Acoustical, sensory, and psychological research data and procedures for their use in predicting effects of environmental noises

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A demonstration field-research study reveals that aircraft noise measured at two one-story houses is ~9 dB less attenuated from measured outdoor levels than is street traffic noise, and, found in other studies, ~14 dB less than railway noise. Comparable differences are found between these noises from the application of basic acoustical formulas for quantifying attenuations that occur on site of one- and two-story houses. Reasonably consistent with those findings are results from attitude surveys showing that daily exposure levels of aircraft must be ~8 dB less than levels of street traffic noise, and ~13 dB less than levels of railway noise to be perceived as an equal cause of annoyance and related adverse effects. However, USA government guidelines recommend that equal exposure levels of noise measured outdoors from vehicles of transportation should be considered as being equally annoying. Changes in present USA noise-measurement procedures and noise-control guidelines are proposed that provide more accurate predictions of annoyance, related adverse effects, and criteria for setting "tolerable" limits of noise exposure in residential areas. Key acoustical and psycho-acoustical principles and data pertaining to predicting correlations between dosages of environmental noises and its effects on people and land noise zoning in residential communities are examined. © *2007 Acoustical Society of America.* [DOI: 10.1121/1.2782748]

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I. INTRODUCTION

A. Quantification of exposures to aircraft, street traffic, and railway noise

Individual and multiple environmental noise events are generally quantified for government mandated "Environmental Impact Statements," Noise Control Act of 1972, in terms of one or more of the following metrics, or their equivalents. These metrics are either measured or calculated to be those present at a point outdoors usually near the closest source-facing façade of existing houses, or at some other common point on sites zoned for residential housing.

1. MaxdB: the maximum decibel (dB) level of instantaneous A-weighted sound pressures integrated over successive 1 s (one-second) intervals during the duration of a noise event. Throughout this text "decibel," unless otherwise specified, refers to units of sound measurements based on 1 s samples of A-weighted sound spectra.
2. SENEL (Single Event Noise Exposure Level, dB): the 1 s average of sound energy integrated over the time a given noise event exceeds the level of background noise, or as a practical matter is less than 10 dB below its MaxdB level. SENEL of point-source moving street, railway and aircraft noise decreases 3 dB per doubling of distance between the source and a more or less stationary receiver.
3. Annualized DNL, or Ldn, (day/night level), dB: the 1 s energy average of the SENEL's of the noise events from a given source at a given location during an annualized average 24 h day. A 10 dB "penalty" is added to events occurring during the time period of 10 PM–7 AM. DNL is the standard environmental noise metric used in the USA. An alternative metric, DENL (day/evening/night level), used in the European Union applies a 5 dB penalty to noise events occurring in the 7 PM–11 PM time period, and a 10 dB penalty to the events occurring between 11 PM and 7 AM. An average difference of ~1 dB is found between DNL and DENL, with DENL being the larger (Miedema and Oudshoorn, 2001).
4. The primary measure for quantifying the annoyance/disturbance felt by people in residential communities to different exposure levels of different environmental noises is the percentages of thusly exposed people who rate their subjective feelings of noise annoyance on numerical scales ranging from 0% to 100%. This numerical scale has been verbally categorized in surveys of environmental noise annoyance as, for example, "not or a little annoyed" (0%–20%); "moderately or more annoyed" (21%–40%); "middle of annoyance scale" (41%–60%); "very or more annoyed" (61%–70%); "highly or more annoyed" (71%–80%); "extremely or more annoyed" (81%–100%). Somewhat different partitioning and verbal categorizations have been applied in different research surveys of noise annoyance, or synonymously, noise disturbance.

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B. The Schultz curve of annoyance from exposure to noise from transportation vehicles

Under contract with the United States Department of Housing and Urban Development, Schultz (1978, 1982) concluded that a single "trend curve" reasonably well describes the relation between: (a) the DNL of either aircraft, street traffic, or railway noise present at some point outdoors near the street-facing façades of houses, and (b) the percentages of thusly noise-exposed residents who report being "highly or more annoyed or disturbed." The surveyed residents reported that the annoyance/disturbance was primarily due to the fact that the noise masked the hearing of speech and other wanted sounds, interfered with sleep and rest, distracted the attention of the listener away from normal behavior and caused startled reactions for impulsive or unexpected sounds.

On the basis of Schultz's findings, USA federal government guidelines hold that equal DNL levels of either aircraft, street traffic or railway noise found outdoors of houses will cause equal annoyance to the residents in the houses. Accordingly as a general criterion, people who rated themselves to be "highly or more annoyed" (in the top ~30% of an annoyance scale ranging from "not or a little annoyed" to "extremely or more annoyed") could, from a public health and welfare point of view, be considered as living in an "unacceptable" level of environmental noise.

Relevant guides include those of the National Academy of Sciences (1977); Environmental Protection Agency, EPA (1978); Federal Interagency Committee on Urban Noise (FICUN), 1980; and Federal Interagency Committee on Noise (FICON), 1992. However, basic data and conceptual models for the assessment and prediction of the effects of these noises have been controversial over that period of time and to the present day (Kryter, 1982, 1983, 1985, 1994; Job, 1988; Schomer, 2002; Fidell, 2003).

II. ACOUSTICAL DOSAGE OF STREET TRAFFIC AND AIRCRAFT NOISE

The goals of the following demonstration study and analyses of on-site noise attenuation were to:

1. Measure, for two one-story houses, the house barrier and transmission attenuation between the outdoor and indoor, rear-to-front and front-to-rear yard, levels of noise events from both aircraft and street traffic.
2. Calculate, using acoustically principled mathematical formulas, the amounts of house barrier and transmission attenuation of aircraft, street traffic and railway noise between the outdoor and indoor, and between the front and back yard levels at one- and two-story houses.

A. Measurement of on-site attenuations of environmental noises

Recordings were made of the noise at ground level from commercial jet aircraft following takeoff operations and of the noise from passing street traffic. The recordings were made of signals from microphones placed at points in the front yards, rooms and back yards of two typical single-story stucco, brick and wood-sided, wood-framed, gabled houses near the Burbank California International Airport, see Fig. 1. The front façades are 14 m from the center of the street, the sides of adjacent neighborhood houses are separated by ~3.1 m and the back yards are ~15 m deep. The windows and doors of the houses were closed when the recordings were made.

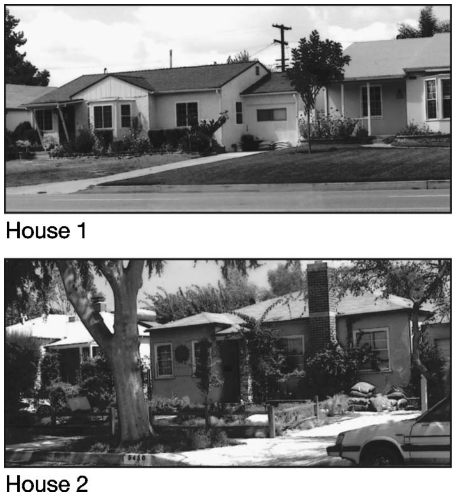

FIG. 1. Photographs of House 1, on Hollywood Way, and House 2, on Auckland Street, Burbank, California.

Microphone M1 was located in the front yard, microphones M2, M3 and M4 were placed in various rooms, and M5 in the rear yard of each house, see Fig. 2. The outdoor microphones, M1 and M5, were placed 1.82 m above ground level and 3 m from the front and rear house façades. The indoor microphones were placed 1.4 m above floor level in mid-room locations.

The 3 m placement of M1 and M5 from house façades was chosen to avoid including significant reflections of sound from the house façade in the noise measurements. It is

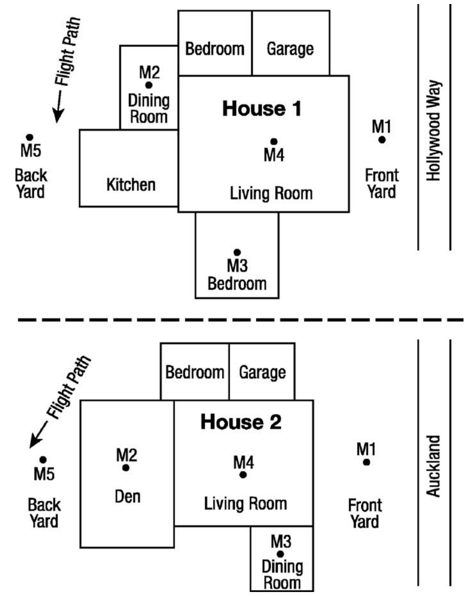

FIG. 2. Schematic drawing of Houses 1 and 2 and locations of microphones outside (M1, M5) and inside (M2, M3, M4) the houses.

presumed that the actual level of a noise at the closest façade surface from the source is fairly represented by the level found at the 3 m (10 ft) away point.

The noise events were recorded and analyzed by Veneklasen Associates of Santa Monica, California. The noises were analyzed for their A-weighted MaxdB, SENEL and octave band levels. A multi-channel digital recorder (Sony, PC16AX1), 1/2 in condenser microphones (Bruel & Kjaer 4155, and Larsen Davis 2559), with appropriate amplification and calibration equipment were used for making the recordings. Instrumentation for data analyses included: the Sony, PC216AX; Bruel & Kjaer 2230 SLM #2 w/Filter; Bruel & Kjaer 2260 Noise Investigator and Enhanced Sound Analysis Software.

B. Special factors

The following factors are germane to understanding the data and discussions to follow:

Factor 1. As a matter of safety for persons and property on the ground, a Federal Aviation Administration (FAA) regulation restricts commercial aircraft from flying over residential areas at altitudes below 1500 ft, ~458 m (FAA Regulation, Title 14, 1991). Furthermore, engine power settings and number of aircraft takeoff and landing operations must be such that the DNL in residential areas directly under the aircraft flight paths are 65 DNL or less [Federal Interagency Committee on Urban Noise (1980); Federal Interagency Committee on Noise (1992)].

With these restrictions and considerations in place, the slant range distance between the aircraft and houses to the right or left of the aircraft flight path will normally become longer. As a result, the noise level at the houses farther from either side of the flight path will be less than DNL 65 dB (or any other designated allowable limit), and are of only academic interest for purposes of aircraft noise control in residential areas.

Note in this regard, that for an aircraft flying at FAA prescribed minimum altitude of 458 m, one finds that with a slant angle of 75°, the slant range distance from the aircraft path to the house is increased to 515 m, and the Leq is decreased by ~0.4 dB. With a slant angle of 45° the slant range distance is increased to 793 m and the Leq is decreased by 2.4 dB. For purposes of regulating noise from commercial aircraft, the slant angle between the aircraft and residential houses should not be less than ~75°, otherwise the estimated impact of the aircraft relative to that of street traffic noise would be unjustifiably decreased.

Parenthetically, the average ~305 m altitude of the jet aircraft when passing H1, as will be reported below, is not anomalous with respect to the FAA regulation of 458 m concerning commercial aviation flights over residential housing. This occurs for this situation because the aircraft were flying over airport and not residential property.

Factor 2. As a general rule, except for the "corner" houses of city blocks, street traffic noise events will almost always move past the front yard and façade of houses on both sides of a street, and the house will significantly barrier-shield the street traffic noise from the rear façade and yard of houses. However, the noise from aircraft flying overhead at normal altitudes in residential areas may fall with minimal house-barrier attenuation on both the front and rear yards and façades of the houses.

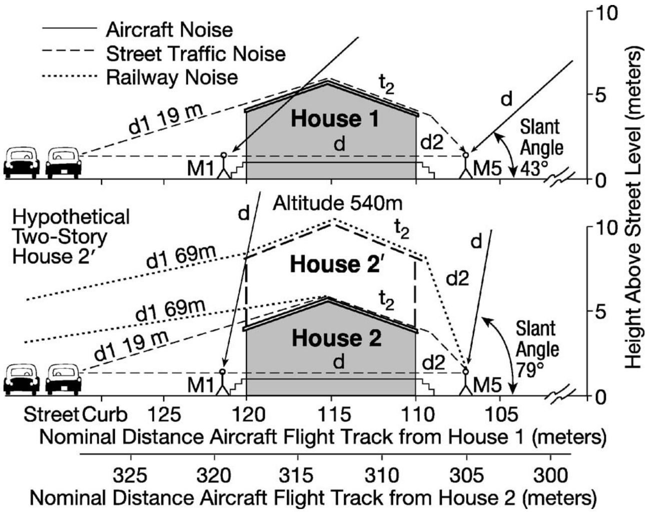

FIG. 3. Schematic showing House 1 and House 2, and hypothetical two-story House 2′, and orientation of street traffic and aircraft to the houses: House 1, aircraft: slant angle ~43°, slant range to M1, 431 m; House 2, aircraft: slant angle ~79°, slant range to M1, 622 m; orientation of street traffic to roof of gable of Houses 1 and 2, slant angle ~16°, range ~19 m; railway to Houses H2 and H2^1, range 69 m.

For aircraft on flight paths that are to some degree parallel with and over or somewhat to a side of the street, for the houses on one side of the street, the closest house façade to the aircraft will: (a) be the rear yard and not street-facing façade, and (b) at the same time, for the houses on the other side of the street the closest house façade will be the reverse, the front yard street and the street-facing façade. The closest house façade to aircraft on flight paths that are to some degree perpendicular to the streets, sometime during the noise event the closest façade for houses on both sides of a street will be: (a) the rear yard and not street-facing façade, and also (b) the front street and yard facing façade of house.

Factor 3. As a practical matter for the present study it is assumed that any reflection or attenuation effects on aircraft or ground based vehicle noise when passing through spaces between the façade and roof surfaces of adjacent houses in typical airport-area residential neighborhoods will be of about the same magnitude for each of the subject noises.

Factor 4. The data in this part of the paper are concerned with differences in source and on-site physical sound and auditory attenuation principles that can cause differences in the levels of the subject noises as heard and perceived by listeners in the interior spaces and yards of houses. These include:

(a) Transmission attenuation due to geometric spherical divergence of sound waves from a moving source as a function of the distance between the source and receiver, herein labeled Adiv(ergence).

(b) Barrier attenuation due to a "thick" barrier, such as a house, of sound waves during transmission from the front yard to the rear yard (or vice-versa) of the house, herein labeled Abar(rier). The graphs in Fig. 3 schematically illustrate straight lines of sight (d) and interposed paths (d1, t,

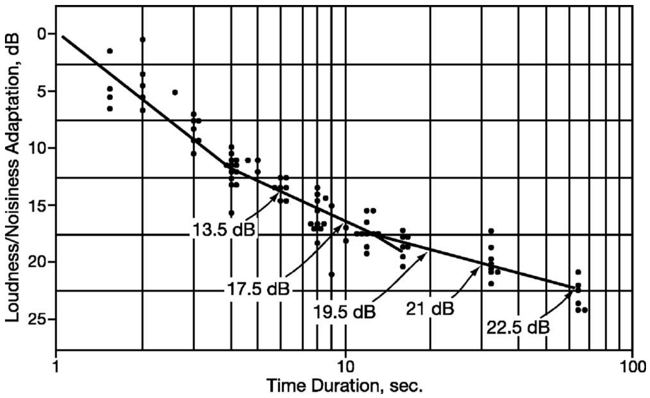

FIG. 4. Relative effect of duration on the perceived attenuation of loudness and noisiness of a sound/noise event. After Kryter and Pearsons (1963); Pearsons (1966).

TABLE I. MaxdB and SENEL for noise events at each house. Average MaxdB's and SENEL's based on event antilogs.

	Street Traffic			Aircraft	
	M1 Front			M1 Front	
House(H)1/ House(H)2	MaxdB	SENEL	House(H)1/ House(H) 2	MaxdB	SENEL
H1, Truck	78	83	H1, Aircraft	80	87
H1, Motor Cy	74	81	H1, Aircraft	88	95
H1, Truck	72	78	Average, H1	86	93
Average, H1	76	81	H2, Aircraft	86	94
H2, Truck	80	85	H2, Aircraft	69	77
H2, Car	66	72	H2, Aircraft	77	86
Average, H2	77	82	Average, H2	82	90
	M5, Rear			M5, Rear	
	60	67		85	92
	56	64		91	99
	53	58	Average, H1	89	97
Average, H1	57	64		86	95
	60	67		72	81
	49	54		78	86
Average, H2	57	64	Average, H2	82	91
	M2, Rm			M2, Rm	
	58	64		63	71
	51	58		69	77
	51	54	Average, H1	67	75
Average, H1	55	60		Not Recorded	
	56	63		51	61
	41	48		61	69
Average, H2	53	60	Average, H2	58	66
	M3, Rm			M3, Rm	
	45	52		58	66
	48	54		64	72
	44	51	Average, H1	62	70
Average, H1	46	52		57	67
	52	58		50	58
	39	47		Not Recorded	
Average, H2	50	55	Average, H2	54	65
	M4, Rm			M4, Rm	
	49	56		66	73
	48	52		72	80
	50	52	Average, H1	70	78
Average, H1	49	54		41	69
	48	52		47	57
	34	43		53	61
Average, H2	45	50	Average, H2	49	65
	N=25	N=25		N=23	N=23
Aver. H1	56	62	Aver. H1	75	82
Aver. H2	56	62	Aver. H2	54	63

and d2) of noise from the street traffic and aircraft sources to the front and rear yards, with H1, H2 and a hypothetical two-story house (H2′) serving as sound barriers. The Department of Engineering of the Burbank Airport furnished the distances and altitudes of the nominal flight paths and altitudes of jet aircraft from the locations of H1 and H2. That information was used to calculate the slant ranges and slant angles given in the caption to Fig. 3.

(c) Absorption attenuation and reflection of sound energy during transmission over ground, herein labeled Agro(und).

(d) Equivalent attenuation of the noises from the different types of transportation vehicles due to differences in the relative accessibility of their sound waves to the façades and roof surfaces of a house, and their transmissibility into a house interior, herein labeled Aacc(ess)/tran(mission):

(e) Equivalent attenuation of the noises from transportation vehicles due to a diminution in the loudness of sound or noise as a function of its duration, herein labeled Aadapt. This "equivalent-to-acoustical" attenuation is attributed to adaptive auditory neural equilibration and/or to temporary auditory receptor-fatigue processes (see Small). The effect appears to be based on physiological mechanisms, and results in decreased sensitivity to components of sounds or noises (see Fig. 4).

C. Results of research study of on-site noise attenuations

1. Measured MaxdB and SENEL

Table I shows the MaxdB and SENEL levels of street traffic and aircraft noise events found at each of five microphone locations at H1 and H2. The attenuations and differences in MaxdB and SENEL of the averages of street traffic and aircraft noise events at each house were derived from the data in Table I. The results are shown in Table II.

The last column of Table II shows that the average differences between SENEL and MaxdB measures of house attenuation is less than 1 dB. In these tables, and those to follow, the raw data are computer carried to multiple decimal places, but, with a few exceptions, i.e., in part of Table II, most of the table-printed data are in whole numbers rounded upward from decimals >0.49 and downwards from decimals <0.50. As a result the average sums of printed whole numbers may differ from their individually printed whole numbers by 1 integer.

2. Calculated attenuation of overall and octave band levels of street traffic and aircraft noise

Two procedures are followed for quantifying differences in on-site attenuations of street traffic, railway and aircraft noise. One procedure is the analysis of the actual measured noise attenuation data from the present study, as shown in Table II. The second is the application of generalized acoustical formulas and principles available for the calculation of expected on-site attenuations of the subject noises.

TABLE II. Measured attenuations: Upper section: differences in levels of street traffic and aircraft noise between M1 and the other microphones; Lower section: same for street traffic but, for aircraft noise, between M5 and the other microphones. Based on Table I.

	Street M1-M2^{a}	Aircraft M1-M2^{a}	Str.-Air.	Street M1-M3^{a}	Aircraft M1-M3^{a}	Str.-Air.	Street M1-M4^{a}	Aircraft M1-M4^{a}	Str.-Air.	Street M1-M5^{a}	Aircraft M1-M5^{a}	Str.-Air.	M1(M2,3,4)^{c} Street	M1(M2,3,4)^{c} Aircraft	Str.-Air.	
H1, MaxdB	21	19	2	30	23	6	27	16	11	19	−4	22	26	19	6.6	
H1, SENEL	21	18	3	29	23	6	26	15	10	17	−4	21	27	19	8.2	Av.
Max-SENEL	0	1	−1	1	0	0	1	1	1	1	0	1	−1	1	−1.6	0.5
H2, MaxdB	24	23	1	27	26	1	32	26	6	20	0	21	28	25	2.7	
H2, SENEL	22	24	−2	27	25	2	31	25	6	18	−1	19	27	25	2.3	
Max-SENEL	3	0	3	1	2	−1	1	1	0	1	0	1	1	0	0.4	1.0
Av., MaxdB	23	21	2	29	25	4	29	21	9	19	−2	21	27	22	4.6	
Av., SENEL	21	21	1	28	24	4	28	20	8	18	−2	20	27	22	5.2	
Max-SENEL	1	0	1	1	1	0	1	1	0	2	0	2	0	1	−0.6	0
		M5-M2^{b}			M5-M3^{b}			M5-M4^{b}			M5-M1^{b}			M5(M2,3,4)^{d}		
H1, MaxdB	21	22	−1	30	27	3	27	19	7	19	4	15	26	23	3.1	
H1, SENEL	21	22	−1	29	27	2	26	19	6	17	4	13	27	23	4.0	
Max-SENEL	0	1	−1	1	0	1	1	0	1	1	0	1	−1	0	−0.9	0.5
H2, MaxdB	24	24	1	27	27	1	32	26	6	20	0	20	28	26	2.0	
H2, SENEL	22	25	−3	27	27	0	31	26	5	18	0	18	27	26	0.7	
Max-SENEL	3	−1	4	1	0	1	1	0	1	1	0	1	1	−1	1.3	0.9
Av., MaxdB	23	23	0	29	27	2	29	23	7	19	2	17	27	24	2.5	
Av., SENEL	21	23	−2	28	27	1	28	23	6	18	2	16	27	24	2.4	
Max-SENEL	1	0	2	1	0	1	1	0	1	2	0	1	0	0	0.2	0.7
Av. Max+SEN	22	23	−1	28	27	1	29	23	6	18	2	16	27	24	2	0.6

[a] In dB, av. anti-logs M1-M2; M1-M3; M1-M4; M1-M5.

[b] In dB, av. anti.logs (M5-M2; M5-M3; M5-M4).

[c] In dB M1-av. sum anti-logs: M1-(M,2,3,4/3).

[d] In dB, av. anti-logs, aircraft noise: M5-(2,3,4/3).

Figure 3 illustrates straight lines-of-sight (d) and interposed paths (d1, t, and d2) of the noise to the front and rear yards of H1 and H2. When the line-of-sight path between a receiver and a source is below the top edge of a thick barrier, such as a house, the receiver is in a "shadow" zone of sound attenuation. When the line-of-sight path from the receiver to the source is at, or somewhat above, the top edge of a barrier, an excess amount of shadow attenuation of from 0 to 5 dB occurs due to sound refraction-interference effects (see Fig. 7.8 in Kurze and Beranek, 1988). Piercy and Daigle (1991) set this "excess" attenuation at a maximum of about 5 dB at a Fresnel N of −0.30.

Table II shows the H1+H2 average of the decibel amounts of house barrier attenuation calculated from measured octave band levels having center frequencies ranging from 125 to 4000 Hz. Similar calculations were applied to average source-to-receiver (human listeners) distances for the one-story houses, and a hypothetical similarly sized footprint two-story house, H2′ (see Fig. 3).

The measured MaxdB street traffic and aircraft noise events data differ from measured SENEL by less than 1 dB on average. For the purposes of measuring or calculating the decibel magnitude of attenuation of the subject noises, one focus of the present study, MaxdB and SENEL provide essentially the same results. This would indicate that for these noises some acoustical effects, such as Doppler frequency shifts, are practically insignificant (<1 dB).

3. Attenuations of street traffic, aircraft, and railway noise

Note that in Table III Abar for street traffic vs. aircraft noise is 17 dB measured and 21 dB calculated for outdoor listening. Ortega and Kryter (1982) found the measured difference in Abar of street traffic vs. aircraft noise by one-story houses to be 19 dB. However, the ~2 dB difference in the respective measured average Abar's is to be expected since the slant angle between the aircraft and one-story houses was somewhat less than the 90° directly overhead aircraft flyovers in the Ortega and Kryter (1982) study.

Fields and Walker (1980, 1982) surveyed annoyance reactions to railway noises of some 1453 respondents in Great Britain, 50% of whom lived in houses whose front, and closest façades were within ~68 m (225 ft) of the railway tracks. In a similar study Andersen *et al.* (1983), with comparable findings to Fields and Walker (1980, 1982), the median distance between the railroad tracks and noise-surveyed houses was shorter, ~38 m.

The average median distances from railroad tracks to median location of the median number of surveyed respondents for these two studies is 53 m. For present purposes, this distance is taken to represent a nominal distance between railway tracks and houses in urban residential areas. In the present study 14 m is the "closest-to-source" distance for street traffic noise.

TABLE III. Comparison measured versus calculated Abar of street and aircraft noise by one-story and hypothetical two-story houses.

	One-story house, average H1+H2										Hypothetical two-story house		
Oct. band c.f., Hz	Street meas., M1 SENEL[a]	Street meas., M5 SENEL[a]	Street M1-M5 Bmeas[b]	Str. calc. Bcalc[c]	Aircraft meas., M5 SENEL[a]	Aircraft meas., M1 SENEL[a]	Aircraft M5-M1 Bmeas	Airc. calc. Bcalc[d]	Str.-Airc. Bmeas	Str.-Airc. Bcalc	Street calc. M1-M-5. Bcalc	Aircraft calc. M5-M1. Bcalc[d]	Str.-Airc. Bcalc
125	63	48	15	13	70	68	−2	n	17	13	20	n	
250	70	51	19	16	72	75	3	n	16	16	23	n	
500	69	52	18	19	81	80	−1	n	19	19	25	n	
1000	71	52	19	22	79	84	5	n	15	22	28	n	
2000	68	49	20	25	74	74	1	n	19	25	31	n	
4000	57	38	19	28	57	60	2	n	17	28	34	n	
Arith. Av.	67	48	18	21	72	73	1	1	17	21	27	3	24
	Street traffic, Bcalc-Bmeas			2	Aircraft, Bcalc-Bmeas			0	Bcalc Str.-Bcalc Air; aver. one+two story				3

[a] Measured octave band levels of street traffic and aircraft noise when events reached maximum overall MaxdB.

[b] Bmeas: octave band levels measured for closest façade, M1, for street traffic, and M5 for aircraft noise, see Table II.

[c] Bcalc: Eq. (3.13): N, (Freznel)=(2/w) (d1+t+d2−d), Eq. (3.14): 10 log(3+30 NK)- Aground, -Aair, Eqs. from Piercy and Daigle.

[d] Aircraft noise, N's are negative (n), set to zero. Transition zone excess attenuation estimated, see Fig. 7.8, Kurze and Beranek.

Table IV shows that for one-and two-story houses, the average amount of calculated geometrical spherical divergence attenuation (A_{div}) of street traffic vs. railway noise between (a) the front façade of houses and the interior rear wall of the house is 2 dB if heard indoors (3−1 dB), and (b) is 3 dB if heard outdoors in the rear yard of the house (4 −1 dB). The distances between the source of the noise and the nominal interior rear wall of the house is 27 m for street traffic and 65 m for railway noise. The noise levels are estimated to be practically homogeneous within rooms due to sound reflections and reverberation. The distance between the source and rear yard is 35 m for street traffic and 75 m for railway noise. The differences in Adiv for the aircraft noise is 0 dB due to the hundreds of meters between the aircraft and noise-measurement at any points around a house.

In real life, the distances between listeners and the levels found at the house façade closest to the source of the noise are not acoustically directly relatable to Adiv at the receiver's (listener's) positions. Piercy and Daigle's (1991) equations (Eqs.) 3.17, 3.18, 3.19, the term r in "ref-20, 10, and $5\log_{10}(r/r_{ref})$", r represents the distance from source to ultimate receiver (listener), and the term r_{ref} is the measured or estimated level that is intermediate between the source and the listener. That is, the effective Adiv is the distance from the source to the listeners, not the distance from the point at of the noise level measurements and the listeners.

Table IV shows that the differences between closest-to source (M1) versus farthest-to-source façade (M5) for the calculated Abar attenuations of street and railway noise are: (a) the same for both one- and two-story houses (0 dB indoors, and 21 dB outdoors); (b) outdoor exposure levels at closest-to-source house façade versus their levels at façades farthest from source (M1-M5) are 6 dB greater for two, than for one-story houses (21 vs. 27 dB), an average of 24 dB for both types of houses.

Table IV shows the differences between closest-to-source façade (M5) versus farthest-to-source facade (M1) Abar attenuations of aircraft noise are: (a) 0 dB attenuated indoors by both one- and two-story houses; (b) and 1 dB attenuated outdoors by one-story and 3 dB attenuated outdoors by two-story houses, an average of 2 dB for both types of houses.

TABLE IV. On-house-site decibel attenuations, and equivalents, of street, railway, and aircraft noise for one- and two-story houses and their sums.

Source to mics, meters	Street 15/27/37 Adiv[a]	Street M1-M5 Abar[b]	Street 15m Agro[c]	Street M1-M[f] Aaccd/tran[d]	Street 6s Aadapt[e]	Street Sum A's	Rail 53/65/75 Adiv	Rail M1-M5 Abar	Rail 53m Agro	Rail M1-M[f] Aacc/tran	Rail 20s Aadapt	Rail Sum A's	Airc. 458m Adiv	Airc. M5-1 Abar	Airc. 0m Agro	Airc. M5-M[g] Aacc/tran[d]	Airc. 10s Aadapt	Airc. Sum A's
One-story houses																		
Indoors	3	0	0	27	14	43	1	0	4	27	20	51	0	0	0	24	18	42
Outdoors	4	21	0	0	14	38	1	21	4	0	20	46	0	1	0	0	18	19
Two-story houses																		
Indoors	3	0	0	27	14	43	1	0	4	27	20	51	0	0	0	24	18	42
Outdoors	4	27	0	0	14	44	1	27	4	0	20	52	0	3	0	0	18	21
Average one and two-story houses																		
Indoors	3	0	0	27	14	43	1	0	4	27	20	51	0	0	0	24	18	42
Outdoors	4	24	0	0	14	41	1	24	4	0	20	49	0	2	0	0	18	20

[a] Adiv 15m to front, 27m rear wall, 37m rear patio; Rail: 53m front, 65m rear wall, 75m rear patio. Eq. 3.18: $L_{eq\ ref}-10\log_{10}(r/r_{ref})$, Piercy & Daigle.

[b] Abar: Measured M1-M5 street, presumed same for railway noise, M5-M1 for aircraft noise, Table III, & Eqs. 3.14, 3.13 and 3.14, Pierey & Daigle.

[c] Agro: Front yrd. 15m street noise, 53m rail noise. Oct. band 500 Hz, source 0.3 m above grass. See Table 3.2, Piercy and Daigle.

[d] Aacc/trans: diff. in size of house facades and roof areas exposed to aircraft vs. street/railway noise (diff. of ~1/2 overall of street/railway vs. airc.).

[e] Aadapt:a loudness/noisiness dimunition due to duration of noise event. Equivalent, on a decibel basis, the exposure level of the noise event. See Text.

[f] M1 – (Average indoor microphones, (M2, M3, M4)/3, Street and Rail. Noise. See Table II.

[g] M5 – (Average indoor microphones, (M2, M3, M4)/3, Aircraft noise. See Table II.

Table IV, based on Table 3.2 of Piercy and Daigle, shows that front yard grass/vegetation/surface sound absorption-reflection (A_{gro}) is taken to be equivalent to an increase of 0 dB for street traffic, and a decrease of 4 dB for railway noise. It is assumed that A_{gro} of these noises in the rear yards are insignificant.

Figure 3 shows that the noise from aircraft falls nearly freely on street-facing and rear façades and roofs of houses, but that the noise from street and railway transportation vehicles will fall freely on only the street- and railway-facing house façades, and approximately one half of the roof surfaces. This is equivalent to the aircraft noise being ~3 dB less $A_{acc/trans}$ than street traffic and railway noise. The measured outdoor levels of street traffic and railway noise were indeed 3 dB less indoors (27 dB attenuation, M1- (M2, 3, 4)/3)), than were the measured outdoor levels of aircraft noise (24 dB attenuation, M5- (M2, 3, 4/3)), see Table II. Likewise, for calculated outdoor levels of aircraft noise, the equivalent measured $A_{acc/trans}$ is 3 dB, 27 dB vs. 24 dB (see Table IV).

The equivalent nominal A_{adapt} attenuations are calculated to be: 14 dB for street traffic (6 s duration), 27 dB for railway noise (20 s duration), and 24 dB for aircraft noise (10 s duration). These values are estimated from the function shown in Fig. 4. Table IV shows that for one- and two-story houses the sums of A's are: (a) for street traffic: 43 dB indoors and 41 dB outdoors, (b) for railway noise: 51 dB indoors and 49 dB outdoors, and (c) for aircraft noise: 42 dB indoors and 20 dB outdoors.

III. EDNL

A. Introduction

The DNL metric is denigrated for its originally intended purpose because it does not adequately take into account established physical principles involved in the transmission and attenuation of environmental noise to the ears of listeners indoors or in the yards of their homes, nor with physiological stimulation of the human auditory system. It is proposed that the findings shown in Table IV be used as a basis for the formulation of a new metric for DNL. This new metric is herein labeled E(ffective)DNL, or EDNL, of transportation vehicle, or other sources of environmental noise.

Four basic premises of the proposed EDNL metric are that:

1. Airborne acoustical energy in environmental noise events present at, or near, the external ear(s) of listeners is the normal adequate stimulus for auditory sensory sensations and perceptions.
2. Squared sound pressure and duration in seconds contribute equally to the perceived exposure level of a sound or noise event.
3. The normal human auditory is a *par excellence* receptor and near real-time analyzer of the spectral and durations aspects of sound and noise.
4. EDNL is applicable in the prediction of the adverse effects of given dosages of noise events on people who have experienced and come to expect the noise events to be part of their living environment.

The proposed EDNL metric is primarily concerned with the measurement and prediction of annoying/disturbing and associated adverse effects of noise due acoustical, sensory, perceptual auditory attributes of unwanted sound. These attributes will be discussed more fully later.

B. Calculation procedures

EDNL of a given, nonaircraft, environmental noise is its measured or calculated DNL value, plus the summed decibels of its on-site attenuations (including equivalent attenuations) minus the on-site attenuations of aircraft, or another environmental designated-reference noise. The EDNL of a given environmental noise compared to the impact of aircraft noise of a given DNL is calculated as follows:

$$\mathrm{EDNL}_x = \mathrm{DNL}_x + (\text{arithmetically summed decibels A's}_x) - (\text{arithmetically summed A's}_{\text{aircraft}}), \qquad (1)$$

where x is a given environmental noise.

Aircraft noise is chosen as an "anchor" reference for effective EDNL of environmental noises in general because it has been the dominant and most researched environmental noise. Note that EDNL does not disturb the numerical relations between the Federal Interagency Committee on Urban Noise (1980) and the Federal Interagency Committee on Noise (1992) calculated DNL and annoyance effects but serves as a means of converting DNL into a more truly *effective* noise-dosage level. Attention is invited to the possibility that to make more accurate and general the DNL and EDNL metrics, it would be appropriate to substitute the so-called D weighting for the A weighting in the measurement or calculation of SENEL of the noises involved. This matter will be discussed later in the paper.

1. Indoors and outdoors listening

Because DNL and EDNL use the equal-energy equation, the effective EDNL for different ratios of the hearing indoors and outdoors of environmental noise events during a typical 24 h day can be calculated as follows:

Step 1. Multiply the arithmetically summed decibels of attenuations, A's, of street, railway, or aircraft noise shown in Table IV, by chosen fractions of annualized 24 h days, when listeners are indoors and when outdoors (in yards) of their homes.

Step 2. The indoor and outdoor decibel sums from Step 1 are added on an energy, antilog, basis with the resulting sums converted to decibels for each type of noise source.

Step 3. Subtracting the results of Step 2 for one noise source from another source gives the relative differences in daily effective, EDNL, noise dosages between the two sources.

Table V shows for various ratios of average percentages of annualized daily time spent by residents indoors vs. outdoors of homes, the decibel sums of on-house-site attenuations (including equivalent attenuations) applied to the dif-

TABLE V. Sums of A's, % indoor +% outdoor listening, and differences between sources.

	Average for one and two-story houses					
	Street	Rail	Aircraft	Diff. dB atten., diff. sources		
Listeners	Sum A's	Sum A's	Sum A's	Rail-Str.	Str.-Airc.	Rail-Airc.
100% Indoors	43	51	42	8	1	9
100% Outdoors	41	49	20	8	21	29
90% Indoors	39	46	38	7	1	8
10% Outdoors	4	5	2	1	2	3
dB attenuation: % ind. + % out.=				8	3	11
80% Indoors	34	41	34	6	1	7
20% Outdoors	8	10	4	2	4	6
dB attenuation: % ind. + % out.=				8	5	13
75% Indoors	32	38	32	6	1	7
25% Outdoors	10	12	5	2	5	7
				8	6	14
70% Indoors	30	36	29	6	1	6
30% Outdoors	12	15	6	2	6	9
dB attenuation: % ind. + % out.=				8	7	15
60% Indoors	26	31	25	5	1	5
40% Outdoors	16	20	8	3	8	12
dB attenuation: % ind. + % out.=				8	9	17

ferent transportation noises, and the differences in summed daily attenuations between each of the respective types of noise.

The selection, as will be discussed later, of the 70% indoor with 30% outdoor "at-home-living" is based on the greater similarity (average differences of less than 2 dB) of the decibel averages of measured synthesis attitude annoyance survey data to calculated on-site attenuations of street traffic and railway noise in comparison to aircraft noise. Table V shows that with less than ~30% outdoors, or more than ~70% indoors, the similarities between annoyance scores and noise attenuations are somewhat less. Annualized 30% outdoor living is perhaps tantamount to about 50% or so outdoor daytime/summer time living with open windows and doors; and that annualized 70% indoor living is perhaps equal to 90% or so indoor/winter time living with closed windows and doors.

2. Monthly annualized effective levels of noise exposure

Figure 5 shows the monthly telephoned rate, compared to annual rate, of annoyance complaints received about aircraft noise as related to the average number per year over a four-year period. The complaints were from residential neighborhoods near four airports in the northeastern quarter of the United States. It is seen that for the about six months of April to October, the average monthly number of complaints increases to a peak in July that is the equivalent of 8 dB increase in SENEL (or DNL) levels.

The "tick marks" above the abscissa on Fig. 5 show the months in which the attitude surveys of noise annoyance in studies were conducted in the fall, winter, or spring in temporal climates. The tick marked studies represent those used by Schultz, and Miedema and Oudshoorn in the derivation of their synthesis curve.

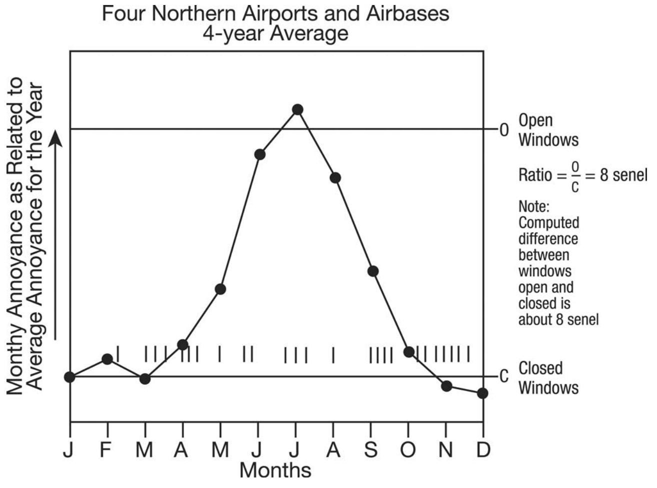

FIG. 5. Total monthly volunteered, via telephone, annoyance complaints over a four-year period by residents near four airports in the northeastern quarter of the United States. After Beranek, Kryter, and Miller (1959). Tick marks above abscissa indicate approximate months of the year attitude surveys of aircraft noise used in the Schultz and Miedema and Oudschoorn synthesis were conducted.

It is surmised that the magnitude of annoying/disturbing effects from transportation noise shown in Fig. 5 vary as function of seasonal temperature changes during typical years. The approximately six months during which the subject annoyance surveys were conducted are those when the residents would spend more time indoors with windows closed, and thus be less impacted by the transportation noises than in the warmer months when the residents would spend more time outdoors and indoors with windows open.

Note that Miedema, Fields and Vos (2005), found a similar pattern of higher annoyance reactions during ′summer′ compared the ′colder′ months of the year to transportation noises. The difference was statistically significant. However, the scoring procedures employed on these later studies does not permit a direct equivalent decibel comparison with the data in Fig. 5.

The 8 dB SENEL peak-month different level shown in Fig. 5 in effective exposure level translates into ~2 dB lesser SENEL/DNL value when referenced to a 12 month averaged effective level of noise from a moving source. It could be argued that annualized DNL or EDNL should be decreased by ~2 dB in order to best represent the average monthly effective exposure level over a calendar year.

The important empirical question is: how closely do different methods for measuring or calculating real-life dosages of environmental noise correlate with listener's self-rated subjective annoyance/disturbance effects and with objectively measured, by independent experts, effects on public health, well-being and welfare? The next section of the paper addresses that issue.

IV. PSYCHOLOGICAL ANNOYANCE AND ASSOCIATED EFFECTS

A. Introduction

Acoustical "noise" is defined as sound that is perceived as being unwanted by a listener. The auditory physiological-

TABLE VI. Percent of people highly or more annoyed by aircraft, street and railway traffic noise, and % point differences.

Section A	DNL55 Aircraft	DNL60 Aircraft	DNL65 Aircraft	DNL55 Street	DNL60 Street	DNL65 Street	DNL55 Railway	DNL60 Railway	DNL65 Railway
Synthesis, Schultz, 1978	3	8	15	3	8	15	3	8	15
Synthesis, Fidell, *et al.*, 1991	3	8	15	3	8	15	3	8	15
Synthsis. Finegold *et al.*, 1994	3	8	14	3	8	14	3	8	14
Average	3%	8%	15%	3%	8%	15%	3%	8%	15%
Section B									
Study, McKennell, 1963[a]	13	20	24	No data	No data	No data	No data	No data	No data
Study, Hall *et al.*, 1981	13	16	29	4	10	20	No data	No data	No data
Synthesis, Kryter, 1982	10	16	29	0	4	10	No data	No data	No data
Synth., Mied. & Oud.'01	14	20	29	6	10	17	2	4	8
Average	12%	17%	29%	3%	8%	16%	2%	4%	8%
% points diff. Section B-A:	+10% pts.	+10% pts.	+13% pts.	+1% pts.	+1% pts.	+1% pts.	−1% pts.	−4% pts.	−7% pts.

[a] McKennell, in Committee on Problem of Noise, Appendix X1, Final Report (1963). HM Stationery, Office London.

sensory and perceptual mechanisms involved in this unwanted ness are in brief that sound:

1. Stimulates sensory-neural cells in the cochlea of the peripheral ear by causing turbulence in the fluids in the cochlea that mask or distort turbulences being simultaneously, or nearly simultaneously, caused by other then occurring sounds that may convey wanted auditory information or auditory sensations. For example: (a) music can be perceived as being noise by a listener who is trying to understand wanted speech sounds that are being physically masked in the cochlea by unwanted music sounds, and (b) speech sounds can be perceived as noise by a listener who is trying to hear wanted music sounds that are being physically masked in the cochlea by unwanted speech sounds.

   Masking automatically occurs independent of any cognitive higher-brain neural activities. Masking is a basic attribute of hearing and a pervasive cause of subjective annoyance and related effects in everyday living activities independently of any psychological attitudes, biases, or abilities that may differ among people or peoples.
2. Such mechanical-neural activity in the cochlea in turn neurally stimulates higher brain centers, vegetative, homeostatic organs and autonomic systems of the body, particularly if the sound (noise) is unexpected. Such reactions arouse a person from quiescence or sleep and may cause emotional feelings of annoyance, fear, and anger. However, cognitively learned "meanings" are not as directly causally related to, controlled by, dependent upon, or validly regulateable, as are the basic unlearned auditory system sensory-perceptual and bodily interactions with unwanted familiar sounds or noises.
3. Cochlear masking and autonomic system stimulations from exposures to noise can also distract the attention of listeners away from, or require more than normal effort to adequately perform mental and motor behavioral tasks that depend upon correctly hearing speech, sounds from operating machinery, audible warning signals, etc.
4. If at a sufficiently intense level, above ~80 dB, and brief, less than ~0.5 s duration, impulsive sounds, e.g. gunshots, sonic booms, breaking objects, etc., cause autonomic-system startle reactions that create feelings of annoyance and fright.
5. The noises of most public concern and research study have been from vehicles of transportation, but the basic acoustical, sensory and psychological research findings from those studies are presumably applicable to assessment of the effects of other environmental noises, such as those from construction activities and industries.

B. Studies of annoyance from aircraft, street traffic and railway noise

The most recent analyses and synthesis of annoyance as a function of DNL and DENL exposure levels to transportation noise are those of Miedema (1993); Miedema and Vos (1998); Miedema and Oudshoorn (2001). Miedema and Oudshoorn (2001) mathematically modeled the data from 20 surveys of annoyance from aircraft, 18 from road/street traffic, and 9 from railway noise. Strict criteria were followed in scaling the annoyance data to insure comparability among the different surveys. The surveys were conducted in residential areas in Australia, Canada, Europe and the United States. Some of their findings, and those from other relevant studies, are shown in Table VI.

Table VI shows, for exposure levels DNL 55, 60 and 65 dB, the percentages of people in residential neighborhoods found in various studies and syntheses of attitude survey data to be "highly or more annoyed" by street traffic, railway and aircraft noise. The bottom line of Table VI shows that the differences between section B minus A, averaged over DNL 55, 60 and 65 dB, are: +11% points for aircraft, +1% points for street, and −4 points for railway noise.

C. Adverse nonauditory effects associated with annoyance

1. Emotional stress

It was found in a series of epidemiological medical field studies that with increases in exposure levels to aircraft noise above DNL 50 dB there are progressive increases in hypertensive blood pressure, prescription drug usage and physi-

TABLE VII. Nonauditory effects, aircraft and street traffic noise.

	% People high blood pressure			% House Depreciation			
	Aircraft	Street traffic		Aircraft: House Price range			
DNL	Knipschild	Lercher and Kofler		DNL	Low	Med	High
50	6%	DNL		50		.	0%
55	9%	<50	0%	55		0%	5%
60	12%	59	0%	60	0%	4%	10%
65	15%	64	0%	65	4%	7%	15%
70	19%	>65	0%	70	6%	11%	20%

cian contacts for general “stress” disorders (Knipschild, 1980). Hypertensive blood pressures were not found in a similar research study (Lercher and Kofler, 1993), with street traffic noise of comparable and greater exposure levels than in the Knipschild studies of aircraft noise, see left-hand section of Table VII. Also, see review by Babisch (1998) of other European studies that also show no consistent adverse cardiovascular effects associated with exposures to street traffic noise at DNL levels equal to levels of aircraft noise that are associated with physiological and psychological stress reactions.

A longitudinal study by Ohrstrom (2004) revealed that the reduction of average 67–55 dB $L_{A24h,eq}$ of street/road traffic noise significantly reduced annoyance and disturbance ratings and feelings of lower psycho-social well-being. ($L_{A24h,eq}=1$ s average of A-weighted levels over the 24 hour day). Note that the application of evening and nighttime decibel penalties would translate the cited $L_{A24h,eq}$ values into somewhat higher DNL and DENL values.

The noises associated with hypertensive blood pressure and other physiological stress responses, when they occur, are putatively not caused by exposure to the sounds per se, but are aftermaths of emotional resentment and anger triggered by the unwanted annoyance/disturbance effects of the noises. These stress responses are normal homeostatic cardiovascular, and autonomic nervous-glandular-system responses of the body to emotions and startle.

2. Depreciation of real estate values

An economic consequence of annoyance from aircraft noise is that people are apparently loath to purchase houses in environments that have DNL levels that exceed ∼55 dB, for “high” priced, ∼60 dB for average/medium priced, and ∼65 dB for low priced house, as shown in the right-hand section of section of Table VIII. These findings represent averages of government sponsored analyses conducted in: USA, Nelson (1979); in Canada, Mieszkowski and Saper (1978); and in England, the Commission on the Third London Airport (1971).

The adverse effects cited above are based on objective data obtained by professional medical personnel and real estate appraisers. As such, these data lend practical meaning to and supportive validations of the subjective annoyance attitude survey data as related to noise level measurements.

D. Relations between EDNL and annoyance/disturbance from transportation vehicle noise

Table VIII shows that the average differences over the range of 50–70 dB between equally annoying EDNL levels of aircraft compared to street traffic noise are: (a) 0 dB by Schultz (1978); Fidell *et al.* (1991); and Finegold *et al.* (1994), (b) 10 dB by: Ollerhead (1980); Hall *et al.* (1981); and Kryter (1982), (c) 6 dB by Miedema and Oudshoorn (2001). The overall average differences between aircraft compared to railway noise are 0 dB according to Schultz and cohorts, and 13 dB according to Miedema and Oudshoorn (2001).

The average, 8 dB, of the Ollerhead (1980), Kryter (1982), Hall *et al.* (1981), and Miedema and Oudshoorn (2001) syntheses plus, again, the Miedema and Oudshoorn (2001) synthesis is herein taken to be the best available acoustical and psychological research data for predicting annoyance and associated adverse effects of street traffic compared to aircraft noise, see Sec. II of Table VIII. The double inclusion of Miedema and Oudshoorn (2001) synthesis justifiably gives it extra weight, but the other syntheses also have merit.

TABLE VIII. Sections I through III: differences in DNL between street, railway, and aircraft noises when ∼30% people are equally annoyed. Section IV, differences between calculated sums of indoor/outdoor attenuations for listeners’ positions at home.

Section:	1	2						3		4		
	[a]Schultz, ’78;	Street-Aircraft						Rail-Airc.	Rail-Str.	Str.-Airc.	Rail.-Airc.	Rail-Str.
DNL	Fidell *et al.* ’91; Finegold *et al.* ’94	Ollerhead, ’80	Kryter,[b] 1982	[c]Av., Hall, Fidell, ’81	Miedema and Oudshoorn, ’01		[c]Aver. Sect. 2	Miedema and Oudshoorn, 2001		Diff. Calc. on-site attenu.-measure diff. DNL-DNL		
50	0[a]	10	10	5	6	6	7	15	9	9	14	10
55	0[a]	10	10	9	7	7	9	15	9	9	14	10
60	0[a]	10	10	10	6	6	8	13	10	9	14	10
65	0[a]	10	13	10	6	6	9	12	10	9	14	10
70	0[a]	10	10	12	5	5	8	10	10	9	14	10
Av.	0[a]	10	10	9	6	6	8	13	10	9 [7][d]	14 [15][d]	10 [8][d]

[a] No differences: Street, Railway, and Aircraft. Schultz and cohorts data not included in section 2.

[b] Average of differences between aircraft-street traffic noise annoyance. Based on Hall *et al.* ’81 and Fidell *et al.* ’81.

[c] Average Ollerhead thru Miedema and Oudshoorn, see text.

[d] [] Av. differences in EDNL between surveyed annoyance for the different noise sources per calculated atten. of noises judged to be equally annoying as aircraft noise at equal DNL, see 70% indoor/30% outdoor, Table V: Diffs. of $(2,-1,2)=$av.1 dB.

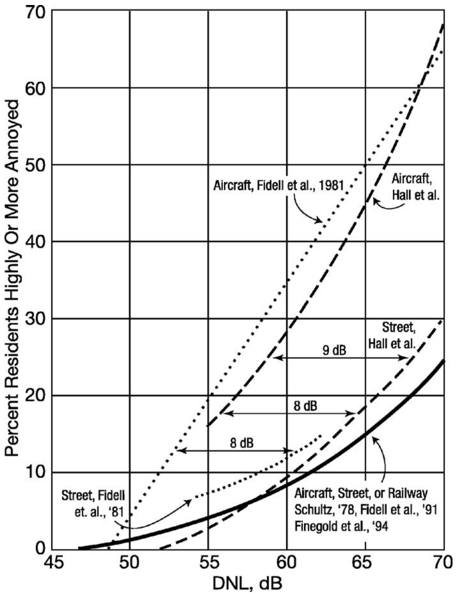

FIG. 6. As function of DNL, decibel differences between percentages of residents highly or more annoyed by aircraft compared to street noise as found by Fidell *et al.* (1981) (dotted curves) and by Hall *et al.* (1981) (dashed curves).

The studies by Fidell *et al.* (1981), and Hall *et al.* (1981) can claim special validity in that the data avoided experimental errors possibly present in other annoyance/disturbance surveys. Unlike most attitude surveys, in these two studies the same residents rated annoyance or disturbance in response to the same attitude questionnaires for both street traffic and aircraft noise, see Fig. 6.

Note that: (a) in the study by Fidell *et al.* (1981) the respondents falling in the top 40% of the annoyance scale were considered to be "highly annoyed," and (b) a bi-modal annoyance questionnaire was used in the study by Hall *et al.* (1981). As a result, the absolute percentages of people considered to be highly or more annoyed in both of those studies could be expected to be somewhat greater than found when ~30%, the usual criterion limit for people being highly or more annoyed, is used. However, the relative differences (~8 to ~9 DNL) found between the annoyance/disturbance data for aircraft vs. street traffic noise should be valid for both studies.

1. Relation between percent people highly annoyed and on-site attenuation magnitudes

Table VIII summarizes functions of DNL 50–70 dB: (a) when ~30% of respondents in attitude surveys are highly or more annoyed/disturbed because of noises from street, railway and aircraft traffic (Secs. I–III), and (b) measured and calculated decibel differences in on-site attenuations of the street, railway and aircraft traffic noises (Sec. IV). Note that as the formula defined, there are no differences between calculated on-site attenuations as a per se function of EDNL-street or railway DNLaircraft noise and further, as noted before, the measured and calculated on-site attenuations differed on average by less than 1 dB.

Data in Table VIII:

Sec. I. The Schultz and up dating, "cohorts," syntheses functions show no differences in DNL exposure levels when ~30% of exposed people were highly or more annoyed by each of the three types of transportation noises.

Sec. II. Shows that, for four other syntheses functions, over the 50–70 DNL range the average decibel difference between street traffic DNL compared to aircraft noise DNL when ~30% of respondents were highly or more annoyed is 8 dB (with Miedema and Oudshoorn (2001) twice weighted).

Sec. III. Shows that over the 50–70 DNL range when ~30% of respondents were highly or more annoyed the average decibel difference between railway DNL compared to aircraft noise DNL is 13 dB, and the average difference between railway DNL and street traffic DNL is 10 dB.

Sec. IV. Shows that over the DNL 50–70 dB range the average decibel differences between on-site attenuations are calculated to be: (a) 9 dB for street traffic-aircraft noise; (b) 14 dB for railway-aircraft noise; and (c) 10 dB railway-street noise. Also shown in brackets [ ] are the decibel differences between the DNLs of the street traffic and railway noises compared to the DNL of aircraft noise when ~30% of respondents judge each of the noises to be highly or more annoying/disturbing. The average of these differences is 1 dB, (2, −1, 2)/3).

Schultz, Fidell *et al.* (1991) and Finegold *et al.* (1994) syntheses curves are implicitly based on the premise that the magnitude of subjective annoyance in residential neighborhoods from different vehicles of transportation is proportional to their SENEL/DNL levels measured at, or estimated for, a common point outdoors near the closest-to-source façade of houses. The differences in on-site attenuations found for the noise from the different transportation sources of noise indicate that this premise is untenable for purely physical acoustic reasons.

Also note that Schultz, Fidell *et al.* (1991) and Finegold *et al.* (1994) did not, as was done for the other studies and syntheses in Table VIII, plot separately for each type of transportation noise the percentages of people who were highly or more annoyed as a function of DNL. Instead, Schultz and cohorts each plotted the annoyance data for street traffic, railway and aircraft noise on a single set of coordinates and fitted a single mathematical-formula curve to the scatter of all the data points: Schultz, a third-order polynomial; Fidell *et al.*, a least-squares quadratic; Finegold *et al.* (1994), a logest. The best-fitting curves for these three syntheses are nearly identical. However, those procedures possibly obfuscated the presence of separate clusterings for each type of noise source.

E. Generality and reliability of EDNL street, railway noise—DNL aircraft noise

Most of the research on annoyance and other adverse effects of transportation noise on people has been centered in urban neighborhoods near commercial jet airports. These neighborhoods, by and large, consist of one- and two-story houses located on lots of approximately one-sixth of an acre

(~640 sq. meters). The setbacks of the front façade of houses to the center of the street are typically ~15 m (50 ft), and 3.2 m (10 ft) between houses. Such distances are promulgated in international building codes for residential housing.

The proposed EDNL procedures can be applied to urban and suburban neighborhoods having different lot sizes, number of stories or building heights, house construction codes, etc.. The procedure would be to calculate, in accordance with formulas specified in Table IV, on-site house attenuations (Adiv, Abar, Agro, Aacc/trans and Aadapt) as needed for the noise from different sources. However, note that Adiv, Agro and Aacc/trans attentions of aircraft noise should generally be zero because of FAA "fixed" minimum allowable altitude of aircraft when flying over residential areas.

On-house-site attenuations for noises having broad frequency bands, e.g., noises of transportation vehicles, should, within limits, be approximately the same regardless of the materials, architectural design, or building codes used in the construction of houses. The presumed reason is that whatever perturbations may be imposed by the per se house structures on the spectrum of the noise of such sources will also be applied to the reference aircraft noise used in the calculation of EDNL. That practically this might be the general case is attested to by the close similarity of decibels of on-site attenuations and decibel equivalents for equal psychological annoyance/disturbance from transportation vehicles (within ~2 dB, average 1 dB, see bottom line Table VIII).

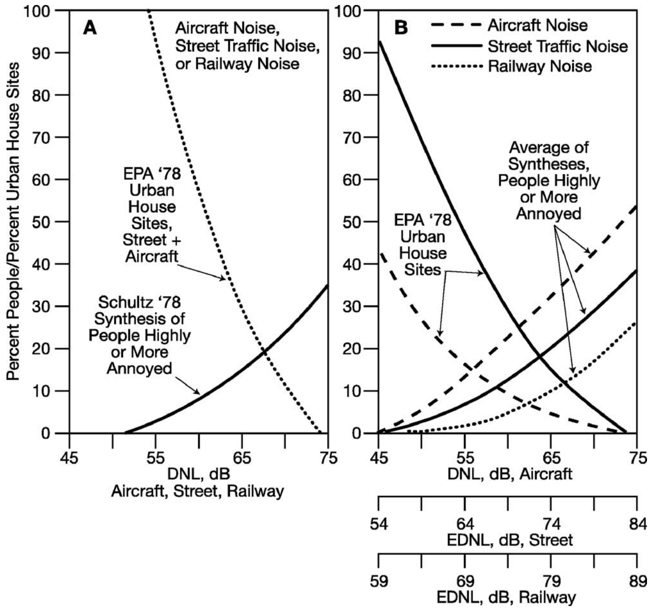

FIG. 7. Section A: Showing, as function of DNL: (1) percent of residents highly or more annoyed by street traffic, railway or aircraft noise (solid curve) according to syntheses by Schultz and cohorts, and (2) sum of percent of USA. urban house sites thusly exposed to street and aircraft traffic (dotted curve) according to Fig. 6, EPA. Section B: Showing as function of DNL: (1) percent of residents highly or more annoyed by aircraft (dashed curve) and, as function of EDNL, street traffic (solid curve) and railway (dotted curve) noise according to average of syntheses other than those of Schultz and cohorts, and (2) percent of USA. urban house sites thusly exposed to street (solid curve) and aircraft (dashed curve) traffic.

F. Predicting annoyance of "special" environmental noises

The Federal Interagency Committee on Urban Noise (1980) and the Federal Interagency Committee documents use A-weighted spectra sound level meters, or equivalent, when measuring exposure levels of noise from typical vehicles of transportations. Most of the sound energy in the noises from these vehicles of transportation have spectra that fall above ~315 Hz, and are in a range where their judged perceived noisiness is fairly proportional to their integrated one-third octave band levels. However, auditory research shows that the A-weighting has limitations when used in the measurement of noises having significant energy in sound frequencies below ~315 Hz. A "D"-weighted sound level meter gives more relative weight than does A weighting for frequencies below 315 Hz. The lesser weight is consistent with the "critical" bandwidth theory (Fletcher, 1940) and measurement of the perceived loudness and noisiness of sounds containing significant energy in the lower frequencies (Kryter, 1970, 1994).

For example, the "backblast" noise from jet aircraft during start of take-off has exceedingly more intense components in the low frequencies (below ~315 Hz) than are present in the noise after take-off. As a result, people in residential areas about two miles behind certain take-off runways of the San Francisco Airport report feelings of annoyance greater than is predicted by A weighted DNL, see Pearsons *et al.* (2000). Similar cases of the lack of accuracy of the A weighting for estimating the annoyance impact in residential areas of more general environmental noises have been reported (Goodfriend, 1991, 2006).

V. EDNL NOISE LEVELS COMPATIBILE WITH RESIDENTAIL LAND USAGE

Schultz (1978) prepared a "decision-maker's tool" for comparing the "costs" of: (a) increases above 15% of exposed populations being highly or more annoyed by aircraft, street traffic or railway noise versus (b) the loss in value of urban land that is identified as being in areas where environmental noise levels exceed limits deemed incompatible with typical residential living. The Federal Interagency Committee on Urban Noise (1980) and Federal Interagency Committee on Noise (1992) recommended criterion of incompatibility for residential-land usage is that no more than 15% of the people should be highly or more annoyed by transportation noise. FICUN and FICON do not reveal a criterion of what percentage of transportation noise-incompatible housing sites might be considered as acceptable by governmental authorities.

Schultz's 'tool-plot,' see Fig. 7(a), provides similar predictions for residential land-use zoning in regards to aircraft, street traffic, and railway noise. Presently available research data plotted on the same coordinates show differences between the different sources of noise, see Fig. 7(b).

Because of the averaging of the data for the subject three sources of noise, the Schultz curve: (a) reduces the apparent prevalence of people highly or more annoyed by aircraft noise by averaging it with the lesser percentage-effective exposure level of street and railway traffic noise as a cause of

TABLE IX. Annoyance and housing-sites impacts per DNL, EDNL, and EDNLm.

	Exposure Level			Percent people highly or more annoyed			
	DNL[a]	EDbNL[b]	EDNLm[c]	DNL[a]	EDbNL[b]	EDNLm[c]	EDNL(m)-DNL
Vehicle	dB	dB	dB	Percent	Percent	Percent	Percent
Aircraft	65	65	63	15%	35%	35%	20%
Street	65	74	72	15%	20%	20%	5%
Railway	65	79	77	15%	10%	10%	−5%
				Percent urban sites incompatible housing			
Aircraft	65	65	63	30%	4%	4%	−26%
Street	65	74	72	30%	15%	15%	−15%
Railway	65	79	77	30%	No data available		

[a] Data from Fig. 7A.

[b] Data from Fig. 7B.

[c] EDNLm = Annualized monthly av. EDNL.

annoyance, and (b) conversely increases the apparent percentage of urban sites to be considered as incompatible for residential housing because of aircraft noise. An additional reason for the lesser differences of noise condemnation of housing from street traffic noise compared to aircraft noise for a given DNL exposure level, is that by a factor of approximately 4, there are more urban house sites exposed to street traffic than to aircraft noise, see Fig. 6 in EPA report.

Table IX shows that the DNL (Schultz curve, Fig. 7(a)) leads, in comparison to the EDNL functions (Fig. 7(b)) to: (a) the underestimation by 20% points the percentage of people to be highly or more annoyed by aircraft noise, 5% points by street traffic noise and −5% points by railway noise; (b) overestimation, by 26% points, the percentage of urban sites to be considered as incompatible for residential housing because of aircraft noise, and 15% points by street traffic noise.

On-site attenuation data, in conjunction with state-of-art analyses of surveys of noise annoyance and associated effects, indicate that to meet the Federal Interagency Committee on Urban Noise (1980) and the Federal Interagency Committee on Noise (1992) criterion of compatibility in residential areas the maximum allowable exposure levels would be:

(a) Aircraft noise, 58 dB DNL (annualized), 56 dB DNL, (monthly average) for moderate climates;

(b) Street traffic noise, 66 dB EDNL (annualized), 64 dB EDNL (monthly average) for moderate climates;

(c) Railway noise, 72 dB EDNL (annualized), 70 dB EDNL (monthly average) for moderate climates.

VI. SUMMARY AND CONCLUSIONS

1. On-site acoustical measurements of aircraft noise and of street traffic noise in the yards and indoor rooms of one-story typical houses revealed that:

(a) Between the closest- and farthest-from source house facades, the outdoor levels were on average attenuated by: (a) 18 dB SENEL, 19 MaxdB for street traffic noise, and (b) 3 dB SENEL, 2 MaxdB for aircraft noise.

(b) Between the closest-to source house façade and the indoor room locations, the outdoor levels were on average attenuated by: (a) 27 dB SENEL, 27 MaxdB for street traffic noise; and (b) 24 dB SENEL, 24 MaxdB for aircraft noise.

2. For the assessment of on-site attenuation purposes, it is concluded that attenuation values in either dB SENEL or MaxdB will, on average, differ by <1 dB.

3. Application of acoustical-principled mathematical formulations of sound attenuations to be expected from the on-site physical conditions present for the measurements made in the present study revealed that compared to aircraft noise street traffic noise is on average ∼9 dB, and railway noise ∼14 dB less attenuated, and railway compared to street traffic noise, is ∼4 dB less attenuated.

4. Excluding those of Schultz, Fidell *et al.* (1991) and Finegold *et al.* (1994), major studies and syntheses of surveys of annoyance from equal DNL exposures show an average measured difference of ∼8 dB DNL between aircraft and street traffic noise, ∼13 dB DNL between aircraft and railway noise, and ∼10 dB between railway and street traffic noise.

5. Laboratory and field research findings of annoyance and associated emotion-related effects are uniformly congruent with measured and calculated house attenuation of street traffic noise compared to aircraft noise.

6. It is concluded that the implicit premise of the DNL methodology for the measurement or estimation of environmental noise dosage that on-site attenuations, if any, of environmental noises are equal, or of no significance, is in error.

7. The differences found in that regard from acoustical theory, formula and measurements are proportional to the subjectively scaled attitudes of noise annoyance and associated adverse nonauditory effects.

8. A new metric, EDNL, is proposed for estimating the percentages of people reporting "high, or more, annoyance" and other adverse effects from exposures to street traffic and railway noise in comparison to percentages from DNL exposures to aircraft noise.

9. A calculated "test" of EDNL, street traffic, railway and aircraft noise for predicting noise-annoyance surveys in moderate-climate urban areas indicated that, on average, the respondents in such areas spend approximately, ∼30% of the day time outdoors and ∼70% indoors of their homes on an annualized basis. It is estimated that the percentage of indoor listening will be significantly greater than 70% during the colder months of the year.

10. A decision maker's tool proposed by Schultz predicts, using DNL exposure data, that a smaller percentage of people will be highly or more annoyed, and a greater number of urban residential building sites will be noise condemnable due to aircraft noise than by street and railway traffic noise. The reverse relations are predicted by findings for exposure to street traffic and railway noise based on EDNL.

11. Further data are needed on the on-site noise attenuations characteristic of housing in typical urban neighborhoods exposed to aircraft, street traffic, railway and other environmental noises.

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