

# Regional Sky Transit III: The Primacy of Noise

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The trend toward rapid urbanization into megacities and the enormous costs for transportation infrastructure that this entails are expected to continue for decades. The strong and consistent preference of individuals for distributed travel in private vehicles rather than for route-limited travel in crowded public transit also has shown no signs of diminishing. These trends have a significant adverse effect on climate change. Regional Sky Transit<sup>1,2</sup> (RST) has been proposed as a system that can drastically reduce infrastructure cost and CO<sub>2</sub> emissions while preserving people's preference for travel in personal vehicles by providing affordable, accessible, fast, and safe flights distributed across urban regions. RST could thus provide a substantial, new, efficient, value-added supply chain. As such, RST could become aviation's largest market in terms of number of flights, significantly contributing to the growth of connectivity and productivity across population centers. The RST mass market could serve travelers on relatively short trip lengths of less than 160 kilometers. This civil mass market derives from the concept of high proximity aviation—extending air travel operations to numerous very small airparks that are close to where people live and work, so as to reduce ground travel time and thereby save time. This can only be achieved if the aircraft used in RST fulfill stringent limitations on allowable noise emissions that will be essential to high proximity aviation. Examination of the extensive prior research on allowable noise emissions shows that noise issues will dictate both the size of airparks and the concept of operations for RST. This paper reveals why this primacy of noise must be respected, and presents detailed examples of the profound constraints it imposes upon V/ESTOL aircraft designs intended to serve the RST mass market. The barriers to developing the ultra-quiet aircraft necessary to RST along with the most promising strategies for efficiently overcoming those barriers are presented. These strategies include models for how electric propulsion and its energy requirements can best be integrated into Sky Taxis that are suitable for the mission requirements of RST. Those integrations will examine the core science and technologies that affect propulsive noise emission and reveal opportunities for further competitive research. The value and benefits of RST will be compared with the costs of bringing about the necessary noise reduction breakthroughs.

## Nomenclature

<i>4D</i>	= a three-dimensional path along which each point has a defined specific clock time
<i>AGL</i>	= above ground level (height or altitude)
<i>ATC</i>	= air traffic control
<i>BMS</i>	= battery management system
<i>CAS</i>	= calibrated airspeed
<i>CL<sub>max</sub></i>	= maximum lift-coefficient
<i>CNEL</i>	= community noise equivalent level
<i>CO<sub>2</sub></i>	= carbon dioxide
<i>CTOL</i>	= conventional take-off and landing
<i>dBA</i>	= decibel noise level, A-weighted scale
<i>DNL</i>	= day night level in dBA, a metric for noise measurement
<i>DtD</i>	= door-to-door
<i>ESTOL</i>	= extremely short take-off and landing

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<i>eta</i>	=	propeller efficiency
<i>fps</i>	=	feet per second
<i>G</i>	=	the acceleration due to gravity at sea level on Earth
<i>GA</i>	=	general aviation
<i>GFC I</i>	=	the 2011 Green Flight Challenge sponsored by Google and prize-funded by NASA
<i>GHG</i>	=	greenhouse gas
<i>GPS</i>	=	global positioning system
<i>GTT</i>	=	ground travel time, the total of non-airborne time in a Regional Sky Transit trip
<i>HA</i>	=	highly annoyed, a metric used in noise surveys
<i>HPA</i>	=	high-proximity aviation
<i>IFR</i>	=	instrument flight rules; e.g., flying with instrument guidance while immersed in clouds (see VFR)
<i>kg</i>	=	kilogram
<i>kph</i>	=	kilometers per hour
<i>km/l</i>	=	kilometers per liter (of fuel)
<i>kWh</i>	=	kilowatt hour
<i>kW</i>	=	kilowatt
<i>last mile</i>	=	the distance from a transit station to one's destination doorstep
<i>lb</i>	=	pound
<i>lbf</i>	=	pound-force
<i>L<sub>den</sub></i>	=	level, usually in dBA, day evening and night, a metric for noise measurement
<i>L<sub>dn</sub></i>	=	level in dB, day and night, another metric for noise measurement
<i>M</i>	=	Mach number
<i>m</i>	=	meter
<i>m/sec</i>	=	meters per second
<i>mph</i>	=	miles per hour
<i>MSL</i>	=	above mean sea level, describing elevation or altitude on a standard day
<i>MPG</i>	=	miles per gallon
<i>NHTS</i>	=	National Household Travel Survey
<i>NPR</i>	=	noise to pavement ratio, dimensionless, based on land area
<i>ops</i>	=	operations, as in flight ops and ground ops at airports
<i>RPM</i>	=	revolutions per minute
<i>RST</i>	=	Regional Sky Transit
<i>sec</i>	=	second
<i>sq.ft</i>	=	square feet
<i>STEM</i>	=	science, technology, engineering and mathematics education
<i>TAS</i>	=	true airspeed
<i>V/ESTOL</i>	=	vertical or extremely short take-off and landing
<i>VFR</i>	=	visual flight rules, flying with a see and avoid strategy
<i>VMT</i>	=	vehicle miles traveled
<i>VTOL</i>	=	vertical take-off and landing
<i>V<sub>so</sub></i>	=	minimum velocity at 1 G at which an aircraft in landing configuration stalls

## I. Introduction

The priority for noise research on small propeller driven aircraft was reduced in the early 1950's when the jet age arrived. This was in part because the noise of propeller aircraft that operated at very large jet airports became relatively less significant. Due to the small market of general aviation (GA), the reduced priority for research on propeller noise persisted for decades. For the anticipated new mass market of RST using pocket airports, research in ultra-quiet propulsion of small aircraft is being rejuvenated, both because of the potential market size and because the noise reductions that will be required appear to be several orders of magnitude lower than those of existing propeller driven GA aircraft. To achieve such extreme noise reduction will require the innovative use of many different technologies in both the fundamental components and overall integration of the aircraft's propulsion system. Initial business projections<sup>3,4</sup> suggest that such noise reducing innovations, when successfully combined with V/ESTOL technologies in future Sky Taxis, could enable the minimal ground travel time (GTT) that will be

crucial to RST's profitability and economic sustainability. The RST mass market will be highly competitive as to which new quiet V/ESTOL Sky Taxis *will be allowed* to succeed. The winners will be those that achieve the requisite noise reductions because only they will be able to comply with the inevitable stringent new noise ordinances that will be enforced at future high-proximity small pocket airparks near quiet residential areas. Permission to provide RST service to those quiet residential areas will thus be the make or break requirement for a successful Sky Taxi design—more so than any other Sky Taxi design requirement save perhaps safety.

This primacy of noise cannot be overemphasized and deserves careful attention by all who plan to design Sky Taxis for the RST market. The high stakes and market risk involved mean that this primacy of noise at the outset merits substantial further research, both public and private. This paper explores this primacy of noise for its effects on aircraft design, on the RST market and on society.

## II. The Importance of Serene Neighborhoods

The majority of trips are those to and from work from one's residence. Serving people who are making those trips will be crucial to the market size for Regional Sky Transit. Such service will demand a very short GTT to and from a high proximity pocket airpark. The proximity of the airpark will depend upon the noise of the Sky Taxis that operate there. In the suburbs, the very place where the more affluent first adopters of RST are likely to live, there tends to be lower density housing with larger lots and a greater value placed on privacy and serenity. Ambient noise levels in such areas during the day can be as low as 40 dB  $L_{den}$ . Such ambient quietness will demand extremely low noise RST aircraft, particularly during the hours of early morning and after dusk.

Those who live in serene neighborhoods are also very protective of their property values. Such residents tend to be people who are capable of organizing effective opposition at local government meetings to any intrusive or annoying land uses nearby. These very real bedroom community acceptance factors will pose extraordinary demands upon the new domain of RST. Acceptance of RST operations in such communities will be the litmus test for it succeeding throughout the region. To pass that test, ultra-quiet take-offs and landings on very small land parcels will be the prime challenge. Sky Taxi designs that cannot fulfill that mission capability and locally enacted noise ordinances will be untenable.

## III. Biomimicry: A Guiding Principle for RST

By dint of millions of years of evolution, nature offers valuable insights into the design of ideal flying machines. Birds have perfected the ability to land and take off wherever they want. Moreover, they accomplish this almost silently. With the exception of hummingbirds, birds tend to avoid hovering during landing. Instead of expending energy in hovering, they expertly manage to dissipate both their kinetic and potential (altitude) energy to near zero at the moment of touchdown. Unless they encounter an adverse gust, a threat or traffic during their final approach, they land by positioning or morphing their control surfaces rather than by flapping them. By this method they minimize their expenditure of calories and accomplish their landing with almost no noise. Remarkably, birds perform this feat while making pinpoint landings every time, onto exactly the perch or tree branch that they select, in nearly all weather conditions. They thus minimize their ground travel time (GTT). Humans should learn from the birds. After the first century of powered human flight, we humans may finally be able to emulate these feats of birds by using fast-acting autonomous flight controls with high lift devices that are capable of executing precision approaches to pin-point landings with minimal energy expenditure.

Owls have evolved an amazingly effective tool to minimize their noise emissions. These have been elucidated by Dr. Justin Jaworski at Lehigh University<sup>5</sup> and others, and are now being studied for implementation on wings and propellers.

Birds, notably the Albatross and other waterfowl, often use their legs to run and accelerate across the ground or water surface to reach flying speed<sup>6</sup>. Electric propulsion using wheel motors in landing gear can offer humans a similar type of low noise take-off capability. It is even possible for such landing gear to articulate with powerful electric actuators that enable the aircraft to actually leap into the air akin to the way a bird does with leg muscles.

The Bar-tailed Godwit exemplifies perhaps the pinnacle of biologic achievement in flight efficiency and range. It routinely migrates non-stop over the ocean for 6800 miles quietly flying along at 56 kph (35 mph) with an efficiency equivalent of more than 31,000 km/l or 73,000 MPG. In Regional Sky Transit, the goal should likewise be to strive toward the ideal combination of the virtues of ultra-quiet efficiency, speed, and range. A main purpose of this manuscript is to emphasize that, for RST, ultra-quietness is the foremost of these virtues.

## IV. Ground Travel Time (GTT)

As shown in previous studies, Regional Sky Transit must have a sufficient market size to be economically sustainable. The market size depends upon how short a trip by air can make sense by providing a sizable savings in time compared to the same trip by ground transportation. It can reasonably be assumed that busy urban millennials and other travelers across urban mega-regions will use RST for short trips if they can save 30 minutes by doing so. It has been shown that, due to the adverse uncertainty of ground travel in urban regions during rush hour, trips on RST as short as 30 km could save 30 minutes of time if the aircraft can cruise at 120 mph. This can only happen if the ground travel time, GTT, to and from the pocket airport is very brief, on the order of 6 minutes, and the airport operations proceed with no delays and at a brisk cadence. A 6-minute GTT can only be reliably achieved by staying off the freeway and by using less congested local streets to reach the airport. In 6 minutes, a 40 kph (25 mph) surface vehicle can travel 4 km (2.5 miles) and a pedestrian can, at the extant average of 5 kph, walk a distance of 0.5 km. These distances will affect the ideal siting of pocket airports.

## V. Noise Regulations

Wikipedia provides abundant explanation of the history and current status of noise regulations in the USA.<sup>7</sup> In general, federal statutes take precedent over those of states, which, in turn, take precedence over those of local government. This section emphasizes that government can and will impose detailed and restrictive noise regulations and ordinances on operations at pocket airports, particularly in noise sensitive areas and bedroom communities. The following italicized text is taken directly from Wikipedia's discussion of noise regulations:

*A Noise Disturbance [or noise nuisance] is defined in legal terms as any sound or vibration which:*

- 1. may disturb or annoy reasonable persons of normal sensitivities or;*
- 2. causes, or tends to cause, an adverse effect on the public health and welfare or;*
- 3. endangers or injures people or;*
- 4. endangers or injures personal or real property.*

*This can also be defined as noise nuisance.*

*The federal government's regulations of noise are mainly found in the Code of Federal Regulations under the EPA Noise Abatement Programs; Parts 201 to 205 and 211 cover railroads, motor carriers in interstate commerce, construction equipment, motor vehicles. They require product labeling and prohibit tampering with noise control devices. Communities may enact regulations that are no more strict than the federal ones so that local enforcement can be carried out. They can enact curfews and restrict vehicle use in established zones such as residential. States also may enact regulations that are no more strict than federal regulations. They may also preempt local ordinances.*

*Maximum Permissible Sound Pressure Levels*

*This provision is an objective immission control. It requires the measurement of sound levels at or beyond a property line and its vertical extension. There are several methods for implementing such a provision:*

- 1. It may not permit any exceedence or may permit exceedence only for a percentage of the measurement period.*
- 2. It may require the measurement method to be instantaneous, such as dB(A) or time-averaged, such as Energy Equivalent Level (Leq).*
- 3. It may be a fixed level limit, such as 55 dB(A), or it may be a level relative to the ambient sound, such as 5 dB(A) above the ambient.*
- 4. It may require measurement of the frequency spectrum, such as one octave bands, or A-weighting, such as dB(A).*
- 5. It may define different maximum levels based on zoning criteria, such as residential, commercial, or industrial.*
- 6. It may define different maximum levels based on time-of-day or day-of-week, such as reduced maxima during night hours or on weekends.*
- 7. It may require reduction of maximum levels based on the character of the sound, such as intermittent or impulsive.*

8. *It may exempt certain classes of sound sources, such as shooting ranges, farm equipment, emergency equipment, railroads, or licensed activities.*

*Most noise ordinances set maximum levels for two time periods: Day (7am to 10pm) and Night (10pm to 7am). San Diego (Article 9.25) sets three periods: Day (7am to 7pm), Evening (7pm to 10pm), and Night (10pm to 7am) and exempts industrial zones from time based restrictions. Seattle, WA (Chapter 25.08) sets two time periods but changes 7am to 9am on weekends and holidays. Several states have maximum permissible land use sound levels in dB(A). Most have Day and Night periods and three use categories: residential, commercial and Industrial. Washington (Chapter 70.107) sets maximum levels in dB(A) but allows 5 dB(A) more if the sound is only 15 minutes in an hour, or 10 dB(A) for 5 minutes in an hour. Numerous cities have fixed levels, permitting excess levels for short times (e.g., Dallas, TX, Chapter 30).*

*Motor Vehicles on a Public Right-of-Way:*

*This provision is an objective emission control. It applies maximum sound levels to various categories of moving vehicles and for several vehicle speeds. It is the backbone of vehicle sound emission regulations. It generally requires a measurement of A-weighted sound level of a moving vehicle at a specific distance from the vehicle path (normally 50 feet). This provision has level restrictions on trucks over 10,000 GVW used locally and in interstate commerce. It also covers motorcycles of two horsepower ratings, mopeds, and all other vehicles on public rights-of-way. The federal government has set maximum levels for heavy trucks used in interstate commerce (40 CFR 202) and for motorcycles (40 CFR 205). Most states and many cities have maximum limits and they generally agree with federal standards where they apply. The most common speed division is 35 mph.*

There have been cases of pure jet aircraft of old being specifically cited as too loud by federal regulations and local ordinances, but the large size of CTOL airports and rarity of such aircraft has generally limited such occurrences. Because of the very small size of pocket airparks, the domain of Regional Sky Transit will be different and may impose noise citations or banishment to aircraft that are too noisy.

According to the FAA, at this weblink:

[https://www.faa.gov/about/office\\_org/headquarters\\_offices/apl/noise\\_emissions/airport\\_aircraft\\_noise\\_issues/](https://www.faa.gov/about/office_org/headquarters_offices/apl/noise_emissions/airport_aircraft_noise_issues/)

*“Aircraft noise is regulated through standards. These standards are set internationally and are applied when an aircraft is acquiring its airworthiness certification. The standard requires that the aircraft meet or fall below designated noise levels. For civil jet aircraft, there are four stages identified, with Stage 1 being the loudest and Stage 4 being the quietest. For helicopters, two different stages exist, Stage 1 and Stage 2. As with civil jet aircraft, Stage 2 is quieter than Stage 1. In addition, the FAA is currently working to adopt the latest international standards for helicopters, which will be called Stage 3 and will be quieter than Stage 2. The FAA has undertaken a phase out of older, noisier civil aircraft, resulting in some stages of aircraft no longer being in the fleet. Currently within the contiguous US, civil jet aircraft over 75,000 pounds maximum take-off weight must meet Stage 3 and Stage 4 to fly. In addition, aircraft at or under 75,000 pounds maximum take-off weight must meet Stage 2, 3, or 4 to operate within the U.S. In addition, by December 31, 2015, all civil jet aircraft, regardless of weight must meet Stage 3 or Stage 4 to fly within the contiguous U.S.*

*One of the goals of the CLEEN program is to develop certifiable aircraft technology that reduces noise levels by 32dB cumulative, relative to the ICAO noise standards.”*

In Chapter 17, “Noise”, in the FAA’s Airports Desk Reference, it is clear that the FAA delegates control of noise compatible land use to local authorities:

*14 CFR Part 150: “The responsibility for determining the acceptable and permissible land uses ...rests with the local authorities...Part 150 is not intended to substitute federally determined land uses for those determined to be appropriate by local authorities in response to locally determined needs and values in achieving noise compatible land uses. “*

From the above it is clear that governments will exercise the authority to impose detailed noise regulations on any vehicle that is capable of causing noise disturbances.

## VI. Factors Affecting Acceptable Noise in Regional Sky Transit

There is abundant prior research regarding people's tolerance of aircraft noise<sup>8,9</sup>, both for those who live near airports and those in quieter settings. There is also extensive evidence that excessive noise exposure can have serious adverse effects on a person's health<sup>10</sup>. The immutable physiology of human hearing suggests that noise tolerance will not change in the coming centuries.

Studies have provided detailed and credible limits for the levels of noise that are tolerable to people who live near airports. From these studies and the ambient noise levels found in quiet bedroom communities, we can infer the amount of noise reduction that will be required at the future pocket airparks that will serve RST in quiet residential areas. Extending RST service to these areas will minimize the ground travel time or GTT. The amount of noise reduction needed inherently conflicts with the relatively large amount of take-off power and thrust demanded by the V/ESTOL capabilities necessary at these small, high proximity airparks. The power and thrust needed are, in turn, directly related to the size and weight of the aircraft and thereby affect the number of passengers or cargo payload weight that can be carried. It becomes obvious that major breakthroughs in noise reduction will have a direct and salutary effect on the amount of fare-paying payload that these future aircraft can deliver.

Amanda Rapoza et al have conducted extensive DOT research on people's tolerance for noise in serene environments such as National Parks<sup>11</sup>. As shown in Figure 1., her work in 2011 consistently showed increased noise sensitivity compared to airport neighbor surveys, if the ambient noise conditions were below about 40 dB, such as could apply in wooded residential areas. Figure 1., shows this sensitivity and emphasizes the extreme quiet that is necessary to minimize annoyance in quiet settings. Notably, her conclusion was that "Equivalent A-weighted sound level (LAeq) provides the most explanatory power. It incorporates both sound level and duration of exposure". This finding was corroborated by Fidel et al in 2011 in the Journal of the Acoustical Society of America.

The frequency of airport operations has been shown to have a profound effect on people's tolerance for noise, with increased number of flights markedly reducing the noise tolerance<sup>12</sup>. With a peak capacity that requires a take-off every 10 seconds, the frequency of flights with RST approximates a continuous noise event whose noise level therefore approaches that of the  $L_{den}$ .

Flights made at night during the hours when people typically are trying to sleep in their homes are also met with markedly increased sensitivity to noise, especially if made frequently. Even local time periods of 7:00 PM to 9:00 PM are times that the elderly and infants are trying to sleep. The ambient noise level in many residential communities can be as low as 30 dBA at night, accentuating noise disturbances from sounds that are otherwise imperceptible in downtown areas of higher ambient noise. This could mean that some pocket airparks that are very close to quiet residential areas will close at sunset.

The current regulatory limit in 36 CFR Ch. 1 (7-1-10 Edition) for machine noise in National Parks is 50 dBA at a 50 ft. sideline distance. This is equivalent to 41.6 dBA at a 40 m sideline, which provides a reputable guideline for the level of quietness that is likely to be demanded in quiet residential neighborhoods. The tolerance for noise during sleeping hours at night becomes even more stringent; 24 dBA measured indoors is the level that 10% of respondents found highly annoying. The sensitivity to be annoyed also rises substantially if there are a large number or frequent flights passing overhead during the night or if the noise is impulsive in nature.

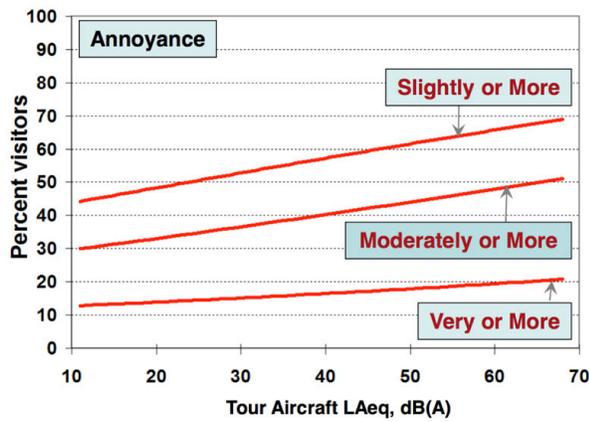
A phenomenon of "virtual noise" has been identified<sup>4</sup> for mainly rotorcraft being perceived as noisier than they really are, by some 4-9 dB<sup>13</sup>. The virtual noise penalty may relate to the impulsive nature of the sound of helicopters or possibly to a perceived threat of vehicles that 'loom' overhead rather than quickly passing by.

Medical studies on the adverse health effects of acute and chronic noise exposure also point to a need for societal attentiveness to reducing noise exposures to safe levels wherever possible<sup>14</sup>.

In general, these acute noise sensitivities suggest that there is almost no lower limit to the level of quietness that will be needed in the future Sky Taxi if it is to provide high proximity aviation (HPA) near quiet suburban residential areas.

Noise levels in  $L_{den}$ , which is the day/evening/night average level, includes penalties for noise occurring after nightfall. As shown in Figure 2, a continuous noise level of 48 dB yields an in  $L_{den}$  of 54.7 dB, which the consensus "EU curve" in Figure 18., shows would produce a 10% highly annoyed (HA) reaction, which FAA guidelines suggest is the allowable limit. Clearly, there is a need for Sky Taxi take-off noise to be as low as possible. The  $L_{den}$  (Day Evening Night Sound Level) shown in Figure 2. is equal to CNEL (Community Noise Equivalent Level), which is the average sound level over a 24 hour period, but with a penalty of 5 dB added for the evening hours or 19:00 to 22:00, and a penalty of 10 dB added for the nighttime hours of 22:00 to 07:00.

## Results: Slightly vs Moderately vs Very



- Short hikes
- Natural Quiet very important: Yes

N = 2600  
4 Natl Parks  
Mainly  
Bell 206L heli  
Amanda Rapoza  
10-40 dBA ambient

- Equal helicopters and fixed-wing

John A. Volpe National Transportation Systems Center

<http://ntl.bts.gov/lib/47000/47200/47259/hastings-asa--2011.pdf>



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Research and Innovative Technology  
Administration

Figure 1. This DOT study shows that, in quiet settings, noise sensitivity can be extreme.

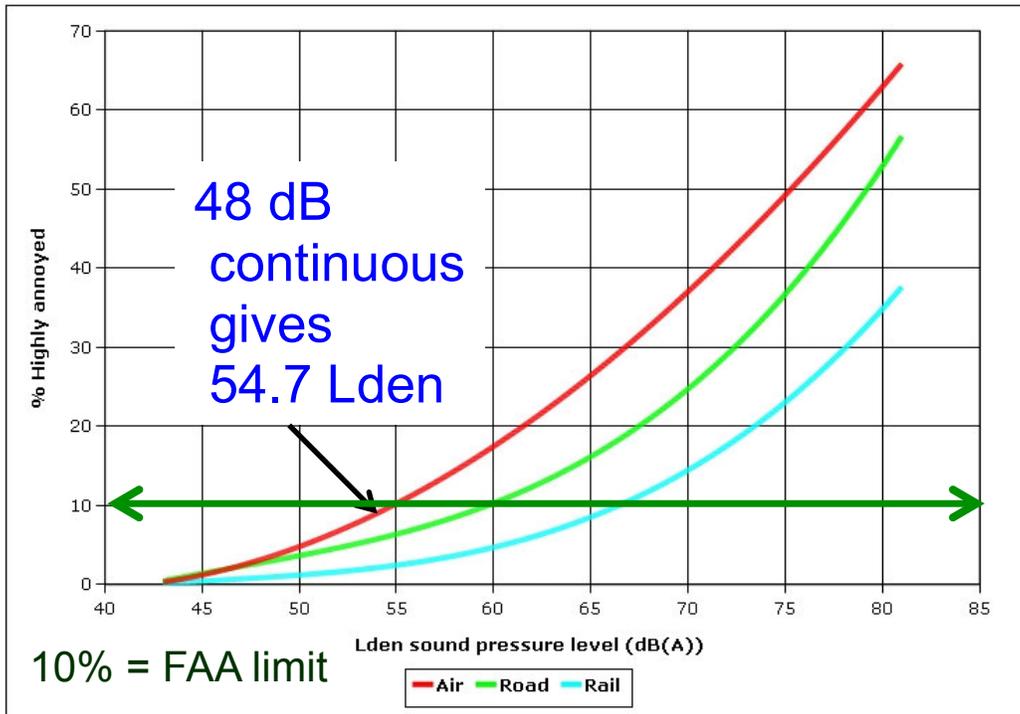


Figure 2. Aircraft noise must be acceptable to 90% of residents near the airpark<sup>15</sup>. A 48 dB continuous aircraft noise level will produce a 54.7 dB L<sub>den</sub>, and fulfills this standard.

<b>L<sub>dn</sub>, dB, outdoor</b>	<b>Environment</b>
78	Urban high density apartment
59	Old urban residential area
40-51	Wooded residential area
39	Rural residential area
<35	Wilderness areas

**Table 1. Ambient outdoor noise levels, per US EPA, 1978<sup>16</sup>, emphasizing the need for ultra-quiet Sky Taxis at pocket airparks near suburban residential areas.**

## VII. The Gutin Formula for Noise Prediction

In 1936, L. Gutin published his formula for computing the noise emission of a propeller operating in still air. The formula accounts for the propeller’s diameter, number of blades, thrust, RPM, harmonic number, the local velocity of sound, the distance and angle from the propeller. Subsequent studies<sup>17, 18</sup> affirmed that the formula’s calculated results yielded “virtually perfect agreement” and were useful even for propellers operating at airspeeds that were below about Mach 0.1. Later work<sup>19</sup> elucidated a disparity between the Gutin-predicted noise and the noise measured by microphone arrays for propellers operating at low RPMs on static test stands. The disparity was attributed to unaccounted “vortex noise”, also known as broadband noise. Other work found that the Gutin formula failed to account for additional sources of noise caused by ground reflection, ground absorption, variations in wind as well as non-axisymmetric angles of attack. The overall combined effect of these several other types of noise is that the Gutin formula tends to underestimate the actual noise that a propeller will produce. More contemporary formulae for calculating and predicting propeller noise have been devised<sup>20, 21</sup>. However, for comparing the predicted relative noise of propellers operating at low forward speeds, the Gutin formula can still be a useful tool. This author has discovered an additional correcting term for the Gutin formula that will be the topic of a subsequent study. This new term is not used in the Gutin formula computations made in this study.

## VIII. Five Other Important Noise Equations

For the purposes of modeling prospective cases of propeller noise and its impacts, there are 5 additional equations that are useful. These are presented below:

- Equation (1), the formula for summing the noise of multiple identical propellers on one aircraft
- Equation (2), the formula for adding the noise of dissimilar noise sources on one aircraft
- Equation (3), the formula for comparing a given noise emission at varying distances
- Equation (4), the inverse square law for comparing a given noise emission at varying distances
- Equation (5), the formula for scaling the effect of power on noise emissions

These 5 equations are as follows:

$$dB_{total} = dB_1 + 10 \times \text{Log}_{10}(n) \quad \text{Equation (1)}$$

where:

$dB_1$  = the noise level of one propeller

$n$  = the number of propellers producing that  $dB_1$

Example: 2 identical propellers are each producing 90 dB. Then, by Equation (1)

$$dB_{total} = 90 + 10 \times \text{Log}_{10}(2) = 90 + 10 \times 0.301 = 93.01 \text{ dB}$$

To sum the noise of dissimilar propeller noise sources on one aircraft, each with its own random phasing, the formula is:

$$dB_{total} = 10 \times \text{Log}_{10}(10^{(L_1/10)} + 10^{(L_2/10)} + 10^{(L_3/10)}) \quad \text{Equation (2)}$$

where:

$L_1$ ,  $L_2$ , and  $L_3$  are the 3 different dB levels to be summed

Example: The sum of the noise of propellers that make 94.0, 96.0 and 98.0 dB. Then, by Equation (2)

$$dB_{total} = 10 \times \text{Log}_{10}(10^{(9.4)} + 10^{(9.6)} + 10^{(9.8)}) = 101.1 \text{ dB}$$

Note that Equation (2) also reveals that when one noise is 12 dB quieter than ambient noise, the quieter sound becomes essentially imperceptible.

Example: The sum of a propeller noise of 48 dB with an ambient noise level of 60 dB, by Equation (2), is:

$$dB_{total} = 10 \times \text{Log}_{10}(10^{(4.8)} + 10^{(6.0)}) = 60.27 \text{ dB}$$

Notice that when 48 dB is added to a noise level that is 12 dB higher, the resulting rise in noise level, from 60 to 60.27 dB, would be imperceptible. This provides a rough idea of how quiet a vehicle must be in order to be imperceptible relative to a given ambient noise level.

To compare a given noise emission at one distance to what it would be at another distance, the formula is:

$$dB_{r_2} = dB_{r_1} - [20 \times \log_{10}(r_2/ r_1)] \quad \text{Equation (3)}$$

where:

$r_1$  = the distance from the sound source at which  $dB_{r_1}$  exists

$r_2$  = the greater distance from the sound source at which  $dB_{r_2}$  will exist

Example: A noise of 48 dB at 40 m, when measured at 80 m, by Equation (3), becomes:

$$41.98 \text{ dB} = 48 \text{ dB} - 20 \times \log_{10}(80/40) = \text{noise at 80 m}$$

Equation (3) is founded upon the “inverse square law”, shown below as Equation (4). In the case of sound propagation, the inverse square law does not account for 2 important influences: sound reflection and sound absorption. If there are reflective surfaces in the sound field, then reflected sounds will add to the directed sound and will cause a louder sound at a distance location than that predicted by the inverse square law. Likewise, barriers between the source and the distance location can cause there to be less sound than that predicted by the inverse square law. Nevertheless, the inverse square law is a reasonable method for estimating the sound level at a distance across a flat, open area. The inverse square law can be expressed as:

$$r_2 = r_1 * 10^{((dB1-dB2)/20)} \quad \text{Equation (4)}$$

Applying Equation (4) to the result in the Example above of 48 dB at 40 m measured at 80 m yields:

$$r_2 = 40 * 10^{((48-41.98)/20)} = 80 \text{ m}$$

NOTE: The term  $(dB1-dB2)$  in Equation (4) must be arranged to yield a positive number.

To ration a noise level across varying distances, the simplest method is to simply double the distance for every 6 dB of quieting. Thus, 54 dB at 40 m becomes 48 dB at 80 m and 42 dB at 160 m. This method ignores the absorption of sound by the ground but is generally useful for quick relative comparisons. Equation (3) is a more precise mathematical formula.

To scale the effect of power on noise, the formula is:

$$dB_{p2} = dB_{p1} - 10 \times \text{Log}_{10}(P_1/P_2) \quad \text{Equation (5)}$$

where:

$P_1$  = the power for  $dB_{p1}$

$P_2$  = the power for  $dB_{p2}$

Example:

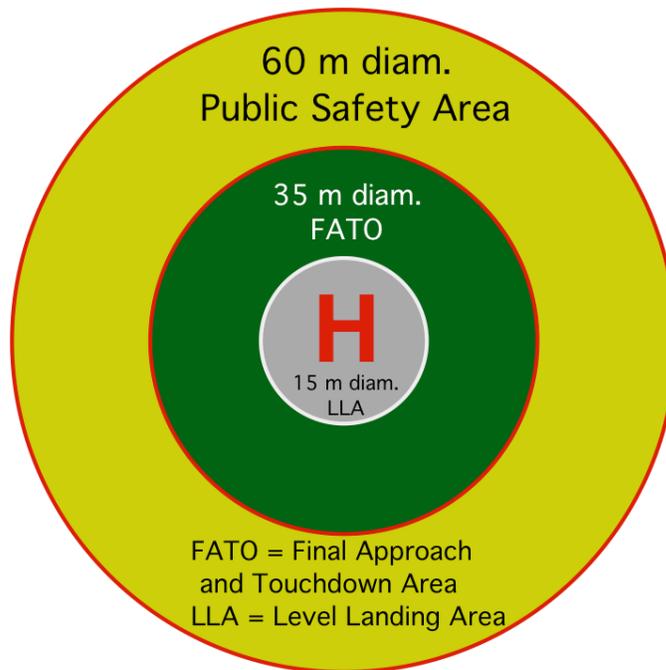
$P_1$  = 298.4 kW (400 BHP) for an 8-seat aircraft

$P_2$  = 37.3 kW (50 BHP) for a 2-seat aircraft

$dB_{p1}$  = 80 dB at 40 m with 298.4 kW

$dB_{p2} = 80 - 10 \times \text{Log} ( P_1 / P_2 ) = 80 - 9 = 71$  dB at 40 m with 37.3 kW

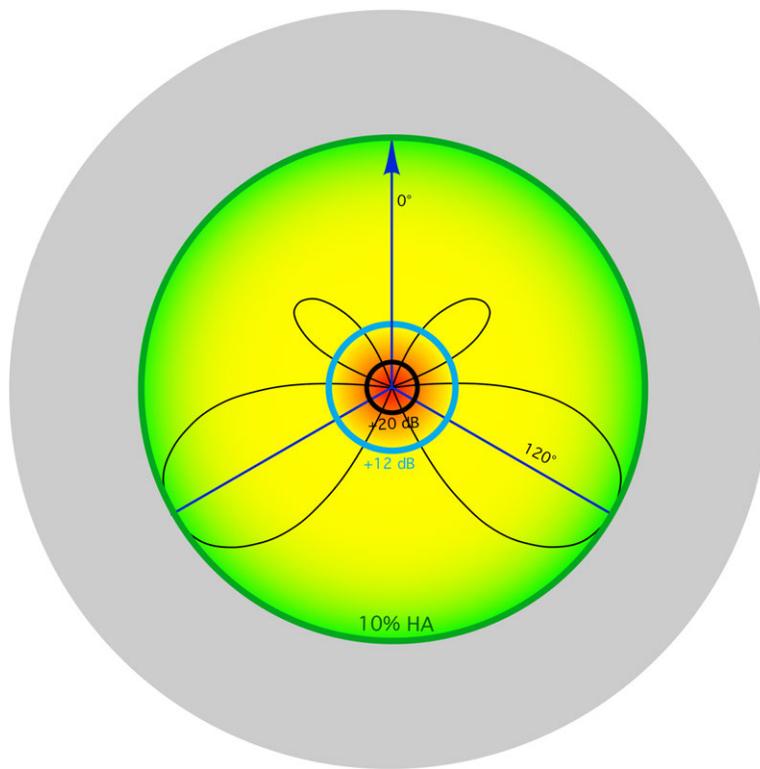
dB reduction with power reduction =  $10 \times \text{Log} (400/50) = 9$  dB



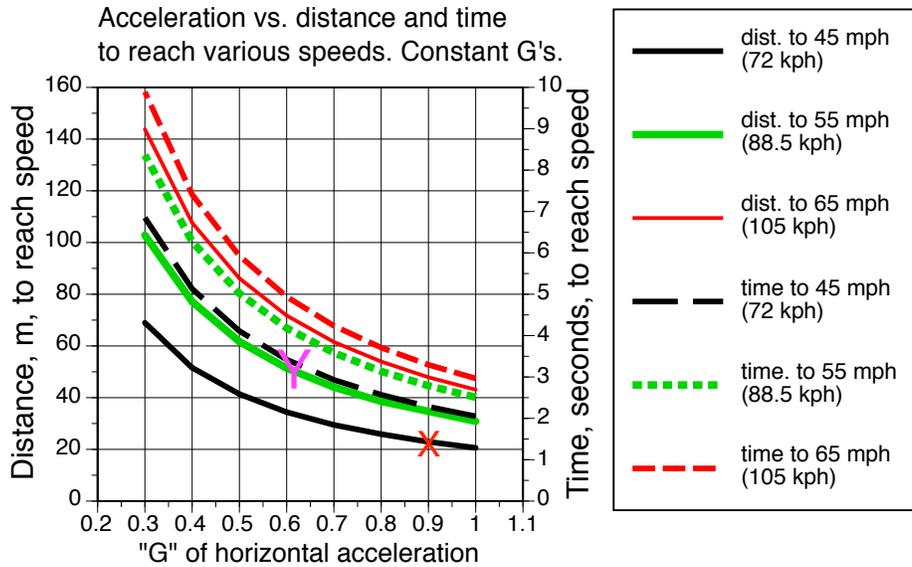
**Figure 3.** This standard helipad diagram shows the size of the designated areas. The central gray “Level Landing Area” is 15 m diameter. This can be considered the minimum pavement area necessary for VTOL operations that carry passengers.

## IX. Noise to Pavement Ratio (NPR): A Guide to Rational Design of Sky Taxis

Prospective new V/ESTOL aircraft designs can be compared according to the relationship between the area of their calculated noise footprint and the area of pavement needed for their no-wind take-off ground roll. For simplicity, the length of the aircraft itself plus its take-off ground roll can define the radius of the aircraft's "pavement circle". The diameter of its "noise circle" can be defined as simply twice the radius at which the aircraft's maximum take-off noise, as calculated by the Gutin formula, reaches a dBA level that, according to the "EU curve" in Figure 18., would cause 10% of airpark neighbors to be "highly annoyed" (HA). In serene residential areas where ambient noise levels can fall well below 40 dB  $L_{dn}$ , the noise level that produces 10% HA may be several dB below that of the EU curve. The area of the noise circle divided by the area of the pavement circle equals the non-dimensional "noise to pavement ratio" or NPR. As will be shown, land area scales steeply with cost. Ideally, a Sky Taxi's NPR should be less than about 0.1, in order that its take-off noise circle might stay within the paved airpark during take-off--a rational match between its short runway capabilities and its noise emissions.



**Figure 4.** The "Noise to Pavement Ratio" (NPR) compares the land *area* necessary to enclose a Sky Taxi's calculated community-acceptable noise footprint (rainbow circle) to the minimum pavement *area* necessary for its take-off (gray circle). The gray circle shown is for an aircraft with a 60 m pavement radius, comprised of 10 m of aircraft length plus 50 meters of take-off ground roll. The concentric black, blue, and dark green circles, respectively, represent the radii at which 50%, 30%, and 10% of residents living near the airpark would be highly annoyed, according to the "EU curve". The rainbow circle shown is of 40 m radius. This NPR is thus 0.444. The butterfly shape represents the general contours of a noise footprint calculated by the Gutin formula and indicates its use to create this footprint. By convention, the propeller axis is 0° and the peak noise azimuth is typically at about 120°, when using the Gutin formula.



Extremely short take offs and landing (ESTOL) are possible with wheel motors.

Y = A 50 m ground roll reaches 55 mph in 4.07 sec. at 0.617 G

X = Tesla 90D: A 22 m ground roll reaches 45 mph in 2.25 sec. at 0.91 G

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**Figure 5. A Sky Taxi with wheel motors could reach a lift-off at 55 mph in 4.07 seconds with a ground roll of just 50 meters (164 feet) at a tolerable acceleration of 0.617 G.**

For most Sky Taxis using surface airparks, the noise circle will tend to be larger than the pavement circle (NPR > 1.0) and will dictate the size of the airpark. A large noise circle will demand a commensurately larger, more remote and more expensive airpark land parcel. Such larger parcels will reduce the proximity of that airpark to its user base. Reduced proximity will increase the GTT and eliminate the advantage of using that airpark for very short flights. See Figure 6. As will be shown, these adverse effects of noisy Sky Taxis could impose such significant cost penalties as to disqualify them from being competitive in the RST market.

For skid-equipped VTOL aircraft which dock where they touchdown, large noise circles also are likely to entail longer times necessary just for passengers to reach and board or de-board their Sky Taxi at that spot. These longer times and the longer time that the VTOL aircraft occupies its landing spot tend to reduce the operational capacity of the airpark to fewer flights per hour, meaning fewer fares per hour, thus making the economic penalty for the large noise circle even more severe. Designers contemplating VTOL aircraft with skids for landing should therefore consider using wheel motor equipped landing gear and possibly tactile active gear (TAG) for their valuable benefit in improving ground ops and airpark capacity.

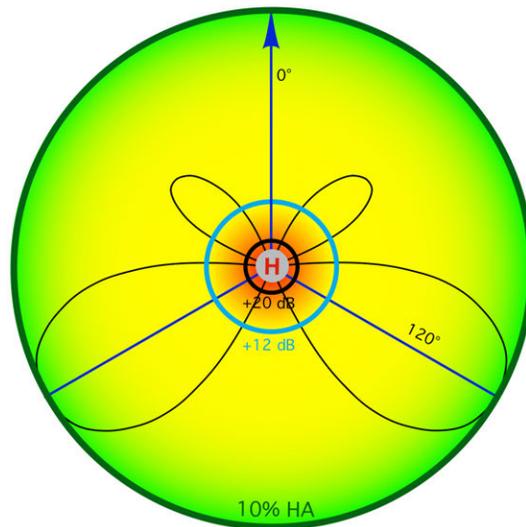
Building tall and expensive sound walls around airparks could pose a safety hazard if built close to the aircraft's lift-off point. Unlike the case for cars, such sound walls would not shield airpark neighbors from the noise of the aircraft once it had climbed above a height of about 10 meters.

The pavement area necessary for a Sky Taxi to perform true V/ESTOL take-offs and landings is a useful metric for evaluating the theoretical minimum size of land parcel required. The standard VTOL helipad shown in Figure 3 depicts a pavement area of just 15 meters diameter. The pavement radius should include the actual size of the Sky Taxi. A standard dimension of 10 meters (32.8 feet) is assumed adequate for the fore-aft length of a 2-seat Sky Taxi, and thus 10 m is added to the actual no-wind ground roll of the aircraft to determine its pavement radius. If the VTOL's ground roll is truly zero meters, then the pavement radius would simply be the 10 m length of the aircraft and the pavement circle would be 20 m in diameter. A 60 m pavement radius would reflect 50 m for ground roll and 10 m for the aircraft's length or ramp footprint.

Available historical airport noise survey data (the red “EU curve” in Figure 18.) as well as open parcel sizes on suburban hardscape maps suggest that a continuous level of 48 dBA at a 40 meter sideline distance would be a reasonable standard for the maximum community-acceptable take-off noise level at a pocket airpark fence for high frequency flights near residential areas. Using this metric, we can define the “noise radius” of any aircraft as that radius at which its take-off noise will reach just 48 dBA. The most serene neighborhoods might require a level below 48 dBA. Noisier Sky Taxis would require larger land parcels for their airparks to achieve this 48 dBA level, airparks that are more expensive to build and tend to be much farther from where people live. Such larger airparks may entail longer turnaround times for the taxiing back and forth from the airpark perimeter to the point of lift-off or touchdown.

Sky Taxis whose VTOL landing approach involves a period of hover and/or slow descent from a noise-tolerable altitude will consume a larger amount of time than one that conducts a continuous 55 mph gliding approach to touchdown. The Sky Taxi’s approach and departure times within the airpark boundary thus depend upon its ‘expeditiousness’ in those phases of flight as well as the diameter of the airpark. The time spent in flight descending across the airpark fence to touchdown and that from the point of take-off brake release to climbing out across the airpark fence each affect the capacity of passenger movement and amount of revenue producing fares that can be generated at that airpark. Smaller airparks thus reduce GTT and airpark cost, as well as shortening the turnaround time and producing more revenue. The sum of the longer on-airpark turnaround time and the longer GTT to reach larger airparks are projected to have a major adverse effect upon market size, profitability, and convenience. In effect, these delays could move the system from being one of affordable high volume public transit to one of being a small volume gentrified air limousine service with a much smaller market and much higher fares. Clearly, ultra-quiet Sky Taxis will be crucial to achieving the mass market necessary to sustain RST.

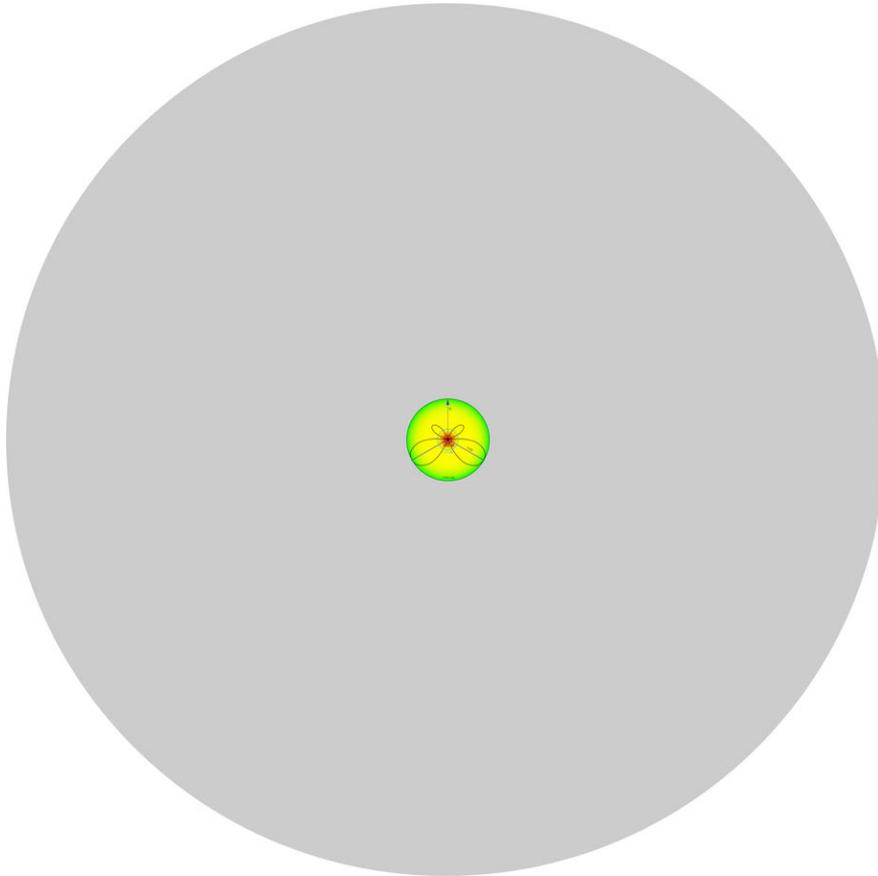
Noise to Pavement Ratio (NPR) = 256  
 Gray pavement circle is 20 m diameter



Large rainbow noise circle is 320 m diameter

**Figure 6. Using 48 dBA at 40 m radius as the required maximum noise at the airpark perimeter, a VTOL aircraft whose helipad is only 10 m in radius but whose take-off noise emission is 60 dB at 40 m, needs a 160 m radius to drop its noise to the requisite 48 dB, resulting in an NPR of 256. This high NPR illustrates a mismatch in this aircraft’s design; the sacrifices in speed, range and L/D made to enable VTOL capability are wasted because the large land area needed to contain its noise will require remote landing sites that disqualify it from landing close-by to where people live.**

Sky Taxi B:  
31 dB at 40 m at 80.5 kph  
Land parcel 1.13 hectares (2.79 acres)  
Noise to Pavement Ratio (NPR) = 0.009  
Gray pavement circle is 120 m diameter  
Rainbow noise circle is 11.3 m diameter

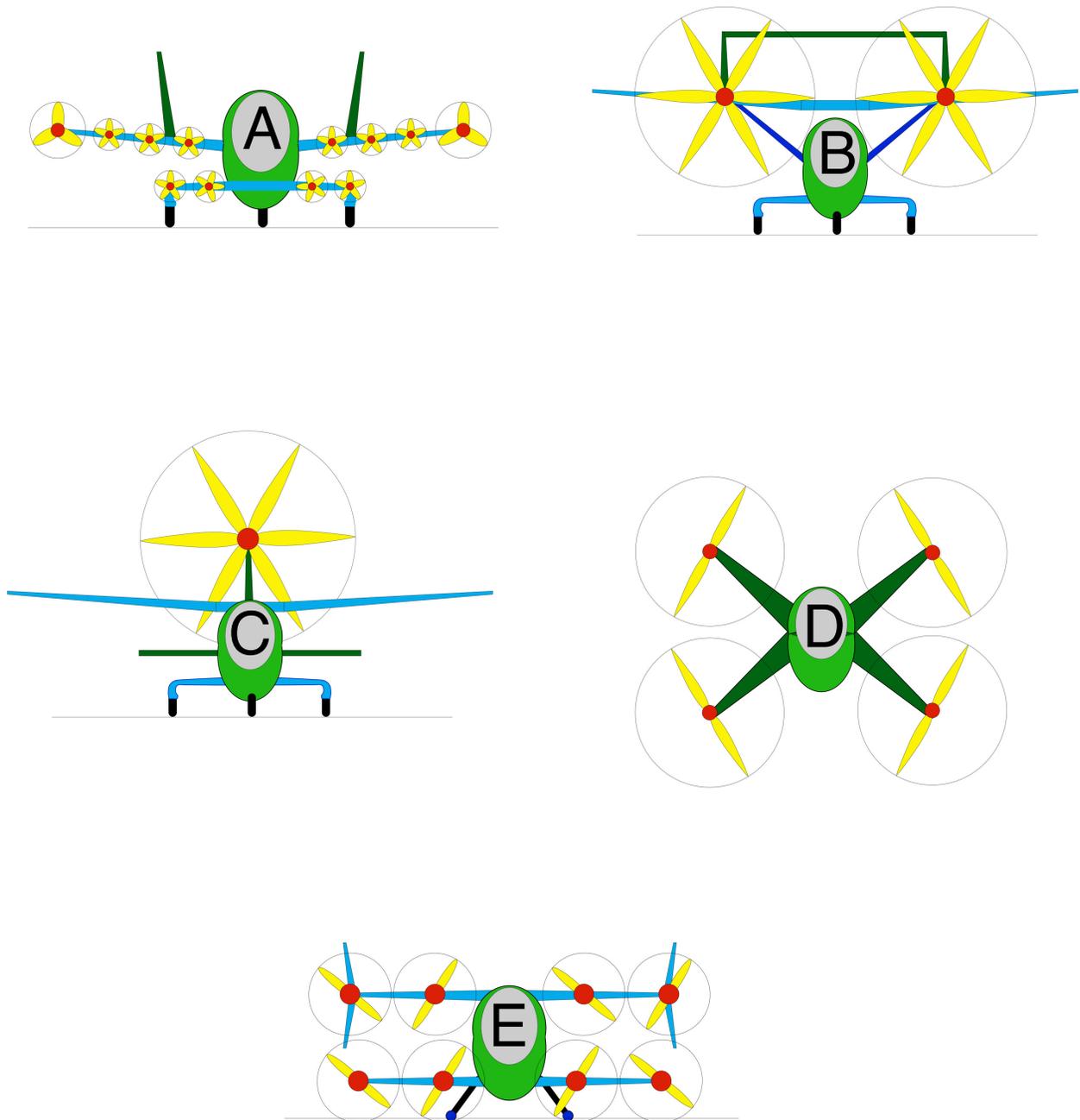


**Figure 7. Sky Taxi B has a favorable NPR of 0.009 due to a noise radius of only 5.66 m. Such a small noise footprint could remain entirely within the airpark’s pavement area during take-off and climb-out to a height at which the noise becomes imperceptible on the ground.**

#### **X. Illustrative Cases: Prospective Calculations of Sky Taxi Noise**

The Gutin formula can be used to evaluate the relative amount of take-off noise that could be expected, at minimum, from various new aircraft design concepts that could be aimed at the market of Regional Sky Transit. Such evaluations can illustrate the trade-offs that face designers when the primacy of noise is confronted.

For the purposes of this evaluation, 5 different Sky Taxi design concepts, lettered “A” through “E” are depicted in a simple generic format that facilitates comparison. See Figure 8. These variants are chosen in order to illustrate the noise effects of using different types, sizes and combinations of propellers that might reasonably be considered.



**Figure 8. The 5 Sky Taxi variants in design concept evaluated in this study are labeled as models A through E, as shown above.**

If we standardize the variant designs to each have a gross weight of 600 kg (1322 lb), the FAA limit used for 2-seat Light Sport Aircraft, we can set reasonable levels for the static thrust required for both the fixed wing and the VTOL design variants. To help ensure the short take-off, brisk climb rates and expeditious airpark operations

<b>Sky Taxi A:</b>	Main prop	Main prop	Main prop	Wingtip Prop	Wingtip Prop	Wingtip Prop
Airspeed, TAS, kph (axial)	1.6	1.6	1.6	1.6	1.6	1.6
Number of blades	5	5	5	3	3	3
Diameter, m	0.457	0.457	0.457	0.813	0.813	0.813
Thrust, N, per prop	180	180	180	570	570	570
Power, kW, per motor	6	5.63	7.1	20	19	22.5
RPM	5702	6800	4980	3600	4222	3384
Activity factor per blade	150	100	189	174	120	190
Efficiency, %	1.67	1.77	1.41	1.27	1.67	1.15
Propeller tip speed, m/sec	137	163	119	153	180	144
Noise, dB @ 40 m, per prop	49.5	58.5	44	65	68	62
Airspeed, TAS, kph (axial)	80.5	80.5	80.5	80.5	80.5	80.5
Number of blades	5	5	5	3	3	3
Diameter, m	0.457	0.457	0.457	0.813	0.813	0.813
Thrust, N, per prop	142	144	151	460	450	478
Power, kW, per motor	6	5.63	7.1	20	19	22.5
RPM	5702	6800	4980	3600	4222	3384
Activity factor	150	100	189	174	120	190
Efficiency, %	52.9	53.55	48.15	51.46	52.95	48.56
Propeller tip speed, m/sec	138	164	121	155	181	146
Noise, dB @ 40 m, per prop	57.5	65	<b>55.5</b>	68	74	<b>67</b>
Airspeed, TAS, kph (axial)	193	193	193	193	193	193
Number of blades	5	5	5	3	3	3
Diameter, m	0.457	0.457	0.457	0.813	0.813	0.813
Thrust, N, per prop	92	93	105	305	293	330
Power, kW, per motor	6	5.63	7.1	20	19	22.5
RPM	5702	6800	4980	3600	4222	3384
Activity factor	150	100	189	174	120	190
Efficiency, %	82.39	82.69	80.06	81.86	82.6	80.39
Propeller tip speed, m/sec	147	171	131	162	188	154
Noise, dB @ 40 m, per prop	60	67.5	57.5	70.5	75	69.5

demanded by RST, a relatively high static thrust to weight ratio requirement of 0.5 for fixed wing designs and 1.25 for VTOL designs is applied for this study. For the 600 kg Sky Taxis A through E presented here this translates to a static thrust requirement of 2940 N (661 lb) for fixed wing designs and 7351 N (1653 lb) for VTOL designs. This amount of thrust can be equally divided amongst the propellers of each design, maintaining the same disc loading for each of the aircraft's propellers of differing diameters.

The Gutin formula, as computed by the excellent Benchmark software<sup>22</sup>, can be used to compute relative estimates of the take-off noise emissions of Sky Taxis A through E. Theodorsen<sup>23</sup> and others have determined that the Gutin formula is reasonably accurate for predicting propeller noise for axisymmetric conditions when the aircraft is at rest or has a forward speed that is very low compared to the speed of sound (e.g., < 0.1M). It should be remembered that the Gutin formula does not account for the vortex noise, wind, angle of attack and other factors and therefore tends to underestimate the actual noise produced, so the results shown in this study are optimistic.

In making these comparisons of fixed wing aircraft variants A, B and C, we apply a reasonable strategy using the Boeing Propeller Chart computations embedded in Benchmark's Propeller Efficiency software module. For each propeller diameter on each aircraft variant, we select three combinations of horsepower, activity factor and RPMs that deliver the lowest calculated noise footprint for each aircraft while still delivering the requisite static thrust at 1.6 kph (1 mph, the take-off condition), as well as the requirement that that propeller achieve  $\geq 80\%$  efficiency at

120 mph, the anticipated cruise speed requirement. This manual selection process involves examination of several different iterations for each variant. In these, we also calculate the propeller noise level that the Gutin formula predicts to occur at a lift-off speed of 80.5 kph (50 mph), as a relevant indicator for defining the noise radius of the fixed-wing design variants. For the VTOL design variants, we calculate the noise at vertical speeds that would fit both the lift-off and brisk climb conditions, 1.6 and 11 kph, respectively. The range of results is illustrative of the interactive relationships between power, RPM and activity factor. Activity factors were limited to realistic values that would keep propeller blade thickness and weights manageable

For VTOL aircraft variants D and E, the downward thrust necessary to lift-off and climb briskly is of paramount importance. Achieving that thrust with the lowest noise and power was the goal in these iterations. The axial airspeeds in vertical flight for VTOL aircraft variant D, the quadcopter type, are not be expected to tilt to the non-axial flow of cruise flight until the aircraft had climbed well above the airpark, so those noise assessments are not included here. This study also presumes that these VTOL aircraft will be engineered to be immune to the constraints of a height-velocity diagram or “dead man’s curve” such as governs lift-offs with conventional helicopters. The assessment of noise for variant D at 193 kph is included for interest only in the table above and is based on the presumption that variant D had turned into a tilt-rotor type aircraft. For VTOL aircraft variant E, the tilting of its canard and main wing maintains axial airflow into the rotors and the higher axial airspeeds are assessed accordingly.

The 3 tables with [blue text](#) contain 3 iterations of different combinations of power, propeller RPM, and activity factor for each Sky Taxi design variant, A through E, at the various relevant airspeeds. Each of these iterations yields calculated values for noise, thrust, efficiency, and propeller tip speed for the aircraft in question when operating at sea level. The noise results are then used to determine the noise radius at which 48 dB would be heard. This radius is then used in calculating the aircraft’s NPR and its resulting turnaround time and GTT.

The power required to take off with a 2-seat Sky Taxi of 600 kg (1322 lb) is shown to vary widely in this study. In general, taking off with less power will produce lower noise levels and reduce noise radius. In addition, the Sky Taxi that can perform its mission with a smaller amount of power will, for a given capacity of battery pack, have a greater range and require fewer battery pack swaps per day. That means consuming less electricity, which can translate into lower GHG emissions. Sky Taxis that require less power will also generally weigh less and cost less.

This assessment generally reveals the relationship between activity factor and noise. Propeller blades with higher activity factor (greater chord per span) enable the delivery of the requisite thrust at lower RPMs and thereby lower noise by lowering propeller tip speeds. However, propeller noise also depends upon the thickness of the propeller blade, which naturally increases with activity factor. The optimization of that trade-off relationship is beyond the scope of this paper.

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Propeller Parameter	Sky Taxi B	Sky Taxi B	Sky Taxi B	Sky Taxi C	Sky Taxi C	Sky Taxi C
Airspeed, TAS, kph (axial)	1.6	1.6	1.6	1.6	1.6	1.6
Number of blades	6	6	6	6	6	6
Diameter, m	3.05	3.05	3.05	3.66	3.66	3.66
Thrust, N, per prop	1470	1470	1470	2940	2940	2940
Power, kW, per motor	20	19.8	22	58	73	58
RPM	399	438	340	351	300	388
Activity factor per blade	105	81	147	117	160	89
Efficiency, %	4.08	3.26	2.97	2.25	1.79	2.82
Propeller tip speed, m/sec	64	88	54	67	57	74
Noise, dB @ 40 m, per prop	28 (est.)	28 (est.)	27 (est.)	27 (est.)	26 (est.)	28 (est.)
Airspeed, TAS, kph (axial)	80.5	80.5	80.5	80.5	80.5	80.5
Number of blades	6	6	6	6	6	6
Diameter, m	3.05	3.05	3.05	3.66	3.66	3.66
Thrust, N, per prop	737	738	798	1927	2203	1929
Power, kW, per motor	20	19.8	22	58	73	58
RPM	399	438	340	351	300	388
Activity factor	105	81	147	117	160	89
Efficiency, %	82.42	82.49	81.06	74.3	67.47	74.37
Propeller tip speed, m/sec	67	73	59	71	62	78
Noise, dB @ 40 m, per prop	29 (est.)	29 (est.)	<b>28 (est.)</b>	28 (est.)	<b>28 (est.)</b>	28 (est.)
Airspeed, TAS, kph (axial)	193	193	193	193	193	193
Number of blades	6	6	6	6	6	6
Diameter, m	3.05	3.05	3.05	3.66	3.66	3.66
Thrust, N, per prop	300	301	334	930	1169	932
Power, kW, per motor	20	19.8	22	58	73	58
RPM	399	438	340	351	300	388
Activity factor	105	81	147	117	160	89
Efficiency, %	80.39	80.6	81.29	85.99	85.83	86.17
Propeller tip speed, m/sec	83	88	76	86	79	92
Noise, dB @ 40 m, per prop	29 (est.)	29.5 (est.)	28 (est.)	28 (est.)	28 (est.)	29 (est.)

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<b>Propeller Parameter</b>	<b>Sky Taxi D</b>	<b>Sky Taxi D</b>	<b>Sky Taxi D</b>	<b>Sky Taxi E</b>	<b>Sky Taxi E</b>	<b>Sky Taxi E</b>
Airspeed, TAS, kph (axial)	1.6	1.6	1.6	1.6	1.6	1.6
Number of blades	2	2	2	2	2	2
Diameter, m	2.44	2.44	2.44	1.219	1.219	1.219
Thrust, N, per rotor	1837.75	1837.75	1837.75	919	919	919
Power, kW, per motor	29	32	58	28	28	38
RPM	1500	1300	814	2850	2431	2250
Activity factor per blade	125	80	153	110	160	167
Efficiency, %	2.83	2.55	1.41	1.46	1.82	1.07
Rotor tip speed, m/sec	192	166	104	182	155	144
Noise, dB @ 40 m, per rotor	86	83	70	86	80.5	78
Airspeed, TAS, kph (axial)	11	11	11	11	11	11
Number of blades	2	2	2	2	2	2
Diameter, m	2.44	2.44	2.44	1.219	1.219	1.219
Thrust, N, per rotor	1725	1754	1818	906	906	919
Power, kW, per motor	29	32	58	28	28	38
RPM	1500	1300	814	2850	2431	2250
Activity factor	125	80	153	110	160	167
Efficiency, %	18.17	16.75	9.58	9.89	9.88	7.39
Rotor tip speed, m/sec	192	166	104	182	155	144
Noise, dB @ 40 m, per rotor	87	84	<b>73.5</b>	86	82.5	<b>79</b>
Airspeed, TAS, kph (axial)	193	193	193	193	193	193
Number of blades	2	2	2	2	2	2
Diameter, m	2.44	2.44	2.44	1.219	1.219	1.219
Thrust, N	403	516	931	446	446	573
Power, kW, per motor	29	32	58	28	28	38
RPM	1500	1300	814	2850	2431	2250
Activity factor	125	80	153	110	160	167
Efficiency, %	74.55	86.47	86.03	85.39	85.32	80.8
Rotor tip speed, m/sec	199	174	117	190	164	153
Noise, dB @ 40 m, per rotor	83	83.5	83	87.5	85.5	87

The Regional Sky Transit II study was based upon a short turnaround time, which was nominally 3 minutes at a 168 m x 99 m airpark operating at maximum capacity of 1 departure and 1 landing every 10 seconds. That turnaround time represented the sum of 10 + 40 + 10 + 30 + 30 + 40 + 10 + 10 = 180 seconds. These, in turn, represented 10 seconds for final approach including touchdown, rollout and turnoff, 40 seconds for taxiing to the most distant parking spot in the loading dock area, 10 seconds to back into that spot, 30 seconds for de-boarding, 30 seconds for boarding, 40 seconds for taxiing to departure point, 10 seconds to the take-off brake release position and 10 seconds for take-off and climb out to the airpark fence. Taxiing times depend upon the airpark size. The 40 seconds of taxiing used in the Regional Sky Transit II study were predicated on a 7.6 m/sec or 27 kph (25 fps) taxiing speed. To determine the turnaround time used in this study, this taxiing speed is applied to any surplus distance beyond 168 meters that is found in the computation of the SkyTaxi's noise radius. In addition to extra time for longer taxiing distances, the turnaround times used in this study for VTOL variants "D" and "E" are increased to reflect the longer time necessary for a VTOL aircraft to land and take-off. Instead of the nominal 10 seconds for take-off and 10 seconds for landing used for the fixed wing variants, the VTOL's take-off time is taken as the nominal 10 seconds plus the additional time calculated in this study for the VTOL to climb at 3.053 m/sec (601 fpm = 11 kph) to a height equal to its noise radius, before leaving the airpark property. Since VTOL's use power during landing, the VTOL's landing time is taken as the nominal 10 seconds plus the additional time necessary for it to descend at 3.053 m/sec from a height above the airpark property equal to its noise radius.

The assessments of Sky Taxis A through E, under standard day, sea level conditions, reveals the following:

Sky Taxi variant:	A	B	C	D	E
Total thrust needed, N	2940	2940	2940	7351	7351
Total combined propeller disc area, sq m	2.679	14.6123	10.52	18.70	9.34
Thrust/disc area, N/sq m	1097.6	201.2	279.4	393.0	787.3
Propeller diameter, main props, m	0.457	3.05	3.66	2.44	1.219
Propeller diameter, wingtip props, m	0.813	na	na	na	na
Thrust per main prop or rotor, N @ 1.6 kph	180	1470	2940	1837.75	918.9
Thrust per wingtip prop, N @ 1.6 kph	569.8	na	na	na	na
Blade activity factor, main prop or rotor	189	147	160	153	167
Blade activity factor, wingtip prop	190	na	na	na	na
Number of blades, main prop or rotor	5	6	6	2	2
Number of blades, wingtip prop	3	na	na	na	na
Power/RPM, each main prop or rotor, kW/RPM	7.1/4980	22/340	73/300	58/814	38/2250
Power/RPM for each wingtip prop, kW/RPM	22.5/3384	na	na	na	na
Power: total installed power, kW	116	44	73	232	304
dB of a main prop or rotor, dB @ 40 m, 1.6 kph	44	27	26	70	78
dB of a wingtip prop, dB @ 40 m, 1.6 kph	62	na	na	na	na
Total noise, all props, dB @ 40 m, 1.6 kph	65.34	30	26	76.02	87.03
Noise radius for 48 dB, m, 1.6 kph	294.5	5.04	3.18	1007	3577.7
Noise area, sq m, 1.6 kph	272471	79.8	31.77	3185726	40212155
Propeller efficiency, main prop, 1.6 kph, %	1.41	2.97	1.79	1.41	1.07
Propeller efficiency, wingtip prop, 1.6 kph, %	1.15	na	na	na	na
Estimated take-off ground roll, m, no wind	50	50	50	0	0
*Pavement radius, m, if 10 m vehicle length	60	60	60	10	10
Pavement area, sq m	2827	2827	2827	314	314
Noise to Pavement ratio (NPR), 1.6 kph	24.09	0.007	0.003	10140	127999
dB of a main prop, dB @ 40 m, 80.5 kph	55.5	28	28	73.5 <sup>@</sup>	79 <sup>@</sup>
dB of a wingtip prop, dB @ 40 m, 80.5 kph	67	na	na	na	na
Total noise, all props, dB @ 40 m, 80.5 kph	<b>71.33</b>	<b>31</b>	<b>28</b>	<b>79.5<sup>@</sup></b>	<b>88.03<sup>@</sup></b>
Noise radius for 48 dB, m, 80.5 kph	<b>586.7</b>	<b>5.66</b>	<b>4</b>	<b>1506.9<sup>@</sup></b>	<b>4014<sup>@</sup></b>
Noise area, sq m, 80.5 kph	1081388	101	50	7133758 <sup>@</sup>	50617913 <sup>@</sup>
Propeller efficiency, main prop, 80.5 kph, %	48.15	81.06	67.47	9.58 <sup>@</sup>	7.39 <sup>@</sup>
Propeller efficiency, wingtip prop, 80.5 kph, %	48.56	na	na	na	na
Noise to Pavement ratio (NPR), 80.5 kph	<b>95.6</b>	<b>0.009</b>	<b>0.004</b>	<b>22707<sup>@</sup></b>	<b>161122<sup>@</sup></b>
**Turnaround time, (calculated), minutes	4.84	3	3	25	64
<sup>+</sup> GTT, one way (calculated), minutes	32.3	6	6	213	1512
Total of Turnaround time + 2 x GTT, minutes	69	15	15	452	3088
<sup>^</sup> Reduction in profits, San Francisco RST, %	<b>88%</b>	0	0	na	na
<sup>^^</sup> Lost annual profits, San Francisco RST, \$USD	<b>\$1.062 B</b>	0	0	na	na

Filename: Primacy.of.Noise.calcs.dB.xlsx and Primacy.of.Noise.Sky.Transit.Profits.2016.D.xlsx

<sup>@</sup> VTOL variants “D” and “E” data for 11 kph axial velocity through rotor, not 80.5 kph rolling take-off

\* Pavement radius = (estimated ground roll plus 10 meter vehicle length)

\*\* Turnaround time = includes take-off, landing, taxiing at 7.6 m/sec, de-board/boarding

<sup>+</sup>GTT nominal is 6 minutes for 168 m airpark.

<sup>^</sup> Reduction in profits from effects of increased GTT, longer average trip lengths, and longer turnaround time

<sup>^^</sup> Lost annual net profits caused by increased noise, if \$20 USD Sky Taxi fares

The data sets in the table above are for static (1.6 kph) and lift-off speed of either 80.5 kph (50 mph) or 11 kph

The larger of its 2 noise radii is used to assess each Sky Taxi’s potential impact on the RST system

Ground travel time (GTT) depends on many factors. These include the time of day, the uncertainty time when using a freeway (40-90% extra), the distance to the airport, the mode of surface travel (walk, bike, car, bus), and other factors. For the purposes of this study, a tabulation was made of the GTT for 19 small to medium-sized general aviation airports that surround the San Francisco Bay area, based upon their land parcel size and their distance in miles from the population center that they serve. The larger airports were typically more remote from the town centers. The results showed an average of 0.121 minutes of GTT per acre of airport land to reach those airports. This average was applied to the noise areas computed in this study for each Sky Taxi design variant A through E, in order to calculate a theoretical GTT for each type aircraft.

In Figure 9., the larger noise radius of Sky Taxi A increases its GTT to 69 minutes from the nominal 15 minutes. This has the effect of more than doubling the Sky Taxi trip distance for which 30 minutes can be saved relative to car travel. That distance increases from 30 km for Sky Taxis B and C to 70 km for Sky Taxi A. By this calculus, the much longer GTT for the noisier VTOL SkyTaxis D and E, are 452 minutes and 3088 minutes, respectively. These are not shown in Figure 9., because D and E cannot provide any time saved relative to a car trip on any of the relevant trip lengths. That is, the car always provides a faster trip speed than Sky Taxi D or E, making them, by this calculus, untenable designs for Regional Sky Transit. In Figure 9., the case for a very short GTT of 7 minutes with the cruise speed of 193 kph (120 mph) is included. This 7 minutes includes the 3-minute turnaround time. This would be the ultimate example of high proximity where the traveler needed only 2 minutes to reach the airport and just 2 minutes to leave it and reach his or her doorstep destination. Note that this 7 minute GTT would allow a time savings of 30 minutes on a trip as short as 28 km (17.4 miles). It is also notable that the 193 kph aircraft with 7 minute GTT offers time-savings that nearly rival that of the 386 kph (240 mph) aircraft whose GTT is 15 minutes, again emphasizing the extreme importance of having airports with high proximity.

Sky Taxi A has a longer turnaround time, 4.84 minutes, than the quieter Sky Taxis B and C, which require just 3 minutes. This, along with the longer trip length of 70 km for Sky Taxi A (to save 30 minutes) reduces the number of passengers who will find Sky Taxi A to be a useful option for travel, since statistically many fewer trips involve that longer distance. From the national data that compare trip length with number of trips, shown in Figure 10., below, the longer trip lengths due to the larger noise radius of Sky Taxi A suggest that it would suffer a nearly 5-fold reduction in potential user market. Making longer trips also reduces the number of trips that a Sky Taxi can perform in a day.

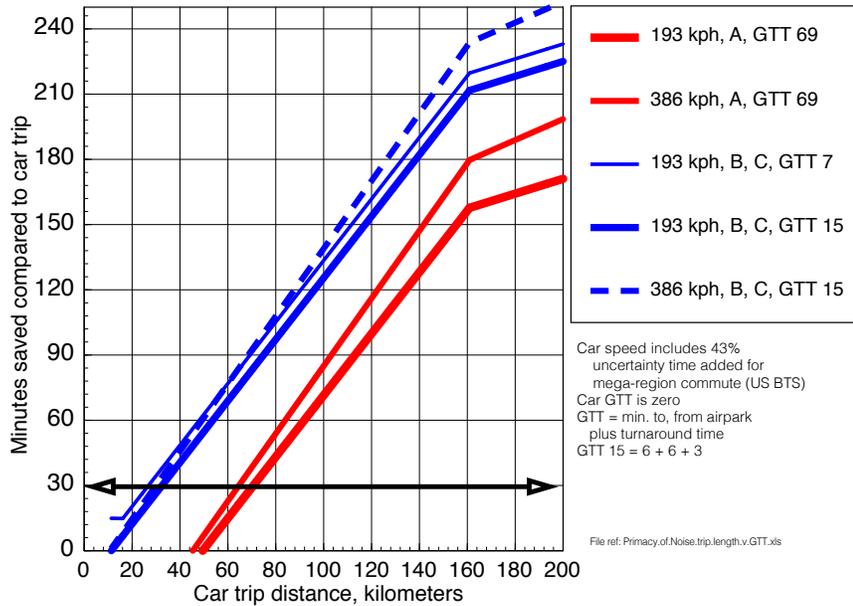
When applied to the business model used for just the San Francisco Bay Area in the 2015 Regional Sky Transit paper, these adverse impacts due to the larger noise radius of Sky Taxi A result in an annual SF Bay area-wide loss of \$1,062,204,214 net profits or 88% compared to the annual net profits earned by the quieter Sky Taxis B and C, which would be \$1,206,567,500. This roughly \$1B loss of profit is computed by using the assumptions of a 40 km average trip length for Sky Taxis B and C and an 80 km average trip length for Sky Taxi A. This business model computation accounts for the longer turnaround times of Sky Taxis A, D and E. It uses the same values for all 5 Sky Taxi design variants for the parameters of Sky Taxi cost (\$200,000), L/D (12), cruise speed (193 kph) and air fare (\$20 USD).

These adverse impacts due to the modest increase in noise of Sky Taxi A emphasize the astonishingly powerful effect of noise in the RST system. If extrapolated across the entire USA, this \$1B loss in the San Francisco Bay Area's RST model could amount to a loss of tens of billions of dollars. Such adverse economic results would be even more extreme with the noisier VTOL Sky Taxi design variants D and E, whose GTT and turnaround times are so much larger as to appear fundamentally untenable. It must be remembered that the noise levels computed in this study are very likely to be *optimistic*. That is, they are probably lower than the actual noise that would occur with each Sky Taxi.

The results of this comparison study clearly show that noise affects nearly everything about RST. The factors influenced by this primacy of noise include:

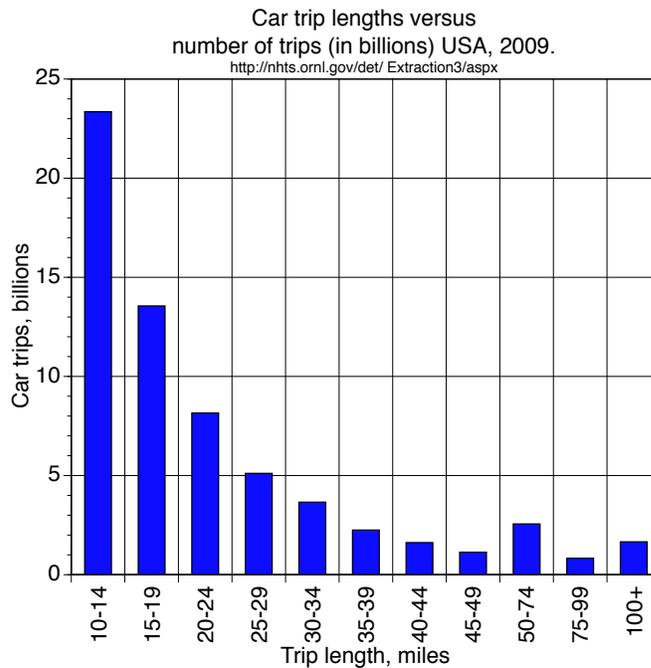
- Profitability
- RST system capacity
- Affordability of RST fares
- Time savings
- GHG savings
- Vehicle manufacturing cost (both by mass production and component costs)
- Aircraft performance: Speed, Range, L/D, MPG, and take-off distance
- Cabin comfort
- Infrastructure cost (both of airports and surface highways)

Ground-Travel Times (GTT) vs time saved relative to a car trip, for fixed-wing Sky Taxis A, B, and C at 193 kph (120 mph) and 386 kph (240 mph).

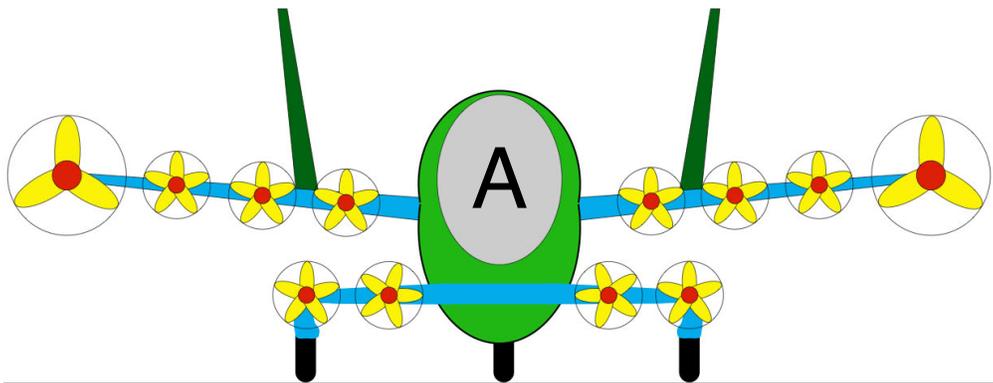


**Figure 9. The 69 minutes GTT of the Sky Taxi A (thick red line) with cruise speed of 193 kph can deliver 30 minutes saved only if the trip length exceeds 70 km (43.5 miles). Sky Taxis B and C at 193 kph can each save 30 minutes on trip lengths as short as 30 km (18.6 miles). These longer trip lengths required by Sky Taxi A due to its higher noise levels translate to a nearly 5-fold reduction in potential user base and an 88% reduction (\$1B) in annual net profits in the San Francisco RST market alone, according to its business model.**

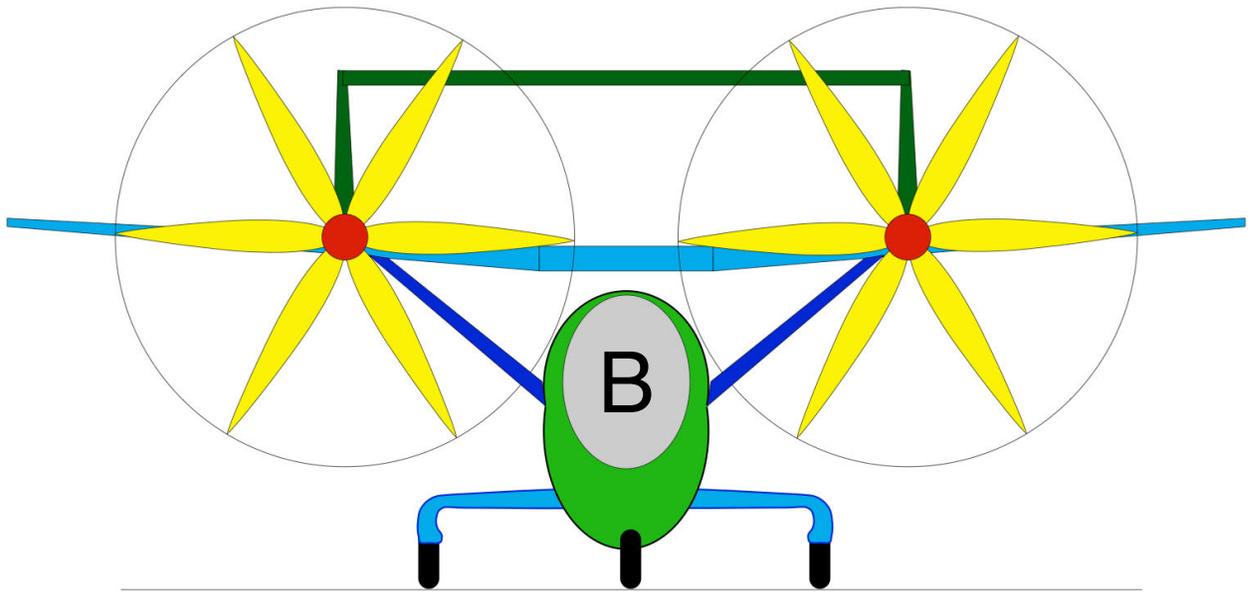
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**Figure 10. Potential RST market size depends upon the shortest trip length by Sky Taxi that can save the user substantial time (e.g. 30 minutes) relative to a car trip<sup>24</sup>.**

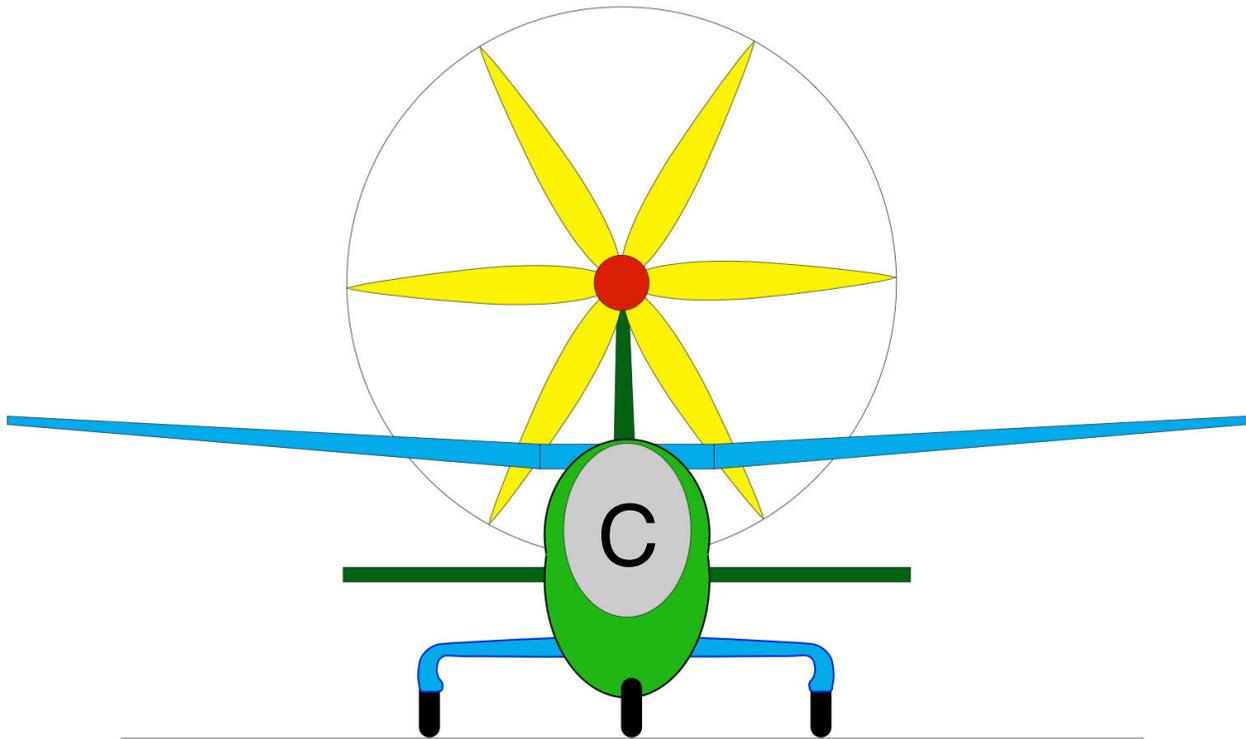


**Figure 11. Sky Taxi “A”—a 12-motored fixed-wing canard-equipped Sky Taxi uses distributed electric propulsion (DEP). It has 10 separate motors that each rotate a 0.457 m (1.5 foot) diameter tractor 5-bladed propeller, along with 2 larger motors on the wingtips, each rotating a 3-bladed propeller of 0.813 m (32 inch) diameter.**

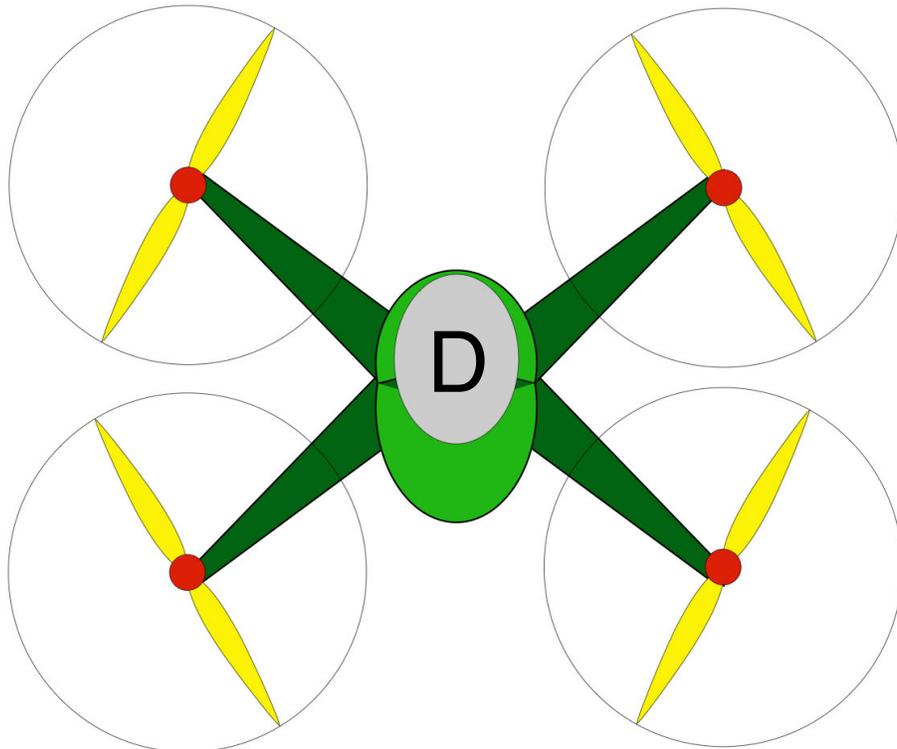


**Figure 12. Sky Taxi “B”--a 2-motored fixed-wing Sky Taxi that uses wheel motors and blown flaps for ESTOL performance. It has 2 tractor 6-bladed propellers of 3.05 m (10 foot) diameter.**

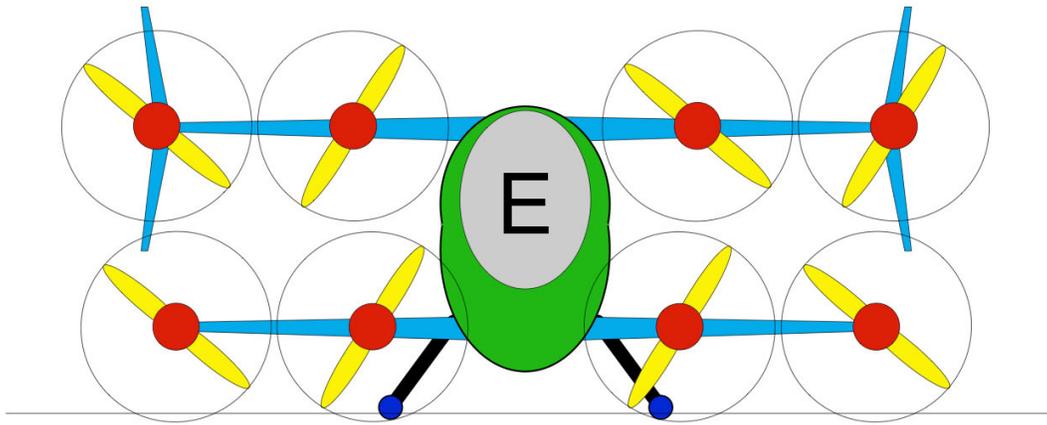
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**Figure 13. Sky Taxi “C”--a single-motored fixed-wing Sky Taxi that uses wheel motors without blown flaps for STOL performance. It has a single 3.66 m (12 foot) diameter tractor 6-bladed propeller mounted atop and in front of its vertical stabilizer.**



**Figure 14. This VTOL quad-copter Sky Taxi “D” has 4 rotors, each of which are 2.44 m (8 foot) diameter and have 2 blades. The 2-seat people pod is maintained at 1.90 meters wide for size reference. Unlike the fixed wing variants, its take-off noise calculation assumes a 1.25 thrust to weight ratio.**



**Figure 15. This 2-seat tilt-wing VTOL Sky Taxi “E” uses eight 2-bladed propellers each of 1.219 m (4 foot) diameter. Like the quadcopter version, its take-off noise calculation assumes a 1.25 thrust to weight ratio.**

## **XI. Aircraft Size Effects**

The scaling of take-off noise with power allows one to mathematically predict the relative take-off noise of aircraft of varying sizes and power requirements (Equation (4)). Happily, the size of aircraft needed to fulfill most trips in Regional Sky Transit will be only 2-3 seats because experience shows that in metro regions, nearly everyone wants to go to a different destination. The amount of power necessary for 2-seat aircraft is relatively small. The infrequent need for a Sky Taxi with 4, 6 or 9 seats and the louder noise that such larger aircraft would entail suggest that design efforts should focus on 2-seat Sky Taxis.

## **XII. Cost to Benefits Ratio**

The comprehensive costs of creating and implementing ultra-quiet Regional Sky Transit include the following:

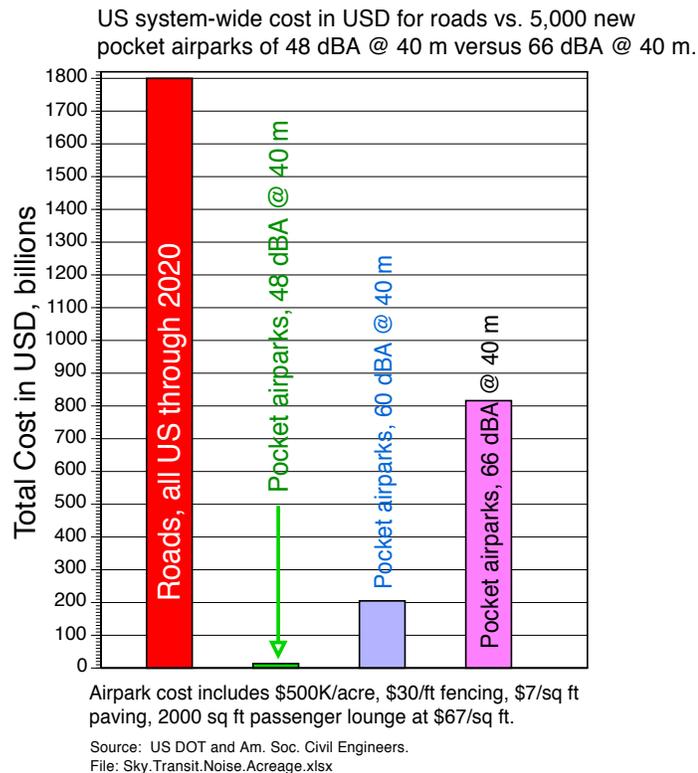
1. the cost of designing and developing the mission-capable Sky Taxi
2. the cost of its certification for carrying passengers for hire
3. the cost of creating an efficient supply chain to serve its manufacturing
4. the cost of creating a mass production facility
5. the cost of designing, land purchase, permits and construction that attend networks of pocket airparks
6. the cost of new air traffic management and the licensing, certifying and regulating of Sky Taxis
7. the cost of providing widespread commercial Regional Sky Transit services across urban regions

The cost of items (1-4) above is currently being borne by mainly non-government funding sources at several entrepreneurial start-up companies, most of them centered near Silicon Valley. The aggregate expenditures of these companies so far is estimated to be on the order of \$300M USD. These competing companies each face the challenge of weighing the costs of being first to market and thereby first to grow market share versus the risk of creating an unsuccessful aircraft--one that cannot meet certification standards or is supplanted or out-performed by one that emerges later from a rival company. In this race to market, the definition of the market, its mission-capabilities and operational requirements are crucial considerations. The primacy of noise in these considerations cannot be overemphasized.

The cost of item (5) above is found to be highly dependent upon the Sky Taxi aircraft’s take-off noise, as shown in Figure 16, below.

The cost of item (6) is expected to be largely a government responsibility as a part of the NextGen and UTM programs. The cost of item (7), absent government subsidy, will be the responsibility of the RST service provider and will evolve according to the profitability of that business. In October, 2016, Uber issued a 98-page white paper

describing the intent to be such a provider. The profitability of RST, as studied in two different business models<sup>25, 26</sup>, appears very promising. However, its profitability and the magnitude of its benefits closely depend upon having RST win a substantial ridership by making sense for the very large number of trips that are as short as 30 km. Making sense for such short trips demands that RST provide ubiquitous pocket airparks with high proximity to where people live so as to minimize ground travel time (GTT). That means having pocket airparks that are as small as possible while still fulfilling the stringent community acceptable noise limits that will surely pertain in residential areas.



**Figure 16. Airpark land and construction costs to implement community-acceptable RST across the US will depend upon the take-off noise emissions of the Sky Taxi.**

The benefits of RST in terms of clearing the air, relieving gridlock, adding to productivity and easing climate change are difficult to quantify. However, it is clear that the magnitude of those benefits will depend upon the level of ridership won by RST, which, in turn will depend upon its Sky Taxis being extraordinarily quiet.

### XIII. Discussion

As the aerospace industry evolves toward a future mass market of Regional Sky Transit, there needs to be a concerted effort to anticipate and avert the problems that have plagued aviation in the past. These problems have included noise, safety, cost, pollution and wasted time. Noise in particular is shown in this study to profoundly affect cost, pollution and wasted time. Noise is arguably the main problem for which aviation has had to apologize for decades. Reducing noise as Job One in the aircraft design process is seen to place several constraints on the designer. Yet such a primacy of noise will clearly be essential to creating a successful future Sky Taxi design.

This study, though preliminary and approximate, suggests that electrically powered aircraft may enable exponential reductions in aircraft noise. The examination of the relative noise predicted for each variant of Sky Taxi herein is a valuable exercise because it elucidates which designs hold the greatest promise of success and which will likely fail to reward the time, energy and funding invested in them. Success can be defined as having the

combination of performance necessary for RST while also fulfilling reasonable and realistic community acceptable noise limits and thereby meriting the high costs of certification for carrying passengers for hire. It can be assumed that without FAA certification, a design will not achieve significant production numbers. It can be expected that new, highly stringent noise regulations and ordinances will be imposed by local government for the high proximity airparks of RST that are sited near serene residential settings.

The 5 generic variants of Sky Taxi propulsion chosen for evaluation in this study are for illustrative purposes only. A range of hypothetical combinations of power, RPM and activity factor was assessed for each design variant's propellers and rotors, keeping constant the gross weight and static thrust requirement. Estimation of each Sky Taxi variant's flying qualities, landing characteristics, stall speeds, L/D and maximum speeds is beyond the scope of this paper.

It is assumed that the take-off noise levels of fixed-wing design variants A, B, and C will far surpass their noise emissions during landing. For the VTOL variants D and E, however, the noise emissions during their power-on landings may rival those of taking off. These issues are not addressed in this paper.

The small differences in take-off noise between variants B and C may not be significant enough to dictate using one versus two propellers. The advantages of having 2 large tractor propellers along the leading edge of the main wing are several: it enables the use of blown wing flaps, it can provide more powerful spoiler effect for steep descents, it avoids the noise increase that accompanies propeller inflow that has been disturbed by fore-body shapes.

Variant A, it must be noted, is a canard-equipped aircraft. The well-known hazard in canard-equipped aircraft, i.e., of being subject to a deep and unrecoverable stall of the main wing, has traditionally been averted by employing a substantial sweep angle for the main wing. It should be remembered that such a sweep angle then poses challenges for the placement of leading edge tractor propellers and blown flaps on that wing.

Variant C, by having its propeller located just in front of the vertical stabilizer, forfeits the opportunity to have the high CLmax of blown flaps, which is present on variants A and B. Nevertheless, in this study, variant C is forecast to achieve the same pavement radius as A and B, just 60 m, by using wheel motors in the landing gear.

Variants A, B, and C are each expected to employ wheel motors to shorten their take-off distances. Variants D and E are not depicted with wheel motors, but could have them to enable quieter and safer ground/ramp operations.

The fixed wing variants A, B, and C may require more pavement to land than to take-off because a portion of the short airpark runway would be used as an over-flight area for a steep quiet descent to touchdown. Considerations of the landing distances of these aircraft are not included in this study, other than to recognize that blown flaps and wheel motors would help enable very short landing distances.

The use of rooftops as the pavement landing areas for Sky Taxis has been suggested as a means to lessen their noise impacts. While this could enable some Sky Taxi access to densely built high-rise city center areas, the noise levels and noise radii found in this study would require a very tall and expensive building for that purpose in a quiet residential area, and that would not seem a compatible land use there. In addition, such a rooftop would impose limitations on turnaround time, loading dock and parking areas for Sky Taxis with limitations on the volume of travelers who could expeditiously arrive via the rooftop. A more attractive and workable solution would likely be to place airparks on piers along the shore of a bay, lake or other body of water, which are often available near population centers.

#### **XIV. Conclusions**

The effect of Sky Taxi noise on Regional Sky Transit is described and evaluated for its potential effects on operational sustainability, aircraft design, public acceptance, costs and profitability. The main points that emerge from this study are the following:

1. Sky Taxi designers should make low take-off noise a foremost design goal.
2. More research and resources should be devoted to exponentially reduce propeller and rotor noise.
3. Wheel motors for quiet and brisk take-off acceleration and taxiing should be developed for use in Sky Taxis to enable them to operate expeditiously and reduce airpark size and cost.
3. The non-dimensional "noise to pavement ratio" (NPR) is an important and useful metric for rationally matching the noise and take-off characteristics of V/ESTOL Sky Taxis and for predicting their land use impact.

4. The benefits of using distributed electric propulsion (DEP) in Sky Taxis must be weighed against its impact on the vehicle's noise footprint and NPR, particularly the impact of small diameter, high RPM propellers and rotors.

5. Sky Taxi design should respect the need for expeditious, high capacity RST operations at pocket airparks with high proximity to quiet residential areas as essential to its economic sustainability.

6. The Benchmark Software Propeller Efficiency module using the Gutin propeller noise formula is a useful tool for making preliminary relative assessments of propeller noise. The accuracy of the Gutin formula can likely be improved in the future by adding to it a computation for vortex noise, and this will be the subject of a subsequent report.

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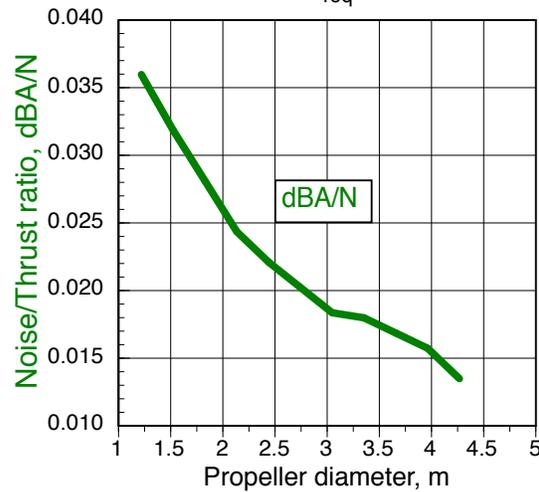
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<sup>26</sup>Ibid # 4.

<sup>27</sup>Ibid # 8.

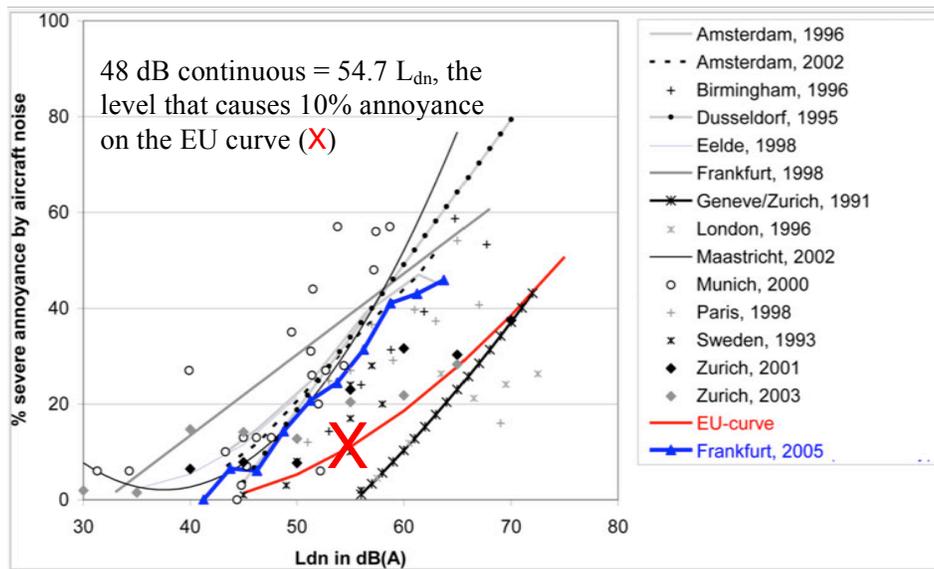
## Appendix

Propeller diameter vs. Noise/Thrust ratio,  
40 m sideline, kW<sub>req</sub> for 2669 N thrust.



6-bladed propeller of ideal RPM and activity  
factor for best efficiency, at 72.4 kph (45 mph)  
using Gutin formula in Benchmark software.  
filename: SA.Prop.Diam.Noise.xlsx

**Figure 17.** The “noise to thrust ratio” (NTR) shows the favorable effect of larger diameter, slower-turning propellers in reducing noise.



**Figure 18.** Severe noise annoyance surveyed in the EU suggests that a continuous noise level of 48 dBA L<sub>dn</sub> would be acceptable to 90% of airpark neighbors at large airports.<sup>27</sup>