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Community acceptance of drone noise: The *drone* of drones

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ABSTRACT

Within the next five to ten years, small package delivery drones and larger human passenger drones will become the next mode of transportation to fill our environment with noise. They are already being used in test markets around the world to gauge community acceptance of the concept; none the least of which being the noise generated by these drones. In fact, along with safety, noise is the prime concern for gaining public acceptance and regulatory approval for widespread use of drones. Title 14 CFR Part 36 contains FAA's current certification requirements for drone flyover noise at the source. But what about receiver noise criteria? This paper will describe some of the drones in use today, the major manufacturers and drone delivery services already well into development, and the current federal regulatory setting for community noise in the United States for various modes of transportation. The paper concludes with a recommended new noise criteria approach (E-weighting), for FAA to consider adopting, that would account for the annoying "drone" of drones, could easily be measured in the field, and that would be compatible with existing community noise numeric limits.

1. INTRODUCTION

Will people around the world accept the noise of a hundred angry little beehives buzzing all around the outside of their homes both day and night? That is an exaggeration, of course, but while the public may have by now accepted the omnipresent noise from transportation sources such as highways, railroads, and aircraft, it remains to be seen if people will accept the noise from drones as readily. Humans are less willing to tolerate changes in noise level, especially if those changes are potentially loud and unexpected sources emitting distinctive pure tones and humming sounds. Yet as ubiquitous as the aforementioned transportation sources are in a community, it is highly likely that the "*drone* of drones" will be a source just as commonly heard in the near future.

Small unmanned aircraft systems (sUAS) package delivery drones and larger urban air mobility (UAM) human passenger drones will become the next mode of transportation to fill our environment with noise. They are already being used in test markets around the world to gauge community acceptance of the concept; none the least of which being noise. In fact, along with safety, noise is the prime concern for gaining public acceptance and regulatory approval for widespread use.

2. EXISTING DRONE INDUSTRY

Dozens of manufacturers are eagerly developing the emerging world of large passenger and small package delivery drones. Drones have been successfully used for decades by the military, agricultural, geological, and entertainment industries. Their usefulness is limited only by people's imagination. In fact, NASA just successfully flew the *Ingenuity* reconnaissance drone on Mars!

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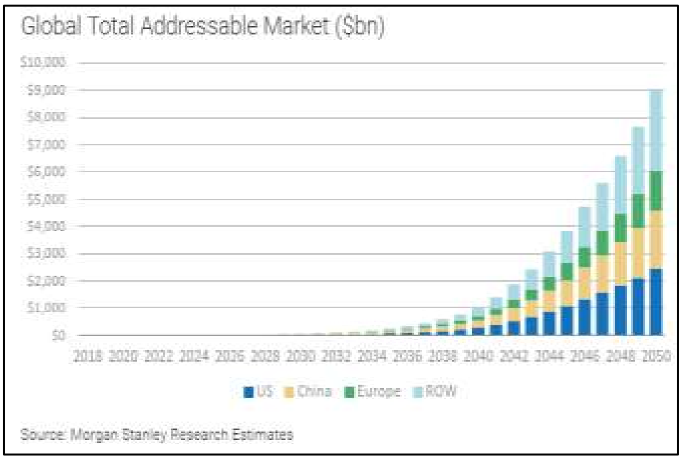
Within the foreseeable future there will be potentially trillions of dollars to be had in the development and operation of commercial drones world-wide. A recent Morgan Stanley(6) market research update suggested it could be $1 trillion by 2040, and $9 trillion by 2050. The advantages of drones are considerable including mission flexibility, direct flight paths, traffic avoidance, remote access, performing dangerous tasks, electronic propulsion, autonomous operation, and quieter vehicles. Who knows - Someday, all travel might be done by drone.



Source: Morgan Stanley Research Estimates

Large passenger drones are currently under intense development by notable vehicle manufacturers and transportation service providers. Companies like Uber (Joby) envision a day soon when you can call for a drone to pick you up just as easily as you call for a car today. Vehicle manufacturers such as Boeing, Kittyhawk, AirBus, Beta, Lilium, Archer, JetBlue, Sabrewing, Volkswagen, Bell, Embraer and Hyundai are all building competitive passenger drones.

Small package delivery drones are being developed by and for companies such as Google Wing, Amazon, Target, Flytrex, Zipline, Wingcopter, UPS, FedEx, DHL, Walgreens and Matternet. They are vying for acceptance, favoritism, and ultimately, needed dependence with the public. Several test market programs have been attempted around the world including in the United States, United Kingdom, Austria, France, Israel, Iceland, Germany and Finland. It is envisioned that these small drones will be able to quickly deliver critical items such as medical supplies as well as everyday items such as a cup of coffee.

3. US FEDERAL NOISE GUIDELINES

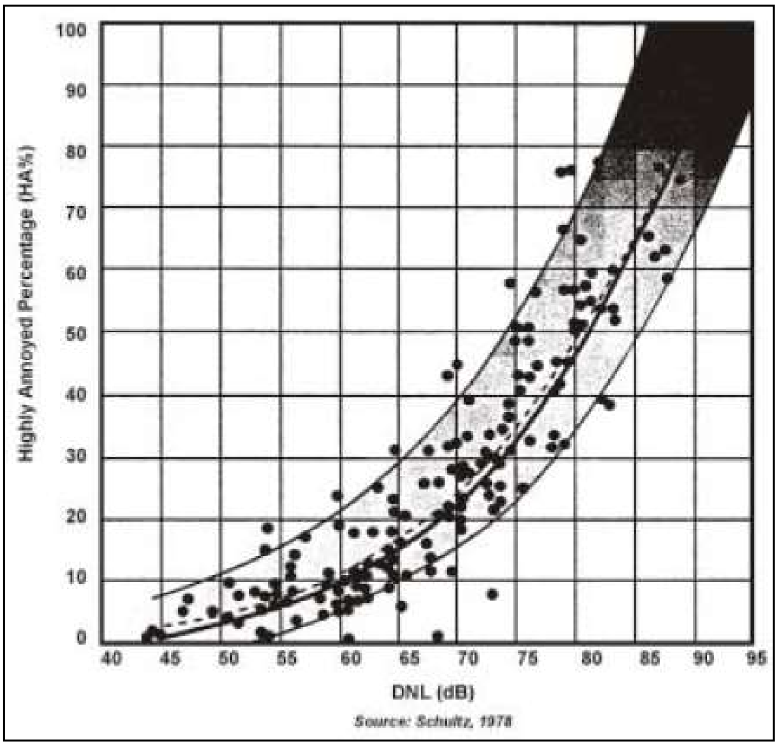
America made its decision in the 1950s that we were going to be a mobile society based primarily on the automobile. The Federal Aid Highway Act, signed by President Eisenhower in 1956, created the Federal Highway Administration (FHWA) and the first 41,000 miles of the Interstate highways. Its goals were two-fold; to link all the contiguous states to promote free commerce and travel, but also to provide a network of roadways for national defense purposes if needed. For example, one mile out of every five along an Interstate highway had to be constructed in a straight line so that a heavy bomber could land on it in an emergency.

This is not to say that America did not vastly expand its heavy and light rail systems and airports as well. Those modes of transportation also expanded greatly due primarily to meet the growing commercial demands to move ever-more products and goods. In 1966, the US Department of Transportation (US DOT) was created which eventually would include the FHWA; the Federal Railroad Administration (FRA) and the Federal Transit Administration (FTA) to oversee heavy and light railways, respectively; and the Federal Aviation Administration (FAA) to manage the growth and safety of the country's civilian airports.

But with all of these modes of transportation came an unwanted byproduct – noise. Noise regulations at the time mainly focused on hearing conservation, not community comfort. Early complaints were often met with the response "Sorry, it's the price of freedom." However, it became anecdotally clear that high levels of community noise exposure were directly associated with depressed socio-economic areas, lower learning abilities in grade schools, and general social unrest and crime. There are also individual health concerns associated with long-term exposure to elevated noise levels such as hypertension, ischemic heart disease, annoyance, and sleep disturbance.

Then in 1970, the National Environmental Policy Act (NEPA) was signed into law by President Nixon, soon followed by the Noise Control Act of 1972 which created the US Environmental Protection Agency (EPA). But it was not until 1978 when a seminal EPA community noise study was performed by Theodore Schultz that the adverse effects of community noise exposure were first quantified. The EPA report(1), known as the "Levels Document", prescribed noise emission standards, identified major sources of noise, and determined appropriate noise levels that would not infringe on public health and welfare.

The results, known as the Schultz curve (**Figure 1**), established an empirical relationship between elevated community noise exposure and people's reaction to it. The percentage of people likely to be highly annoyed (HA%) was a predictable function of the Day-Night Sound Level (Ldn or DNL). The Ldn is a 24-hour acoustic-energy-averaged sound metric expressed in A-weighted decibels in which a 10 decibel penalty is added to the nighttime hours from 10 PM to 7 AM to account for people's greater sensitivity to noise intrusion during those hours. The Ldn has since gone on to be the most often referenced sound metric in setting community noise guidelines in the United States.



Source: Schultz, 1978

Figure 1: The Schultz Curve

However, one size does not fit all when it comes to establishing appropriate community noise criteria. Each of these Federal agencies promulgate guidelines to regulate transportation noise sources, however they all use different noise metrics to do so. Thus, it can be difficult to determine a community's total noise exposure when multi-modes of transportation affect people simultaneously. This becomes even more problematic when it comes to funding necessary noise mitigation measures because, ideally, the agency that makes the noise should be responsible to control it.

4. US DOT TRANSPORTATION NOISE CRITERIA

4.1. FHWA Traffic Noise Criteria

The FHWA has promulgated traffic noise criteria to be used in all Federally-funded highway projects intended to identify community receptors impacted by traffic noise, thus warranting mitigation considerations. FHWA's *absolute* traffic noise abatement criteria, shown in **Table 1**, come from 23 CFR Part 772: *Procedures for Abatement of Highway Traffic Noise and Construction Noise*(2). In addition, most State Transportation Agencies define a loud *relative increase* in traffic noise as an impact as well. The preferred noise metric is the loudest-hour Equivalent Sound Level (Leq), expressed in A-weighted decibels. Thus, a receptor is defined as being impacted by traffic noise if the future noise level "approaches" the FHWA noise abatement criteria within 1 or 2 dBA, or if the predicted future traffic noise level exceeds the existing traffic noise level by 10 to 15 dBA, depending in which state the project is located.

FHWA's traffic noise criteria differentiate between types of receptor land-use, or activity category, as well as whether the noise is evaluated inside or outside the building. For example, a Category B noise receptor, such as a residence or a multi-family residence, will be considered to be impacted by traffic noise if its future exterior traffic noise level is predicted to be 67 dBA Leq or more and/or if it is expected to experience an increase of 10 to 15 dBA or more relative to existing traffic noise levels.

Table 1: FHWA Traffic Noise Abatement Criteria (NAC)

FHWA Activity Category	Traffic Noise Criteria Loudest-Hour Leq in dBA	Description of Activity Category (Land-Use)
A	57 (exterior)	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purposes.
B	67 (exterior)	Residential.
C	67 (exterior)	Active sport areas, amphitheaters, auditoriums, campgrounds, cemeteries, daycare centers, hospitals, libraries, medical facilities, parks, picnic areas, places of worship, playgrounds, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, recreation areas, Section 4(f) sites, schools, television studios, trails, and trail crossings.
D	52 (Interior)	Auditoriums, day care centers, hospitals, libraries, medical facilities, places of worship, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, schools, and television studios.
E	72 (Exterior)	Hotels, motels, offices, restaurants/bars, and other developed lands, properties or activities not included in Categories A-D or F.
F	None	Agriculture, airports, bus yards, emergency services, industrial, logging, maintenance facilities, manufacturing, mining, rail yards, retail facilities, shipyards, utilities (water resources and treatment, electrical), and warehousing.
G	None	Undeveloped lands that are not permitted.

Source: 23 CFR Part 772, Procedures for Abatement of Highway Traffic Noise and Construction Noise

4.2. FRA/FTA Rail/Transit Noise Criteria

The FRA and the FTA use the same approach to define community noise impacts from heavy or light rail operations. The basic goals of the noise criteria are to minimize the adverse noise impacts on the community and to identify areas where feasible and reasonable noise control may be necessary. FRA/FTA noise impact criteria are founded on the Schultz curve community reaction to absolute noise level as well as on changes in noise levels using a relative increase scale. Although more rail noise is allowed in neighborhoods with high levels of existing noise, as existing noise levels increase, smaller increases in total noise exposure are allowed than in areas with lower existing noise levels.

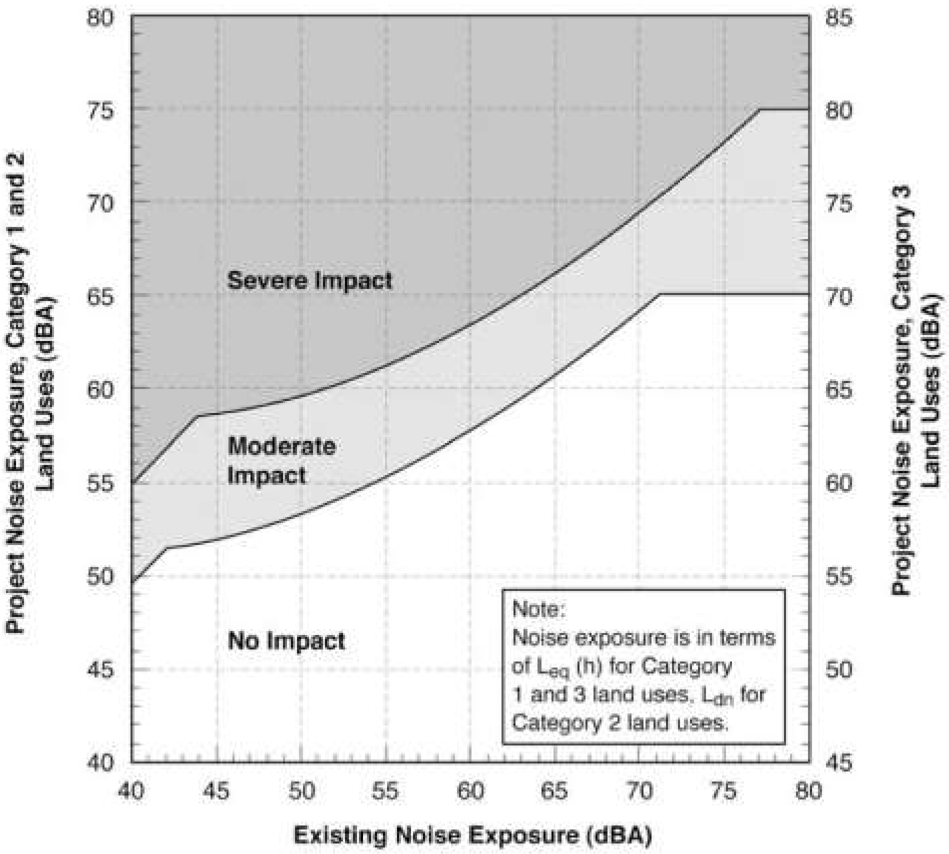
FRA/FTA guidelines(3) define noise impacts for various land-use categories using different noise metrics, as shown in **Table 2**. For residential receptors (i.e. Category 2) adjoining the transit corridor, the Ldn noise descriptor is used due to the receptor's use for sleeping at night. For institutional and some commercial receptors (i.e. Category 3) involving daytime and evening uses, the Leq(h) noise descriptor is used for the noisiest hour of transit-related activity during which human activities may occur at these locations.

Table 2: FRA/FTA Noise Receptor Land-Use Categories

Land-Use Category	Applicable Noise Metric in dBA	Description of Land-Use Category
1	Outdoor $L_{eq}(h)$	Tracts of land where quiet are an essential element in their intended purpose. This category includes lands set aside for serenity and quiet, and such land-used as outdoor amphitheaters and concert pavilions, as well as National Historic Landmarks with significant outdoor use. Also included are recording studios and concert halls.
2	Outdoor L_{dn}	Residences and buildings where people normally sleep. This category includes homes, hospitals, and hotels where a nighttime sensitivity to noise is assumed to be of utmost importance.
3	Outdoor $L_{eq}(h)$	Institutional land-uses with primary daytime and evening use. This category includes schools, libraries, theaters, and churches where it is important to avoid interference with such activities as speech, meditation, and concentration on reading material. Places of meditation or study associated with cemeteries, monuments, museums, campgrounds and recreational facilities are also in this category. Certain historical sites and parks are also included.

Source: US Department of Transportation, Federal Railroad Administration and Federal Transit Administration

FRA/FTA noise impact criteria are based on a comparison of the existing outdoor noise levels (Leq(h) or Ldn depending on land-use category) and the future outdoor noise levels produced by the proposed project. It considers both *absolute* criteria, which is the noise generated solely by the transit noise source, and *relative increase* criteria, which gauges annoyance due to the change in the noise environment caused by the transit project. As shown in **Figure 2**, noise impact severity is categorized as "No Impact", "Moderate Impact", or "Severe Impact" as determined by comparing the project-generated noise exposure with respect to existing noise exposure at a given receptor's location.



Source: US Department of Transportation,
Federal Railroad Administration and Federal Transit Administration

Figure 2: Noise Criteria Limits for Rail/Transit Projects

4.3. FAA Airport/Aircraft Noise Criteria

4.3.1. FAA Airport Noise Regulation

The FAA's community noise criteria, promulgated in 14 CFR Part 150: *Airport Noise Compatibility Planning*(4) and shown in **Table 3**, is perhaps the most difficult to understand and to determine on a case by case basis. It is based on the exterior sound level considered to be conducive or compatible with the receptor's intended land-use. Land-uses of various kinds are recognized, each with its own noise criteria expressed in dBA Ldn when inbound and outbound flight operations are *averaged over a full year*. However, receptors can be exposed to louder levels of aircraft noise so long as certain noise control mitigation is incorporated into the buildings, thus providing for a lower interior noise level.

For example, to be eligible for noise mitigation consideration, a residence is defined to be impacted if it is exposed to aircraft noise levels exceeding 65 dBA Ldn. However, a residence exposed to 65 to 75 dBA Ldn can still be considered compatible so long as 25 decibels-worth of noise reduction is built into the structure.

4.3.2. FAA Drone Noise Regulation

Title 14 CFR Part 36: *Noise Standards: Aircraft Type and Airworthiness Certification*(5) contains FAA's current certification requirements for tiltrotor aircraft as a source noise emission level. The standard was written for traditional fixed wing and rotor (helicopter) aircraft, so it does not apply well to smaller, and typically quieter, drone noise. As shown in **Figure 3**, 14 CFR Part 36 sets noise limits in Effective Perceived Noise Level (EPNL) expressed in EPNdB as a function of aircraft maximum gross weight (kg) for approach, take-off and flyover noise levels. The EPNL is the Perceived Noise Level adjusted for spectral content and event duration.

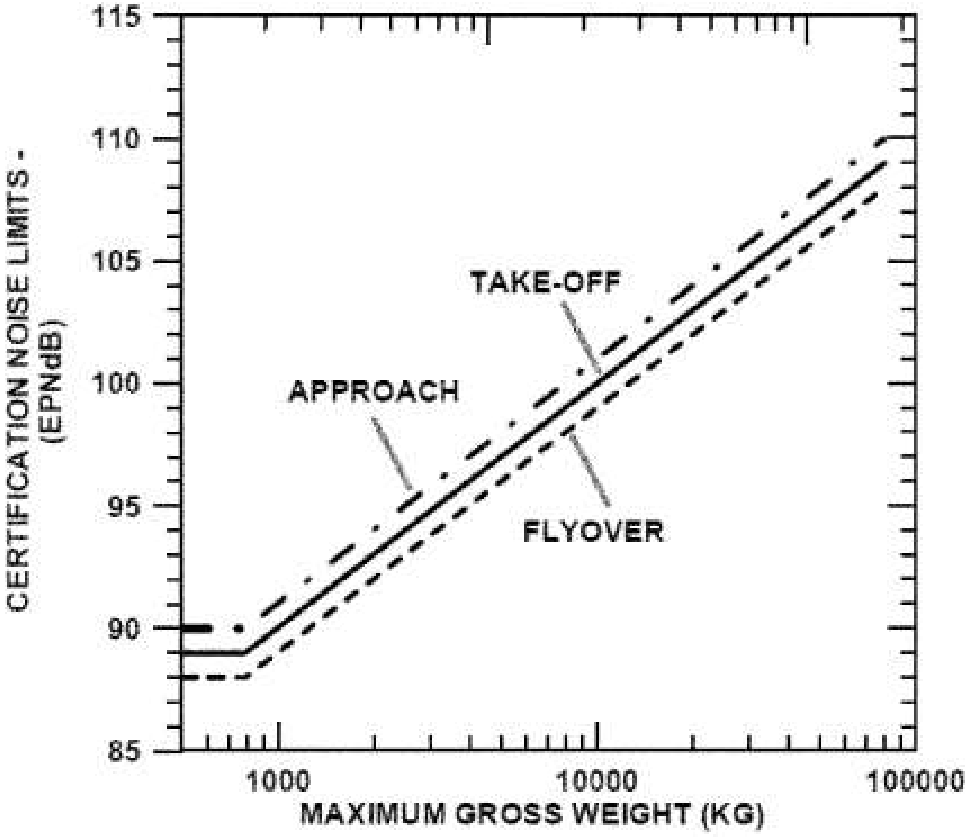


FIGURE K4.
TILTROTOR NOISE LIMITS

Source: 14 CFR Part 36, Noise Standards: Aircraft Type and Airworthiness Certification

Figure 3: FAA Tiltrotor Noise Emission Limits

FAA's current certification test for drone noise consists of a flyover test at a nominal height of 250 feet and at an airspeed of 90% of the drone's maximum airspeed. After adjusting the noise measurement data for reference speed and altitude, the final drone noise metric of interest will be the Sound Exposure Level (SEL) expressed in A-weighted decibels using a 'slow' time response (dBAs). The SEL is the acoustic-energy average of a sound "event" normalized to have occurred in just one second. Thus, the severity of noise events of different durations can be directly compared to one another. The timeframe over which the SEL is measured for drone noise tests is defined by the 10 decibel down points relative to the flyby's maximum sound level (Lmax) as the drone approaches and passes the test site. To pass FAA's drone noise certification test, the adjusted final result needs to be less than or equal to 78 dBAs SEL.

Table 3. FAA Aircraft Noise Land-Use Compatibility

Land-Use	Yearly Day-Night Average Sound Level Ldn in dBA					
	Below 65	65-70	70-75	75-80	80-85	Over 85
Residential						
Residential, other than mobile homes and lodgings	Y	N(1)	N(1)	N	N	N
Mobile home parks	Y	N	N	N	N	N
Transient lodgings	Y	N(1)	N(1)	N(1)	N	N
Public Use						
Schools	Y	N(1)	N(1)	N	N	N
Hospitals and nursing homes	Y	25	30	N	N	N
Churches, auditoriums, and concert halls	Y	25	30	N	N	N
Governmental services	Y	Y	25	30	N	N
Transportation	Y	Y	Y(2)	Y(3)	Y(4)	Y(4)
Parking	Y	Y	Y(2)	Y(3)	Y(4)	N
Commercial Use						
Offices, business and professional	Y	Y	25	30	N	N
Wholesale and retail - building materials, hardware	Y	Y	Y(2)	Y(3)	Y(4)	N
Retail trade - general	Y	Y	25	30	N	N
Utilities	Y	Y	Y(2)	Y(3)	Y(4)	N
Communication	Y	Y	25	30	N	N
Manufacturing and Production						
Manufacturing, general	Y	Y	Y(2)	Y(3)	Y(4)	N
Photographic and optical	Y	Y	25	30	N	N
Agriculture (except livestock) and forestry	Y	Y(6)	Y(7)	Y(8)	Y(8)	Y(8)
Livestock farming and breeding	Y	Y(6)	Y(7)	N	N	N
Mining and fishing, resource production, extraction	Y	Y	Y	Y	Y	Y
Recreational						
Outdoor sports arenas and spectator sports	Y	Y(5)	Y(5)	N	N	N
Outdoor music shells, amphitheaters	Y	N	N	N	N	N
Nature exhibits and zoos	Y	Y	N	N	N	N
Amusements, parks, resorts and camps	Y	Y	Y	N	N	N
Golf courses, riding stables and water recreation	Y	Y	25	30	N	N

Source: 14 CFR Part 150, Airport Noise Compatibility Planning

Notes: Y (Yes) = Land-use and related structures compatible without restrictions.
N (No) = Land-use and related structures are not compatible and should be prohibited.
OINR = Outside to Inside Noise Reduction for a building, measured in decibels (dB).
= Land-use and related structures generally compatible; mitigation to achieve OINR of ## dB must be incorporated into design and construction of structure.
(1) Where the community determines that residential or school uses must be allowed, mitigation to achieve OINR of at least 25 dB and 30 dB should be incorporated into building codes.
(2) Mitigation to achieve OINR 25 dB must be incorporated into the design and construction of portions of these buildings where the public is received, office areas, and noise sensitive areas.
(3) Mitigation to achieve OINR of 30 dB must be incorporated into the design and construction of portions of these buildings where the public is received, office areas, and noise sensitive areas.
(4) Mitigation to achieve OINR 35 dB must be incorporated into the design and construction of portions of these buildings where the public is received, office areas, and noise sensitive areas.
(5) Land-use is compatible provided special sound reinforcement systems are installed.
(6) Residential buildings require an OINR of 25 dB.
(7) Residential buildings require an OINR of 30 dB.
(8) Residential buildings are not permitted.

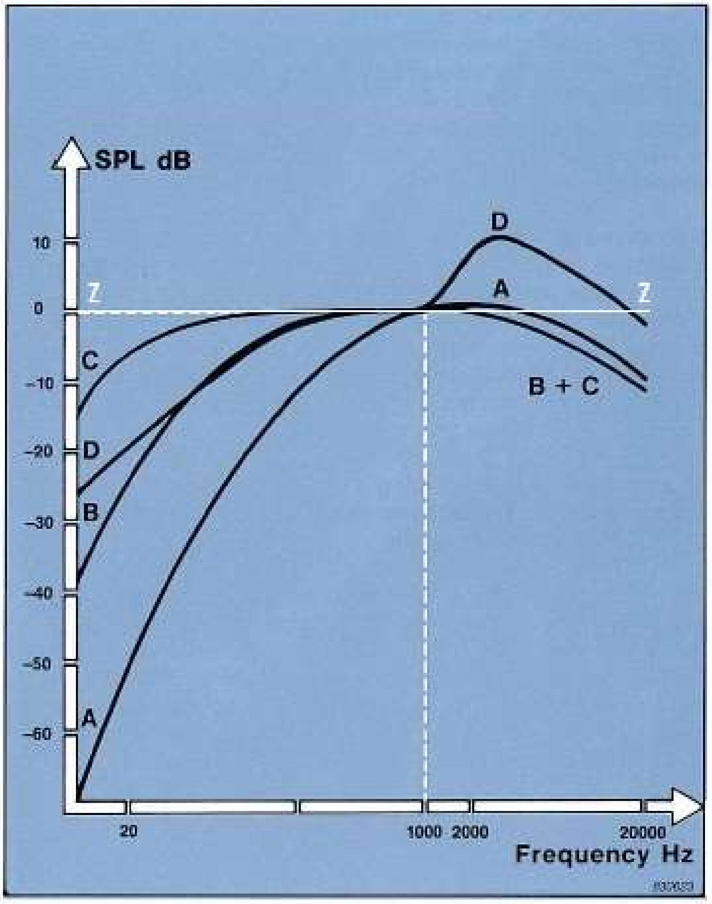
5. ACCEPTED FREQUENCY WEIGHTINGS

5.1. A, B, C, D-Weightings

There have been dozens of audio frequency weighting networks (filters) proposed over the decades. These are broadband frequency weighting adjustments to simulate how human beings hear and interpret sound levels over the entire audible spectrum (20 Hz to 20,000 Hz).

The four most accepted and widely used audio frequency weightings, as shown in **Figure 4**, are called A-weighting, B-weighting, C-weighting, and Z-weighting, the latter of which is no weighting at all and used to be called Linear, Unweighted, or Flat weighting. A-, B-, and C-weighting filter shapes are the inverse curve shapes of the 40, 70 and 100 Phon curves, respectively, of perceived equal loudness when tested with responsive human subjects. At low sound levels (dBA), human being's sensitivity to various frequencies of sound is poor at low frequencies, peaks at mid-frequencies between 1,000 Hz and 4,000 Hz, and then decreases slightly again at high frequencies. At moderate loudness levels (dBB), humans can hear better at low frequency. And at high sound levels (dBC), humans can hear almost equally well at all frequencies. All these weighting networks are normalized (equalized) at 1,000 Hz to have an adjustment of 0 dB, and have been standardized in American National Standards Institute (ANSI) Standard S1.4.

Figure 4 also shows the D-weighting network which had been used specifically for assessing aircraft noise. Because the calculation procedures for perceived noise level (PNL) is fairly complicated, a similar more direct measure that would allow an immediate estimate of the acoustical effect of an aircraft flyover was developed back in the 1970s. The D-weighted sound level (dBD) was an attempt to account for the annoyance due to the whining of turbojet aircraft engines. Use of dBD was source-specific to aircraft noise only. It has fallen largely out of use now that aircraft are much quieter Stage 3, 4 and 5 types per FAA requirements found in 14 CFR Part 36.



Source: ANSI Standard S1.4 Modified by the Author

Figure 4: Audio Frequency Weighting Networks

5.2. Proposed Drone Noise E-Weighting

The following is the author's conceptual proposal for a new audio frequency weighting network called ***E-weighting*** (dBE) specially for use with small drone noise sources. All due respect is given to Stanley Stevens who suggested the Mark VII method E-weighting shape in 1971 to assess aircraft sonic boom noise, but which was never officially adopted. This newly proposed E-weighting method is an attempt to address the annoyance caused by the whine of small drone propellers.

The author has performed carefully controlled measurements of A-weighted (slow) sound levels emitted by small package delivery drones as they flyby overhead at a speed of 98 feet/second and at a height of 131 feet. The results are shown in **Figure 5** for two small drones of various designs. While Drone B is notably quieter than Drone A, both drones produce distinct pure tone whining in the third-octave frequency band range of 400 Hz to 1,250 Hz. This 'buzzing' noise can be described, in jest, as sounding like an "angry beehive". But it is exactly this buzzing sound that will annoy people in communities once small drones are as ubiquitous and routinely used to deliver household and office packages as FedEx, UPS, Amazon, and the US Postal Service are used today.

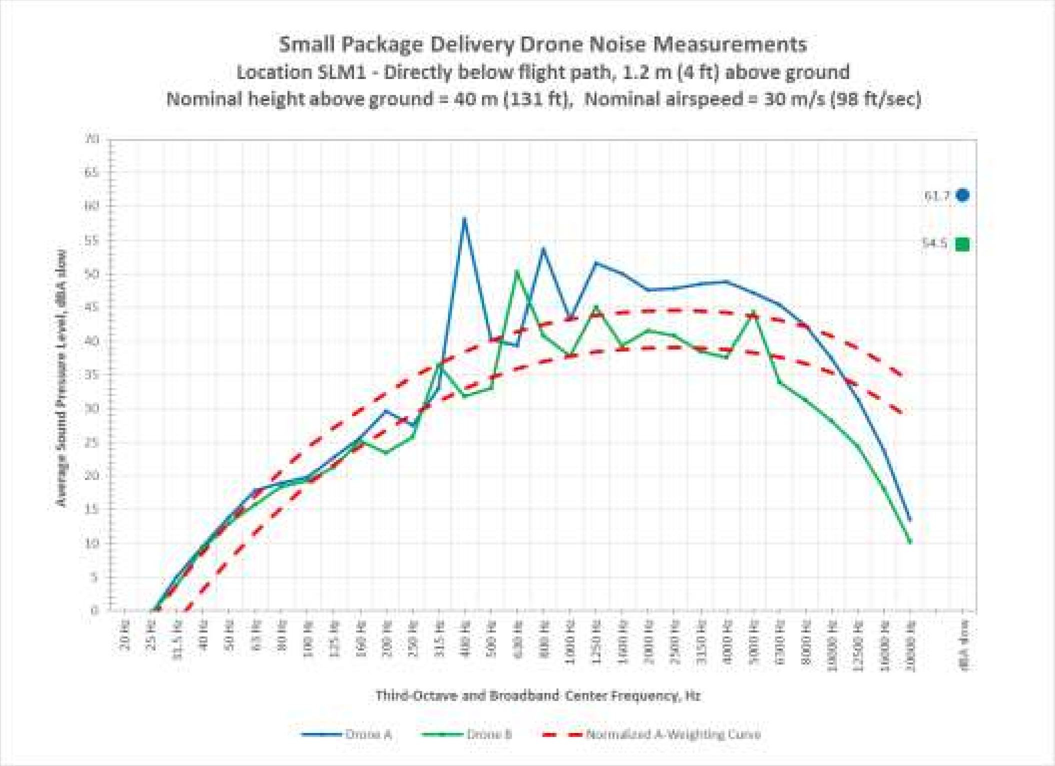


Figure 5: Example Small Drone Noise Spectra

Figure 5 also has the A-weighting (dBA) curve superimposed over the flyby A-weighted noise spectra for Drone A and Drone B, normalized at 1,000 Hz for comparison. As can be seen, the aforementioned frequency bands from 400 Hz to 1,250 Hz notably protrude above the standard A-weighting curve, thus indicting that those bands would be much more easily heard by people.

Much like the D-weighted network was used in years past to assess annoying jet aircraft whine noise, the E-weighting network, shown in **Figure 6**, is hereby proposed for industry consideration for assessing small package drone noise. As can be seen, the E-weighting network would over emphasize the sound levels between the 400 Hz and 1,250 Hz third-octave bands. The particular adjustments (dB) in each band shown in **Figure 6** were computed simply by averaging the differences in each band in **Figure 5** between Drone A and Drone B and their respective normalized A-weighted band levels, plus some curve smoothing to fill in the six third-octave bands from 400 Hz to 1,250 Hz. The rest of the E-weighting network would follow the same shape as the standard A-weighted curve. Many more small delivery drones would need to be averaged together with Drone A and Drone B in order to reasonably represent the majority of various manufacturers' small drone noise emission spectra. In doing so, sound levels measured in dBE would inherently take into account the uniquely annoying aspects of small drone buzzing noise.

Drone flyby sound levels measured in E-weighted decibels could then be evaluated for community acceptance using the *same criteria limits* that are currently established and are in wide use based on A-weighted sound levels. There would be no need to develop new criteria numerical limits. One would simply measure small drone noise in E-weighted decibels, and then compare the results against previously established community noise criteria expressed in A-weighted decibels.

Sound levels measured in dBE would always be numerically greater than sound levels measured in dBA for the same source (by about 3.6 decibels broadband). The additional annoyance due to drones buzzing would be inherently included in the measured result. Thus, there would be *no need to change* the currently accepted community noise numerical criteria limits based on A-weighted sound levels; they would simply be evaluated using E-weighted sound levels instead of A-weighted sound levels when assessing small drone noise.

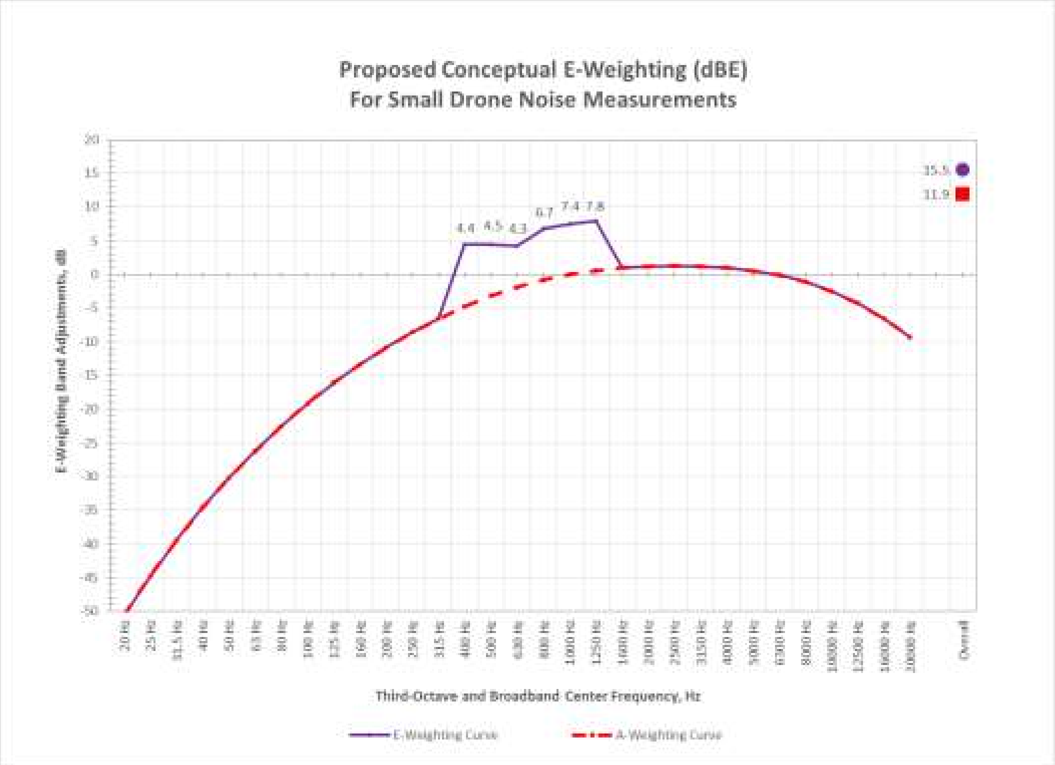


Figure 6: Proposed Small Drone E-Weighting Concept

6. CONCLUSIONS

The widespread use of drones for transportation of passengers and delivery of packages is inevitable and inescapable at this point. The fledgling industry simply has too many eager investors, corporate developers, and commercial gains to be had to lose its momentum now. The two largest factors holding back widespread public acceptance of the concept are safety and noise. Thus, the acoustical industry has an opportunity and a responsibility right now to establish acceptable community drone noise criteria that will balance the drone manufacturers' need to operate with the public's need for peace and quiet.

To that end, this paper has proposed a new broadband frequency weighting network, called E-weighting, that would account for the annoying buzzing tones produced by small package delivery drones. The advantages of the E-weighting method would include:

- The E-weighting filter shape could easily be programmed into digital sound level meter for simplicity in performing drone sound level measurements in the field.
- There are sufficient number of drone manufacturers from which to draw statistical averages for the eventual final shape of the E-weighting curve.
- Previously established and accepted community noise criteria numerical limits, expressed in A-weighted decibels, could still be evaluated for small drone noise using E-weighted decibels.
- The acoustical industry will have supported the emerging drone market with good advice.

7. ACKNOWLEDGEMENTS

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The author also wishes to thank his son, William Thalheimer, CEO of REGENT Craft, for his assistance in understanding the history and current state-of-the-art involving passenger drones.

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