrust (one engine in front and one in back) rather than conventional twin-engine aircraft where an engine failure presents an asymmetric thrust condition that can be quite challenging to manage.

Infrastructure and Operations

To enable on-demand VTOL operations within a city, it will be essential to tailor the infrastructure and operations needs based on patterns of local demand. The extent of infrastructure that will need to be developed in any given metropolitan area will be dependent not solely on demand and models of efficient operations, but on the current infrastructural footprint and if that infrastructure requires any repurposing. In many instances, both the suitability of existing infrastructure and scale of relevant infrastructure may be lacking.

Developing a city's required VTOL infrastructure will require a data-driven understanding of current transport demand and modelled future patterns of commuting. Operators must also proactively engage with local resident communities and with local, state and national governments to help identify and mobilize private sector investment to develop VTOL-related infrastructure that benefits consumers, communities and the network's sustainable operations. What follows is an initial overview of the infrastructure and operational issues that a city and its many partners will need to carefully evaluate as they consider the prospect of VTOL service. Engagement across multiple levels of government, local communities, and the private sector will surface many additional concerns that will need to be factored into infrastructure development and flight operations, as well as vehicle design.

In the subsequent sections we discuss:

- **City Infrastructure:** How are heliports and helistops (or vertiports and vertistops) designed today, and how might this infrastructure be tailored to VTOL ridesharing in the future? How might a city think about choosing takeoff/landing sites for aircraft, and how does infrastructure interact with airports, maintenance hubs, and routing?
- **Infrastructure Simulation:** Based on data from long trips on Uber today, how do we expect demand aggregation to influence the location of vertiports/stops in cities?
- **Charging Vehicles**: How will VTOLs be charged, and what infrastructure is required to support?
- **Operations:** How will operators unlock operational efficiency of urban VTOL networks and solve the airspace challenges they will bring, as well as those introduced by inclement weather? What will they need to consider with regards to security and public concerns?

City Infrastructure

Vertiport and Vertistop Development

In the U.S. there are 5,664 helipads with all but 66 for private use[74], that is, developed for use by the property owner without public assistance. Most of this infrastructure is essentially unused. After years without use, many helipads have been declared inactive and for emergency use only. Many of these are located in highly desirable downtown locations that could provide rapid access into urban areas. Los Angeles alone has over 40 high-rise helipads in the immediate downtown. Cities such as San Francisco also have many high rise building helipads, however none has permitted use due to local ordinances that are highly restrictive due primarily to noise concerns.

Over the past two years NASA has studied the idea of VTOL air-taxis operating in dense urban areas[75]. Specifically, they chose San Francisco as one metropolitan area to provide detailed geographic, land use, infrastructure, weather, and operational constraint considerations to bring real world issues into their study. This permitted NASA to develop a detailed Concept of Operations (CONOPs) for how the vehicles would be used and where the required supporting infrastructure could be placed. This NASA study provides a number of insights that help better understand the feasibility of conducting very dense operations (far more than any existing city experiences with helicopters today).

A VTOL fleet will likely be supported in a city through a mixture of both vertiports and vertistops. Vertiports would be large multi-landing locations that have support facilities (i.e., rechargers, support personnel, etc.) for multiple VTOLs and passengers. Following the heliport examples used in New York City and other locations, vertiports would be limited to a maximum capacity of around 12 VTOLs at any given time to achieve a compact infrastructure size while enabling capacity for multiple simultaneous VTOL takeoff and landings to maximize trip throughput. Vertistops, on the other hand, would be single vehicle landing locations where no support facilities are provided, but where VTOLs can quickly drop off and pick up passengers without parking for an extended time. An example of a vertistop includes small helipads that are atop high-rise downtown buildings today.

Vertiport and Vertistop Designs

NASA investigated a combination of different approaches to determine potential vertiport and vertistop designs.

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[74] https://www.bostonglobe.com/metro/2016/01/22/public-use-heliports-like-one-pondered-boston-are-rare-nationally/wnwxtvevXEE8uPIsll8uHJ/story.html

[75] Silicon Valley as an Early Adopter for On-Demand Civil VTOL Operations, Kevin Antcliff et al, AIAA Paper 2016-3466, June 2016

Floating barge vertiports were proposed in the San Francisco city area to provide approach and departure aircraft paths over the water that limit community annoyance and risk, as well as the need to build infrastructure among existing, densely packed buildings. These types of barge/pier vertiport infrastructure are already in use in New York City, Vancouver, and many other cities with existing operational procedures. To accommodate increased flight operations, these vertiports could use a short-range, ground-based navigational aid that can sequence the timing of the approach and departures of VTOLs automatically.

Another novel NASA proposed vertistop solution is shown in the figure below for a Silicon Valley highway cloverleaf.[76]In this case, major roadway cloverleaves are re-purposed with

[76] Intra-Urban Vertical Flight Air-Taxi's, Potential Feasibility and Early Adoption Paths, Mark Moore, NASA Langley Research Center, August, 2016

raised helipad structures. FAA guidance documents[77] for heliport setbacks and operational concerns were used to compare with typical cloverleaf diameters. Typical cloverleaves were found to be approximately 225' diameter to accommodate car deceleration and turning. A typical helipad requires a 50' pad, a 115' diameter Final Approach and Touchdown (FATO) area, and a ~200' diameter Public Safety Area (PSA). NASA suggested a raised platform to permit the vertistop to be at the same height as the overpass to provide the maximum height clearance above any road traffic and minimize distraction to ground traffic. An elevated platform also permits the underneath area to be used for additional vertistop functionality, such as a passenger pickup and waiting area. These types of public vertistop locations are meant to be highly synergistic to current ridesharing trends, and not meant to require parking or storage of either VTOLs or ground cars. Imposing private ownership vehicle models on vertiports or vertistops would increase the size of the required infrastructure and increase the cost. Extensibility of diverse vertistop infrastructure ideas is currently being investigated by NASA and MIT in joint studies of other metropolitan areas such as Los Angeles.

This highway cloverleaf-based infrastructure approach has a number of operational advantages including the re-use of existing Department of Transportation land. Aircraft approach and departure trajectories could be performed over major roadways with no flights over neighboring private property below 500 feet. Also existing highway noise is well matched to the proposed noise levels of VTOLs to assist in limiting community annoyance. This type of infrastructure couples into existing ground roads to help minimize ground travel time, and provides a good fit with emerging ride-sharing business models to avoid the need for ground or air vehicle parking facilities. The NASA study also noted that one potential form of vertiports could be at private company campuses, which have large setbacks to neighboring property.

Similarly, the top level of parking garages offers a particularly compelling opportunity to repurpose otherwise unused real estate as a vertiport. Raised parking structures additionally provide operational advantages, such as helping to ensure that unobstructed glide path angles can be achieved to satisfy FAA guidance for safe operations. Such structures have already been proposed as shown in the figure below relating to the Los Angeles airport[78].

In terms of considering use of different potential airportal infrastructure, vertiports offer a compact footprint with VTOLs operating at steep glide slope angles to avoid overflying neighboring properties. Using anything other than vertical flight capable aircraft would

[77] http://www.faa.gov/documentLibrary/media/Advisory_Circular/150_5390_2c.pdf
[78] http://www.lawa.org/uploadedFiles/board_agenda/ManagementReports/boac130709xP4%20Heliport%20Status%20Update.pdf

require significant ground resources and land use. NASA considered conventional, short, and extremely short runway vehicle solutions in their Urban VTOL Air-taxi studies but found those approaches wouldn't be feasible for built-up metropolitan areas because of the extensive land purchasing costs and other land use issues such as ensuring the avoidance of overflight of neighboring private property at altitudes below 500 feet. Burdening neighboring property with low altitude flights that have long approach paths due to shallow angles isn't just a matter of good neighbor operations. Legal precedent prevents low altitude overflight of private property (e.g., United States v. Causby)[79]. The U.S. Supreme Court ruling established that private property ownership extends to the airspace immediately above the property, along with refuting the claim that ownership extends indefinitely upward. While the precise altitude airspace ownership reaches to is under significant legal debate and being investigated by MIT's Operational Aspects of On-Demand Mobility study, VTOLs must operate so as to respect the rights of bystanders and landowners on the ground.

Ridesharing Infrastructure for VTOLs

An additional reason why vertical takeoff and landing capability is critical for urban operations is the need to accommodate different wind directions and gusts during takeoff and landing. While Short Takeoff and Landing (STOL) and Extreme STOL (E-STOL) aircraft require less power for takeoff and landing, if these vehicles are to operate across a wide range of wind directions and conditions, then they may require runways in several directions. This is because cross-wind landings are particularly difficult at slow takeoff and landing speeds. Because of winds, a STOL or E-STOL airport in some locations would require more real estate than a single runway, and might require land flyover rights in many directions due to their shallow climb angles compared to a VTOL which has no dependence on runways and can point itself into the wind direction during hover, takeoff, or landing.

[79] Legal Information Institute, "United States v. Causby et ux.," Cornell University Law School. May 1946. https://www.law.cornell.edu/supremecourt/text/328/256 [cited: 5 May 2016]

We developed the below artist's rendering to illustrate many of the potential vertiport features and better visualize the type of infrastructure envisioned for use with on-demand VTOLs as part of a ridesharing network. In this example, the top of an eight story downtown parking garage has been converted to a vertiport capable of supporting 12 VTOLs. For the purposes of the illustration, we have assumed that the urban location must be capable of satisfying the FAA helipad guidance criteria[80] for an unobstructed glide slope in the proposed departure and arrival paths. This requirement will prevent use of a location surrounded by tall buildings on all sides.

Since VTOL ridesharing operators will conduct regular service at a given vertiport, we've depicted two 50' diameter touchdown pads. Although there is no formal requirement with regard to spacing, pads will need to be maximally separated to minimize operational risk. The separation helps to avoid interference between the two pads, and potentially offer simultaneous arrivals and departures. The touchdown pads are classified by the FAA as Touchdown and Lift Off (TLOF) areas, with another larger area classified as the Final Approach and Takeoff (FATO) area. The FATO is approximately 100' diameter, and mandates that there are no structures, lighting or other obstacles in this area to ensure flight safety. Typically a vertiport or vertistop will also have a Public Safety Area (PSA) that provides an additional

[80] FAA Aircraft Circular 150/5390-2C, April 24, 2012
http://www.faa.gov/documentLibrary/media/Advisory_Circular/150_5390_2c.pdf

setback of about a 200’ diameter which must be controlled. However, for rooftop locations, the PSA is not required since if it extends beyond the rooftop (since the area is controlled).

Parked VTOLs are kept away from the touchdown areas unless actively arriving or departing. Each of the parking spots provides a conventional charger with two offering rapid chargers. During peak operations, VTOLs will be flying so the majority of the parking spots would be empty. The two touchdown pads would each offer rapid chargers, as well. These rapid chargers will enable a VTOL that only intends to land and then reload passengers to recharge for a short time, which will maximize the amount of time in flight. Recessed charging plugs might even automatically deploy after motors stop.

The active flight operations area is restricted by a building that provides the security, screening, waiting area, and other functions; with access to the touchdown pads only through the building. The customers only walk a short distance to the touchdown pad, and only when the aircraft propulsion is inactive. The parked VTOLs are kept away from users to minimize interaction with the vehicles. VTOLs will require the ability to taxi with a wheel motor on the ground short distances to move between pads and parking areas. Another portion of the rooftop permits customers to be dropped off and access automobile or pedestrian egress points to complete their trip.

Vertiport and Vertistop Placement

Initially, VTOLs are unlikely to carry passengers directly door-to-door, but instead between vertiports and vertistops. However, depending on local regulations and space constraints, VTOLs could potentially take off and land at private residences. The locations would need to be registered and surveyed for approach and departure routes. In California, for example, personal use "airports" are perfectly legal in unincorporated areas. That said, point-to-point trips would be less likely to have overlap with other trips (as compared to a vertiport/stop network with limited, high-throughput nodes), so these passengers would need to be willing to pay a relative premium.

Given this, operators will likely focus primarily on a carpool-enabled VTOL network consisting only of multimodal trips among vertiports/stops. As discussed below in the Rider Experience section, Uber is used in the first/last mile today in conjunction with public transit, and we already successfully ask riders to walk to an uberPOOL pickup in New York City (in exchange for higher likelihood to share a ride, thus lower prices for all riders). Leveraging multimodal transport allows us to maximizes network throughput and time savings while also minimizing walking/driving time to/from stops.

The greatest operational barrier to deploying a VTOL fleet in cities is a lack of sufficient locations to place landing spots. Even if VTOLs were certified to fly today, cities simply don't have the necessary takeoff and landing sites for the vehicles to operate at fleet scaling. A small number of cities already have multiple heliports and might have enough capacity to offer a limited initial VTOL service, provided these are in the right locations, are readily accessible from street level, and have space available to add charging stations. But if VTOLs are going to achieve anything approaching their potential, infrastructure will need to be added.

Operators such as Uber can be helpful in identifying locations for and removing barriers to build out vertiports and vertistops to enable VTOL service; we demonstrate some example analysis in the Infrastructure Simulation section below. While the exurban ends of commuter corridors will have more and cheaper land, dense urban cores will have very limited space, and rooftops may not have been constructed such that they can be retrofitted. Surrounding high-rise buildings may necessitate increased rates of vertical climb at takeoff, adding potentially significant power demands, and can also create micro-climates, such as wind tunnels, that will need to be carefully considered.

Many cities heavily restrict heliport development to specific locations and helicopter flights to limited time windows. Most of the public objections which prompt these, however, don't apply to electric VTOLs. Reviewing public comment on hospital helicopter siting, for example, shows that the vehicles in question would generate far higher short-term noise levels than any VTOL operation would.

Airports and Vehicle Maintenance Hubs

Most urban areas have a variety of existing airports. In the San Francisco Bay area for example, there are three major air-carrier terminals, two decommissioned military airports, one federal/civil airport, 7 general aviation airports, a private airport and a private seaplane base, all within about 35 miles of SFO. Each of these locations is a good candidate for initial VTOL operations, and the simulation below built off our first-principles analysis in the greater Los Angeles area indicates the same.

Any city or region will also require maintenance and support locations for the hundreds of VTOLs to be serviced, inspected, and parked when not in use. This function will certainly be distinct from the vertiports or vertistops (although a maintenance base would also serve as a vertiport for passengers), and likely be part of a local Fixed Based Operator (FBO) support role for this new market. Mobile maintenance will be required at any vertiport to address non-airworthy aircraft. In the case that an emergency landing or equipment failure results in a VTOL requiring service, this would require maintenance personnel to be deployed to the location, similar to current helicopter operations. This is another reason for VTOLs to embrace fully redundant propulsion and control design that can provide a ‘limp home’ mode of operation.

Routing

Beyond locating and constructing vertiports and vertistops, VTOLs will need a route structure from any one location to any other to make integration with air traffic control practical. While there is no provision yet for dedicated VTOL routes in the U.S. National Airspace System (NAS), an equivalent construct is simple to define by negotiation with ATC, just as news reporting and medical aircraft have defined routes. For the foreseeable future, aircraft operating in urban areas will still use voice communications with ATC to allow for the variety of traffic, but in the next few years all aircraft will have readily available cockpit displays showing all the other nearby aircraft. Through experience with piloted operations along the same routes, it will be possible to demonstrate the basis of an autonomous route structure, which will evolve to avoid conflict with existing aircraft operations.

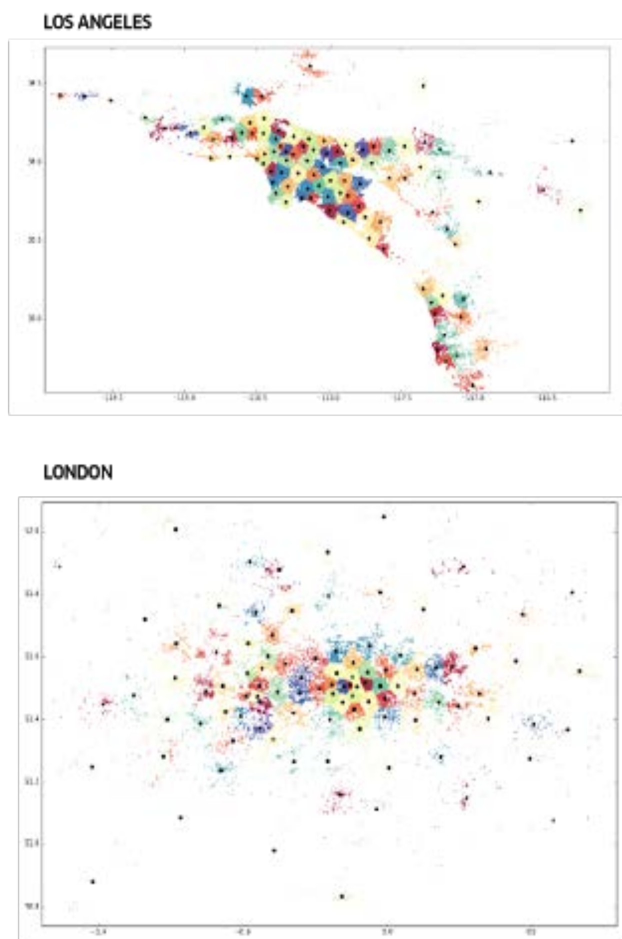
In some areas, such as the San Francisco Bay area, there are natural features such as the bay itself that lend themselves to VTOL routing. The tools for developing routing are the same as employed today for other low altitude traffic. This is another area where careful routing optimization will be key. For instance it will be possible to avoid the difficulties experienced when FAA implemented NextGen approach routing into SFO (residents complained of noisy aircraft appearing one after the other in precisely the same location) by randomizing route structure to a certain extent while remaining within corridors defined in coordination with ATC. Low altitude, maneuverable and quiet aircraft present unique opportunities that have not been present in previous air traffic planning scenarios.

Infrastructure Simulation

We know from our core business that network optimization is one of the most fundamental drivers for the efficacy of complex transportation systems. Given a large number of eligible vertiports, choosing the specific subset to utilize has strict implications for both the facility and transportation costs. The choice of vertiports also influences the total volume of the population served by VTOLs as well as their desirability relative to other transportation options.

We performed an initial analysis of potential vertiport locations in the greater Los Angeles and London areas using a September 2016 week of long-distance Uber trips whose Haversine ("as the crow flies") distance exceed 20 miles. Unfortunately, long distance trips on Uber are still far too expensive for the average consumer and thus result in a limited amount of data. That said, there are enough trips over several years of service to make an analysis of latent demand for traditional non-Uber commuting on long-distance routes.

Set of 100 candidate locations overlaid on clustered trip origin and destination points



Given a candidate set of vertiport locations, we developed a model to select an optimal subset to maximize trip coverage subject to a host of constraints. These include time saved relative to driving, limiting the total number of vertiports selected, and spatial constraints around vertiport selection. We first applied a k-means clustering algorithm to the set of trip origin and destination points to reduce the number of candidate locations for consideration to 100 (represented by black dots). These were used as input for the next stage of the problem. Out of these, we selected 25 through a large-scale optimization model to maximize accessibility for VTOL itineraries, where eligible itineraries are generated such that the estimated time saved relative to the ground trip exceeds 40%[81].

As a note, we'll use the terms *vertiport* or *vertistop* in this section generically for hubs, but the size of each will be

[81] We explore additional sensitivities with this threshold in the Output section

dependent on the throughput as shown. As we add more hubs in a city, the throughput of each marginal hub will decrease; smaller hubs will best serve as a vertistop instead given that their primary purpose will be to add network efficiency rather than as a critical, high-throughput node containing charging infrastructure.

Assumptions

We made the following assumptions throughout our simulation:

1. All riders are to take no more than one VTOL leg (i.e., VTOL layovers are not considered).
2. Max VTOL distance is 120 miles.
3. En-route VTOL airspeed is 170 mph.
4. We add 60 seconds and 75 seconds for takeoff and landing times, respectively.
5. Loading and unloading time of riders take 3 and 2 minutes respectively.
6. We estimate the time from a rider's origin (rider's destination) to a departure (arrival) hub by first converting the Haversine distance to an estimated routing distance using a factor of 1.42, and then applying the average speed from the actual trip.
7. A rider is eligible for a VTOL route if and only if the estimated duration of the route is at least 40% faster relative to the estimated duration of the ground trip.
8. All requests are met on an on-demand basis and scheduling rides in advance are not considered.

Model

In order to decide the best set of vertiport locations we consider assigning every rider a specific itinerary which is comprised of either: (i) a ground trip or (ii) an itinerary containing three segments: one from the rider's origin to the VTOL departure hub, the VTOL segment, and the VTOL arrival hub to the rider's destination. We seek to choose the subset of hubs that maximize total trip coverage of long-distance riders throughout the network.

Our model ensures the following conditions are met:

- The number or vertiports selected is not to exceed a maximum allowable number
- All riders are covered by exactly one itinerary
- No two pair of vertiports that are sufficiently close to one another, as defined by the user's specification, are to be simultaneously chosen
- Any vertiport that is not selected must not be assigned to any rider

Our model is solved by means of a large-scale integer program using a third party commercial optimization solver.

Analysis and Discussion

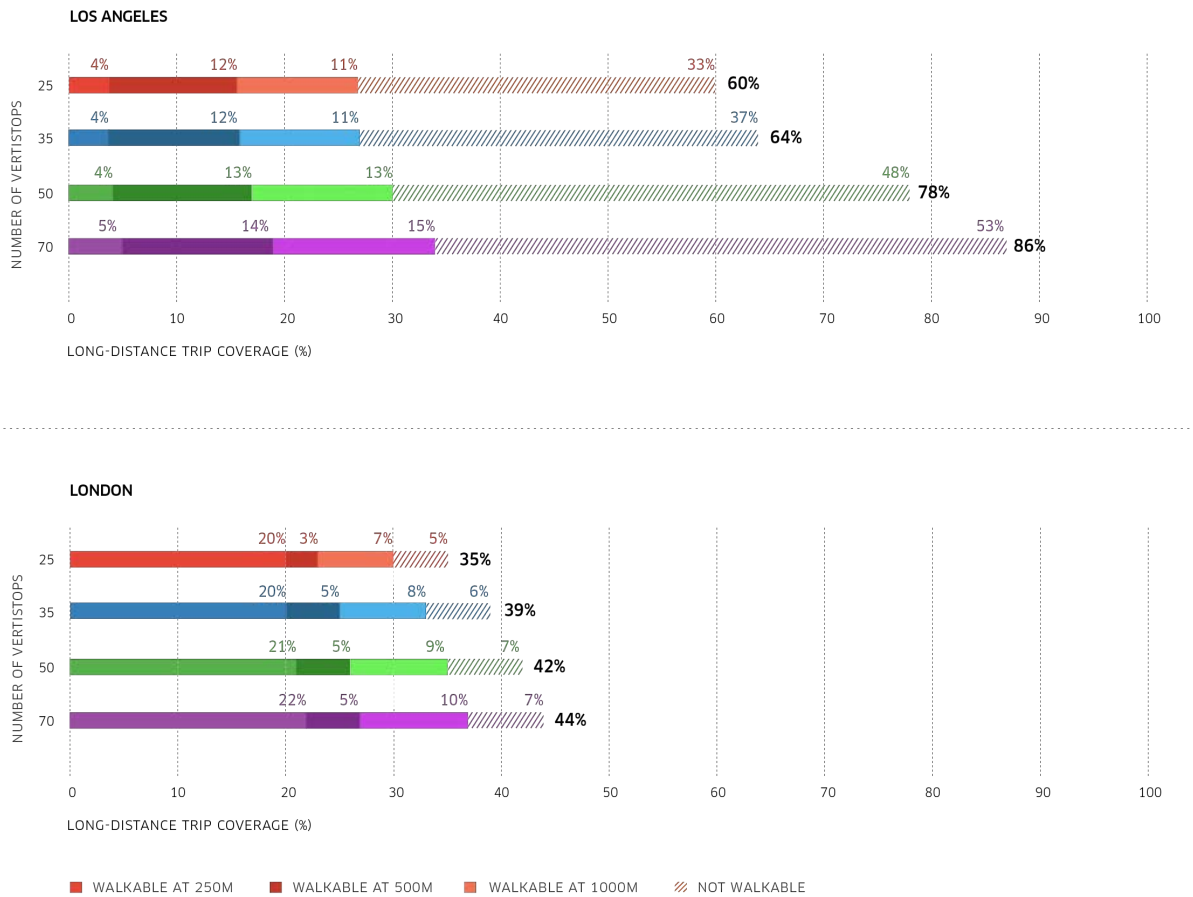
The data and analysis reveal some intriguing differences between estimated infrastructure deployment in cities, as illustrated by London and Los Angeles.

Specifically the main differences we explore focus on: the way in which urban geography and design characteristics drive aggregation of demand across a city or its exurbs and suburbs, the role that existing public transport nodes may play in VTOL infrastructure siting and multi-modal trips and the ways in which limited ground-based infrastructure sub-optimally serving existing (or suppressing latent) demand could be supplemented by alternative infrastructure options.

The first 25 vertiports that we choose capture 60% of all long-distance trips in Los Angeles and 35% in London. Long-distance trip coverage in both cities increased as we added additional vertiports, but it did so sublinearly considering each marginal vertiport had diminishing marginal trip coverage. Unsurprisingly, there is a high density of long-distance trips starting or ending in the central business districts and mass transit hubs. This is particularly evident at large airports like Los Angeles International, London Heathrow, and London Gatwick.

Some trips may have an origin or destination sufficiently close to a vertiport precluding the need for a car for the initial or final leg of that trip. We define an itinerary leg to be *walkable* if the Haversine distance for either leg before or after the VTOL leg is less than some threshold, with 250m, 500m and 1000m displayed above. The share of trips with a walkable leg is higher in London, largely attributed to the significantly larger share of trips to a local airport as compared to Los Angeles.

Estimated Vertistop Trip Coverage



Trip coverage numbers may not sum due to rounding

Demand Aggregation and Multi-Modal Benefits

In Los Angeles, fewer vertiports cover a larger portion of long-distance trips, while London exhibits far lower trip coverage across the same number of hubs. This implies that cities which demonstrate travel patterns across a significantly longer tail of origin and destination locations, such as London, may face an increased infrastructure burden to achieve trip coverage parity with other cities.

Conversely, a higher net percentage of London's VTOL trips are walkable at the 250m threshold—nearly five times as much as LA. This is due to the fact that London has numerous mass transit hubs which overlap with our predicted vertiport locations (the Tube, multiple airports) in comparison to Los Angeles whose metro is not nearly as prominent and has its major international airport closer to the city center. As such, cities which have more limited public transit (thus potentially with more latent demand for VTOL) and existing transit hubs may find that building out vertistop infrastructure actually induces increased clustering of existing travel patterns. In the interim, these cities will also see a larger share of multi-modal itineraries containing automobile legs, rather than walking.

The simulation demonstrates many of the commuting patterns that characterize day-to-day commutes within and around a city. Particularly prominent are the demand centers of main airports—in London: Heathrow, Gatwick, City, Stansted, Luton and London City; in Los Angeles: LAX, Burbank, Orange County, and Long Beach.

Underserved Routes

However, journeys *between* airports in a city is an intriguing source of demand that has potential implications for leveraging existing aircraft-related ground infrastructure to enable aerial routes that supplement sub-optimal ground infrastructure. The data show journeys between several of London's main airports - Heathrow to Gatwick and Heathrow to Luton as prime examples. Connections between London's Heathrow Airport in the west of the city and London's Gatwick Airport south of the city, for example, are notoriously challenging though many international travelers originate in one of the airports only to connect onto a flight from the other often times with tight connection times. Transit passengers need to navigate a ground journey of approximately 38 miles between the two airports, but this journey can take upwards of one hour and thirty minutes during peak traffic times meaning missed connections and added stress. A VTOL at 200 mph would take ten minutes including takeoff and landing.

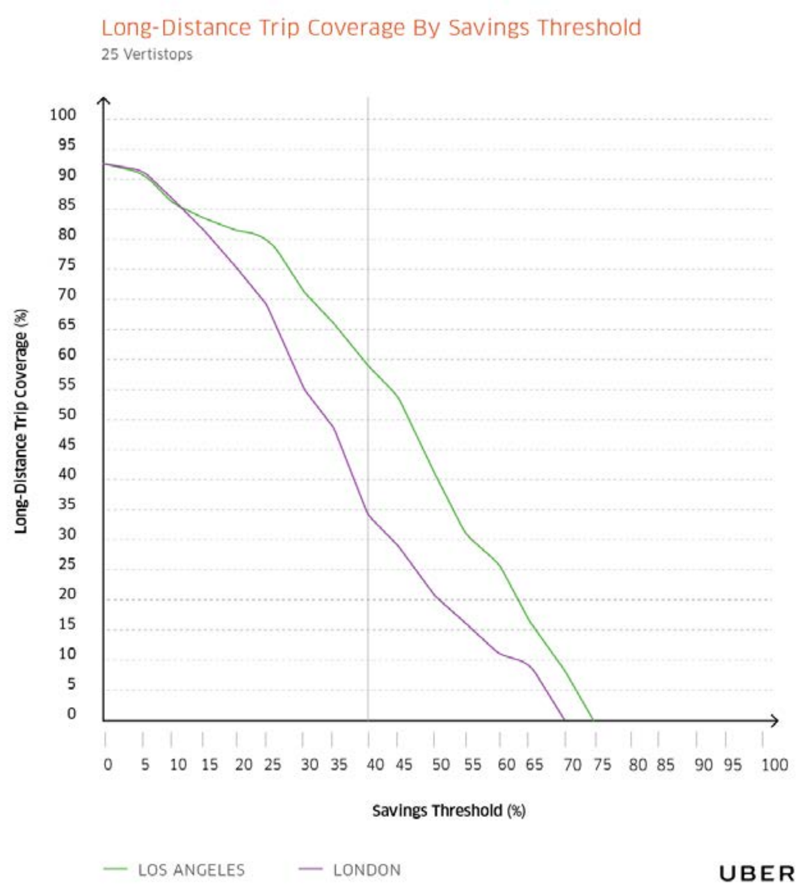
In London, the airport examples touch on the east-west and ring road(s) travel challenges that exist around the city's periphery, which is due to either limited existing road and rail infrastructure or simply congested to the point of gridlock at peak times. Where London has limited existing helicopter-related infrastructure, leveraging the extensive airport network infrastructure and the aerial links these would open up to poorly served economic centers on the periphery of the city could be compelling for VTOLs. In LA, the predicted vertistops emulate travel patterns undertaken by residents for work (e.g. Orange County to hubs in Hollywood or Silicon Beach) or leisure (various locations to Malibu Beach, for example). It may be possible that revitalizing pre-existing helipads present on many of the city's downtown buildings would satisfy the type of demand that we see in our simulation model; similar cities such as Sao Paulo might exhibit analogous behavior.

Even from this basic simulation with a relatively narrow dataset, we are able to identify important infrastructure model differences that VTOL networks will need to consider on a city-by-city basis. We know that there are many root causes that influence urban transport demand patterns driving differences and similarities across locations that can have implications for the design of a VTOL infrastructural network. While we explore several of these above, there is a range of factors that many stakeholders will be eager to analyze to plan optimal VTOL-related operations. Factors such as the underlying transport mix and quality of the infrastructure for both public and private transit modes often influence living locations for citizens, which drives corridors of demand and population density. Topographic challenges—from bays (e.g. Vancouver and Hong Kong) to mountains (e.g. Bogota)—impact accessibility to central business districts and peripheral technology, business and light manufacturing parks. The sheer distance and layout to be covered for day-to-day activities given the location of key districts influence when and how peak demand flows impact a typical commute. We see some of these attributes reflected in this basic simulation, but there are many more factors to analyze on a city-by-city basis.

Ultimately, VTOL operators will want to work closely with any given city's leadership, transport experts and existing transport network managers and planners to identify the clear near-term and projected future use cases that rapidly and potentially fundamental transform commuting within and around their cities.

Time Savings

We benchmarked the above analysis on a time savings threshold of 40% when considering the speed of driving the entire route versus taking a VTOL and driving or walking to/from the closest of 25 vertiports.



We also tested the sensitivity of various savings thresholds from 0 to 100%, finding that after a savings threshold of 70% and 75% in London and Los Angeles, respectively, no time-saving VTOL trips were possible. This makes sense intuitively because average driving speed directly between two vertiport/stops would be at least 40 mph as compared to a VTOL at 170 mph (assumption for this analysis) so the savings for any given VTOL itinerary asymptotes near 70-75%.

We also found that commute trips (under the aforementioned conditions) in Los Angeles tended to be lengthier overall—30.4 miles on average—as compared to 26.0 miles in London. LA also had a longer-tail of very long trips versus London: 75th percentile—32.1 and 26.8 miles, 95th percenitle—53.1 and 38.4 miles, 99th percentile—82.5 and 51.9 miles, respectively. This exercise further validates that VTOL will provide the greatest time savings for lengthier trips; as such, a city with greater spread between commute endpoints may exhibit more latent demand for urban flight alternatives to their automobile commutes.

Charging Vehicles

VTOLs will need to move off the landing pad at vertiports to accommodate other VTOLs if they need to recharge, or if another passenger trip isn't already scheduled. However, if energy is sufficient and if passengers are ready, then the VTOL will only stay on the pad long enough to deplane and enplane passengers. Achieving a minimum turnaround time is important to achieve high vehicle productivity. Taxiing the VTOL to a vertiport parking space for passenger egress would take a prohibitive amount of time, as well as require passengers to be on the tarmac during active operations by other vehicles. Batteries will need to be topped off between flights to achieve maximum utilization. Each vertiport will have multiple high voltage rapid chargers, as well as sufficient lower voltage chargers for each vehicle vertiport parking slot to recharge at a slower rate.

Our current vertiport modeling assumes that one-third of the chargers be high voltage/high capacity based on the ratio of required recharging to achieve a greater than 2000 hour annual vehicle utilization. Tesla has already shown the efficacy of rapid chargers, achieving an 80% battery charge within 30 minutes. However, high voltage chargers are significantly more expensive than conventional slow chargers, and rapid charging can introduce significant damage[82] to the battery, reducing projected battery life. Providing the right mix of chargers is a market-specific fleet optimization question. However, infrastructure will likely have chargers for every VTOL to enable overnight recharging. Matching the battery charge and discharge characteristics (specific power and C rating which indicate how quickly electrons can be added or taken from the battery) are critical requirements across the vehicle, mission, and infrastructure.

Battery swapping is another alternative to help maximize vehicle productivity and utilization. Tesla invested in developing a robotic battery exchange system capable of a battery swap within 90 seconds[83]. While swapping optimizes the vehicle performance, it causes a significant logistics burden, which was one reason for Tesla's discontinuation of their battery swapping program. Ensuring an appropriate distribution of batteries across all vertiports is required, which may require ground trucking of batteries between vertiports. An additional factor is that batteries are a major expense, and requiring multiple battery sets per vehicle would be a significant additional fleet expense. The certification challenge of reconfirming overall vehicle flight safety after adding a new battery, which the FAA will consider a flight-critical vehicle component, is an important additional consideration.

[82] Tesla super chargers use a high voltage, smart charging system that's able to use the battery management system to closely monitor cell voltages to avoid damaging batteries. If a typical battery is charged rapidly without high voltage or closely monitoring cell temperatures than damage can result that will reduce the cycle life of the battery.

[83] https://techcrunch.com/2013/06/20/tesla-shows-off-a-90-second-battery-swap-system-wants-it-at-supercharging-stations-by-years-end/

Operations

Air Traffic

The operational footprint and demand within urban airspace today varies by city with large aerial transit hubs having significant commercial airline activity and other metropolitan environments much more modest in terms of the demands on their airspace. Due to the underlying drivers of demand for commercial helicopter operations, their impact on urban airspace remains largely limited. Only a few cities worldwide, including Sao Paulo and New York, have scaled commercial urban helicopter activities to any reasonable degree—Sao Paulo has the largest registered fleet at a 420 helicopters supported by an infrastructure consisting of 193 active helipads.

Considering the significant potential for on-demand urban VTOL operations, the latent demand for fast 3D travel will likely necessitate a significantly higher frequency and airspace density of vehicles operating over metropolitan areas simultaneously. To meet this demand the operational complexity of managing airspace will increase *exponentially* beyond today's operational activities. It will be critically important that the aircraft operating community, regulators, and others develop alternative solutions to enable safe, efficient and high-capacity operational urban environments to accommodate this dramatic increase in aerial traffic density.

Current aircraft traffic management and de-confliction advancements such as ADS-B technology are a great starting point for initial low density operations, but more comprehensive low altitude airspace solutions will be required to meet near to long-term VTOL operational capacities. Emerging concepts such as the NASA Unmanned Aircraft System Traffic Management (UTM) initiative are a start towards an airspace system that will enable the autonomous trajectory management systems necessary for the future operating environment. However, these steps alone are unlikely to be sufficient to handle the future of urban airspace, given the project demands of on-demand VTOL networks.

Following UTM, there are at least three compelling potential developments that would help to unlock operational efficiency of urban VTOL networks and solve the airspace challenges they will bring:

1. High volume voiceless air traffic control interactions
2. UTM-like systems that address higher altitudes intersecting with General Aviation aircraft
3. VTOL-related traffic integrating seamlessly with low-altitude commercial airline approach-and-departure trajectories near metropolitan hub airports.

1) High Volume Voiceless Air Traffic Control Interactions

For VTOL aircraft, flights in Instrument Meteorological Conditions (IMC) need to be as simple and low-burden to pilots as VFR flight. Voice-based pilot-to-airspace controllers create a serial capacity bottleneck that will limit the capability and scalability of an airspace system. Transitioning to voiceless communication-and-navigation interaction has been ongoing for years as Future Air Navigation Systems (FANS) equipment such as Controller Pilot Data Link Communications (CPDLC) is being developed. This type of system replaces air traffic control instructions and read-backs, automating ATC processes.

However, the challenge of such systems is that they only complement, instead of replace, voice communication so they're expensive and can only reduce workload in a portion of situations, which means increased pilot training since the pilot needs to be familiar with both types. Operators will likely want to explore standard adoption across all aircraft types (UAVs, General Aviation, VTOLs, and Commercial Airlines) and determine how to enable this implementation. The FAA will understandably wish to see the potential demand within aviation markets, such as that being established by logistics firms pushing adoption of delivery drones and operators promoting VTOL air travel, before providing high capacity airspace solutions.

2) UTM-like Management Extended Above 500 Feet Altitudes

NASA's UTM system is currently focused on achieving an airspace management system for small UAVs operating below 500 feet altitude. This approach segregates small UAVs from other air traffic which typically flies at higher altitudes. However, it is unlikely that even small UAVs will be able to operate in a completely segregated fashion due to private property altitude restrictions and the need for separation assurances from General Aviation and Commercial traffic. A simpler approach, segregation of airspace across aircraft types, is likely not a long-term solution.

Expanding the application of UTM to general aviation aircraft, both cooperative and noncooperative[84], through an expanded NASA-Industry-University collaboration would provide a comprehensive air traffic management solution up to several thousand feet. Similar to high volume voiceless ATC, NASA will need to point to demand for high capacity airspace technologies to justify embracing this expanded scope in a timeframe that supports rapid market implementation.

3) Seamless Integration with Airports and Terminal Areas

Nearly all major cities have large airports nearby, with some cities such as Los Angeles having a hub airport close to the downtown area. These airports have Class B, C or D airspace extending control over a 5 to 10 mile radius from the ground up to about 2000 feet, and over up to a 35-mile radius in tiers reaching 10,000 feet. In Los Angeles, 43% of the city's land area is within these air traffic control sectors, and flight requires controller approval in some parts and voice interactions throughout. However, most of this controller-managed airspace is rarely utilized; MIT's Operational Aspects of On-Demand Mobility study indicates that airline

[84] Non-cooperative traffic (aircraft not carrying suitable equipment to cooperate) is likely not to be a problem in the urban areas where VTOLs will be launched, as nearly all of them will be subject to mandatory ADS-B operation by 2020.

operations only access 5% of this reserved area. This limited use of reserved, controlled airspace is partly due to recent improvements in precision approach and departures that has greatly reduced the trajectory variations.

Such data suggest that it may be possible for hub airport airspace to embrace ‘cutouts’ or more precise airspace delegation that can dynamically open up more airspace to non-controller managed flight, as exists today for example in the VFR special flight rules route over LAX. These operations would likely be dependent upon wind conditions and active traffic pattern, and already have equipage requirements to ensure safe operations in close proximity to Part 121 airline traffic traffic. This type of new airspace management approach would embrace dynamic allocation, and instead of static airspace charts take full advantage of digital communication and navigation solutions that are already available.

Other challenges will also require attention as VTOL traffic volume increases, such as efficiently managing the scheduling and sequencing of vehicle and vertiport resources in a manner that achieves high system capacity and efficiency while optimizing door-to-door travel times and variations for users of the system. Additionally, as we have seen with self-driving vehicles, it will be important to consider the standards that manage the way that different fleets govern their autonomous travel decision making. Small differences in how vehicles are programmed to respond to (or learn how to respond to) operational situations or impediments can lead to potential conflicts, particularly if the decision making parameters or tolerances in interpretation of the rules of the sky differ across different network managers’ fleets autonomy systems. We believe manufacturers, regulators and fleet operators will reach consensus on suitable standards to manage these challenges, and discussions in this space are already underway. Increased vehicle behavior uniformity will result in more efficient and safer fleet management.

While the science of dynamic spatial deconfliction—mimicking the instinctive behavior of animals such as fish swimming in schools—has been understood for centuries, sensors and portable computing power make dynamic spatial deconfliction eminently feasible in a vehicle. This type of optimization across the fleet and airspace is one where Uber can draw from experience with our core business and, as such, help bring value in maximizing both the productivity of the vehicles and airspace utilization.

Fortunately, the technology for many of these advancements is actually available readily today—the major obstacle so far to adoption of these technologies, such as ADS-B, has been high cost due to inherently small scale manufacturing of general aviation aircraft. Future developments, such as UTM-like autonomous trajectory management, will likewise be very expensive if built at small scale. Standardization of building blocks such as ADS-B has already been accomplished. Finally, operators, such as Uber, that unlock latent customer demand will spur significant VTOL manufacturing demand, which will drive down the aviation technology acquisition costs to the point where utility and general aviation will be able to adopt new technology at low cost.

4) Building Infrastructure Toward Autonomy

We anticipate that VTOL systems such as Uber's will have its own internal communications network as part of its Part 135 operating procedures, allowing precision navigation and positioning even while the vehicles have onboard pilots. Development of infrastructure in the piloted phase will flow directly toward the requirements for autonomous operation. Primary navigation will be based on existing global navigation satellite systems (GNSS) with simultaneous reception of GPS, GLONASS and whatever other international systems become available in this time, such as GALILEO (Europe) and BeiDou (China.) Precision positioning for approaches to vertiports and vertistops may also be required, using a combination of WAAS-augmented GPS and microwave transponder technology. As with UTM for unmanned vehicles, FAA is not expected to provide separation services for low altitude VTOLs as they do for airline and GA traffic. It must be possible for VTOLs to navigate independently of ATC while they are in airspace not used by conventional aircraft. All of these requirements are shared with the UAS community and it is likely that the same approach will evolve in parallel for VTOLs, at a higher level of reliability for passenger-carrying flight.

The communications or datalink portion is likely to be a combination of ADS-B, existing cell phone and low earth orbit satellite networks, and low power terrestrial microwave datalinks. From the outset the system is expected to be triply redundant to handle all contingencies; full functionality will be maintained with at least two of the networks inoperative. The data bandwidth required is quite low for essential functions that require network-wide visibility. Higher bandwidth and shorter latency will be required when vehicles are in close proximity to each other, but several approaches are already being developed in the UAS space with this capability; NASA's UTM program is leading the way here and we anticipate working closely with them as it develops.

Sequencing and spacing will necessarily be vertically integrated through the Uber airborne rideshare ecosystem. Not only must a vehicle and vertiport/stop space be available, but airspace for the flight must be reserved, and status and position of each vehicle monitored in real time. This field is under continuous development today for larger aircraft with the NASA/FAA NextGen program, and VTOLs can use a similar approach scaled to meet their own flight requirements. This is an area where continuous development of microprocessor speed and memory capacity maps directly the the ability to handle denser air traffic, to a higher degree of precision.

Trip Reliability

As explained in the introduction, trip reliability is a primary factor in the end-to-end *request-to-drop-off time*, which itself is the primary manifestation of the time-saving value prop we aim to deliver. Trip reliability is a function of the state of the network, i.e. the number and distribution of vehicles in service relative to the demand. This can be measured by *request-to-arrival time*, i.e. how long the user has to wait after the request for the vehicle to show up. This, in turn, is driven by a number of factors, such as vertiport/vertistop locations, duty cycle of the vehicles and, more so than for cars, *weather*.

Weather, discussed in the next section, is a complicating factor for flight, with serious challenges created by fog, icing, wind, and thunderstorms. VTOLs will need to leverage additional technologies to augment visibility, maneuver effectively in gusty wind conditions, handle most icing concerns, and take advantage of enhanced weather information and prediction to maximize the percentage of operational time available, all of which in turn will maximize vehicle utilization and economic feasibility: as VTOL operations scale, there will be increasing motivation and resources to innovate in these areas. Technologies ranging from auto-deicing to autonomous piloting, which will increase both vehicle control precision and the uniformity of flight suitability decision making, should significantly increase VTOL availability over time.

Whatever the gap in availability of VTOLs, the multimodal aspect of a network like Uber's helps with system reliability: if a VTOL must land due to a problem, including weather, another form of transportation can be automatically coordinated to continue the trip from the landing point. Of course, this constitutes a degraded form of service, so there will be a lower bound of VTOL availability below which VTOL service will not be considered reliable enough for users to depend upon. For early deployments, therefore, we will select locations with conditions that are favorable to availability, like consistent good weather.

Weather

Due to the increased consequences of a failure enroute, environmental conditions and weather have more acute implications for aircraft than automobiles. Thunderstorms that create large wind shear, icing, and low visibility during the takeoff, departure and landing approaches are the largest sources of aircraft operations interference. Heavy precipitation and wind gustiness create volatile conditions that cause further disturbances during takeoff and landing can make it difficult to maintain vehicle control and reasonable safety margins. Ensuring the highest safety without embracing operational complexity (i.e. spraying vehicles to remove ice prior to takeoff such as airliners) will be particularly important in the early years of any large VTOL network, which has implications for the specific urban locations where we'll focus in the near-term.

Our economic analysis assumes that no more than 16% of addressable operational time will be affected by weather. However, in markets such as New York and London, commercial airline operations are restricted due to atmospheric constraints, mostly due to thunderstorms, low clouds, fog and icing. In commercial airline operations, these conditions are mitigated by rerouting flights to alternate airports or adding delays, strategies which won't work for urban VTOLs. In general we would expect VTOLs to be available at any time the nearest airport is still able to conduct commercial airline operations; severe weather conditions, such as severe thunderstorms, will delay all aircraft including VTOLs in any market. This means that VTOL operators are likely to prioritize initial VTOL operations in markets that do not present prohibitive environmental or weather conditions.

As the technology underlying VTOLs evolves and operational capacity in a diverse range of more challenging weather environments becomes possible, wider VTOL adoption across various markets is likely to be supported further if a set of key hurdles is overcome:

Density Altitude

Operations at higher altitudes and higher effective altitudes (i.e. density altitude[85]) typically have two primary, adverse effects on aircraft operations. First, reduced air density means that higher true airspeeds and/or rotor speeds are required to generate required lift forces. Second, for non-normalized, internal combustion engines, the reduced air density means reduced engine power is available. Since electric motors are not affected by this power reduction, assuming sufficient cooling is maintained, reduced power-available at altitude is not a concern for electric aircraft. Airbreathing engines will lose greater than 30% of their power depending on how they're designed (i.e. mechanical gearbox limits), which presents a tremendous challenge for conventional helicopters. While VTOLs will nominally operate at low-altitudes relative to ground level (e.g. <3000'), operations in high-altitude areas such as Denver CO on a hot summer day equate to operations above 10,000' in a standard atmosphere.

Ice

Snow and ice stick to and can form on rotors and airframe components, adding weight and changing the shape of the airfoil. Icephobic coatings[86], which are in the very exploratory stage of development by NASA and others, repel ice formation on the wings and propellers to eliminate the need for costly active de-icing systems (i.e. pneumatic boots and heating leading edges). Icing conditions are not solely a cold-weather environment phenomenon; these conditions exist even in Florida and California at certain altitudes during occasional weather conditions. While VTOLs are unlikely to operate at higher altitudes where they would routinely encounter airframe ice, electric propulsion offers a unique operational safety advantage of permitting extremely high levels of power to be generated for short periods of time until the motor reaches its thermal limit (typically 30 to 120 seconds of operation). This capability can be used for short bursts of power in an emergency condition, or for short term high rates of

[85] Warmer air has more energy than cooler; the gas molecules move around more and push each other out of the way so there are fewer of them in a given volume when it's hot than when it's cold..
[86] https://en.wikipedia.org/wiki/Icephobicity

climb to penetrate an altitude icing layer rapidly before ice can build up. While not available today, the combination of icephobic coatings and electric propulsion would enable much colder markets such as Manhattan or London to operate with similar availability as Los Angeles or Bangkok.

Visibility

Even with traditional IFR operations (with the exception of a few very expensive aircraft), the last few seconds of flight must allow the pilot to see the landing environment. An airport “below minimums” means that at the closest safe approach point, this ability to see the landing environment doesn’t exist. VTOLs can fly an approach at much slower speeds than conventional airplanes, leading to reduced requirements (as permitted also for helicopter approaches), but until they are fully autonomous, visual conditions will still be needed.

Vision systems that are able to use the infrared spectrum to see through fog have already been developed and deployed on business-class jet aircraft. This type of vision enhancement is typically combined with mapping data creating synthetic vision systems that provide clear terrain depictions (typically derived from the worldwide NASA Space Shuttle Radar Thematic Mapper dataset) while also capturing atypical obstacles (e.g., cranes). These types of systems augment low visibility conditions but aren’t able to work in zero visibility conditions.

Ultimately, autonomy will ensure vehicle/obstacle avoidance and clear path to a landing site in the long term through Light Detection and Ranging (LIDAR) and laser scanning systems. These systems are already used on UAVs with increased range and tolerance to rain and dust vision obstruction; their costs are rapidly decreasing due to their mass fabrication spooling up for implementation on self-driving cars. Comprehensive vision systems that combine all these solutions are not yet available, and projections indicate they would introduce a significant weight penalty for smaller aircraft. However rapid progress is taking place, and there is considerable confidence that highly capable synthetic vision systems will be able to permit operation in lower visibility conditions. As a mass market is created for UAVs and VTOLs, availability of these systems will expand and costs will become much more affordable as standard aircraft equipage.

Gusty Winds

Gusts can be particularly challenging around high-rise buildings in urban environments. VTOLs will need to observe safe clearances from any man-made object, with the FAA requiring any fixed-wing aircraft to maintain at least 500 foot separation from any structure. Such buffers will need to be built into the map systems for VTOLs to insure that they avoid these safety zones, especially in dynamic cityscape environments where a crane can be erected in a few hours. The extra power available for short periods mentioned with regard to icing is also applicable here, as additional control authority is available to counteract gusty conditions. Operating a network of linked VTOLs that monitor and share the atmospheric conditions they experience permits real-time and historical mapping of gusty locations enabling dynamic routing and approach procedures that minimize exposure to gusts. This type of detailed and highly distributed weather sampling will also be able to improve local weather prediction accuracy. Currently, weather information for aviation doesn't provide high accuracy for localized geography, with the additional fleet weather data enabling greater confidence in performing short flights in non-optimal weather conditions.

Security

Ensuring that security screening is seamlessly integrated into the smooth operations of the VTOL will be essential. App-based operators are uniquely positioned to leverage our technology to integrate and minimize the inconvenience of any security requirements while eliminating time-consuming steps which riders are subjected to today in aviation. For example, our self-driving cars in Pittsburgh feature tablets in the backseat which will one day verify the rider's identity without any human oversight in-car.

Additionally, the data required to verify a rider's identity and associated preferences will likely be persistent as part of a ridesharing provider's mobile app; as such, operators may develop systems similar to the FAA TSA PreCheck[87] which permits rapid and reduced airport security screening if the passenger is determined to present a low risk through machine learning and other inputs. While Part 135 aircraft operations do not require the same levels of security screening as if a passenger were boarding a commercial airline, VTOL operations will want to explore the optimal mix of pre-flight, technology-enabled screening with sensible on the ground security parameters to enable safe, secure and enjoyable journeys.

[87] https://www.tsa.gov/precheck

Embracing Public Perspectives

Operators, city and national governments, regulators and communities will give careful thought to how VTOLs and their vertiports/vertistops will impact local communities. The emergence of drone technology and its increasingly widespread use has already surfaced a number of concerns, which will be instructive for the development of VTOL in urban settings. Local communities will have valuable feedback on issues that will undoubtedly impact vehicle and infrastructure design and operations. Consulting with prospective users and local communities on VTOL will enable operators, regulators, vehicle manufacturers and communities to share development of this potentially transformative transport solution. Conversely, if operators, government bodies, vehicle designers, regulators and other stakeholders do not effectively engage, from the outset of this journey, with the very constituents who stand to benefit from and contribute to this new form of transport, we miss a significant opportunity. If users and local communities do not see the potential application for VTOLs to improve their lives then support for VTOL operations will be restricted. Communities have a variety of means, most notably the zoning process, by which they can delay, restrict, or even prohibit operations.

Communities necessarily will want to understand how VTOLs (and operators, policymakers and regulators) will address the challenges below.

- Safety and security. While safety is primarily the concern of federal regulators, communities will also worry about safety. Operators will need to communicate the safeguards inherent in the VTOL design to develop the level of trust needed. Local communities will also have concerns regarding the security of these aircraft, including their vulnerability to hijacking and hacking. Local law enforcement and national transportation security agencies will necessarily be closely involved in the operational details of any new VTOL service, but local communities will be given a complete understanding of the security safeguards that have been put in place. While not fully autonomous initially, VTOLs are inherently trajectory-controlled rather than state-controlled, which means that the flight path can be modified remotely if needed. With suitable safeguards for network security, capability can be provided for remote pilots to override the on-board pilot in an emergency. Operators will appreciate that vertiports and vertistops will become new or more visible features of urban landscapes. Ensuring the safety and security of these sites for both operational purposes and seamless, unobtrusive integration into the fabric of cities will undoubtedly be a joint effort across local communities, local law enforcement, national security agencies and network operators.

- Noise. One of the primary issues with aviation and communities is noise. The construction of new vertiports/vertistops or alterations of flight patterns around airports are understandable and important issues of concern. It will be essential to determine what level of noise, both from VTOL operations and any related increase in vehicle traffic around Vertports, is acceptable to communities in return for offsetting benefits, such as the possibilities of reduced commute times. Every neighborhood has a unique soundscape that is part of the life of the people who live and work there, and it will be important to provide VTOL service without significant acoustic impact. This requires planning around and close coordination between vehicle design, landing site and route planning, and dynamic scheduling of each flight. Siting of infrastructure and planning of VTOL operational patterns will rely on ensuring that flight patterns can be accomplished without exceeding the target noise level at the endpoints and over the route to be flown, based on actual acoustic monitoring. Measuring physiological loudness and annoyance terms in real time can enable dynamic operational planning to address the community noise standards that are developed. Dynamic noise measurement and operational planning could enable operators to direct traffic to locations - distances being equal - that have a higher acoustic reserve (having handled fewer recent flights or having a higher background level) over the quieter one.

- Visual pollution. While VTOLs will be clearly visible during takeoff and landing, the impact that they will have on city skylines and in areas of natural beauty when flying at much higher altitudes between A and B is harder to imagine. Simulations can be produced to visually model different densities of VTOLs from the perspective of a person standing on the ground to determine any locally specific challenges. Visual pollution concerns can be addressed via trip route modifications to avoid particularly sensitive vistas or consolidating traffic to existing commute corridors such as above highways.

- Privacy. Communities have reacted to privacy issues with drones by pressuring state legislatures across the U.S., resulting in new laws. As VTOLs spend most of the time at altitude, privacy issues are likely to become more relevant when VTOLs are descending or ascending. Operators will need to dynamically and precisely route each flight over less sensitive areas, maintaining appropriate clearance above private property. In the US, fixed-wing aviation is allowed to overfly densely populated areas at 1,000 feet above the highest obstacle within 2,000 feet. In less populated areas the limit is 500 feet, in both cases subject to any other airspace restrictions, and helicopters are not subject to these limits.

Rider Experience

At Uber we're customer-obsessed, meaning we're relentless in figuring out what matters to our customers and then doing everything in our power to deliver it. Uber was founded because we wanted to make getting from point A to B in a car a magical experience every single trip.

As we look at the commercial and personal aviation markets, we observe that consumers experience many of the same sorts of challenges. From easily identifying cost-competitive flight options for complex itineraries to inefficient security and pre-boarding processes to the increasing commoditization of the on-flight experience, the average consumer is rarely treated to an effortless and pleasurable end-to-end flight experience. To realize the full potential of on-demand urban transportation, operators will need to integrate the experience into multi-modal transportation options, ensuring that VTOL options are seamlessly incorporated into the broader way that consumers travel for work or leisure within and around cities. The request, boarding, on-trip and arrival experiences must address today's passenger experience challenges, but they must also look beyond these to how small aircraft will have to cater to and improve the in-flight journey for the many consumers who have never experienced today's helicopters or small general aviation aircraft.

We care deeply about how electric VTOLs, infrastructure, and operations will all come together to create the user experience. In our core business today, drivers are independent contractors who utilize their own cars so we guide and incentivize driver-partners to help ensure their riders have consistently smooth and comfortable journeys. With self-driving cars, we are able to directly specify more aspects of the on-trip rider experience. This includes standardizing the exterior and interior of vehicles for aesthetics, performance, and comfort, personalizing environmental aspects like temperature and audio/video content, and providing new user interfaces, such as the backseat tablets in our current self-driving vehicles that provide information and controls to riders. We do not expect that VTOLs deployed on ridesharing networks will be owned by individuals, as they will be significantly more expensive and more complicated to operate than cars. As such, rideshare operators like Uber will be able to specify the on-trip experience to a degree similar to that of self-driving cars, even for piloted VTOLs. The following sections paint a picture of what the end-to-end rider experience might look like.

Request Experience

As outlined earlier in the Infrastructure section, the density of vertiports in any service area will likely be limited by the return on investment of building out marginal infrastructure. Due to this, longer distance trips that can gain time efficiency from VTOL will likely not always be completely point-to-point. Instead, these trips will be multimodal to some degree — at best, riders can walk to/from each vertiport/stop; at worst, riders will take an Uber ground car before and after their VTOL trip.

Riders are already accustomed to using ridesharing as a supplement to other modes of transportation. During London's morning rush hour, 30% of Uber rides in the outer city boroughs end within 200 meters of a tube or train station, and 1 in 4 of Portland's Uber trips start or end near a public transit station. Across the world, nearly one-sixth of all Uber bookings are to or from an airport. In New York City, we have already begun asking uberPOOL riders to walk up to 250m to their ride as we've found that this allows for much more efficient network utilization. Riders are willing to do so because we can offer these trips at lower prices with faster ETAs.

We imagine the in-app Uber VTOL experience would feature clear time and price tradeoffs between VTOL and car options, just as we offer between uberX and uberPOOL today. Selecting VTOL would display an itinerary with sequenced walking and driving legs on either end, as needed.

Boarding Experience

Taking a VTOL journey needs to be an intuitive and enjoyable experience that any passenger can embark on easily with minimal assistance. We anticipate that many urban VTOL journeys will originate and complete in vertiports and vertistops that are situated on top of familiar structures such as parking garages and high rise buildings. As an example in a parking structure, a customer could be dropped off by an automobile at the entrance to the arrivals/departures portal. Alternatively, if the customer walked, then the building stairs or elevator would connect them directly to this same portal. This portal structure provides a necessary safety and security barrier between the active VTOL arrivals/departures and the customers, as well as providing shelter from the elements. In some locations, there may be customer facilities such as restrooms and refreshments, as well as briefing and instructional information and signage to help passengers understand what to expect.

Once inside we will clearly direct passengers where to go and what to do to embark or disembark on their VTOL journey. In locations with more than one helipad the passenger would be directed to the relevant departure gate to meet their VTOL. On the way to that departure door, we imagine a rapid and seamless process whereby the rider's identity, security checks and even the weighing of the rider and their luggage (if necessary) can all be done. Alternatively checking the passenger and luggage weight may happen as soon as the rider and luggage are aboard the VTOL as part of the vehicle pre-flight check through embedded landing gear deflection sensors. When the VTOL is ready at the takeoff/landing pad, the confirmed rider would be invited into the aircraft area by means of an automatic door, and she would walk the short distance on a marked pathway to the VTOL. Due to the use of electric motors, there will not be delays while waiting for rotors to spin up or down as with helicopters, nor will there be any significant taxiing that other aircraft usually need, so VTOLs will be able to turnaround rapidly. Upon reaching the VTOL, the rider will get in, buckle up, and after short pre-flight checks, the VTOL will ascend vertically a short distance before transitioning to forward flight and heading toward the destination.

On-Trip Experience

Existing helicopters have levels of Noise, Vibration, and Harshness (NVH) that are unsatisfactory in a transport mode customers might choose to use on a daily basis. High levels of NVH are largely attributed to a helicopter's large rotors and their cyclic variation of loads which are inherent to helicopters. VTOLs will need to embrace multiple, smaller rotors that achieve lower cyclic load vibration. Helicopters address interior cabin noise today through noise-canceling headphones, but we do not expect passengers to wear these on a recurring commute. Interior noise is likely to scale with exterior noise, with VTOLs initially being 15 dB or more quieter than existing helicopters, bringing them more in line with regional commercial aircraft.

VTOL rides will also need to achieve ride quality that avoids bumpiness which causes passenger discomfort. Ride quality has shown to be highly correlated to the wing loading/rotor disc loading[88], with low wing loading having bumpy rides from wind gusts, while higher wing loading/rotor disc loading achieves relatively smooth rides even with wind gusts. Minimizing gust bumpiness is particularly important when flying at lower altitudes, which is crucial given variable weather conditions at these altitudes. As VTOLs, sensor capabilities, and avionics develop long-term, we believe there is potential to couple Doppler radar or LIDAR with the digital fly-by-wire control and DEP to achieve rapid, high bandwidth, active gust alleviation and a smooth ride experience for customers.

Entering and exiting the VTOL will need to be practical for passengers with large access doors at ground level. Passengers will also need to be seated close to the center of gravity of the aircraft in order to mitigate longitudinal and lateral accelerations that cause motion sickness. Ground interaction flows during hover can also lead to ride quality issues, with potential for vehicle oscillations. This can contribute to visually induced motion sickness since the ground provides a clear reference for the relative vehicle motion during approach and takeoff. Vehicle configurations that offer rapid control response rates through a combination of sufficient control power across pitch, roll, and yaw axes throughout all phases of flight will likely

[88] http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19840012087.pdf

address this issue. Vehicle interiors will also, at the very least, provide passengers real-time trip information including location and remaining time, as well as additional monitoring features as we introduce autonomy.

Accessibility for riders with reduced mobility will be an important priority as VTOL networks build out. Initial vehicles are unlikely to cater to all accessibility needs, but over time as VTOL networks grow, vehicle capabilities expand and services encompass more riders, some markets will warrant a tailored offering that provides accessible vehicles and vertiports (a la UberWAV for automobiles).

We understand that the optimal user experience—from booking to disembarkation—will differ from market to market given infrastructural constraints and social contexts in which VTOL will operate. Moreover, as we look forward 5-10 years where fleets of VTOL may be deployed across urban environments internationally, we believe that the ways in which cities, personal technology, and urban mobility will change mean Uber needs to future-proof our network's infrastructural design and engagement with customers. We look forward to engaging with user and community groups to begin exploring these topics and learning potential implications from the outset.

Economics

VTOL aircraft will enable riders to travel from A to B much faster than they can in a car today or will be able to in the future even with autonomous vehicles. Initially, VTOLs are likely to be most effective for satisfying long-distance commutes given the net time savings over these longer routes, as well as the limited infrastructure that will likely exist when VTOL services commence. We believe that initial VTOL trips will be suitable for commuters willing to trade off cost and/or privacy for time savings. However, to satisfy our mission, we believe that over time urban air transportation must be accessible to everyone, everywhere—having similar reach and affordability to peer-to-peer car-based ridesharing services. In order to achieve this goal, VTOL transit options would need to be competitive with automobiles (owned or on-demand) not only in travel time, but also cost.

To understand the potential economics of vehicles, the wider network and the travel costs for commuters, we started with the physics of transport efficiency. In the subsequent sections, we first walk through an analysis comparing the motion efficiency of flying versus driving when both forms of transport are burdened by inefficiencies due to the physics of the vehicle and logistics of a typical trip. We then detail the assumptions of our bottoms-up economic model for a VTOL network around vehicle usage (utilization, load factor, routing considerations), capex (vehicle cost, life, and infrastructure), as well as opex (pilots, maintenance, indirects).

Motion Efficiency

Motion efficiency, in the context of transportation, is the amount energy required to travel a certain distance. This measure is derived by dividing vehicle velocity by the power required to move the vehicle, which is equal to the inverse of the force required to travel a certain distance (since power is a product of force and velocity).

Computing the motion efficiency for an automobile requires determining the drag force at the speed the vehicle is traveling. A car has two main drag forces, aerodynamic friction drag of the atmosphere as the car moves (often called parasite drag) and rolling resistance drag caused by the friction between the tires and the ground[89]. These two forces are a similar magnitude for a typical automobile at about 50 mph. At lower speeds, the aerodynamic friction drag is lower than the rolling resistance drag. At higher speeds, the aerodynamic friction drag is higher because a greater force is required to move through the atmosphere.

A significant portion of a car’s aerodynamic friction drag comes from open wheel wells, blunt rear bodies, mirrors and bumpers—all of which are required for an automobile to perform its

[89] http://wps.aw.com/wps/media/objects/877/898586/topics/topic02.pdf

mission. Additionally, there's significant drag from the underbody which operates in close proximity to the ground and creates a restricted channel flow which creates additional aerodynamic drag. Some cars have achieved low aerodynamic friction drag, which is often measured by a term called "flat plate drag"[90]—the equivalent amount of drag experienced if a flat plate were placed perpendicular to the air flow at the same speed.

Rolling resistance drag is a product of the weight of the vehicle and the coefficient of friction as it moves (i.e., how slippery the tires are). Since cars need traction to stay on the road and brake, tires are intentionally designed with high rolling resistance coefficients.

The result is that a typical internal combustion car traveling at average speeds of about 30 mph achieves a motion efficiency of about 1 mile/kWh, while a typical electric car achieves much higher motion efficiency due to the nearly three time higher efficiency of electric powertrains than internal combustion powertrains (thus a third of the force required to power it).

Similarly, to determine the motion efficiency of a VTOL the drag force needs to be determined at the speed the vehicle is traveling. At cruise, a VTOL has two main drag forces, aerodynamic friction drag and the drag due to lifting the aircraft (often called induced drag). An aircraft achieves its highest cruise efficiency at the speed when the aerodynamic friction drag is equal to the induced (lift) drag. At lower speeds, the aerodynamic friction drag is low and the induced drag is high. At higher speeds, the aerodynamic friction drag is high and the induced (lift) drag is low.

Aircraft are designed to achieve significantly lower aerodynamic friction drag (or flat plate drag) than cars to minimize their power required at high speeds. This is possible because they don't have the same functional requirements as cars (side mirrors, wheel wheels, blunt rear bodies, bumpers are all unnecessary). A low-drag two-passenger aircraft, such as the Stoddard-Hamilton Glasair III, has a flat plate drag of 1.7, less than half that of the GM EV1 (3.9 square feet, one of the lowest drag levels achieved by a car). A newer, four-passenger aircraft such as the Cirrus SR-22 or the Pipistrel Panthera have a flat plate drag area of 3.4 and 2.6, respectively—again both are approximately half that of the Tesla Model S (6.2 square feet). While typically aircraft benefit from cruising at altitudes where the density is lower (and thus the aerodynamic friction drag forces are lower), this isn't true for VTOL aircraft which will be operating at altitudes of 1,000 to 5,000 feet.

The induced drag of a VTOL is weight-based since it's based on how much lift must be generated. One of the reasons why aircraft are typically more expensive than cars is because they're built to be lighter (typically from carbon fiber composites in modern small aircraft) to decrease the induced drag. Electric aircraft have a heavy energy storage system, depending on the range the aircraft intends to fly. With current battery technology, VTOLs designed to have a 100-mile range plus meet FAA reserve requirements are comparable to the weight of aircraft

[90] https://en.wikipedia.org/wiki/Drag_coefficient

designed for typical small aircraft ranges (e.g., 500 miles). If VTOLs are designed for 200 or more miles, the weight penalty from battery energy storage becomes quite significant (until battery specific energy improves).

The result is that an electric VTOL designed with a similar level of aerodynamic efficiency as the previously referenced SR-22 achieves a motion efficiency of about 2 miles/kWh when operating at it's best speed of about 125 mph. This is less efficient than an electric car, however, the VTOL is traveling at a much faster speed for any reasonable motion efficiency. These examples for car and VTOL have only considered the energy required to cruise at a specific speed, and doesn't include the additional energy required to get the vehicle to cruise for either the car (acceleration) or VTOL (takeoff). In the case of the VTOL especially, the vehicle expends significant energy to lift and accelerate the vehicle to the cruise condition.

Comparative Analysis

We modeled the motion efficiency of a car and VTOL for a 50-mile trip, using characteristics of electric luxury cars such as the Tesla Model S and estimates for an electric VTOL such as the Joby Aviation S4 aircraft. The VTOL efficiency model was also calibrated to recent advanced small aircraft such as the Pipistrel Panthera and as such the efficiency model is substantially different than current helicopters. We assumed the VTOL cruise efficiency to be about three times better than a helicopter because of the design bias toward achieving high cruise efficiency through wing-borne flight instead of using rotors, as discussed in the Vehicle Design section above. At shorter trip distances, the VTOL is less energy efficient per mile because it spends less time in the more efficient cruise mode while the power required for vertical takeoff and landing remains constants. As such, Vehicle Burdened VTOL motion efficiency improves at longer distance and decreases at shorter distances.

VTOLs and ground cars were compared in three different cases across a wide range of speeds:

1. **Ideal:** Accounting only for the efficiency at a moment in time at the vehicle cruise speed.
2. **Vehicle Burdened:** Accounting for the vehicle inefficiencies associated with the extra energy required for a car to accelerate and brake multiple times relating to traffic lights/stop signs; and for the VTOL to take off, accelerate to cruise speed, and land vertically.
3. **Trip Burdened**: Accounting for the trip inefficiencies of congestion on roads for the car; and the more direct routing that a VTOL experiences on most trips.

Vehicle Burdened

Both car and VTOL are assumed to be highly efficient electric vehicles so motor efficiency doesn't impact the resulting analysis. There are additional drivetrain and gearbox losses in the car that don't exist in the air, but likewise there are propulsive efficiency losses from a propeller that are similar. So these inefficiencies are considered equal for this analysis.

For the VTOL, achieving vertical takeoff and landing adds an extra ~50% in energy consumption above the cruise energy required for the 50-mile trip. This extra VTOL energy use is greater than current helicopters because instead of using large rotors to bias the vehicle design for hover efficiency, the VTOLs can focus on achieving low noise and high cruise efficiency.[91] VTOLs are assumed to require less than a minute each for takeoff and landing operation because they'll only operate from established vertiport locations, instead of having the flexibility of operations of a helicopter which can operate from unprepared locations almost anywhere. Another reason for the higher VTOL energy use is the additional weight of batteries[92], despite the fact that electric motors are currently about five times lighter than aviation piston engines.[93] Since the VTOL would likely only be climbing at most a few thousand feet in altitude, with descent recovering the majority of the potential energy, no additional energy consumption was added for climb.

Trip Burdened

Analysis of Uber trip data indicates that uberX trips drive a distance 1.42 times longer than the Haversine distance between their origin and destination. As such, we'll refer to 1 mile of VTOL travel to be the "ground mile equivalent" of 1.42 miles of automobile travel. For the purposes of our motion efficiency comparative analysis, we assessed an additional 1.1 factor *penalty* for ground cars to account for congestion trip inefficiency by calibrating to fleet estimates at automobile average speeds.

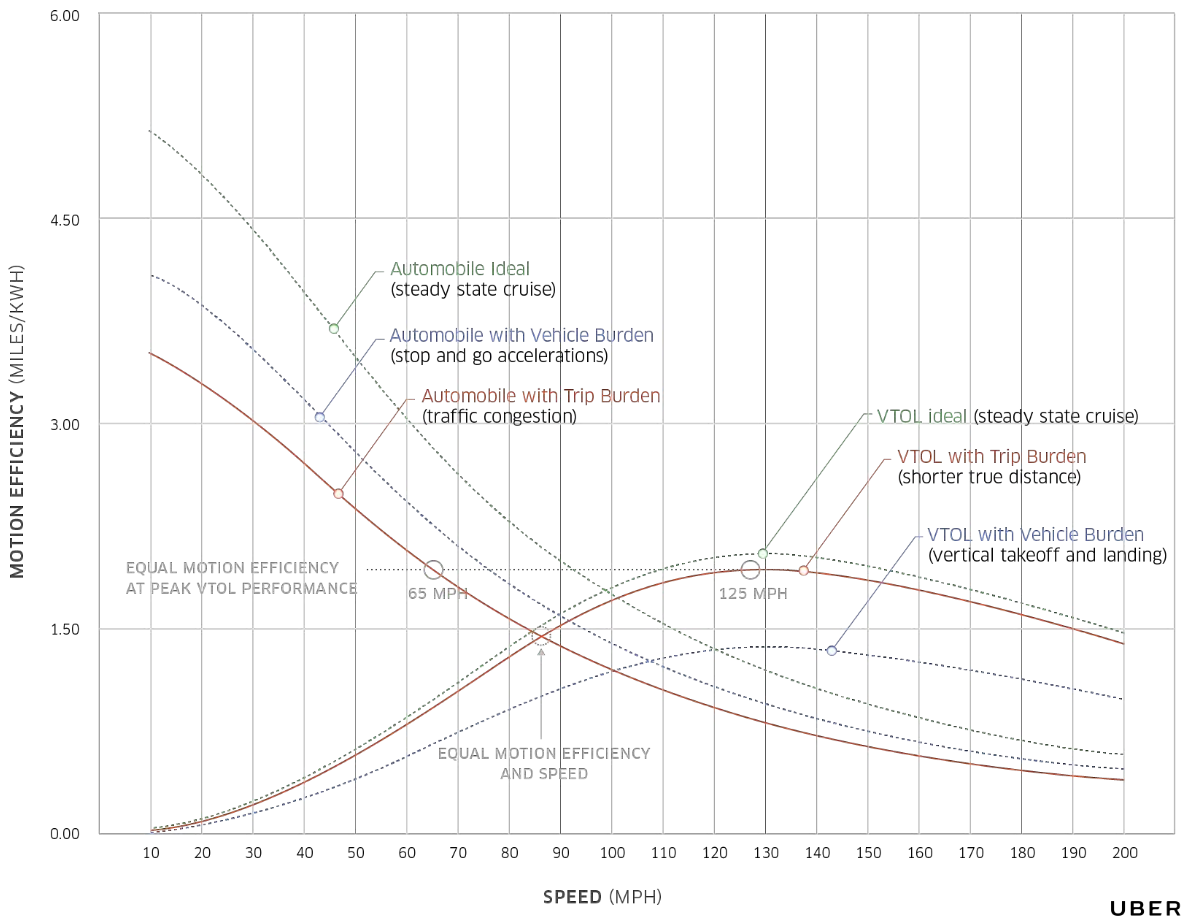
We feel that these assumptions are reasonable given that Robinson Helicopters account for these same factors in their operating cost buildup by applying a 1.5x factor when comparing to car trips[94] and NASA's sampling of typical Silicon Valley trips found typical road trips were 1.35x greater than aerial trips. NASA accounted for an additional mile of ground travel at either end the VTOL trip to account for travel to/from vertiport/stop, but this distance will decrease as a function of increased infrastructure density.

The resulting comparison is shown below, including each of the three cases of ideal, vehicle burdened, and trip burdened analysis across the range of speeds used by cars and VTOLs.

[91] For example a Robinson R-44 four person helicopter requires 185 kW for takeoff; however the VTOL analysis included an assumption of 500 kW for takeoff power.
[92] The R-44 is a piston engine using 100 Low Lead aviation fuel that weighs 2500 pounds, while the VTOL was assumed to weigh 4000 pounds. The increase in VTOL weight is due to the batteries (assumed to achieve 400 Wh/kg specific energy at a pack level)
[93] http://www.engineering.com/ElectronicsDesign/ElectronicsDesignArticles/ArticleID/12805/Inside-Siemens-Record-Breaking-Electric-Aircraft-Motor.aspx
[94] http://robinsonheli.com/price_lists_eocs/r44_2_eoc.pdf

Motion Efficiency, Comparative Analysis

Automobile vs VTOL



Car and VTOL Motion Efficiency Comparison

In the highly optimistic case that a car performs its entire trip at an average velocity of 65 mph (but few people can access a highway directly from their origin so this is unrealistic) the analysis shows that the motion efficiency for a car at 65 mph is the same as the motion efficiency for a VTOL traveling at 125mph. At higher car and VTOL speeds, the VTOL's motion efficiency gains an advantage over the car, but at lower motion efficiencies for both. Electric VTOLs present a transport mode that is as efficient or has higher efficiency than attempting to use cars at high ground speeds.

This analysis only considers a 50-mile trip. Longer trip distances would experience high cruise efficiency for a larger portion of the trip, making the VTOL compare even more favorably to the car. Shorter distance trips will have a higher VTOL acceleration/takeoff burden factor resulting in lower motion efficiencies and being less competitive to the car.

Electric vehicle technology improvement over time (e.g., lighter motors and batteries) will make the VTOL motion efficiency compare more favorably to the car. Any potential future ground congestion will decrease the car motion efficiency, but it's unknown at what capacity VTOLs will also experience route or vertistop congestion resulting in indirect routing penalties.

The number and distribution of vertiports, as well as the impact of airspace restrictions / frequent weather impacting operations will alter the trip burden analysis and will be significant factors to address when exploring VTOLs for use in specific locations.

Economic Model

We consulted closely with stakeholders who are actively performing VTOL studies to develop a set of attributes that define a VTOL for the purposes of our model and the assumptions surrounding those attributes. In our economic model, we assume that a VTOL includes:

- **Capacity:** 4-place capacity (including pilot, if there is one)
- **Load Factor:** Pooling match rates will allow for an average of 67% of revenue-producing seats to be filled by a paying passenger
- **Gross Vehicle Weight:** 4,000 lb
- **Batteries:** 400 Wh/kg specific energy batteries at the pack level with 2,000 cycle life,
- **Power:** 500 kW short-term takeoff power with 1 minute of full power at takeoff and landing,
    - 71 kW power required at 150 mph cruise, 120 kW required at 200 mph,
- **Utilization:** 2,080 hours of annual utilization
- **Electricity Cost:** $.12 per kWh electricity cost

In addition to the assumptions above, we further developed three cases to explore sensitivities for time-based assumptions across **Piloting, Vehicle Price, and Battery Cost,** below. We conclude the cost per vehicle mile outputs of our model across each case compared to today's costs of taking an Uber or owning a vehicle.

VTOL Assumptions	PILOTING COSTS	VEHICLE PRICE (4-person, without battery)	BATTERY COST (140kWh, 2000 cycles)
INITIAL Existing helicopter production (100 vehicles/yr)	$75K/yr Professional helicopter pilot @ $50k/year with 1.5 pilots per vehicle	$1.2M Lamborghini-like production rate (100/year)	$56K @ $400/kWh Current high-performance battery costs
NEAR-TERM Best current manufacturing near-term case	$75K/yr Professional helicopter pilot @ $50k/year with 1.5 pilots per vehicle	$600K Best recent helicopter production rate (500/year)	$28K @ $200/kWh DOE near-term high-performance battery costs
LONG-TERM Aggressive, long-term case	$60K/vehicle Autonomous avionics kit to replace pilot	$200K Specialty car-like production rate (5000/year with production tooling)	$14K @ $100/kWh DOE longer-term high-performance battery costs

UBER

We include a more detailed discussion of the basis for each of these assumptions below.

Vehicle Usage

Vehicle Utilization

Privately owned cars are used only a few hundred hours per year while the average commercial helicopter is used about 300 hours per year, and general aviation aircraft about 110 hours/year[95]. Such low use rates cause the vehicle cost to be amortized over a low number of hours, resulting in the vehicle cost being a significant portion of the overall operating costs. At the opposite end of the utilization spectrum, models such as ridesharing cars or commercial aviation achieve extremely high use of 3,000 to 5,000 hours/year.

Maintaining high rates of vehicle utilization is a key assumption in our operating and economic models. Electric vehicles have very low direct operating costs due to their low energy use, but recharging plays an important role in how many hours the VTOL is available for flight services. The assumption of 2,080 operating hours per year is based on the vehicle being flight ready for 50% of the time between 6am and 10pm each weekday (8 hours/day) for 260 days/year. Due to the relatively high VTOL purchase price, it is critical to be able amortize the capital cost over as many operational hours as possible during the year. Because of high vehicle utilization assumptions, in our model the vehicle depreciation/financing cost is only ~10% of the baseline direct operating cost. Thus the vehicle utilization is tightly linked to the acceptable vehicle acquisition price described below.

Vehicle Efficiency/Energy Use

Distributed electric propulsion (DEP) technology takes advantage of the scale-invariant[96] nature of electric motors to achieve high specific power and efficiency at any size, and combined with electric motor compactness and high reliability, DEP permits thrust to be optimally positioned on the airframe where propulsion can enhance the aerodynamic and control characteristics. Technological advancements in electric propulsion by Siemens and other European companies have already achieved turbine-like specific power, but with more than triple the efficiency of small helicopter turboshaft engines. Featured in new X-plane flight demonstrators, such as the NASA Maxwell X-57, DEP enables a five-times improvement in the vehicle efficiency for a General Aviation Conventional Takeoff and Landing (CTOL) aircraft[97].

Importantly, large efficiency improvements are possible because DEP enables *fixed-wing* VTOL aircraft that avoid the fundamental limitations of helicopter edgewise rotor flight, while wings provide lift with far greater efficiency than rotors. Because helicopters have such poor aerodynamic efficiency, far lower than CTOL aircraft, DEP VTOL aircraft will likely be able to achieve a ten-times efficiency improvement compared to existing helicopters.

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[95] https://www.faa.gov/data_research/aviation_data_statistics/general_aviation/

[96] Scale-invariant in this context means that there is no inherent penalty for increasing the number of electric motors in a VTOL design. They each obviously compensate for far more than their own weight and have no need for mechanical linkage between them.

[97] Borer, Nicholas, Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator , http://arc.aiaa.org/doi/pdfplus/10.2514/6.2016-3920

Achieving high operating efficiency for the vehicle is critical for both low energy costs and because this determines the size of the battery, which has a significant impact on the resulting vehicle weight and mission range capability. The mission profile is assumed to be a series of two 50-mile trips with VTOL takeoff and landing at each location, along with a wait time of 10 minutes per stop with rapid charging during wait times. The battery is assumed to be 140 kWh capacity to permit both trips prior to recharging, while also providing sufficient energy for IFR reserves of 30 minutes at minimum cruise power and a short detour to an alternate landing location. The bottom 20% of the battery would only be used in the case of needing to use reserves to achieve a long battery life of 2,000 cycles. After the two trips, the VTOL would recharge a minimum of 30 minutes before conducting additional trips.

Electricity pricing, unlike other energy pricing structures, depends not just on energy but also strongly on monthly peak power demand. If charging centers have a rather low energy delivery, but high peak power demands, then one could expect a much higher per kWh rate. In such a context, it is compelling to consider clever local energy storage solutions (e.g., terrestrial battery packs) at the vertiports to aggregate grid energy, and reduce peak demands. However, for this analysis an electricity cost based on a U.S. estimated rate of $.12 per kWh[98] is used with an electric powertrain achieving a 92% efficiency and aerodynamic efficiency equating to an L/D of 17 at 150 mph and 13 at 200 mph. The resulting energy costs are modelled to be ~12% of the baseline direct operating costs.

Vehicle Load Factor

The vehicle load factor determines how many revenue generating passengers occupy the vehicle on average. Large commercial airlines achieve load factors greater than 90% due to their use of a hub and spoke feeder system to get as many passengers as possible into a few locations for vehicle transport. Regional airliners aren't able to achieve this same packing efficiency and have a more typical load factor of ~70%. Car use has very low load factors with the average car having just a single occupant for the short trips typically taken, with the load factor increasing to 1.6 to 1.7 people per car for longer trips. We assume that VTOL carpooling would allow for a load factor of 67% against three seats in the piloted Initial and Near-Term cases and four seats in the Long-Term case.

Ground-Air Equivalent Miles (True Distance Traveled)

Traveling by VTOL offers the potential to achieve a more direct trip route. Currently, helicopter manufacturers such as Robinson use a 1.5x factor to indicate the decrease in air miles traveled by helicopter versus the indirect miles traveled by car on ground roadways. Uber trips in the Bay Area today drive a distance 42% longer than the Haversine route between origin and destination, which drives the distinction between a VTOL's *vehicle miles* and *ground-equivalent-miles*. That said, VTOLs will not be door-to-door; they will be

[98] The industrial (high monthly utility users) average electricity rate is $.07, but we projected a conservative higher rate of $0.12/kWh which is the recent residential rate due to typically higher electricity rates in urban areas, with use at peak time of day as well as high peak charging loads.

supplemented by ground cars for first/last-mile connections. As such, a true door-to-door trip would not, on average, achieve the full 42% benefit of traveling straight-line; NASA estimates that a VTOL trip in the San Francisco Bay Area might receive closer to a 35% benefit over ground trips. The true factor will likely be somewhere in between, depending on the specific city geography (bridges and other ground travel constraints significantly increase ground indirectness). We assume a 1.42 reduction in trip miles by VTOL compared to a car ground trip. This assumption is highly linked to the distribution and number of vertiports in a city to achieve close proximity to the desired travel location.

Deadhead Ratio

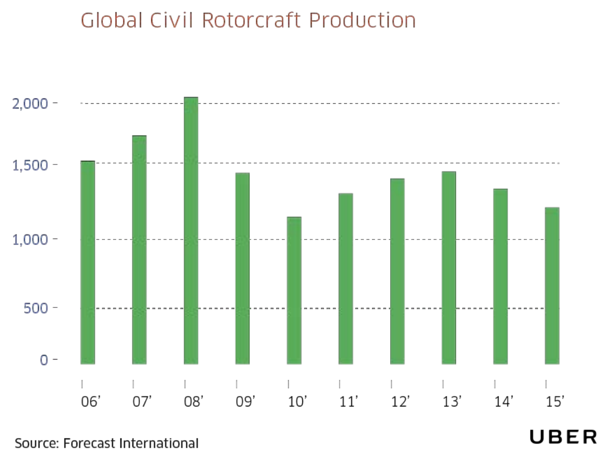
For any taxi or ridesharing vehicle, a portion of the trip miles traveled are non-revenue miles required to reposition the vehicle to pick up the next paying customer. This factor is called the 'Deadhead' ratio, and for VTOLs relates to the flight miles traveled to reposition the VTOL to another vertiport to meet the next passenger. The factor depends greatly on the fleet size versus the geographic area served. Prior attempts to create air-taxis by companies such as DayJet were burdened with a large number of deadheads because they were operating aircraft capable of flying a long distance to serve a large geographic region (the Southwest U.S.), and with a relatively small number of aircraft. Due to operations being confined to a small metropolitan area (100 mile diameter around a major city), and through deployment of a sufficiently large fleet size to achieve a uniformity of operations across locations, we assume that 20% of VTOL flights (across all three cases) will be non-revenue repositioning flights. Commuting trends tend to be one-way during peak travel times, which ensures that some portion of flights will require repositioning without passengers. However, potential deadheading can be further reduced using flexible (lower) cost structures that encourage travel on the repositioning flights to recover a portion of the vehicle cost for those trips.

Capital Expenses

Vehicle Acquisition Cost

An essential question is whether VTOLs can achieve a sales price point below the current price of commercial helicopters. If VTOLs are expensive, then the market size will be limited due to poor value for consumers, which feeds back to further limit vehicle production. This snowballs into VTOLs being a cottage industry for the wealthy not unlike Lamborghinis. Although helicopters have existed for decades, their commercial appeal has not grown to the point of breaking out of the low production and high vehicle cost cycle. In fact, global non-military rotorcraft production is projected to total just 1,050 in 2016[99].

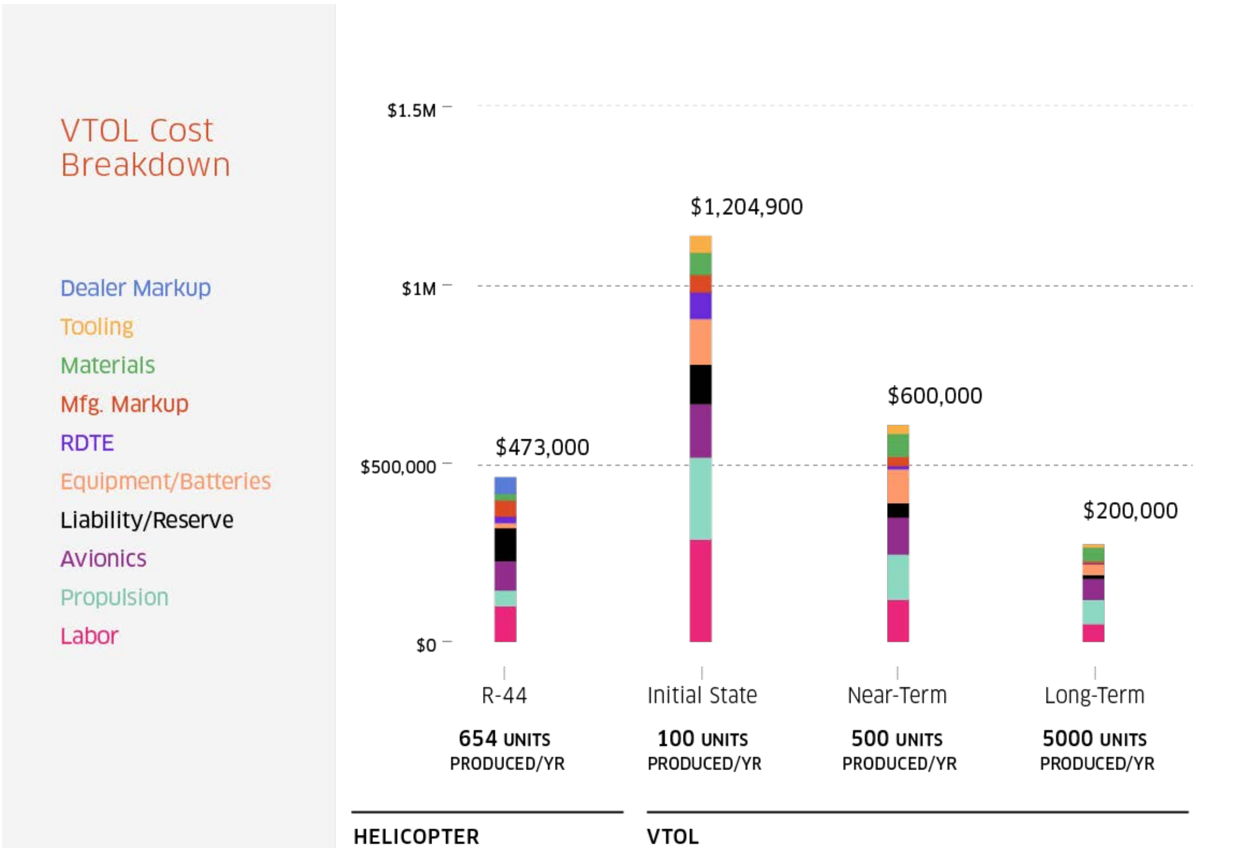
[99] https://www.theatlas.com/charts/HkcxY-qY; Forecast International



Rotorcraft vehicle price is highly dependent on the production rate (setting aside underlying costs based on differing types of engine, avionics and other inputs). However, due to uncertainty around consumer demand, manufacturers have difficulty achieving meaningful economics of scale, which keeps prices high and ensures demand remains low. In 2015 the Robinson R-44 piston engine helicopter ($473,000 price) was produced at the highest rate of any helicopter that year with 196 units manufactured, while a base model Bell 206 turboshaft helicopter had only 12 units produced ($900,000+ price). A typical learning curve for aerospace and automotive products is 85%, meaning that for each doubling of aircraft production, the cost decreases by 15%. If everything else was equal (same engine, same components) and only the production volume changed for an aircraft that is built at 12 units/year for $900,000, then fabricating 192 units/year would cost $469,000 each; at 1,536 units/year production the cost would be $288,000; and 6,144 units/year would cost $208,000. For reference, a speciality low volume production car such as the Aston Martin DB-9 has a production of ~1,500 units/year with a price of $238,000.

Obviously many more details determine the ultimate vehicle price beyond mere quantity. The difference in cost between a piston and turboshaft engine alone is hundreds of thousands of dollars. But clearly, it's very challenging to achieve competitive pricing for a sizeable consumer market when a product is made by hand with thousands of hours of touch labor, and very limited tooling at such low rates. The number of units produced is highly dependent on the market and fleet size that is implemented. Additional cost uncertainties exist in many of the VTOL components, especially concerning the vertical lift system and electric propulsion. Because of this uncertainty, we evaluate several different VTOL prices: $1.2M for the initial case, $600,000 for the near-term case, and $200,000 for the long-term case. Conducting this sensitivity analysis permits the impact of uncertain production volumes and component costs to be understood.

We do not attempt to justify a single VTOL price; however, our intent is to deploy VTOL fleets over many cities as soon as the vehicle, infrastructure, and city approvals can be put in place. Such deployments will require production rates greater than any existing helicopter production capacity. The initial price case is justified by a fully optioned Bell 206 including IFR avionics which is ~$1.2 million dollars at a production rate of 12 units per year. It is likely that to achieve the $600,000 near-term price an annual production of ~500 units per year would be required, and to achieve the $200,000 price an annual production volume of ~5,000 units per year would be required. Achieving such high production volumes would be transformative for the vertical lift industry (even across all of aerospace). Such production rates have not been seen with any aircraft since 1946 when ~48,000 small aircraft were produced over a dozen or so model types. This post-WWII high production was a result of industry attempting to repurpose to civil markets, with a large number of pilots suddenly having been introduced to the market place. In the years after 1946 there was a sudden reduction in annual production and manufacturing rates have never again risen to 1946 levels.



VTOL battery costs (not included above) are assumed to be $56K (Initial), $28K (Near-Term), $14K (Long-Term). Dealer Markup is only shown for R-44 helicopters.

Vehicle Life

While cars are designed to have a maximum life of about 250,000 miles, aircraft and helicopters are designed for far longer life spans. VTOLs are assumed to be designed for a longer lifetime than ground cars, which enables their cost to be amortized over a long period of time. We assume a design life of 25-27k hours for the VTOL to permit 13 years of service with the 2080 hour/year utilization. This enables the vehicle to provide 400,000 miles of service each year and about 5 million miles of service life before the aircraft is salvaged at a residual value of 30%. We see the useful life of a VTOL as about twenty times greater than a car; however, this assumption may be high and needs to be reviewed across manufacturers to better understand the vehicle cost implications of this relatively high lifetime.

That said, commercial aircraft and personal cars have average lives of 32 and 10 years, respectively. We project that a $200k autonomous VTOL could fly up to 5 million miles considering an annual overhaul between $90-95k per year. This allows the VTOL a life of 13 years at 2,080 hours per year. On the other hand, a car with a range of 250k miles would have a lifetime of only 3 years.

Infrastructure Burden

To ensure the maximum time savings benefit and enable efficient system throughput, an urban air transportation network will require a high level of distributed take-off and landing locations. Costs are modeled based on an initial fleet distributed across 3-4 cities and 1,000 VTOLs, with a total of 83 vertiports each capable of supporting up to 12 VTOLs at a time. This type of infrastructure is assumed to be highly similar to the type currently present in New York City with development costs and yearly operating costs all matched to those facilities. While the initial infrastructure repurposing development cost for these 83 vertiports is large ($121 million), this cost is amortized over a 30 year period. This initial cost relates to building modifications (such as retrofit of parking garage structures to use the top level as a vertiport), along with a combination of 3 high voltage and 9 low voltage chargers (one for each VTOL vertiport parking spot). High voltage chargers are assumed to be an estimated cost of ~$250,000 each (i.e., $750,000 per vertiport), while low voltage chargers are only ~$10,000 each (i.e., $90,000 per vertiport). The yearly infrastructure cost estimate for the vertiports is estimated at $86K/year per VTOL ($86 million to serve the 1000 VTOL fleet) which accounts for fleet support and use of the 83 vertiports (lease fees, maintenance, security, personnel support, etc.).

Additional vertistops and use of the extensive existing heliport/helipad infrastructure are assumed to be part of the infrastructure that do not provide recharging services and only accommodate a single VTOL for a temporary drop-off and pick-up (similar to helipads today that reside at corporate offices and many high rise buildings).

Combined, the initial and yearly infrastructure costs account for ~20% of the baseline VTOL direct operating costs.

Operating Expenses

Piloting and Avionics Costs

A fully burdened pilot cost of $50,000 per year is assumed, with 1.5 pilots required for each VTOL. This burdened cost is in line with current commuter and regional airlines. Pilot certification is assumed to be similar to existing Part 135 commercial airplane training requirements, with yearly recurrent training. In later years (likely a 10-20 year transition to autonomous flight), as automation is able to replace the pilot (this assumption is only used in the long-term case), a cost of $60,000 per vehicle is added to account for the upgraded avionics and sensors. 'Bunker' ground pilots are also assumed to provide assistance to each vehicle at a rate of one per eight vehicles, with the same cost as a pilot. Piloting costs account for ~36% of the baseline direct operating costs.

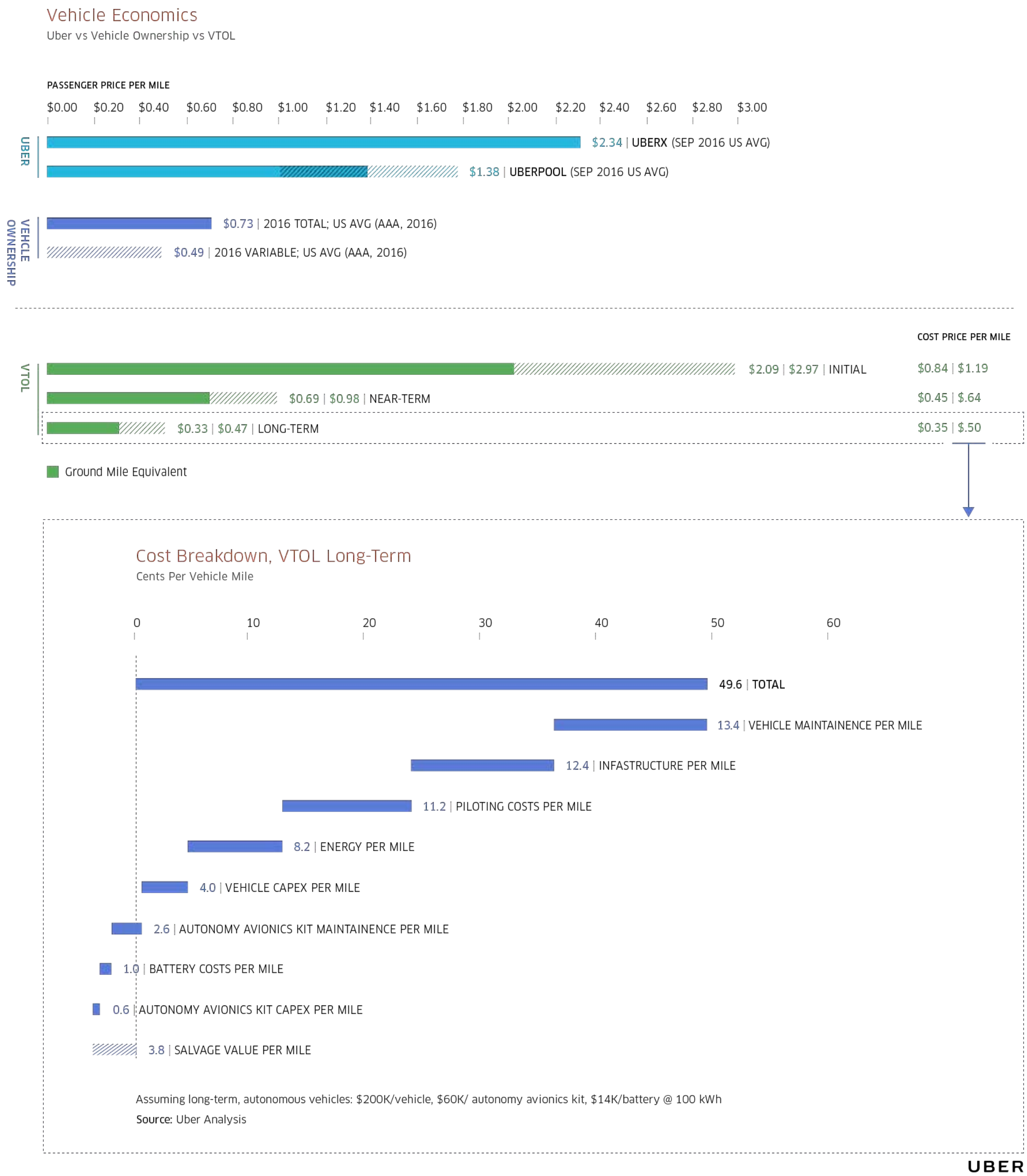
Vehicle Maintenance Costs

Our assumption is that maintenance costs per flight hour for electric VTOLs will be comparatively much lower than existing light helicopter maintenance costs, so we model a roughly 50% reduction in overall maintenance costs. The reduced maintenance cost hypothesis is based on elimination of all cyclic rotor components, as well as electric motors being able to achieve a 10,000 hour Time Between Overhaul (TBO) due to only having a single moving part (bearings). Maintenance labor rates are assumed similar to existing helicopters, with daily visual inspections, and 100 hour interval minor maintenance checks. A major maintenance service would be performed yearly to bring the vehicle back up to original service specifications. The maintenance and labor costs account for ~22% of the baseline VTOL direct operating costs.

Indirect Operating Costs

Indirect operating costs account for non-vehicle specific costs, such as credit card processing fees, registration and permit fees, insurance, and other smaller fees. Indirect costs in commercial aviation can be quite high (and additional 50% over direct operating costs) due to the significant overhead that exists for commercial operations, including overheads for booking agents. Much of commercial aviation cost also resides in indirect taxes linked to fuel use, landing fees, and other airspace operation overhead. In the case of VTOLs, the indirects are assumed to be relatively low due to the use of private infrastructure. A great deal of uncertainty exists as to the indirect overhead, which is an area that will require further study across all the stakeholders. Currently the indirect costs are modeled as an additional ~12% on top of direct operating costs in the baseline case.

Economic Conclusions



Our analysis shows that in the long-term autonomous case, direct costs per vehicle mile will approach 50 cents per mile (equivalent to 35 cents per ground mile). We can expect that the price[100] for a 45-mile pool VTOL, which would replace a 60-mile automobile trip, could approach as low as $21 for the 15 minute journey.

[100] Based on a 15% IRR for the all-in VTOL operation

We believe there is a path to making VTOLs economically favorable to private vehicle ownership and a viable alternative to ridesharing on the ground, so long as VTOL customers are willing to trade off some cost and/or privacy for large gains in speed. We expect an initial carpooled VTOL product will be priced similarly to uberX today, and as ridesharing prices on the ground decline with advancements in self-driving technology, our analysis indicates that VTOL pricing will decrease even more steeply. Ultimately, an uberX on the ground will have a similar price to an uberPOOL in the air; a VTOL uberX would be more expensive due to lower load factor. With this, we offer urban air commuters a value proposition that hits the privacy/speed/cost curve in a similar way that uberX and uberPOOL do for our car service today.

These prices, however, are only for the VTOL component of a rider's trip which, as indicated in the Rider Experience section, may often be bookended by walking or driving segments to/from a vertiport/stop. As such, rider all-in itinerary pricing per mile will be lower on average, while still realizing the majority of the time savings from the VTOL portion of the trip.

Our analysis further indicates that on-demand VTOL transportation may very well become more appealing than owning a car. The visual above depicts AAA's estimate for per-mile car ownership costs. These costs will decline somewhat over the next decade due to gains in fuel efficiency, but many of these cost declines will be offset by projected gas price increases. Other components such as depreciation of the vehicle capital expenditure itself will not decrease significantly.

As such, our projections suggest that in the future those who already own a car might not see large, direct financial benefits from taking VTOL. However, those who do not own a car would save money by using on-demand urban air transportation rather than purchasing an automobile. Of course, economic savings aside, car owners who take a VTOL in place of automobile commutes will save significant amounts of time formerly spent stuck in traffic or looking for parking.

Operators can further minimize the indirect miles traveled, as well as routing deadheads by working closely with cities, private enterprise and communities to ensure that high quality, well-distributed vertiports and vertistops enable an efficient urban air transport network. It's also reasonable to assume operators could potentially pool more people in a VTOL than a car; VTOLs offer such a significant speed advantage that riders would likely be willing to wait a few minutes to allow for batching a la uberHOP in NYC. This would lower VTOL prices to be further competitive with pooled automobiles.

Our economic model considers the most prominent assumptions, but we will refine these as we confer with stakeholders. We welcome any and all feedback or thoughts at elevate@uber.com.

Next Steps

We see serious potential for a leap forward with VTOL transportation but this vision can only be accomplished in collaboration with numerous stakeholders. As we described throughout our analysis, we believe the urban air transportation ecosystem will only be successful with the participation of entrepreneurial vehicle manufacturers, city and national officials from across the globe, regulators, users, and communities who will be keen to interact with one another to understand how the ecosystem can shape the future of on-demand urban air transportation. While we have explored internally how to fast forward to a future of on-demand urban transportation, we have a considerable amount to learn from a wide, experienced and varied set of stakeholders.

The publication of this white paper marks the start of that journey. From here, Uber will be reaching out to cities, vehicle manufacturers, prospective representative users, and community groups along with key business, infrastructural and regulatory stakeholders to listen, learn, and explore the implications of this urban air transportation movement. In the coming weeks and months, we plan to delve into the political, policy, infrastructural, and socio-economic issues that will need to be addressed. These will be important to sustainably and inclusively develop vehicles that meet sophisticated consumer demand and are able to operate safely, quietly and reliably in cities. We encourage municipalities and entrepreneurs within them to reach out to us and either share their direct feedback or note their interest in exploring how Elevate could be brought to life within their city. While we will endeavor to consult with a wide range of public and private sector stakeholders around the globe in the coming 4-6 months, we will necessarily be limited in terms of where we are able to do so.

As such, we are additionally looking forward to convening a global Elevate Summit to bring together a wide set of vehicle manufacturers, regulatory bodies and public and private sector city stakeholders. We will do so with the intent of exploring the issues and solutions that are raised during our outreach and to surface joint, shared perspectives as well as solutions that can help to accelerate urban air transportation becoming a reality. We view this event as an excellent opportunity for cross-pollination of ideas and networking with a view toward creating lasting working relationships that best serve the future of urban mobility. We are planning for this to occur in early-2017 and will be extending invitations in the near future.

We are passionate about the profound and positive impact on-demand urban air transportation can have on urban mobility. To share your feedback or express your interest in building this vision with us whether as a pioneer city, VTOL manufacturer, regulator, infrastructure developer, user group or any other stakeholder, please contact us at **elevate@uber.com**.