A first-principles model for estimating the prevalence of annoyance with aircraft noise exposure

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Numerous relationships between noise exposure and transportation noise-induced annoyance have been inferred by curve-fitting methods. The present paper develops a different approach. It derives a systematic relationship by applying an *a priori*, first-principles model to the findings of forty three studies of the annoyance of aviation noise. The rate of change of annoyance with day-night average sound level (DNL) due to aircraft noise exposure was found to closely resemble the rate of change of loudness with sound level. The agreement of model predictions with the findings of recent curve-fitting exercises (cf. Miedma and Vos, 1998) is noteworthy, considering that other analyses have relied on different analytic methods and disparate data sets. Even though annoyance prevalence rates within individual communities consistently grow in proportion to duration-adjusted loudness, variability in annoyance prevalence rates across communities remains great. The present analyses demonstrate that 1) community-specific differences in annoyance prevalence rates can be plausibly attributed to the joint effect of acoustic and non-DNL related factors and (2) a simple model can account for the aggregate influences of non-DNL related factors on annoyance prevalence rates in different communities in terms of a single parameter expressed in DNL units—a "community tolerance level." © *2011 Acoustical Society of America*. [DOI: 10.1121/1.3605673]

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I. INTRODUCTION

Hundreds of social surveys of community response to transportation noise have been undertaken in the last half century (Bassarab *et al*., 2009). Meta-analyses that attempt to characterize their findings have been conducted for descriptive, explanatory, and interpretive purposes by Alexandre (1973), U.S. EPA (1974), Schultz (1978), Fields and Walker (1982), Fidell, Barber, and Schultz (1991); Green and Fidell (1991), FICON (1992), Miedema and Vos (1998); Fidell and Silvati (2004), Oudshoorn and Miedema (2006), and Gjestland (2010), *inter alia*.

These efforts have typically relied on a cumulative measure of noise exposure such as day-night average sound level (DNL) as a sole predictor variable to characterize the central tendencies of sets of social survey findings via regression techniques, or by other expedient means. None has proven entirely satisfactory, in part because annoyance has long been understood to have both acoustic and non-DNL related determinants (McKennell, 1963; Job, 1988), and DNL is oblivious to the non-DNL related determinants of annoyance. Debate thus continues about optimal metrics for predicting transportation noise impacts; about the relative importance of acoustic and non-DNL related influences on annoyance; about effects of transportation modality, national and regional differences; about temporal trends in sensitivity to transportation noise; and so forth.

Figure 1 illustrates the great variability of measurements of aircraft annoyance prevalence rates across communities. The uncertainty associated with variability across communities with similar exposure levels compromises the credibility and utility of interpretive relationships between aircraft

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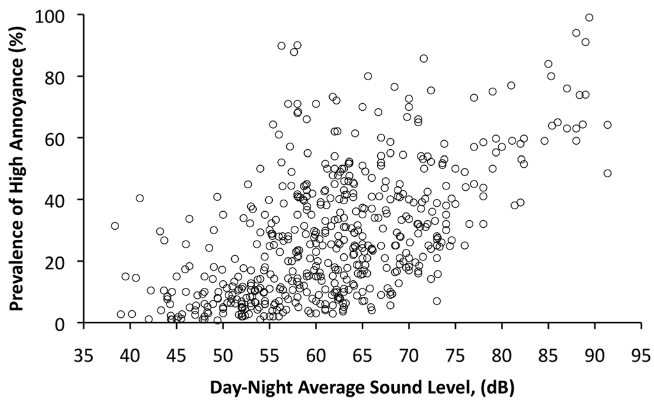

FIG. 1. Illustration of variability in annoyance prevalence rates as a function of cumulative noise exposure. Each point represents an estimate of the prevalence of high annoyance at a single interviewing site.

noise exposure and its predicted impacts (cf. ICAO/CAEP, 2007). A prediction that some percentage of a hypothetical average community will be highly annoyed by some level of aircraft noise exposure can be misleading when similar annoyance prevalence rates are commonly observed in communities with noise exposures that differ by $\pm$ 15 dB. When predictions of noise impacts are made for purposes of disclosing environmental noise effects of proposed projects, the uncertainty of predictions can be so great that no meaningful differences can be discerned among existing, no action, and alternative scenarios.

Because the variability of annoyance prevalence rates greatly compromises the usefulness of predictions developed from descriptive curve fits, an alternate approach to prediction is developed below, based on an explanatory model which relies on the findings of Stevens (1972), Fidell, Schultz, and Green (1988), and Green and Fidell (1991). The latter two references adapt concepts of signal detection theory (Swets, 1964) to the modeling of community annoyance to distinguish between physical and situational elements of perceptual decision making. The current model adds one predictor variable to DNL—a standardized "community tolerance level" (abbreviated CTL, and represented symbolically in mathematical expressions as L_{ct}). As defined and discussed below, this additional parameter facilitates analyses of the characteristic variability of findings of social surveys of the annoyance of transportation noise, while accounting for more variance in annoyance prevalence rates than predictions based on DNL alone.

II. BACKGROUND

Schultz's (1978) early examination of findings of community noise surveys is among the best known. Following Schultz's approach, subsequent efforts to develop summary relationships between transportation noise and community response have focused on predicting the prevalence of a consequential degree of annoyance among survey respondents ("%HA") from estimates of DNL values of their cumulative noise exposures. The curve fits resulting from these summary efforts, however, can reflect their analytic goals, methods, and assumptions as much as the data sets that they examine (Fidell and Silvati, 2004).

Schultz's (1978) effort was intended simply to describe and summarize the world literature on community response to transportation noise. The original "Schultz curve" ($\%\mathrm{HA} = 0.85L_{\mathrm{dn}} - 0.040{L_{\mathrm{dn}}}^2 + 0.00047\,{L_{\mathrm{dn}}}^3$) was an informal fit to 161 "clustering" data points derived from five aircraft and six rail and road noise surveys. For similar descriptive purposes, Fidell, Barber, and Schultz (1991) developed a least-squares quadratic fit ($\%\mathrm{HA} = 0.036{L_{\mathrm{dn}}}^2 - 3.26L_{\mathrm{dn}} + 79.92$) to the 161 points considered by Schultz, augmented by 292 additional data points from aircraft, rail, and street traffic noise studies published after completion of Schultz's 1978 synthesis.

In an effort to understand the determinants of noise-induced annoyance, Fidell, Schultz, and Green (1988) and Green and Fidell (1991) suggested a systematic approach to modeling self-reported annoyance as a decision-like process. This approach is based on the hypothesis that the community annoyance of transportation noise grows at the same rate as duration-adjusted loudness. Deviations from this hypothesized growth rate are attributed to non-DNL related influences on annoyance judgments, and/or to errors of measurement.[1]

For interpretive and regulatory purposes, FICON (1992) endorsed a curve fit ($\%\mathrm{HA} = 100/\left(1 + e^{(11.13 - 0.14L_{\mathrm{dn}})}\right)$ that Harris (Finegold, Harris, and von Gierke, 1994) developed by logistic regression to a sub-set of the data points compiled by Fidell, Barber, and Schultz (1991). Harris conducted a single regression for all transportation noise sources, but omitted a number of observations from studies in which the linear correlation between the prevalence of annoyance and DNL did not differ significantly from zero. FICON's prediction method remains in routine use in the United States to justify transportation noise environmental policies and assessments.

For both descriptive and policy-related purposes, Miedema and Vos (1998) based their analyses on individual respondent-level data made available to them by researchers. Their conclusion, derived from respondent-level data by more formal statistical methods[2,3] than those employed by Schultz (1978), was that annoyance prevalence rates inferred from separate fitting functions for road, rail, and aircraft noise yielded more useful predictions than a generic "transportation noise" relationship such as that adopted by FICON (1992). The curve fit to the findings of Miedema and Vos for aircraft noise [$\%\mathrm{HA} = -0.02(L_{\mathrm{dn}} - 42) + 0.0561(L_{\mathrm{dn}} - 42)^2$] predicts a considerably greater prevalence of annoyance with aircraft noise than does FICON's generic prediction of the annoyance of all transportation noise sources.

Although the curve fits to the analyses of Miedema and Vos were based on more elaborate statistical assumptions and methods than other curve fitting exercises, the resulting predictions of annoyance prevalence rates are not necessarily more accurate or precise. For example, predictions of the prevalence of high annoyance due to aircraft noise derived from the analyses of Miedema and Vos differ little from simple mean values of the reported proportions of highly annoyed respondents (vida infra).

For interpretive purposes, Fidell and Silvati (2004) analyzed aircraft noise-induced annoyance reported by nearly 53 000 respondents at 326 sites, from twelve aircraft noise surveys in addition to the sixteen analyzed by Green and Fidell (1991). A logistic regression produced a fitting function [$\%\text{HA} = 100/(1 + e^{5.854 - 0.075 L_{dn}})$] that accounted for 47% of the variance in the data set.

Fidell and Silvati described two other fitting functions as well: (1) a linear approximation to the logistic ($\%\text{HA} = 1.49\, L_{dn} - 68.85$) that accounts for nearly as much variance (46 vs 47%) within the range of exposure values of greatest practical interest for regulatory purposes and (2) a sample size-weighted least-squares regression fit to 312 of the 325 less extreme data points. They also noted, however, that a continuous fitting function is not essential to determine whether noise exposure produces a "significant" noise impact. For purposes related to disclosure of environmental noise impacts in assessments, point estimates of annoyance prevalence rates at DNL values of potential interest suffice.

Using a refinement of the averaging method described by Fidell and Silvati (2004), Gjestland (2010) has recently developed a dosage-response relationship based on averaging of survey data within 1 dB-wide intervals. The resulting smoothed relationship is monotonic and seemingly continuous above an obvious breakpoint at about $L_{dn} = 55$ dB. Gjestland also noted that variables other than noise exposure contribute to the characteristic scatter of the data, implying that prediction of annoyance from DNL alone is unlikely to provide a full account of the data.

III. METHOD

A database of social survey findings about the prevalence of transportation noise-induced annoyance was constructed from site-wise pairs of observations of DNL values and percentages of respondents highly annoyed. Instead of fitting a curve to the entire data set, however, each set of survey-specific findings was characterized by *its* fit to an exponential function with a fixed growth rate equal to that of the growth of loudness with sound level (Stevens, 1972). [This is the growth rate of loudness implicit in the familiar rule of thumb that a change of 10 dB in sound pressure level is perceived as a factor of two change in loudness, $(10^{L/10})^{0.3}$.]

In other words, it was hypothesized for modeling purposes that the prevalence of annoyance with transportation noise *should* increase at the same rate as the duration-adjusted loudness of exposure.[4] A duration adjustment for loudness adds 3 dB to every doubling in duration, to reflect the rate of growth of annoyance associated with duration (see, for example, Fig. 3 of Fidell *et al.*, 1970). The fit of individual data sets to the "effective loudness hypothesis" was found by converting the DNL value for each interview site into an estimated noise dose, m, calculated as $m = (10^{(\text{DNL}/10)})^{0.3}$. Predicted annoyance prevalence rates for the calculated dose were next computed as $p(\text{HA}) = e^{-(A/m)}$, where A is a non-acoustic decision criterion, *per* Green and Fidell (1991).

The function $e^{-(A/m)}$ is the simplest of transition functions. The community-specific constant, A, is found by minimizing the least square difference between the annoyance prevalence rates predicted by an exponential function with a slope equal to the rate of growth of loudness with level ("the effective loudness function") and those observed at the interviewing sites in each community. This process slides the effective loudness function along the DNL axis to the point at which a best fit (minimal least squares difference) between the predicted and observed points occurs. The value of A that yields the best fitting value for the effective loudness function to a community's response data may then be linearly transformed into a value on the exposure axis that reflects the aggregate influence of all non-DNL related factors on annoyance judgments in a given set of field observations. These factors include errors of measurement and acoustic parameters to which DNL is not sensitive (including, for example, low-frequency spectral content and signal onset rates).[5]

Any arbitrary point on the effective loudness function could be used to anchor the function to the DNL axis. For example, DNL values corresponding to the 10% or 90% highly annoyed points could serve to describe the position of the effective loudness function along the DNL axis. Since the choice is arbitrary, the midpoint of the effective loudness function—the point corresponding to a 50% annoyance prevalence rate—was selected as a convenient anchor point for present purposes. In terms of the parameter A, this value of CTL is given by $L_{ct} = 5.31 + 33.33 \log_{10} A$.[6] The position of the effective loudness function on the DNL axis thus corresponds to the value of DNL at the effective loudness function's midpoint.

This value of DNL is termed the Community Tolerance Level (CTL). CTL so defined represents a DNL value at which half of the people in a community describe themselves as "highly annoyed" by aircraft noise (and half do not). Normalizing CTL to some other point would affect only an arithmetic constant. Normalizing CTL to the 50% point has no regulatory implications, and neither the name adopted for the community-specific constant nor its normalization affects its explanatory value. The utility of CTL for explanatory purposes is that it provides a value in decibel units that characterizes community—rather than individual—level differences in reactions to transportation noise exposure.

Figure 2 shows CTL values computed for half a dozen surveys of communities exposed to aircraft noise. These CTL values for the different communities vary over a range of 30 dB.

IV. RESULTS

The panels of Fig. 3 display the fit of the findings of several social surveys to the effective loudness function. Each

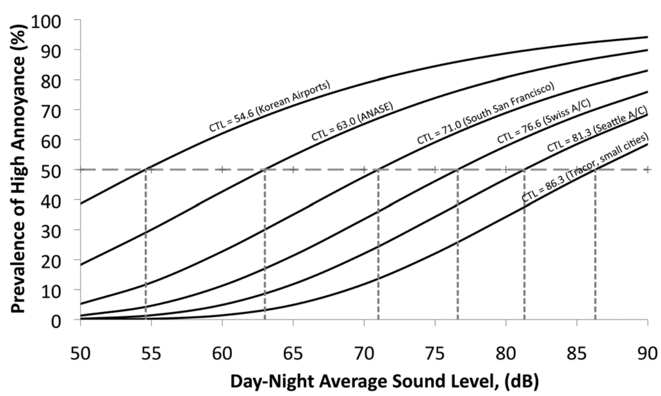

FIG. 2. CTL values computed from the findings of six surveys of communities exposed to aircraft noise. Note that CTL values for the different communities shown vary over a range of 30 dB

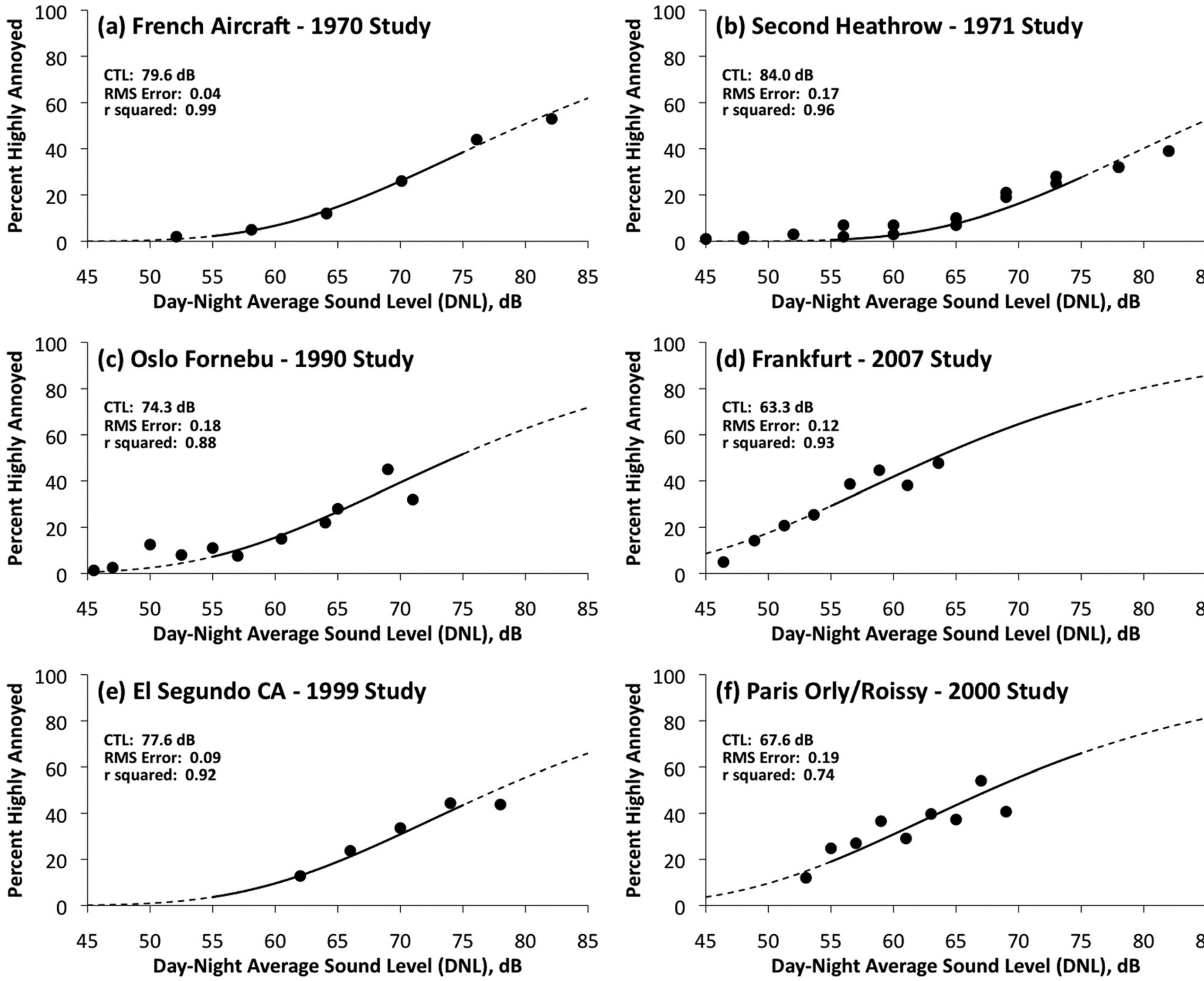

FIG. 3. Fit of data for the indicated surveys to the effective loudness function: (a) French Airport, Alexandre (1970), (b) second Heathrow, MIL Research (1971), (c) Fornebu, Gjestland *et al*. (1990), (d) Frankfort, Schreckenberg and Mies (2007), (e) El Segundo, Fidell *et al*. (1999), (f) Orly/Roissy, Vallet *et al*. (2000).

data point shown in these panels represents a paired observation of the prevalence of high annoyance among respondents at an interviewing site with the site's aircraft noise exposure level. The solid portion of the effective loudness function in each panel of Fig. 3 is the range of primary interest for policy and regulatory purposes. The dashed extensions show the behavior of the function outside the range of primary interest.

Not all of the data sets fit the effective loudness function as well as the examples shown in Figs. 3(a)–3(f). Table I summarizes estimates of CTL values, as well as the rms error between the predicted and observed annoyance prevalence rates, for the best fit of the observed annoyance in each data set to the effective loudness function. On average, the effective loudness function accounts for two-thirds of the variance in the association of observed and predicted annoyance prevalence rates in the 43 aircraft noise studies tabulated in Table II. The data from the studies tabulated in Table II have been previously described and summarized by Schultz (1978), by Fidell and Silvati (2004), or by the original researchers in the cited references. Previously undescribed findings are documented at http://www.volpe.dot.gov/acoustics/docs/2000/description-otherwise-undocumented-data-points.pdf (last viewed April 22, 2011).

For three-quarters of the individual social survey findings, the effective loudness function accounts for at least half of the variance in the association between observed and predicted annoyance.[7] In the nine studies for which the effective loudness function accounts for less than half of the variance, the relationship between annoyance prevalence rates and DNL also is poor, as, for example, at Burbank Airport.[8]

The grand mean of the 43 CTL values shown in Table I is 73.3 dB, while the standard deviation is 7.0 dB.[9] Figure 4 shows the fit of the entire data set to the grand mean of the calculated CTL values (73.3 dB) for each of the data sets considered. Figure 5 compares the dosage-response relationship produced by fitting the data to the effective loudness function with the dosage-response relationship derived by Miedema and Vos (1998). The two curves are nearly identical in the noise exposure range of primary interest.

In principle, DNL and CTL should be independent from one another. In fact, they are modestly correlated ($r = 0.3$), but share less than 10% common variance.[10] Thus, CTL and DNL are not collinear, and CTL may be usefully added to DNL in a multiple regression prediction of annoyance

TABLE I. Values of CTL calculated for a half-century of aircraft noise survey findings.

Study	Study year(s)	Primary authors	Report year	Number of interviews	Field's catalog reference	Community tolerance level	rms error	r^2
First Heathrow	1961	McKennell—"Wilson report"	1963	1731	UKD-008	77.6	0.21	0.81
French A/C	1965–66	Alexandre	1970	2000	FRA-016	79.6	0.04	0.99
Second Heathrow	1967	MIL research, HMSO SS 394	1971	4699	UKD-024	84.0	0.17	0.96
Tracor, large cities, phase I	1967–69	Connor and Patterson	1976	3590	USA-022	74.3	0.67	0.62
Tracor, large cities, phase II	1967–69	Connor and Patterson	1976	2912	USA-032	72.6	0.29	0.94
Munich A/C	1969	Rohrman *et al.*	1973	660	GER-034	78.0	0.73	0.76
Tracor, small cities	1970–71	Connor and Patterson	1972	1960	USA-044	86.3	0.06	0.98
Swiss A/C	1971–72	Grandjean *et al.*	1973	2995	SWI-053	76.6	0.29	0.95
Scandinavian A/C	1972	Rylander *et al.*	1972	2900	SWE-035	79.6	0.33	0.65
LAX	1973	Fidell and Jones	1975	940	USA-082	72.6	0.14	1.00
Canadian A/C-street	1978	Hall *et al.* (1979, 80, 81, 82)	1983	673	CAN-168	68.6	0.38	0.36
Burbank airport	1979–80	Fidell *et al.*	1985	5041	USA-203	63.0	1.17	0.03
Australian A/C	1980	Hede and Bullen	1982	3575	AUL-210	79.0	0.55	0.39
U.S. airbase	1981	Borsky	1983	874	USA-338	75.6	0.64	0.46
Orange County A/C	1981	Fidell *et al.*	1985	3103	USA-204	63.6	0.15	0.82
Westchester A/C	1982	Fidell *et al.*	1985	1465	USA-301	70.3	0.24	0.05
Decatur airport	1982	Schomer	1983	231	USA-250	78.6	0.07	0.91
Pittsburgh airport	1983	Fidell	1983	140	PIT	83.0	0.00	0.00
British ANIS	1985	Brooker *et al.*	1985	2173	UKD-243	72.6	0.54	0.50
Brussels airport	1980–85	Jonckheere	1988,89	677	BEL-288	82.3	0.21	0.79
French A/C-road	1984–86	Vallet *et al.*	1988	1032	FRA-239	74.6	0.12	0.93
German A/C-road	1987	Kastka *et al.*	1996	516	GER-373	62.6	0.77	0.45
Oslo A/C	1989	Gjestland *et al.*	1990	3337	NOR-311	74.3	0.18	0.88
Long Beach	1989	Fidell and Silvati	1989	2505	LGB	65.0	0.23	0.89
Atlanta	1991	Fidell and Silvati	1991	922	USA-349	72.3	0.13	0.66
Trondheim Værnes	1990–91	Gjestland *et al.*	1994	1195	NOR-366	77.3	0.09	0.97
Bodø Lufthavn	1992	Gjestland *et al.*	1994	3267	NOR-328	83.0	0.05	0.97
Small airports	1988–93	Rylander and Björkman	1997	513	SWE-419	70.0	0.18	0.51
Vancouver round 1	1995	Fidell *et al.*	2002	1000	CAN-385	84.0	0.18	0.65
Seattle A/C	1995	Fidell *et al.*	1998	1444	USA-431	81.3	0.17	0.53
Osaka international airport	1996	Yamada and Kaku[a]	1996	215	JPN-491	68.3	0.34	0.23
Minneapolis (MSP)	1996	Fidell *et al.*	1996	2880	USA-428	74.3	0.43	0.31
El Segundo, CA (LAX)	1997	Fidell *et al.*	1999	644	USA-432	77.6	0.09	0.92
Orly/Roissy	1998	Vallet *et al.*	2000	1334	FRA-395	67.6	0.19	0.74
Vancouver round 2	1998	Fidell *et al.*	2002	1067	YVR	70.6	0.44	0.17
South San Fransisco	1999	Fidell and Silvati	1999	1250	SFO	71.0	0.21	0.12
Swiss Zurich-Kloten	2001	Brink *et al.*	2008	1520	SWI-525	68.0	0.71	0.23
Richfield, MN (MSP)	2002	Fidell *et al.*	2002	495	MSP	72.6	0.21	0.84
Swiss Zurich-Kloten	2003	Brink *et al.*	2008	1444	SWI-534	69.0	0.70	0.11
Korean airports	2004	Lim *et al.*	2006	753	KOR-554	54.6	0.69	0.55
Frankfurt	2005	Schreckenberg and Meis	2007	2309	FRA	63.3	0.12	0.93
Cincinnati	2005	Fidell and Sneddon	2005	1606	CVG	71.0	0.24	0.06
ANASE	2005	Le Masurier *et al.*	2007	2132	UKD-604	63.0	0.84	0.62

[a]Private communication, 2010.

prevalence rates. A linear multiple regression on all of the data points accounts for nearly two thirds of the variance ($R^2 = 0.66$) in the association between annoyance prevalence rates, DNL, and CTL. Adding a second predictor variable (CTL) to DNL accounts for about half-again as much variance as can be accounted for by DNL alone. [Fidell and Silvati (2004) show that the predictive function relationship identified by Miedema and Vos (1998) accounts for 44% of the variance in the relationship between DNL and the prevalence of aircraft noise-induced annoyance.] However, the actual prediction equation, $\%(\mathrm{HA}) = 1.64(\mathrm{DNL}) - 1.67(L_{ct}) + 46.93$, is of little practical utility until CTL values for communities can be estimated *a priori*.

Figure 6 shows that the form of the distribution of CTL values for the 43 aircraft noise surveys contained in Table I does not differ significantly (Kolmogorov–Smirnov = 0.63, $p = 0.2$) from a Gaussian distribution with a mean and standard deviation of 73.3 and 7.0 dB, respectively. The standard error of CTL is 1.1 dB, and the 95% confidence bounds on the statistic are about 71.2 dB $\leq L_{ct} \leq$ 75.4 dB. It follows that CTL values in 68% of communities will lie within in the range 66.3 dB $\leq L_{ct} \leq$ 80.3 dB, and that CTL values in 95%

TABLE II. Social survey findings on annoyance of aircraft noise exposure.

Fields Catalog Reference	Point Number	DNL	HA (%)	Fields Catalog Reference	Point Number	DNL	HA (%)	Fields Catalog Reference	Point Number	DNL	HA (%)
AUL-210	1	53.7	4.2	NOR-311	1	39.0	2.7	UKD-604	1	65.6	80.0
AUL-210	2	55.6	6.3	NOR-311	2	45.5	1.3	UKD-604	2	64.2	61.4
AUL-210	3	56.7	8.8	NOR-311	3	47.0	2.5	UKD-604	3	62.8	50.0
AUL-210	4	56.8	4.2	NOR-311	4	50.0	12.5	UKD-604	4	62.2	72.1
AUL-210	5	57.0	14.4	NOR-311	5	52.5	8.0	UKD-604	5	62.3	62.1
AUL-210	6	58.0	8.3	NOR-311	6	55.0	11.0	UKD-604	6	57.2	57.1
AUL-210	7	58.2	12.3	NOR-311	7	57.0	7.6	UKD-604	7	52.9	32.2
AUL-210	8	59.2	15.2	NOR-311	8	60.5	15.0	UKD-604	8	53.0	37.7
AUL-210	9	59.6	7.8	NOR-311	9	64.0	22.0	UKD-604	9	48.5	24.2
AUL-210	10	60.2	15.0	NOR-311	10	65.0	28.0	UKD-604	10	55.2	32.2
AUL-210	11	60.4	16.3	NOR-311	11	69.0	45.0	UKD-604	11	55.5	14.3
AUL-210	12	60.6	13.6	NOR-311	12	71.0	32.0	UKD-604	12	53.4	10.2
AUL-210	13	61.0	4.4	NOR-328	1	49.4	0.7	UKD-604	13	58.6	40.0
AUL-210	14	61.0	10.8	NOR-328	2	54.4	2.1	UKD-604	14	61.8	73.3
AUL-210	15	61.8	15.2	NOR-328	3	59.4	3.0	UKD-604	15	61.2	50.0
AUL-210	16	62.6	7.8	NOR-328	4	64.4	8.8	UKD-604	16	52.1	4.8
AUL-210	17	62.9	3.6	NOR-328	5	69.4	19.9	UKD-604	17	58.7	44.3
AUL-210	18	62.9	4.2	NOR-328	6	74.4	24.8	UKD-604	18	52.1	11.7
AUL-210	19	62.9	6.3	NOR-366	1	42.0	1.1	UKD-604	19	51.7	10.9
AUL-210	20	63.0	26.8	NOR-366	2	47.0	4.0	UKD-604	20	58.1	40.7
AUL-210	21	63.2	6.3	NOR-366	3	52.0	6.9	UKD-604	21	56.4	44.3
AUL-210	22	64.0	12.5	NOR-366	4	57.0	7.6	UKD-604	22	59.1	55.0
AUL-210	23	64.0	24.1	NOR-366	5	62.0	18.0	UKD-604	23	55.2	28.8
AUL-210	24	64.4	18.8	NOR-366	6	67.0	24.9	UKD-604	24	60.9	42.6
AUL-210	25	65.2	7.1	NOR-366	7	72.0	32.0	UKD-604	25	64.1	45.0
AUL-210	26	65.9	5.0	PIT	1	69.7	17.9	UKD-604	26	52.2	33.9
AUL-210	27	66.1	23.4	SFO	1	60.0	15.0	UKD-604	27	58.1	21.7
AUL-210	28	67.5	45.9	SFO	2	65.0	25.4	UKD-604	28	65.3	49.1
AUL-210	29	67.6	35.4	SFO	3	61.0	29.8	UKD-604	29	53.5	6.5
AUL-210	30	68.2	9.3	SFO	4	56.0	27.9	UKD-604	30	63.1	41.5
AUL-210	31	68.7	16.7	SFO	5	58.0	14.4	UKD-604	31	66.7	68.3
AUL-210	32	68.7	29.2	SFO	6	53.0	17.0	UKD-604	32	62.4	25.8
AUL-210	33	68.9	12.8	SWE-035	1	44.5	1.0	UKD-604	33	63.5	51.7
AUL-210	34	71.1	18.5	SWE-035	2	50.0	3.0	UKD-604	34	48.3	3.4
AUL-210	35	71.4	39.1	SWE-035	3	52.0	6.0	UKD-604	35	46.0	25.4
AUL-210	36	71.5	21.4	SWE-035	4	54.0	1.0	UKD-604	36	45.2	1.9
AUL-210	37	72.0	42.5	SWE-035	5	54.5	6.0	UKD-604	37	49.9	17.2
AUL-210	38	73.3	24.6	SWE-035	6	54.5	7.0	UKD-604	38	55.3	3.8
BEL-288	1	70.7	19.6	SWE-035	7	54.5	18.0	USA-022	1	44.4	2.2
BEL-288	2	73.1	15.8	SWE-035	8	60.0	3.0	USA-022	2	52.4	4.5
BEL-288	3	73.1	27.5	SWE-035	9	60.0	23.0	USA-022	3	62.4	47.8
BEL-288	4	67.7	11.2	SWE-035	10	61.0	4.0	USA-022	4	72.4	75.4
BEL-288	5	64.8	15.6	SWE-035	11	62.5	8.0	USA-022	5	43.6	10.4
BEL-288	6	88.7	64.3	SWE-035	12	65.5	21.0	USA-022	6	51.6	10.4
BEL-288	7	69.7	34.5	SWE-035	13	66.0	4.0	USA-022	7	61.6	25.4
BEL-288	8	74.6	26.7	SWE-035	14	70.5	39.0	USA-022	8	59.4	25.4
CAN-168	1	58.0	23.4	SWE-035	15	74.0	35.0	USA-022	9	69.4	54.5
CAN-168	2	60.0	29.3	SWE-035	16	76.5	32.0	USA-022	10	79.4	55.2
CAN-168	3	62.0	33.3	SWE-419	1	56.4	28.0	USA-022	11	54.4	9.7
CAN-168	4	64.0	40.7	SWE-419	2	54.4	17.0	USA-022	12	62.4	8.2
CAN-168	5	66.0	40.9	SWE-419	3	57.4	20.0	USA-022	13	72.4	23.9
CAN-168	6	68.0	58.6	SWE-419	4	55.4	2.0	USA-022	14	82.4	51.5
CAN-168	7	70.0	72.7	SWE-419	5	48.4	3.0	USA-022	15	91.4	48.5
CAN-168	8	72.0	53.9	SWE-419	6	54.4	10.0	USA-022	16	64.6	18.7
CAN-168	9	74.0	32.0	SWE-419	7	49.4	8.0	USA-022	17	74.6	40.3
CAN-385	1	71.0	16.7	SWE-419	8	44.4	1.0	USA-022	18	84.6	59.0
CAN-385	2	44.0	7.6	SWI-053	1	47.8	1.0	USA-032	1	44.4	2.2
CAN-385	3	53.0	10.6	SWI-053	2	52.0	2.0	USA-032	2	52.4	4.5
CAN-385	4	54.0	11.3	SWI-053	3	56.1	5.0	USA-032	3	62.4	17.2
CAN-385	5	52.0	5.1	SWI-053	4	60.3	9.0	USA-032	4	51.6	14.9

TABLE II. *Continued*

Fields Catalog Reference	Point Number	DNL	HA (%)	Fields Catalog Reference	Point Number	DNL	HA (%)	Fields Catalog Reference	Point Number	DNL	HA (%)
CAN-385	6	50.0	4.5	SWI-053	5	64.5	16.0	USA-032	5	61.6	31.3
CVG	1	44.3	6.0	SWI-053	6	68.6	25.0	USA-032	6	71.6	50.0
CVG	2	47.8	9.3	SWI-053	7	72.8	33.0	USA-032	7	59.4	20.9
CVG	3	52.2	17.7	SWI-053	8	77.0	45.0	USA-032	8	69.4	41.8
CVG	4	56.5	26.5	SWI-053	9	81.1	59.0	USA-032	9	79.4	59.7
CVG	5	62.0	9.8	SWI-053	10	85.3	80.0	USA-032	10	88.4	73.9
FRA	1	44.0	8.5	SWI-053	11	89.4	99.0	USA-032	11	62.4	33.6
FRA	2	46.4	4.9	SWI-525	1	55.7	33.3	USA-032	12	72.4	52.2
FRA	3	48.9	14.2	SWI-525	2	51.7	2.6	USA-032	13	82.4	59.7
FRA	4	51.3	20.7	SWI-525	3	47.1	5.6	USA-032	14	91.4	64.2
FRA	5	53.6	25.4	SWI-525	4	40.6	14.5	USA-044	1	52.4	2.2
FRA	6	56.5	38.7	SWI-525	5	49.4	7.8	USA-044	2	62.4	7.5
FRA	7	58.9	44.6	SWI-525	6	61.5	40.4	USA-044	3	72.4	14.2
FRA	8	61.1	38.1	SWI-525	7	58.7	31.4	USA-044	4	81.4	38.1
FRA	9	63.6	47.7	SWI-525	8	51.2	13.3	USA-082	1	63.0	34.0
FRA-016	1	52.1	2.0	SWI-525	9	57.3	44.4	USA-082	2	82.0	58.0
FRA-016	2	58.1	5.0	SWI-525	10	67.2	30.5	USA-203	1	56.0	61.0
FRA-016	3	64.1	12.0	SWI-525	11	62.6	35.7	USA-203	2	57.0	71.0
FRA-016	4	70.1	26.0	SWI-525	12	57.9	23.0	USA-203	3	57.0	28.0
FRA-016	5	76.1	44.0	SWI-525	13	42.2	10.4	USA-203	4	58.0	68.0
FRA-016	6	82.1	53.0	SWI-525	14	41.0	40.4	USA-203	5	58.0	71.0
FRA-239	1	53.0	5.3	SWI-525	15	38.4	31.4	USA-203	6	59.0	16.0
FRA-239	2	58.0	21.3	SWI-525	16	53.1	8.5	USA-203	7	59.0	66.0
FRA-239	3	63.0	21.3	SWI-525	17	50.9	7.7	USA-203	8	60.0	71.0
FRA-239	4	73.0	38.8	SWI-525	18	53.7	14.0	USA-203	9	61.0	33.0
FRA-239	5	78.0	58.5	SWI-525	19	63.5	10.7	USA-203	10	62.0	62.0
FRA-395	1	53.0	12.0	SWI-525	20	59.8	27.6	USA-203	11	63.0	31.0
FRA-395	2	55.0	24.8	SWI-525	21	58.7	39.6	USA-203	12	64.0	42.0
FRA-395	3	57.0	27.0	SWI-525	22	56.4	10.6	USA-203	13	65.0	70.0
FRA-395	4	59.0	36.6	SWI-525	23	55.5	25.2	USA-203	14	66.0	47.0
FRA-395	5	61.0	29.1	SWI-525	24	51.5	7.6	USA-203	15	66.0	37.0
FRA-395	6	63.0	39.7	SWI-525	25	45.6	2.7	USA-203	16	68.0	10.0
FRA-395	7	65.0	37.3	SWI-525	26	40.2	2.8	USA-203	17	69.0	28.0
FRA-395	8	67.0	54.1	SWI-534	1	57.4	48.9	USA-203	18	70.0	21.0
FRA-395	9	69.0	40.7	SWI-534	2	53.2	36.8	USA-203	19	71.0	66.0
GER-034	1	63.0	5.0	SWI-534	3	48.9	6.1	USA-203	20	77.0	73.0
GER-034	2	63.0	10.0	SWI-534	4	49.4	40.8	USA-204	1	58.0	41.0
GER-034	3	67.0	9.0	SWI-534	5	43.7	26.7	USA-204	2	59.0	41.0
GER-034	4	73.0	7.0	SWI-534	6	47.2	8.9	USA-204	3	59.0	43.0
GER-034	5	73.0	21.0	SWI-534	7	60.2	20.0	USA-204	4	59.0	45.0
GER-034	6	74.0	30.0	SWI-534	8	58.2	23.4	USA-204	5	61.0	43.0
GER-034	7	74.0	38.0	SWI-534	9	54.0	29.3	USA-204	6	62.0	45.0
GER-034	8	75.0	50.0	SWI-534	10	50.4	11.2	USA-204	7	63.0	50.0
GER-034	9	75.0	50.0	SWI-534	11	65.0	24.1	USA-204	8	63.0	43.0
GER-034	10	76.0	25.0	SWI-534	12	60.4	27.1	USA-204	9	65.0	51.0
GER-034	11	77.0	57.0	SWI-534	13	56.1	23.0	USA-204	10	67.0	51.0
GER-034	12	78.0	41.0	SWI-534	14	33.1	3.9	USA-204	11	67.0	52.0
GER-034	13	79.0	50.0	SWI-534	15	30.3	0.0	USA-204	12	68.0	55.0
GER-034	14	79.0	75.0	SWI-534	16	50.8	6.3	USA-250	1	55.0	2.0
GER-034	15	79.0	75.0	SWI-534	17	48.3	5.1	USA-250	2	61.0	6.0
GER-034	16	80.0	57.0	SWI-534	18	52.8	2.8	USA-250	3	63.0	11.0
GER-034	17	81.0	77.0	SWI-534	19	62.2	10.7	USA-250	4	66.0	24.0
GER-034	18	85.0	84.0	SWI-534	20	58.2	11.1	USA-301	1	52.9	8.4
GER-034	19	86.0	65.0	SWI-534	21	58.0	13.3	USA-301	2	53.8	10.8
GER-034	20	87.0	63.0	SWI-534	22	56.2	11.5	USA-301	3	55.1	15.7
GER-034	21	87.0	76.0	SWI-534	23	53.9	4.9	USA-301	4	55.3	28.8
GER-034	22	88.0	59.0	SWI-534	24	50.6	8.9	USA-301	5	56.1	10.9
GER-034	23	88.0	63.0	SWI-534	25	43.3	4.0	USA-301	6	57.4	13.5
GER-034	24	88.0	94.0	SWI-534	26	39.5	15.0	USA-301	7	57.7	30.1
GER-034	25	89.0	74.0	UKD-008	1	48.0	6.1	USA-301	8	57.8	6.5

TABLE II. *Continued*

Fields Catalog Reference	Point Number	DNL	HA (%)	Fields Catalog Reference	Point Number	DNL	HA (%)	Fields Catalog Reference	Point Number	DNL	HA (%)
GER-034	26	89.0	91.0	UKD-008	2	54.0	14.2	USA-338	1	51.3	6.2
GER-373	1	44.5	10.0	UKD-008	3	60.0	18.4	USA-338	2	55.3	28.1
GER-373	2	45.0	15.0	UKD-008	4	53.0	6.3	USA-338	3	55.5	5.7
GER-373	3	46.0	10.0	UKD-008	5	59.0	9.9	USA-338	4	60.7	25.0
GER-373	4	48.0	10.0	UKD-008	6	65.0	20.9	USA-338	5	61.3	19.4
GER-373	5	48.0	15.0	UKD-008	7	65.0	15.8	USA-338	6	61.8	5.6
GER-373	6	49.0	30.0	UKD-008	8	70.0	18.2	USA-338	7	61.8	2.9
GER-373	7	49.5	10.0	UKD-008	9	70.9	32.0	USA-338	8	62.4	28.1
GER-373	8	50.0	35.0	UKD-008	10	76.0	48.9	USA-338	9	64.3	36.1
GER-373	9	50.0	5.0	UKD-024	1	45.0	1.0	USA-338	10	65.0	35.1
GER-373	10	54.0	50.0	UKD-024	2	48.0	1.0	USA-338	11	65.6	25.0
GER-373	11	54.5	35.0	UKD-024	3	52.0	3.0	USA-338	12	65.8	11.1
GER-373	12	55.0	30.0	UKD-024	4	56.0	2.0	USA-338	13	67.6	17.8
GER-373	13	58.0	35.0	UKD-024	5	60.0	3.0	USA-338	14	68.0	5.6
GER-373	14	58.0	90.0	UKD-024	6	65.0	7.0	USA-338	15	69.1	27.8
GER-373	15	59.0	15.0	UKD-024	7	69.0	19.0	USA-338	16	69.2	33.3
GER-373	16	59.5	35.0	UKD-024	8	73.0	25.0	USA-338	17	69.7	22.6
GER-373	17	60.0	15.0	UKD-024	9	78.0	32.0	USA-338	18	69.8	66.7
GER-373	18	62.0	50.0	UKD-024	10	82.0	39.0	USA-338	19	71.5	53.1
GER-373	19	68.0	40.0	UKD-024	11	45.0	1.0	USA-338	20	72.1	25.0
GER-373	20	70.0	70.0	UKD-024	12	48.0	2.0	USA-338	21	73.6	51.8
GER-373	21	71.0	65.0	UKD-024	13	52.0	3.0	USA-338	22	85.4	63.9
JPN-491	1	70.0	40.0	UKD-024	14	56.0	7.0	USA-349	1	66.3	34.0
JPN-491	2	64.0	45.5	UKD-024	15	60.0	7.0	USA-349	2	68.8	43.0
JPN-491	3	58.0	41.7	UKD-024	16	65.0	10.0	USA-349	3	71.3	54.0
JPN-491	4	67.0	60.0	UKD-024	17	69.0	21.0	USA-349	4	73.8	53.0
JPN-491	5	63.0	15.4	UKD-024	18	73.0	28.0	USA-349	5	68.8	41.0
JPN-491	6	57.0	20.0	UKD-024	19	78.0	32.0	USA-349	6	71.3	37.0
KOR-554	1	32.9	12.2	UKD-024	20	82.0	39.0	USA-349	7	73.8	58.0
KOR-554	2	43.2	29.6	UKD-243	1	57.5	10.6	USA-428	1	58.7	12.0
KOR-554	3	45.9	17.3	UKD-243	2	57.5	16.7	USA-428	2	60.0	25.7
KOR-554	4	46.4	18.4	UKD-243	3	53.4	10.6	USA-428	3	63.3	41.6
KOR-554	5	46.4	33.7	UKD-243	4	50.5	6.4	USA-428	4	59.8	29.7
KOR-554	6	54.9	39.8	UKD-243	5	53.4	6.7	USA-428	5	64.2	24.6
KOR-554	7	54.5	21.4	UKD-243	6	63.6	52.3	USA-428	6	68.5	16.4
KOR-554	8	52.7	44.9	UKD-243	7	63.6	51.7	USA-428	7	62.2	24.0
KOR-554	9	63.0	45.9	UKD-243	8	71.7	40.2	USA-428	8	65.3	18.7
KOR-554	10	63.5	45.9	UKD-243	9	67.4	43.7	USA-428	9	62.1	17.2
KOR-554	11	56.3	52.0	UKD-243	10	71.0	28.9	USA-428	10	65.2	23.1
KOR-554	12	55.4	64.3	UKD-243	11	64.5	31.6	USA-428	11	63.3	14.0
KOR-554	13	58.1	68.4	UKD-243	12	62.5	25.4	USA-428	12	66.7	34.0
KOR-554	14	68.4	76.5	UKD-243	13	59.2	3.8	USA-428	13	71.2	31.1
KOR-554	15	57.6	87.8	UKD-243	14	55.8	4.1	USA-428	14	64.1	22.3
KOR-554	16	56.3	89.8	UKD-243	15	62.2	9.9	USA-428	15	66.8	41.0
KOR-554	17	71.6	85.7	UKD-243	16	60.5	6.1	USA-428	16	73.6	51.2
LGB	1	51.0	9.0	UKD-243	17	56.4	3.3	USA-428	17	75.0	38.5
LGB	2	52.0	11.0	UKD-243	18	63.4	17.8	USA-428	18	63.2	31.0
LGB	3	53.0	12.8	UKD-243	19	59.8	17.1	USA-428	19	65.2	37.0
LGB	4	58.9	28.7	UKD-243	20	54.5	6.1	USA-431	1	61.7	9.0
LGB	5	61.8	47.8	UKD-243	21	64.1	25.0	USA-431	2	65.2	17.0
LGB	6	59.9	28.5	UKD-243	22	64.1	29.1	USA-431	3	67.4	21.0
LGB	7	59.6	41.9	UKD-243	23	59.0	37.7	USA-431	4	68.0	9.0
LGB	8	62.6	49.0	UKD-243	24	64.5	29.9	USA-431	5	73.5	26.0
LGB	9	60.5	39.1	UKD-243	25	63.8	30.6	USA-431	6	65.5	16.0
LGB	10	58.3	40.6	UKD-243	26	64.1	29.2	USA-431	7	68.5	25.0
LGB	11	62.0	54.0	YVR	1	70.0	17.0	USA-431	8	71.0	16.0
LGB	12	60.5	38.3	YVR	2	44.0	8.4	USA-431	9	71.8	31.0
MSP	1	62.5	40.1	YVR	3	53.0	6.3	USA-431	10	73.0	27.0
MSP	2	67.5	36.5	YVR	4	61.0	51.6	USA-432	1	62.0	12.8
MSP	3	72.5	36.0	YVR	5	52.0	4.8	USA-432	2	66.0	23.7

TABLE II. *Continued*

Fields Catalog Reference	Point Number	DNL	HA (%)	Fields Catalog Reference	Point Number	DNL	HA (%)	Fields Catalog Reference	Point Number	DNL	HA (%)
				YVR	6	49.0	18.1	USA-432	3	70.0	33.6
				YVR	7	51.0	11.8	USA-432	4	74.0	44.4
								USA-432	5	78.0	43.8

of communities will lie within the range 59.3 dB $\leq L_{ct} \leq$ 87.3 dB. In other words, the 95% prediction interval for CTL values approximately equals the $\pm 2\ \sigma$ range in CTL values of 59 to 87 dB. This range is quite similar to the roughly 30 dB range in DNL values for similar annoyance prevalence rates of Fig. 1.

V. DISCUSSION

A. Adequacy of effective loudness hypothesis

The close fits for three-quarters of the airports in the current database to an *a priori* prediction—as opposed to a descriptive curve fit—support the hypothesis that the rate of growth of community annoyance with aircraft noise exposure is closely related to the rate of growth of effective loudness of noise exposure. As in any non-experimental analysis, it remains unclear whether the good fits "prove" that effective loudness is indeed the underlying acoustic determinant of annoyance; whether both loudness and annoyance are closely related to some other variable(s); or whether the good fit is simply adventitious. For whatever reason, however, the hypothesis may be considered pragmatically correct, in the sense that it generates useful predictions.

The "real" reasons for the good fits are unknowable because highly controlled, intentional manipulations of community exposure to aircraft noise are not feasible in real world settings. The close agreement between the descriptive dosage-response relationship of Miedema and Vos (1998) and the current model's prediction (cf. Fig. 5), however, confirms the reasonableness of the hypothesis that the rate of growth of annoyance with aircraft noise exposure is closely related to the effective loudness of exposure.

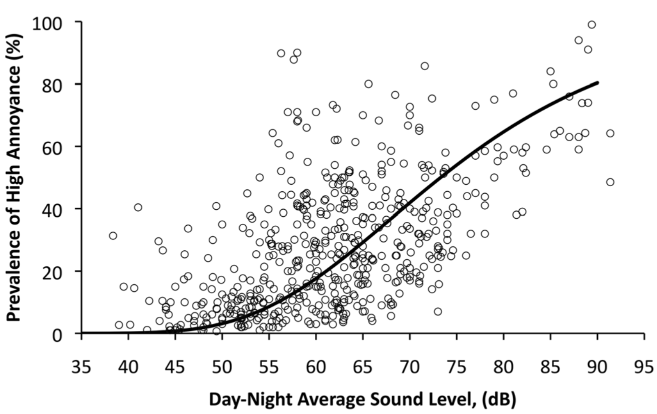

FIG. 4. Fit of all aircraft annoyance data to effective loudness function for a CTL value of approximately 73 dB.

B. Ambiguities in definition of "community"

The term "community response" to transportation noise is not generally defined with exactness. Although "community" often implies the residential population of a particular political jurisdiction, the meaning is sometimes stretched to refer to geographically contiguous populations with shared values, experiences, and expectations. The term is sometimes used more amorphously yet; for example, to refer to airport-vicinity residents anywhere. Defining a community-specific predictor variable (CTL) for a normative model of annoyance calls attention to such ambiguities in the meaning of "community."

"Community" has little substantive meaning in estimates of annoyance prevalence rates derived from descriptive curve fits which use noise exposure as a sole predictor variable. This is the case whether the fitting curve is derived from site-specific survey data (as is FICON's 1992 relationship), or from combined data from individual respondents with similar noise exposure at different sites (as is the 1998 Miedema and Vos relationship). In the former case, "community response" implies little more than a mathematical transform of noise exposure ($\%\text{HA} = 100/(1 + e^{11.13 - 0.141 L_{dn}})$, with no further explanatory value or deeper meaning. In the latter case, the analytic focus on individual annoyance tacitly assumes that community-level effects are intractable, or otherwise do not warrant systematic consideration.

In contrast, definition of groups of survey respondents who may be considered part of the same community for purposes of computing CTL values requires consideration of matters beyond similarity of exposure levels. Analysis of the

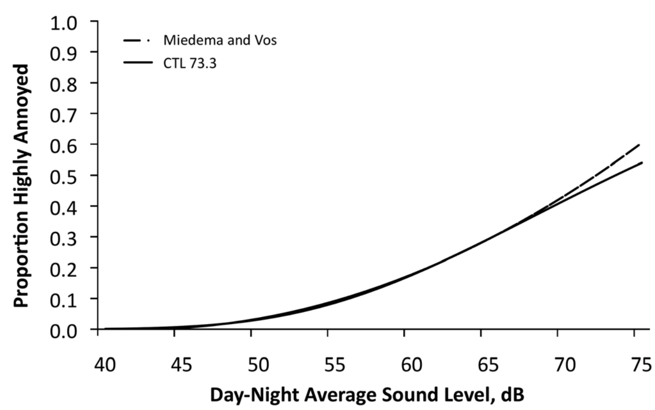

FIG. 5. Comparison of shapes of exponential function with a slope equal to the growth rate of loudness with sound level for a CTL value of 73.3 dB (solid line) and the polynomial approximation (dashed line) to the dosage-response relationship for aircraft noise derived by Miedema and Vos (1998) by logistic regression.

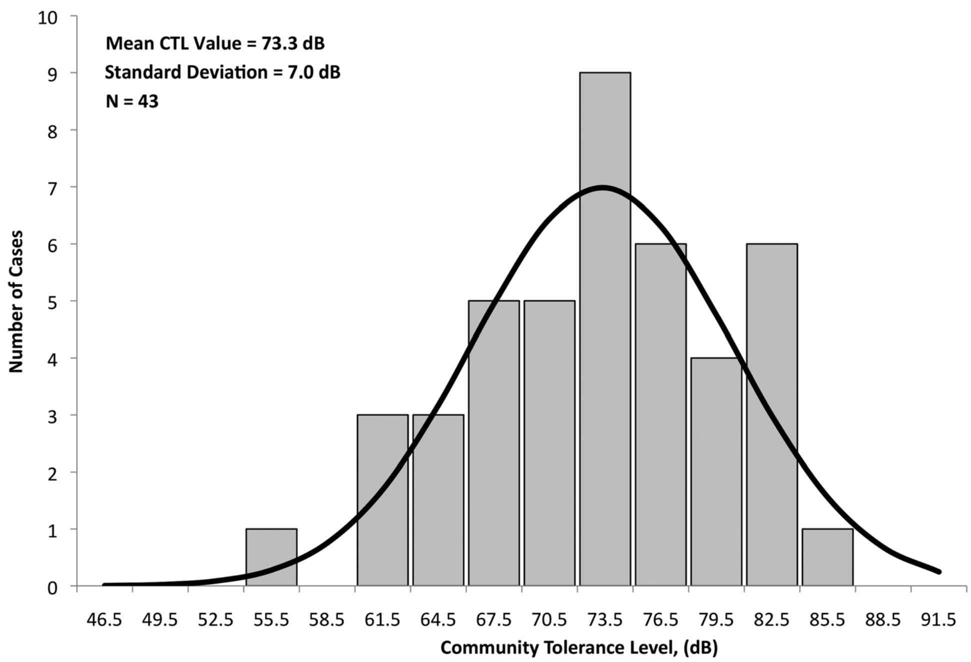

FIG. 6. Distribution of CTL values by survey compared to Gaussian distribution of similar mean and variance.

findings of a rail noise survey (Öhrström and Skånberg, 1996) illustrates the issue. Öhrström and Skånberg report a survey of the annoyance of rail noise in six Swedish cities. They describe three of the six cities (Säffle, Kungsbacka, and Partille) as exposed to high levels of train-induced vibration, and the other three (Hässleholm, Huskvarna, and Lund) as exposed to "low vibration levels" due to trains. Miedema and Vos (1998) analyze the data from this Swedish rail noise study (Fields Catalog SWE-365) by combining annoyance responses of individual respondents across all six sites within common noise exposure categories.

Figure 7 shows that the fit of the overall study data to the CTL function is poor. Figures 8(a)–8(f), however, show that the fits of the data to the CTL function from respondents in each city are improved. The average CTL value in the three high vibration cities was 75.3 dB, while the average CTL value in the three low vibration cities was 90.2 dB. In other words, respondents in the three low vibration cities were 15 dB more tolerant of train noise than respondents in the three high vibration cities. The 15 dB offset in CTL values resembles the 10 to 20 dB offset reported by Schomer and Neathammer (1987) for vibration and rattling induced by helicopter noise. Thus, community-based differences (in this case, in vibration levels) support a simple and plausible explanation for otherwise unexplained variability in the findings of individual-based analysis.

Estimates of CTL values are sensitive not only to site-specific factors (such as the differences in vibration levels described above), but also to definitions of "community" boundaries. Care should be taken in the design of original research to define interviewing site boundaries in an unambiguous and community-relevant manner.

Few reports of findings of transportation noise surveys supply exact definitions of communities of the sort most directly useful for CTL-based analyses. Some studies report findings collected at a single point in time from several geographically distinct areas, while some studies report findings from multi-site or multi-national surveys conducted over months or years. Plausible definitions of "community" can be constructed *post hoc* in many cases. When results from multiple interviewing areas are described only by noise exposure categories, however, the term "community" has only a diffuse meaning. This meaning is sometimes limited to "a set of respondents living in the same general area at about the same time." In general, better fits of the effective loudness function are found for studies with better-defined communities.

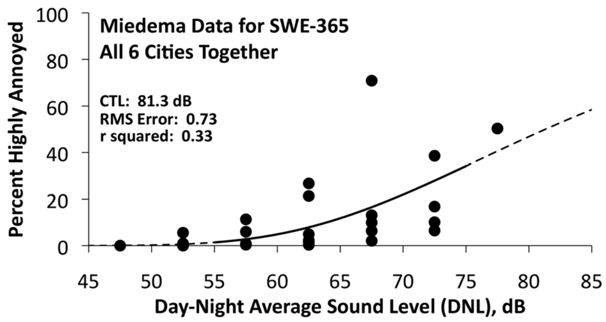

FIG. 7. Poor fit of the CTL function to the composite data for the Swedish railroad noise survey in six (Swedish) cities.

C. Comparisons among groups of survey findings based on CTL values

Several exploratory analyses of relationships between CTL values and a number of site-specific, non-DNL related factors were conducted. Since most original studies were not concerned with non-DNL related influences on annoyance, they typically contain only limited quantitative information about them. The analyses described below should therefore be considered as suggestive, rather than definitive.

Relationships between CTL, total numbers of airport operations, and numbers of nighttime operations are difficult to establish for lack of reliable historical operational

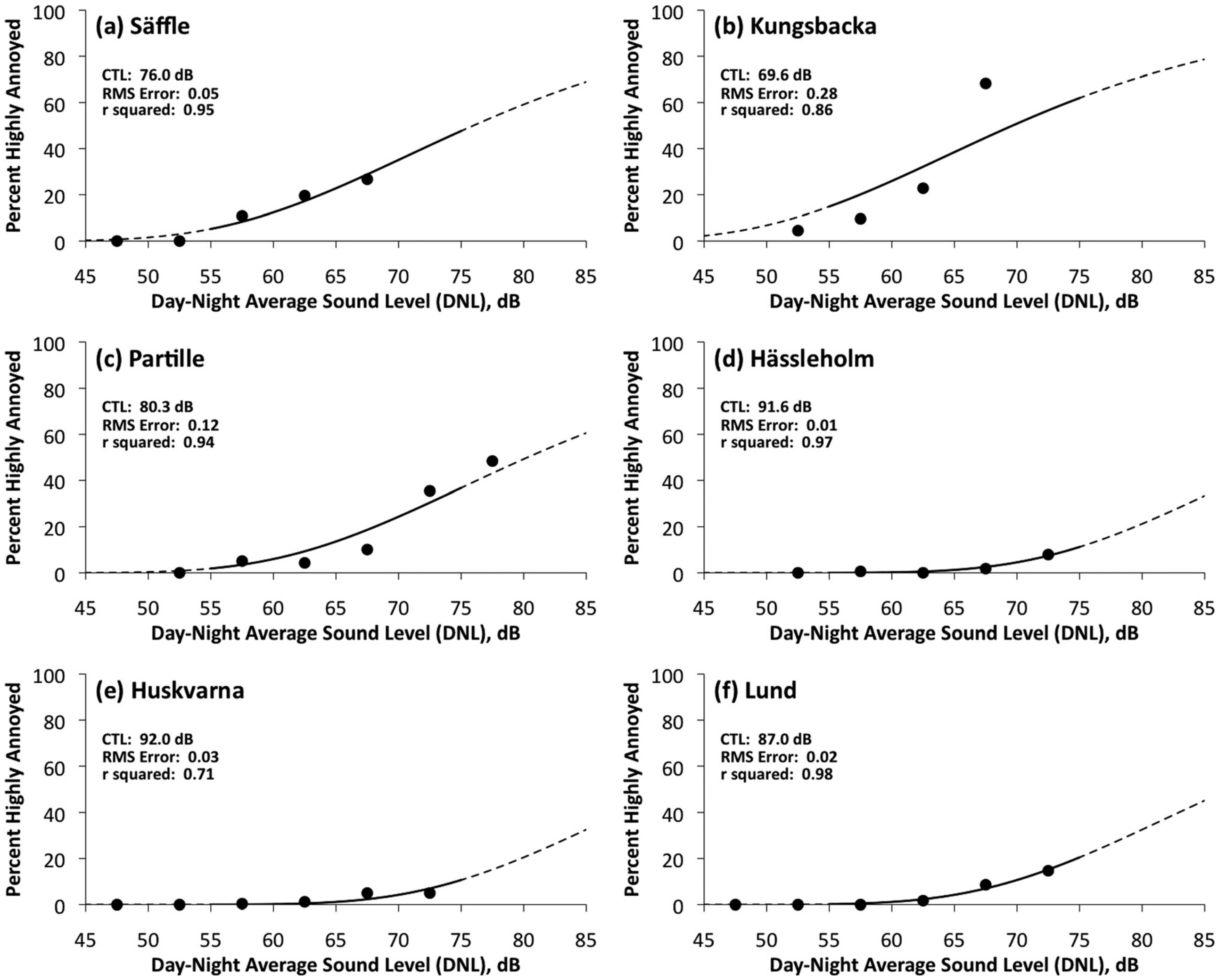

FIG. 8. Fits of data collected in six individual cities in the Swedish railroad noise survey to the CTL function. Note the improvement in fits with respect to Fig. 7.

information. An "airport size" surrogate variable was therefore constructed from total recent (2008 or 2009) operations. This variable was divided by 100 000 to create a ten-category scale of airport size.[11] Figure 9 shows that airport size has no meaningful relationship to CTL.

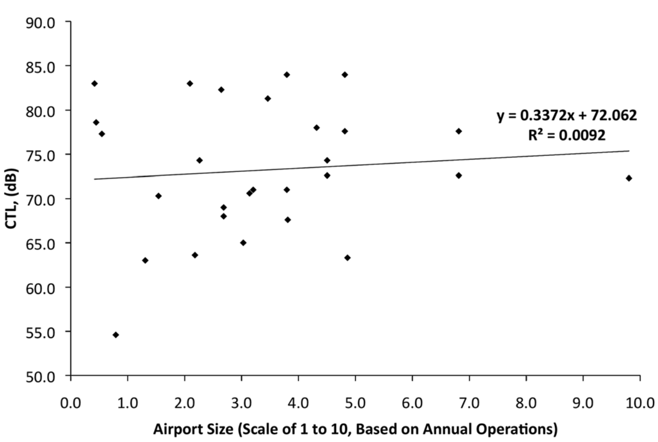

FIG. 9. Illustration of lack of meaningful relationship between airport size and CTL.

On the other hand, the average CTL value of regional airports (defined for present purposes as those within 250 km of a major international airport) was 65.9 dB, while that of major airports was 75.2 dB. If this difference in CTL values can be confirmed, it suggests that increasing numbers of operations at regional airports can engender greater increases in annoyance prevalence rates than increasing operations at nearby major airports.

Note, however, that the finding may be influenced by a sample bias, since surveys are generally conducted at airports with noise controversies, not at randomly selected regional airports.

Climate variables such as warmest and coldest month average temperatures and rainfall do not account for appreciable amounts of variance in CTL values. Speculation about the importance of cold weather housing construction and outdoor lifestyles as determinants of community response to aircraft noise is thus unsupported. Economic variables, however, seem to be more closely related to CTL values. Average housing values at U.S. domestic sites (as represented by median home values from the 2000 decennial census) account for 21% of the variance in CTL values, while annual average household income accounts for 14% of the variance in CTL values. Relationships among economic variables and CTL values warrant closer scrutiny, including extensive normalizations to adjust for intrinsic differences across real estate markets and economic conditions during different time periods.

Temporal trends in the annoyance of noise exposure may also be explored by means of CTL-based analyses. Among others, Guski (2003a, 2003b, 2004) and van Kempen and van Kamp (2005) have questioned whether increased numbers of operations by quieter airplanes in recent years have led to increases in the annoyance of aircraft noise exposure. (This hypothesis is a *de facto* challenge to the "equal energy hypothesis" on which DNL is based.) Figure 10 shows a weak trend in CTL values toward reduced tolerance for aircraft in noise surveys over the years. As noted by Brooker (2009), the trend accounts for relatively little variance, and is strongly affected by the findings of a small number of recent studies. It is therefore difficult to determine definitively whether the trend violates the "equal-energy hypothesis" (that number, level, and duration of noise events are freely interchangeable determinants of annoyance); whether it reflects decreased rattle associated with lower levels of low-frequency engine noise; whether it coincidentally reflects other contemporaneous social trends; or whether it is merely an artifact of methodological or other non-causal factors.

D. On the role of uncertainty in useful estimates of annoyance prevalence rates

Miedema and Oudshoorn (2001) observe that the annoyance of "a group of individuals can be predicted on the basis of the exposure only with a large amount of uncertainty," but that this uncertainty "can be described by the prediction interval for individuals or groups." They argue further, however, that the uncertainty of concern for policy purposes is limited to that of the "exact relationship between exposure and response in the population," as described by "the confidence interval around the [prediction] curve."

The practical implications of these two observations are difficult to reconcile. Even though the great uncertainty of

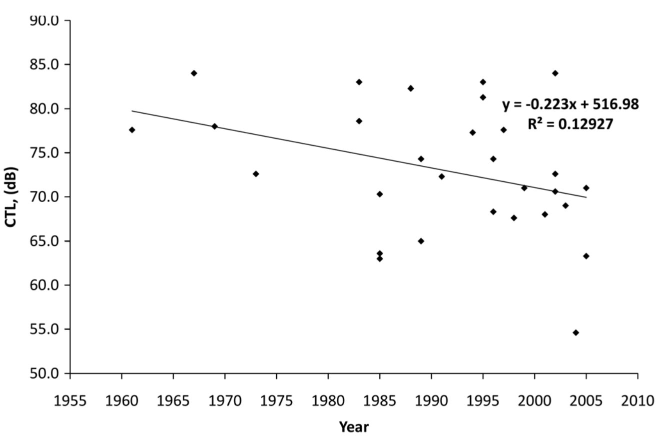

FIG. 10. Temporal trend in CTL values for surveys conducted in last 40+ years.

predicting community response to aircraft noise exposure may be tolerable for some policy purposes, it remains unacceptable for others. As Fidell (2003) notes, no systematic explanations are available for large differences in annoyance prevalence rates in different communities with the same noise exposure, nor for changes in annoyance associated with changes in noise levels. The benefits of costly measures intended to mitigate noise exposure cannot be evaluated with confidence; regulatory policies intended to balance conflicting societal interests remain largely arbitrary and poorly supported by technical analysis; and decisions about the expenditure of enormous sums to subsidize construction of transportation infrastructure ostensibly rest on the shape of a purely descriptive fitting function unsupported by quantitative, theory-based, or other systematic understanding of the origins and mechanisms of community reaction to transportation noise.

For practical purposes, how accurately a dosage-response relationship characterizes the central tendency of a cloud of data points is at best half of the story. The utility and credibility of predictions of noise impacts depend at least as critically on their uncertainty. It is therefore essential that predictions of annoyance prevalence rates associated with exposure to transportation noise be accompanied by clear statements of the uncertainties of the predictions themselves, and not merely by statements of the uncertainty of the predictive relationship.

Conventional confidence intervals quantify ranges of values that have a high probability of including a true population value that can only be estimated from finite samples. The common interpretations of confidence bounds (e.g., 68% of the distribution of sample values lie within ± 1 standard deviation of the mean) assume Gaussian distributions of sample values.

A prediction interval, on the other hand, quantifies a range of values which encompass a stated proportion of a set of empirical estimates of annoyance prevalence rates (cf. Fidell and Schomer, 2007). Within a given data set, for example, one can identify a range of annoyance prevalence rates that includes, say, 90% of all observed values. Those making decisions about disclosures of predicted noise impacts, as well as affected communities, require such information to make sense of environmental assessment documents, because a 90% prediction interval can differ greatly from a predicted annoyance prevalence rate. For example, when the mean predicted annoyance prevalence rate is 15%, a 90% prediction interval may extend from zero to 50%.

E. Limitations of the present model

CTI values in the current model are derived from a hypothesized rate of growth of annoyance with noise exposure levels. Perhaps the chief limitation of the model is that not enough is yet known about the development of community attitudes toward noise exposure to estimate a CTL value for a given community on an *a priori* basis. This is due in part to the narrow focus and limited amount of research on community reaction to noise in recent decades, and in part to uncritical acceptance of dosage-response analyses based on acoustic factors alone, despite the widely-acknowledged understanding of the influence of non-DNL-related factors on annoyance prevalence rates.

For pragmatic reasons,[6] the present model does not distinguish between the influences of non-DNL related factors and simple errors of measurement and modeling on annoyance prevalence rates. This is because no objective means exist for characterizing the relative magnitudes of errors in modeling and measuring aircraft noise in the many studies of the last half century. As the state of the art of modeling aircraft noise exposure improves, the magnitude of modeling errors may decrease. For the present, however, it is suggested that ten percent or more of the variance in the observations summarized in Table II could well be an artifact of error in acoustic measurement and/or modeling.

The current modeling approach can be improved in a variety of ways, notably by improving estimates of duration-adjusted loudness (for example, by creating loudness level-based exposure estimates and/or accounting for low-frequency spectral content and vibration associated with transportation noise); by more sophisticated estimation of measurement error; and by devising means for quantifying CTL values other than from comparisons between empirically observed and predicted annoyance prevalence rates.

VI. SUMMARY

Despite the addition of hundreds of data points about the annoyance of aircraft noise exposure to those assembled by Schultz in the 1970s, no clearer clustering of findings is discernable in the observations summarized in Table II. Indeed, the most prominent feature of these data is the great difference in annoyance prevalence rates among communities with similar aircraft noise exposure. For practical applications, accounting for the variability of survey findings is as important as estimating the central tendency of the data.

The present model, built on two simple assumptions about the exponential form of distributions of subjective response criteria and annoyance growth rates, offers a systematic approach to understanding the characteristic variability of social survey findings about the annoyance of transportation noise. The model enables straightforward comparisons of community reaction to noise observed at different places and times; permits calculation of decibel-unit offsets between the annoyance of aircraft, road, and rail noise; permits calculation of prediction error intervals that are more appropriate for noise impact analysis than confidence intervals around regression equations; and more fully informs regulatory policy decisions than a non-explanatory, one-size-fits-all curve fit.

The model characterizes the findings of individual surveys of aircraft noise annoyance in terms of a single-valued parameter (community tolerance level or CTL). This parameter quantitatively describes the aggregate influences of non-DNL related variables which account for differences in annoyance prevalence rates among communities. Although predictions of annoyance prevalence rates based on CTL and DNL values together account for two-thirds of the variance in the observations in Table II, the non-DNL related factors (i.e., those represented by CTL values) account for only about half as much variance in the prevalence of high annoyance as the acoustic factors (those represented by DNL values). This means that annoyance and adverse community reaction to aircraft noise at any given airport cannot logically be attributed primarily to non-DNL related factors.

CTI *per se* has nothing to do with regulatory criteria, nor how much noise is too much noise. A CTL value is simply a quantitative expression of site-specific differences in social survey findings, not a scale for regulating noise. As such, CTL can provide a rationale for policy decisions about the amounts of noise exposure (created by various sources, in urban vs rural settings, in different nations, at different times, etc.) that various populations tolerate to the same degree.

That the factors which determine CTL values cannot yet be estimated *a priori* does not alter the fact that non-DNL related contributions to annoyance prevalence rates can differ greatly from community to community, nor the fact that the acoustic contributions to annoyance prevalence rates are fairly well predicted by duration-corrected loudness. Research intended to further refine the current model should focus on *a priori* means of predicting CTL values for individual communities. Such research is likely to contribute more to a complete understanding of community response to aircraft noise than additional conventional studies of annoyance prevalence rates, or of individual differences in annoyance.

One promising avenue of investigation may be the use of complaint rates (not obviously related to exposure levels) to predict CTL values. As described by Fidell and Howe (1998), dozens of major airports with modern operations and noise monitoring systems routinely create detailed databases of information about noise complaints. When coupled with retrospective estimates of CTL values in overflown areas, these databases can be used to explore relationships between CTL values and many aspects of complaints (*per capita* rates of unique complainants, temporal trends, relationships to airport expansion proposals, etc.).

Another area in which the model predictions might be further improved might be in the estimation of effective loudness of exposure. Reliance on *A*-weighted measures of aircraft noise exposure to estimate loudness is an expedient. A loudness-level based estimate of cumulative noise exposure levels could well yield a further useful increase in the variance of annoyance prevalence rates for which the current model can account.

VII. CONCLUSIONS

(1) The effective (duration-corrected) loudness of noise exposure appears in most cases to provide a good account for social survey findings on the prevalence of aircraft-noise induced annoyance. This finding, derived from analyses of interviews conducted with nearly 76 000 respondents at hundreds of sites over the last half century, is unlikely to change appreciably as additional social survey data become available in the foreseeable future.

(2) The aggregate influences of non-DNL related factors in a given community can be usefully described by a single variable, a "community tolerance level," normalized to the DNL value at the middle of the best-fitting effective loudness function for each community.

TABLE III. Predicted annoyance prevalence rates for three levels of noise exposure and three degrees of community tolerance for noise exposure.

DNL	%HA FOR $L_{ct} = 73.3$ dB	%HA FOR $L_{ct} = 66.3$ dB	%HA FOR $L_{ct} = 80.3$ dB
55 dB	8.6%	1.9%	22.0%
60 dB	17.6%	6.0%	34.3%
65 dB	29.3%	13.6%	46.9%

(3) For the grand mean CTL value (73.3 dB), the form of the dosage-response relationship for the prevalence of aircraft noise-induced annoyance, that is, predicted by the current model closely resembles both that derived by Miedema and Vos (1998), and the empirical means of aircraft noise survey data, per Fidell and Silvati (2004).

(4) Table III summarizes predicted percentages of communities highly annoyed by aircraft noise at three potential policy points (DNL values) for the grand mean CTL value (73.3 dB), as well as for CTL values $\pm 1\sigma$ from the mean. The range of predicted annoyance prevalence rates in the latter two columns encompasses approximately two thirds of all communities.

(5) CTL values appear to be little influenced by airport size *per se*, but may be related to airport type. They also appear to be unrelated to climate variables, but may be related to economic factors such as median housing values and annual household incomes.

(6) Community-specific, non-DNL related factors may play a large enough role in social survey finding about the annoyance of aircraft noise that they make it difficult to detect individual-level differences in annoyance (cf. Fields, 1993; Miedema and Vos, 1999). Individual-level effects might therefore be more apparent if normalized by CTL values. Such a normalization (accomplished by adding the signed difference between a study's CTL value and a grand mean average CTL value to the estimated noise exposures of individuals) could adjust for site- and study-specific effects.

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[1]The form of the relationship between the probability of high annoyance (HA) and community noise exposure posited by Green and Fidell (1991) is $p(\mathrm{HA}) = e^{-A/m}$, where A is a decision criterion (expressible as a DNL threshold value above which people describe themselves as highly annoyed), and m is the mean of the exponential density of annoyance reactions, $1/m\ e^{-x/m}$. The community-specific DNL value above which social survey respondents describe themselves as highly annoyed—the only free parameter of the present model—translates the effective loudness function $[(10^{(\mathrm{DNL}/10)})^{0.3}]$ along the abscissa. The exponential form of the hypothesized distribution of residential annoyance with noise exposure is an assumption of convenience, adopted primarily to yield tractable calculations. Any other reasonable distribution assumption (such as assumption of a Gaussian distribution of residential annoyance, for example) would require fitting more than a single parameter, and would complicate calculations, for little return in utility of predictions. It is unimportant for immediate purposes whether individuals perfectly integrate the loudness of multiple discrete aircraft noise events over the course of 24 h. Other forms of "interrupted integration" are also plausible (cf. Gjestland, 1980), and may be more appropriate for predicting annoyance caused by forms of transportation noise other than aircraft. It suffices for modeling purposes that aircraft noise-induced annoyance can be usefully predicted by an exponential function with a form based on the assumption that individuals act as though their annoyance were based on an integration of all aircraft noise.

[2]To satisfy statistical requirements for cardinal (ratio scale) data, Miedema and Vos (1998) converted annoyance responses originally made on differing response scales into common units on an arbitrary 100 point scale. The conversion was based on two assumptions: (1) an "equal interval" assumption that "each category from a set of response alternatives occupies an equal portion of the annoyance continuum" and (2) an "equal extremes" assumption that "the extreme (lower and upper) category boundaries from different sets of annoyance response alternatives coincide." Neither of these assumptions, made for purposes of tractable calculations, is fully supportable. Thurstone (1927) scaling of response category labels for terms commonly used on annoyance response scales has shown that they are *not* equidistant from one another on a continuum of annoyance (Fidell and Teffeteller, 1980). The distances of the category labels of a commonly used five point absolute judgment scale for annoyance, for example, are as follows: not at all annoyed, 0; slightly annoyed, 2.05; moderately annoyed, 2.76; very annoyed, 3.05; and extremely annoyed, 4.35. Similarly, Schultz (1978, p. 381) notes that the names given to the initial and final steps in Langdon's (1976) London street traffic noise study ("definitely satisfied" and "definitely unsatisfied") provide "a very mild description of the most extreme form of annoyance that a subject can feel, compared to the other surveys." Schultz therefore counted as "highly annoyed" respondents who described themselves as annoyed to the degree indicated by the upper 27–29% of response scales with unnamed end points, but also counted as "highly annoyed" those who so described themselves on scales with unambiguous category labels (such as "very" and "extremely" annoyed on a five point scale). The approach of Miedema and Vos also differs from other meta-analytic approaches in that it treats self-reported annoyance of individuals within noise exposure categories, rather than annoyance prevalence rates within communities, as the basic datum of interest. In other words, the Miedema and Vos approach analyzes individual reports combined across interviewing sites within studies rather than site-specific combinations of opinions. Combining individual reports across interviewing sites by noise exposure alone precludes detection of potential community-specific differences.

[3]Even though the optimal level of epidemiologic analysis is the individual, estimation of noise exposure for sub-sets of respondents is routinely based on outdoor measurements of exposure levels, rather than on individual, at-ear dosimetric measurements. This approximation alone probably limits the amount of variance that can be explained in the association between noise exposure and annoyance to considerably less than 100%. Schomer (2004) has suggested that a standardized house filter transformation, in combination with a loudness based-analysis, may reduce the error of measurement by more adequately estimating what people actually hear indoors.

[4]DNL is in any event an expedient but imperfect predictor of loudness, since it is an A-weighted rather than a loudness level-based noise metric. In the context of the total uncertainty of measurements of both transportation noise exposure and annoyance, however, DNL yields demonstrably useful estimates of the duration-adjusted loudness of transportation noise. Schomer, Suzuki, and Saito (2001) and Schomer (2004) have suggested specific duration-adjusted loudness formulations that appear to account for some of the differences between the annoyance of rotary and fixed-wing aircraft, and between takeoffs and landings.

[5]In the present formulation, the community-specific constant also reflects random errors of measurement. Refinements of the present estimation method could, in principle, segregate error of measurement into one or more epsilon values formally independent of both exposure and communities. For lack of an objective and straightforward method of estimating study-specific errors of measurement, however, and for reasons of parsimony, no effort is made at present to isolate estimates of the community-specific constant from study-specific errors of measurement. Further elaboration of the model, as well as applications to road and rail noise, are anticipated at a later date.

[6]The form of the CTL equation for which CTL equals the DNL value at which 50% of the population is highly annoyed is derived from the transition function $e^{-(A/m)}$. When $100\ e^{-(A/m)} = 50\%$, then $A/m = 0.693147$. The effective loudness function using DNL as the duration corrected loudness is defined as m, and $m = (10^{(\mathrm{DNL}/10)})^{0.3}$. So, $A = 0.693147m$ or, $A = 0.693147(10^{(\mathrm{DNL}/10)})^{0.3}$. Then, $33.33\log(A) = 33.33\log(0.693147) + 33.33\log(10^{(\mathrm{DNL}/10)})^{0.3}$ or $33.33\log(A) = 33.33\log(0.693147) + \mathrm{DNL}$. In this case DNL is equal to CTL, so $L_{ct} = 33.33\log(A) - 33.33\log(0.693147)$ or, finally, $L_{ct} = 33.33\log(A) + 5.31$.

[7]The estimates of variance accounted for at individual sites, derived as R^2 values, are less reliable for studies with observations of %HA proportions at small numbers of interviewing sites than for studies with larger numbers of observations, and should not be viewed as definitive.

[8]Speculative "explanations" for indifferent fits between data sets and the effective loudness function are readily found for most data sets. In the case of the Burbank data (Fidell *et al*., 1985), for example, major changes in runway use caused dramatic shifts in aircraft noise exposure at various interviewing sites from month to month. It is likely that annoyance prevalence rates had not stabilized at steady state levels at the times of interviewing in various neighborhoods. Lim *et al*. (2007) suggest forty other reasons that survey findings can differ from one study to another. *Post hoc* attributions of differences in survey findings to peculiar local circumstances, however, are ultimately of less systematic value than quantifying the differences in a manner that supports consistent interpretations.

[9]Estimates of population values of CTL based on the present data are reasonably robust. Summary values of CTL may be computed either for all of the individual interviewing sites, or for each study. The former approach weights studies by numbers of interviewing sites, while the latter gives equal weight to each study. The two estimates of the grand mean CTL value are within ± 0.6 dB of one another. Excluding one of the 43 cases (Lim *et al*., 2004) as an outlier affects the mean and standard deviation by only 0.5 dB. The grand mean changes from 73.3 dB (43 cases) to 73.8 dB (42 cases), while the standard deviation changes from 7.0 dB (43 cases) to 6.5 dB (42 cases). Estimating CTL from 541 individual data points rather than by study has a similarly minor effect on the grand mean and standard deviation. The grand mean CTL as estimated from individual data points is 72.1 dB, while the standard deviation is 7.2 dB.

[10]The Fisher r to z transform for this correlation yields a Z_r of 0.31. The standard error of Z_r value for the 43 cases in hand is 0.16. Since the 95% confidence interval for the correlation between DNL and CTL extends to zero, DNL and CTL do not appear to be meaningfully correlated with one another.

[11]Although airports may have had a different role at the time of interviewing than in recent years, there is little reason to believe that is the case for any of the airports examined in the current analysis.

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