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On the Stability of Community Tolerance for Aircraft Noise

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Summary
Although aircraft noise-induced annoyance prevalence rates vary greatly for similar noise exposure levels in different times and places, some suggest that communities have recently reacted more strongly to aircraft noise than in the past. Others regard claims of greater annoyance over time at similar exposure levels as inconclusive. The current study examined Community Tolerance Level (CTL) values for aircraft noise annoyance studies for temporal trends in 62 studies conducted between 1961 and 2015. The airports studied were classified as "high-rate-of-change" (HRC) and "low-rate-of-change" (LRC) airports. HRC airports experienced large changes in their operational patterns within three years prior to interviewing, or announcement of controversial plans for major changes, and/or extensive public discussions and media focus on operational issues. LRC airports experienced only minor changes in operations and no major noise-related controversies. No significant temporal trend in CTL values was observed over the past 50 years. However, lower tolerance for noise was observed in communities around HRC airports than in communities around LRC airports. Greater numbers of surveys of annoyance at HRC airports in recent years confound differences in CTL values with recency of assessment.

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1. Introduction

Annoyance prevalence rates in communities exposed to aircraft noise may increase over time either because exposed populations experience more noise, or because community tolerances for aircraft noise have decreased over time. Ideally, temporal trends in annoyance prevalence rates would be investigated via longitudinal studies of consistent design, in communities with stable noise exposure. Changes in airport communities' tolerance for noise exposure and changes in exposure levels, however, are more often than not confounded with other factors. Long-term changes in community exposure to aircraft noise may be either incremental or abrupt, and the accuracy and precision of survey and noise assessment methods have generally improved over time.

Fidell *et al.* [1] have introduced the concept of Community Tolerance Level (CTL). This is the noise exposure level at which 50% of the population of a specific community is highly annoyed. In their research paper they also relied on a fixed shape of the dose response function with its position relative to the exposure axis (x-axis) the only variable. The CTL value is a single number description of the prevalence of annoyance in a specific area (for instance the community around an airport). The CTL value thus represents a convenient tool for doing inter-study comparisons. The population of an area with low CTL value is less tolerant to noise than the residents of an area with a high CTL value, and vice versa.

Guski [2] interpreted the results of a repeated Swiss study on aircraft noise reported by Oliva [3] as producing no evidence of significant differences in annoyance reactions over the period 1971–1991. Kastka *et al.* [4] reported a large increase in annoyance prevalence rates between studies conducted in 1987 to 1995 at Düsseldorf Airport. Results of the 1995 study may have been influenced by fears that a newly built replacement for the main runway would attract additional air traffic.

Gelderblom *et al.* [5] replicated a 1991 study [6] of aircraft noise-induced annoyance at two airports in Norway. They observed no significant change in annoyance prevalence rates between 1991 and 2014. Although the airports experienced no major operational changes in the period between the studies, study methods differed slightly with respect to wording of questions, annoyance scales and noise metrics used.

Babisch *et al.* [7] adopted an indirect approach to analyzing temporal trends by comparing the average annoyance prevalence rates at four major European airports to the EU standard curve [8, 9]. In this "HYENA" study, Babisch *et al.* distinguished between aircraft noise annoyance during the day and night, but did not ask for overall

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annoyance due to aircraft noise. Vincent *et al.* [10] have shown that general annoyance cannot be determined from annoyance reports for specific periods of the day. Further, the sample of four airports studied by Babisch[1] *et al.* is less diverse than the set of studies used to construct the EU curve. The HYENA study nevertheless concluded (in part) that annoyance due to aircraft noise had increased over time.

A meta-analysis of trends in annoyance prevalence rates at different times and places is one alternative to the conduct of longitudinal studies. Several researchers ([11, 2, 12, 13, 14] *inter alia*) have attempted to discern consistent trends over time intended to yield a universal exposure-response function. (ISO 1996-1 [15]) summarizes many such efforts). Often, however, such analyses have effectively ignored trends in airport operational patterns over time.

Guski [2] found that a quarter of survey respondents were highly annoyed at a noise exposure level of $L_{\mathrm{den}} = 68$ dB in 1965, but the same percentage of respondents were highly annoyed at $L_{\mathrm{den}} = 61$ dB in 1990. Guski fitted a second order polynomial ($r^2 = 0.40$) to 18 data sets provided by Miedema and Vos [9]. A linear regression line ($r^2 = 0.38$) fitted to the same data sets indicates a decrease in tolerance for aircraft noise exposure of 0.31 dB/year.

Janssen *et al.* [12] analyzed the data from 34 aircraft noise studies spanning the period from 1967 to 2005. They found a significant increase over the years in expected annoyance at a given level of noise exposure. They pointed at high rate of expansion as a possible explanation of this year effect, but could neither confirm nor rule out this factor due to uncertainty in attributing the change-status to an airport.

Janssen and Guski [13] subsequently analyzed the findings of 32 aircraft noise annoyance surveys contained in a TNO database for the period 1961 to 2005. Janssen and Guski focused on the percentage of survey respondents describing themselves as highly annoyed at an exposure level of $L_{\mathrm{den}} = 55$ dB. They found that at $L_{\mathrm{den}} = 55$ dB, the prevalence of high annoyance had increased from about 10 percent in 1960 to about 30 percent in 2000. They also found that the sound level associated with an annoyance prevalence rate of 25 percent had decreased from about $L_{\mathrm{den}} = 65$ dB in 1970 to about $L_{\mathrm{den}} = 55$ dB in 2000.

Janssen and Guski [13] defined two classes of airports as follows: *For the purposes of this review, we call airports "low-rate change airports", as long as there is no indication of a sustained abrupt change of aircraft movements, or the published intention of the airport to change the number of movements within 3 years before and after the study. An abrupt change is defined here as a significant deviation in the trend of aircraft movements from the trend typical for the airport. Each trend is calculated by means of total movement data during a five year period. If the typical trend is disrupted significantly and permanent, we call this a "high-rate change airport". We also classify this airport in the latter category if there has been public discussion about the operational plans within 3 years before and after the study.* However, Janssen and Guski did not conduct separate analyses of the two types of airports.

Brooker [11] reported that although some indications may be found of a decrease in tolerance for noise exposure over the last 25 years, the reported trends are weak, and could also be attributed to sampling and/or methodological differences among studies. Van Kempen and Van Kamp [14] proposed several explanations for reported reductions in tolerance for aircraft noise over time, but found consistent and credible evidence lacking. Janssen *et al.* [12] observed that the annoyance scale used was an important source of heterogeneity in annoyance response, but dismissed it as a fully satisfactory explanation for the observed trend of a decrease in tolerance.

Noise exposure grows gradually at many airports, but in some cases, new runway construction, fleet changes, extension of operating hours or an increase in numbers of night flights or other events can cause abrupt changes. Such abrupt changes affect annoyance prevalence rates [16, 17, 18, 19]. Likewise, public debate and fear of future increases in aircraft noise exposure can also increase annoyance prevalence rates [14] when residents expect an abrupt change in noise exposure.

A temporal trend analysis should therefore take into account differences in reported aircraft annoyance prevalence rates in communities near low- and high rate of change ("LRC" and "HRC", respectively) airports, as defined by Janssen and Guski. A set of 62 aircraft noise annoyance survey outcomes was assembled and classified as either HRC or LRC for this purpose. The findings of these studies were then analyzed for temporal trends in community tolerance for aircraft noise exposure.

2. Method

The assembled field studies were classified as HRC or LRC airports as proposed by Janssen and Guski [13]. The criterion for classification as an HRC airport required a change in noise exposure and/or operational pattern to have occurred within three years of interviewing. An HRC classification also required that experienced or expected step-changes in airport operations last for more than three months. Information needed for this classification was gathered from several sources: that presented in original publications; that presented in Bassarab *et al.* [20]; that contained in the Airports Council International "Annual world airport traffic report" (ACI, 2014); at the relevant airport web sites; and through personal communications with researchers.

Note that classification of an airport as HRC is not determined solely by a step change in noise exposure. An airport is also classified as HRC if major changes in the operational pattern have been introduced or have been announced. Changes in the operational pattern may imply

[1] The HYENA study was conducted at six airports. The results at two of these (MXP and ATH) were excluded by the authors themselves.

Table I. CTL scores and rate of change classification of 62 aircraft noise annoyance studies conducted between 1961 and 2015. CRC: Change rate class (0 = LRC, 1 = HRC). (continued).

Study	Study year(s)	Primary authors	Report year	Number of interviews	Study Code	CTL	CRC
First Heathrow	1961	McKennell "Wilson report"	1963	1731	UKD-008	77.6	0
French A/C	1965–66	Alexandre	1970	2000	FRA-016	79.6	0
Second Heathrow	1967	MIL research, HMSO SS394	1971	4699	UKD-024	84	0
Tracor, large cities, phase II	1967–69	Connor and Patterson	1976	2912	USA-032	72.6	0
Tracor, large cities, phase I	1967–69	Connor and Patterson	1976	3590	USA-022	74.3	0
Munich A/C	1969	Rohrman *et al.*	1973	660	GER-034	78	0
Tracor, small cities	1970–71	Connor and Patterson	1972	1960	USA-044	86.3	0
Swiss A/C	1971–72	Grandjean *et al.*	1973	2995	SWI-053	76.6	0
Scandinavian A/C	1972	Rylander *et al.*	1972	2900	SWE-035	79.6	0
LAX	1973	Fidell and Jones	1975	940	USA-082	72.6	0
Canadian A/C-street	1978	Hall *et al.* (1979, 80, 81, 82)	1983	673	CAN-168	68.6	0
Burbank airport	1979–80	Fidell *et al.*	1985	5041	USA-203	63	1
Australian A/C	1980	Hede and Bullen	1982	3575	AUL-210	79	0
Orange County A/C	1981	Fidell *et al.*	1985	3103	USA-204	63.6	1
U.S. airbase	1981	Borsky	1983	874	USA-338	75.6	0
Westchester A/C	1982	Fidell *et al.*	1985	1465	USA-301	70.3	0
Decatur airport	1982	Schomer	1983	231	USA-250	78.6	0
Brussels airport	1980–85	Jonckheere	1988,89	677	BEL-288	82.3	0
Pittsburgh airport	1983	Fidell	1983	140	PIT	83	0
Glasgow	1984	Atkinson *et al.*	1985	608	UKD-238	70	0
Amsterdam	1984	Miedema	1987	581	NET-240	71.6	0
French A/C-road	1984–86	Vallet *et al.*	1988	1032	FRA-239	74.6	0
British ANIS	1982	Brooker *et al.*	1985	2173	UK-242	72.6	0
German A/C-road	1987	Kastka *et al.*	1996	516	GER-373	62.6	0
Small airports	1988–93	Rylander and Björkman	1997	513	SWE-419	70	0
Long Beach	1989	Fidell and Silvati	1989	2505	LGB	65	0
Oslo A/C	1989	Gjestland *et al.*	1990	3337	NOR-311	74.3	0
Trondheim Værnes	1990–91	Gjestland *et al.*	1994	1195	NOR-366	77.3	0
Atlanta	1991	Fidell and Silvati	1991	922	USA-349	72.3	0
Zurich + Geneva	1991	Oliva	1998	2052	SNS1990	72.6	0
Bodø Lufthavn	1992	Gjestland *et al.*	1994	3267	NOR-328	83	0

new flight procedures and/or new flight tracks but not necessarily a change in number of aircraft movements. Residents living near an HRC airport may or may not experience an actual increase or decrease in noise exposure. Noise exposure itself can remain unchanged, noise exposure patterns can change without a corresponding change in DNL, or both exposure levels and cumulative noise metrics can change.

3. Measure of change in community response

As described in Annex H of the current revision of ISO 1996-1 [15], a CTL value is a predicted value of a Day-Night Average Sound Level (DNL) at which half of the survey respondents report high annoyance with aircraft noise exposure. Large values of CTL indicate a high tolerance for noise exposure in a community, while small values of CTL indicate a low tolerance for noise exposure. Differences among survey findings may be characterized in decibel-denominated units via simple comparisons of CTL values across communities.

The shape of the dose-response function is fixed in CTL analysis, rather than derived from a curve fitting analysis. Its shape is based on the observation that the rate of change of annoyance with DNL closely resembles the rate of change of loudness with sound level. The CTL approach accounts for half again as much variance in the relationship between aircraft noise exposure and annoyance prevalence rates in communities as conventional analyses [1].

The position of the CTL dose-response function on the exposure (X) axis for a given community is determined empirically, from social survey data. The location of the dose-response function is fully specified by a single parameter which anchors the function to the X-axis. The slope of the dose-response relationship[2] is steepest at the 50% point, so that uncertainty in the percentage highly

[2] In conventional regression analysis, the shape of the dose-response relationship is an artifact of the analysis technique. Logistic regression, for example, yields a dose-response relationship of sigmoidal shape whose slope and position on the abscissa are determined by a best fit criterion to a set of data points. CTL analysis yields a dose-response relationship with a pre-defined shape. The only free parameter of CTL analysis is the position of the assumed relationship on the exposure axis.

Table I. Continuation.

Study	Study year(s)	Primary authors	Report year	Number of interviews	Study Code	CTL	CRC
Seattle A/C	1995	Fidell *et al.*	1998	1444	USA-431	81.3	0
Vancouver round 1	1995	Fidell *et al.*	2002	1000	CAN-385	84	0
Amsterdam	1996	Breugelmans *et al.*	2007	11812		62.3	1
Birmingham	1996	Witfield	2003	1072		66	1
Osaka international airport	1996	Yamada and Kakua	1996	215	JPN-491	68.3	1
Minneapolis (MSP)	1996	Fidell *et al.*	1996	2880	USA-428	74.3	0
El Segundo, CA (LAX)	1997	Fidell *et al.*	1999	644	USA-432	77.6	0
Vancouver round 2	1998	Fidell *et al.*	2002	1067	YVR	70.6	0
Frankfurt	1998	Kastka	1999	1147	FRA1	62.3	1
Orly/Roissy	1998	Vallet *et al.*	2000	1334	FRA-395	67.6	1
South San Fransisco	1999	Fidell and Silvati	1999	1250	SFO	71	0
Munich	2000	Kastka	2001	775	MUC	58.6	0
Swiss Zurich-Kloten	2001	Brink *et al.*	2008	1520	SWI-525	68	1
Amsterdam	2002	Breugelmans *et al.*	2007	640	GES-2	63.3	1
Richfield, MN (MSP)	2002	Fidell *et al.*	2002	495	MSP	72.6	0
Swiss Zurich-Kloten	2003	Brink *et al.*	2008	1444	SWI-534	69	1
Korean airports	2004	Lim *et al.*	2006	753	KOR-554	54.6	0
Amsterdam	2005	Breugelmans *et al.*	2007	478	GES-3	63.3	1
Cincinnati	2005	Fidell and Sneddon	2005	1606	CVG	71	1
ANASE	2005	Le Masurier *et al.*	2007	2132	UKD-604	63	0
Frankfurt	2005	Schreckenberg and Meis	2007	2309	FRA	63.3	1
Ho Chi Minh	2008	Nguyen *et al.*	2011	880		75.5	0
Hanoi-Noi Bai	2009	Nguyen *et al.*	2011	824		68.2	1
Da Nang	2011	Nguyen *et al.*	2012	528		75	0
Bodø	2014	Gelderblom *et al.*	2014	302		81.3	0
Trondheim-Værnes	2014	Gelderblom *et al.*	2014	300		82.3	0
Oslo-Gardermoen	2015	Gelderblom *et al.*	2016	300		68	1
Stavanger-Sola	2015	Gelderblom *et al.*	2016	302		80	0
Tromsø-Langnes	2015	Gelderblom *et al.*	2016	300		83	0
Hanoi-Noi Bai	2014	Thu Lan Nguyen	2015	890		65.6	1
Hanoi-Noi Bai	2015	Thu Lan Nguyen	2015	1121		63	1

annoyed introduces only relatively small inaccuracies in CTL values.

Various techniques can be used to fit the dose-response function to an existing data set. In this paper we have used a least-square technique. Other methods may be more appropriate. This is further explained in in a paper by Taraldsen *et al.* [21].

Fidell *et al.* [1] found a grand mean CTL value of 73.3 dB for the 43 aircraft noise studies that they analyzed. They also showed that for their predicted dose-response function, this average CTL differed only negligibly from the dose-response curve derived by Miedema and Vos [9] and recommended by the European Union. Higher annoyance prevalence rates with aircraft noise than predicted by the EU curve are associated with CTL values lower than 73.3 dB, and vice versa.

4. Data

For their initial CTL analysis, Fidell *et al.* [1] compiled a set of 43 studies conducted during the period 1961 to 2007. The present study combines the 43 studies analyzed by Fidell *et al.* with nine additional studies analyzed by Janssen and Guski [13], but not analyzed by Fidell *et al.* The present data set also includes the findings of five post-2007 studies from Vietnam [22, 23, 24, 25] and five studies from Norway [5, 26]. The entire dataset analyzed contains 650 paired observations of aircraft noise exposure and prevalence of high annoyance, measured in 100,631 interviews conducted in the course of 62 field surveys of aircraft noise annoyance conducted between 1961 and 2015.

Table I lists all 62 surveys, including their CTL values and HRC/LRC classification. The average unweighted CTL value for all 62 surveys is equal to 72.3 dB, with a standard deviation of 7.2 dB. Table II presents the rationale for the HRC classification.

5. Linear Regression Models

With CTL as the predicted variable and study year as predictor variable, simple linear regression is the simplest form of temporal trend analysis.

Univariate model:

$$\mathrm{CTL} = \beta_{\mathrm{intercept}} + \beta_{\mathrm{year}} x_{\mathrm{year}} \tag{1}$$

Table II. Basis for the HRC classification.

Study	year(s)	Rationale
Burbank airport	1979–80	Closure and reopening of runways due to major repairs. Main runway was closed from September 1979 to October 1980
Orange County A/C	1981	Evaluation of three different departure procedures for jet carriers fall 1981
Amsterdam	1996	Extensive public discussion about airport expansion
Birmingham	1996	Announced changes. In 1997 a major restructuring program that would double the airport capacity would be started
Osaka international airport	1996	Original plans to close the airport after opening of Kansai Airport in 1994, but in 1996 the airport was partly closed and rebuilt to serve domestic travel
Frankfurt	1998	More or less continuous protests against the airport since 1973. A new terminal that opened in 1994 allowed a large expansion over the following years
Orly/Roissy	1998	Evaluation of large increase in noise levels at Roissy Airport (CDG), personal communication, M. Vallet
Swiss Zurich-Kloten	2001	Public discussion about change of flight paths. Personal communication, M. Brink
Amsterdam	2002	Discussions about expansion. 6th runway completed in 2003
Swiss Zurich-Kloten	2003	New flight procedures were implemented. Personal communication, M. Brink
Amsterdam	2005	Changes in operations after 6th runway was completed
Cincinnati	2005	Large expansion of jet aircraft operations prior to study
Frankfurt	2005	US Air Force Base was closed and the location of maintenance facility for Airbus A380 was decided
Hanoi-Noi Bai	2009	Decision to expand airport
Oslo-Gardermoen	2015	High Court decision on economic compensation to some residents. Discussions about a third runway
Hanoi-Noi Bai	2014	Expansion nearly completed
Hanoi-Noi Bai	2015	Opening of new terminal. 20% increase in aircraft movements

This model can be extended by adding a second (HRC) predictor variable,

Multivariate model:

$$\mathrm{CTL} = \beta_{\mathrm{intercept}} + \beta_{\mathrm{year}} x_{\mathrm{year}} + \beta_{\mathrm{HRC}} x_{\mathrm{HRC}} \qquad (2)$$

High rate of change (x_{HRC}) is a dichotomous (True/False) variable. Its value depends on the recent occurrence or near-future expectation of abrupt, long-lasting changes in airport operations according to the definition above.

Response variables in a regression model should be weighted if they are of unequal variance. In case of a sufficient study sample size, the uncertainty of CTL values originates from often-unknown factors and uncertainties in noise estimates and survey methods. Weightings based on sample size would produce a questionable bias in favor of larger studies in the present case [21].

Brooker [11] notes that improvements in survey and noise estimation methods over time render CTL values of studies from 30-40 years ago more uncertain than those of more recent studies. The change of uncertainty over time is, however, difficult to quantify.

The univariate linear regression was therefore performed twice: once on the entire dataset of 62 studies, and once on a subset containing all surveys conducted within the last three decades. This subset contained 52 studies from 1978 and later.

6. Results

Figure 1 and Table III show the results of a simple linear regression analysis of the entire data set of 62 surveys, with study year as the sole predictor variable (Univariate model). The trend toward lower CTL values over time indicates a decrease in tolerance for aircraft noise exposure over time. The trend is a weak one that accounts for only 9% in the variance of the relationship between study year and CTL value, but its slope, −0.15 dB in CTL value per year, is unlikely to have arisen by chance alone.

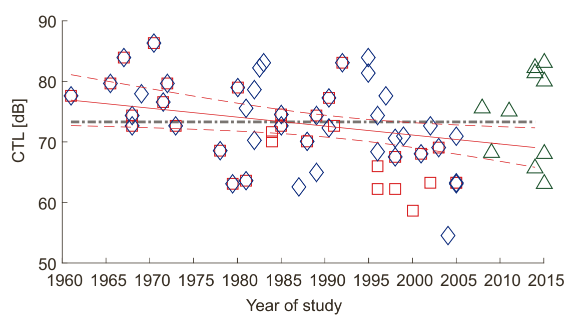

Figure 1. (Colour online) CTL values for 62 aircraft noise annoyance studies conducted between 1961 and 2015 (diamonds: Janssen and Guski, squares: Fidell *et al.*, triangles: Vietnam and Norway. The solid line ($R^2 = 0.09$) shows the linear fit of all data, including confidence intervals (dashed lines). The dash-dot line shows a constant CTL of 73.3 dB for comparison with the EU guideline.

Taken at face value, this finding suggests that people's tolerance for aircraft noise is currently about 8 dB lower than in the 1960s. Similarly, the aircraft noise exposure necessary to highly annoy 50% of residential populations

Table III. Linear regression results for the univariate model for the 62 aircraft noise annoyance studies conducted between 1961 and 2014.

Coefficient	Estimate	p
$\beta_{intercept}$	367	0.004
β_{year}	−0.15	0.020

Table IV. Linear regression results using the multivariate model for the 62 aircraft noise annoyance studies conducted between 1961 and 2014.

Coefficient	Estimate	p
$\beta_{intercept}$	161	0.17
β_{year}	−0.04	0.5
β_{HCR}	−8.7	0.00002

in 1970 is about 4.5 dB lower than that necessary to yield the same effect in 2000. This is less than half of the difference found by Janssen and Guski [13], but the present analysis also suggests a decrease in community tolerance for noise exposure. Additionally, the difference between the dash-dot line and the model fit indicates that communities in 2015 are about 4.5 dB ±3 dB less tolerant of aircraft noise than predicted by the EU dose-response curves.

Table IV shows the results of the multivariate linear regression. The effect of study year is reduced in the multivariate regression from 0.15 to 0.04 dB per year, and is not significant at $p \leq 0.05$. In other words, field study evidence does *not* support a claim that tolerance for aircraft noise has decreased over time in this analysis.

Figure 2 shows the results of the linear regression on the multivariate model with two predictive variables. The square symbols represent HRC studies, while triangular symbols represent the rest of the studies. The dichotomous nature of x_{HRC} results in two possible outcomes of the model. Tolerance for aircraft noise is 9 dB ±3 dB lower in studies at HRC airports; an effect unlikely to have occurred by chance alone. A CTL value of 73.7 dB ±3 dB in 2015 for steady-state conditions remains in good agreement with the earlier average of 73.3 dB reported by Fidell *et al.* [1].

After categorization by rate of change, the extended model accounts for 33% of the variance in the data. The data no longer exhibit a meaningful trend over time. Further, the year in which a study was conducted has a smaller effect on CTL than the univariate model suggests, and the fit does not predict the prevalence of aircraft noise-induced annoyance in 2015 to be significantly greater than the European guideline levels.

The above analysis weights all studies equally, even though the uncertainty of CTL estimates from earlier studies may be greater than of later studies. The analysis was therefore repeated for all airport surveys undertaken later than 1978. (The rationale for selecting 1978 as cut-off year is described above).

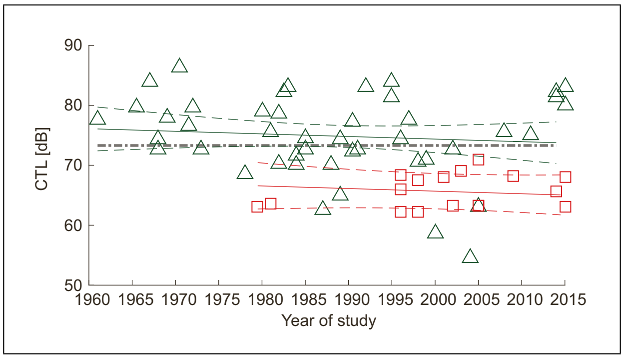

Figure 2. (Colour online) CTL values for 62 aircraft noise annoyance studies conducted between 1961 and 2015 categorized by HRC (squares) or LRC (triangles) (see text). The solid upper and lower lines show their respective linear fits ($R^2 = 0.33$), including confidence intervals (dashed lines). The dash-dot line shows a constant CTL of 73.3 dB for comparison with the EU standard curve.

Table V. Linear regression results using the univariate model for the 52 aircraft noise annoyance studies conducted between 1978 and 2015.

Coefficient	Estimate	p
$\beta_{intercept}$	166	0.4
β_{year}	−0.05	0.6

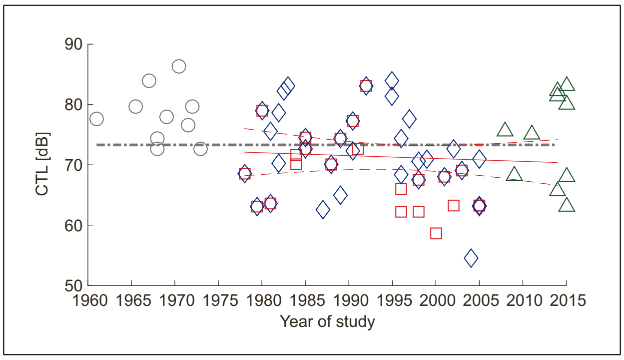

Figure 3. (Colour online) CTL values for 52 aircraft noise annoyance studies conducted between 1978 and 2015 (diamonds: Janssen and Guski, squares: Fidell *et al.*, triangles: Vietnam and Norway). The circles indicate excluded studies. The solid line shows the linear fit of all data ($R^2 = 0.005$), including confidence intervals (dashed lines). The dash-dot line shows a constant CTL of 73.3 dB for comparison with the EU standard curve.

Table V and Figure 3 show the result of a linear regression with only study year as a predictive parameter based on the 52 studies completed since 1978. Again, this univariate model explains only 9% of the variance in CTL scores, but for this subset, the effect of year is no longer significant at a significance level of $p \leq 0.05$. If a trend in tolerance for noise exposure exists, its magnitude over 40 years is no more than 2.1 dB. However, the CTL estimates for all years lie below the Fidell *et al.* [1] average (suggesting lower tolerance for noise), even though the confidence intervals for the fit are almost everywhere wide enough to include it. In short, CTL values appear to have been stable

Table VI. Linear regression results using the multivariate model for the 52 aircraft noise annoyance studies conducted between 1978 and 2015.

Coefficient	Estimate	p
$\beta_{\text{intercept}}$	−49	0.8
β_{year}	0.06	0.4
β_{HCR}	−8.7	0.00003

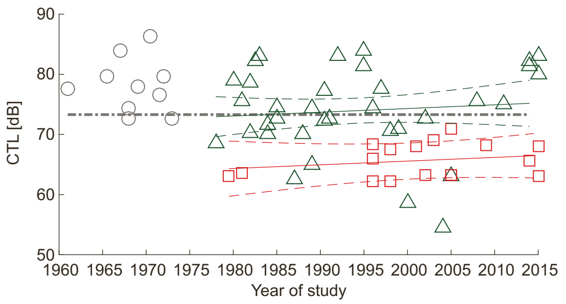

Figure 4. (Colour online) CTL values for 52 aircraft noise annoyance studies conducted between 1978 and 2015 categorized by HRC (squares) or LRC (triangles)(see text). The circles indicate excluded studies. The solid upper and lower lines show their respective linear fits ($R^2 = 0.3$), including confidence intervals (dashed lines). The dash-dot line shows a constant CTL of 73.3 dB for comparison with the EU standard curve.

in the past forty years, even if categorization is not taken into account.

Table VI and Figure 4 show the results of the multivariate model (considering HRC/LRC classification) from 1978 onward. Study year once again has no significant predictive value, and its effect size is negligible. Extending the model again improved the fit considerably, however, with the variance accounted for increasing to 30%.

CTL values in LRC communities are 75 dB ±7 dB, in good agreement with the European guideline. Tolerances for aircraft noise exposure noise at HRC airports were 9 dB ±4 dB lower than at the LRC airports.

The distribution of the two types of studies (LRC vs. HRC) explains these findings. The great majority of the HRC studies were conducted relatively recently (later than 1996). This group is therefore (overly) well represented in the past two decades.

As a result, the results from HRC studies depress the average CTL of studies from the past two decades. HRC studies do not affect the average CTL of studies earlier than 1978, as there is no evidence of HRC studies from this period.

7. Discussion

7.1. Classification of airports by rate of change

All 62 airports in this study were classified as LRC-airports by default. A re- classification to HRC was only done when information that matched the classification criteria defined by Janssen and Guski [13] could be found. As noted above, classification of studies was based on the original study publication *e.g.* journal articles, scientific reports etc., individual annual reports from the relevant time period by the airports themselves, and annual reports published by national and international bodies. Whenever feasible the scientists who conducted the different studies were contacted, and the HRC/LRC issue was discussed with them. About half of the studies had previously been classified by Janssen and Guski, and their classifications were re-assessed, and in a few cases reversed. After this process, about a quarter of the airports were classified as HRC-airports, see Table I. The rationale for the HRC classification has been listed in Table II.

7.2. Sensitivity of findings to misclassification of airports by rate of change

Since many of the field studies that were analyzed were conducted decades ago, information about rates of operational changes and other relevant classification information at some airports may be imperfect. The classification task has also a certain subjective element. In principle, an airport could thus have been misclassified as HRC instead of LRC, or *vice versa*. A simple Monte Carlo simulation was conducted to quantify the influence of potential misclassification errors.

Each of the 62 studies in Table I was assigned a random number, U, between 0 and 1. To determine the effect of, say, an incorrect misclassification rate of 5%, each survey assigned a U value less than 0.05 was re-classified from HRC to LRC or *vice versa*. The rate of change of classifications for surveys with U values greater than 0.05 were unchanged, and a new linear fit was performed for the complete data set as shown in Figure 4. Each new linear fit predicted two new CTL values (one for each category) for the year 2015. This procedure was repeated 100,000 times, yielding 100,000 estimates for today's CTL value for each category. Finally, means and standard deviations for these estimates were calculated. Similar calculations were performed for all other U values in the range 0 to 0.5 (in steps of 0.05), corresponding to 0% to 50% misclassification rates. The results are plotted in Figure 5.

The figure shows that the difference in CTL value for the two types of airports decreases as the percentage of classification errors increases. At a 50% misclassification rate (random classification), the difference between the two types disappears. A significant difference in CTL values between the two types of airports persists as long as at least 76.5% of the studies are correctly categorized. Given the care taken in making classification decisions about airports, it seems quite unlikely that mis-classification errors could have been made in 14 (23.5%) of the 62 cases considered.

7.3. Potential effects of population mobility

The temporal dynamics of noise-induced annoyance provide the broader context for understanding the results de-

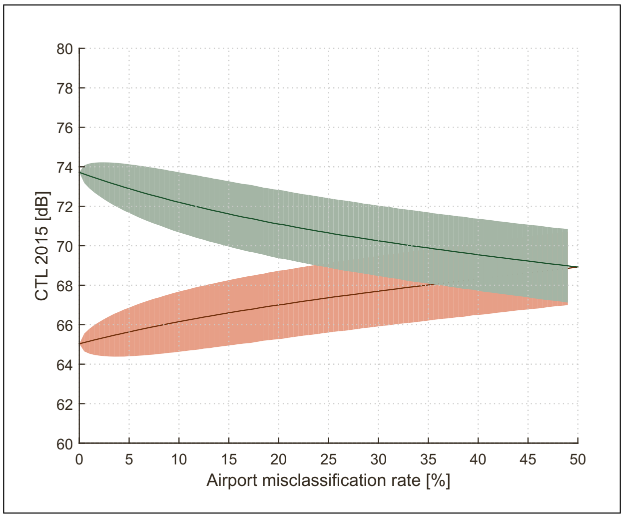

Figure 5. (Colour online) The influence of incorrect study classification. The two curves show the predicted CTL ($\pm 2\sigma$) in 2015 for an HRC airport (red) and an LRC airport (green) as a function of erroneous classification of rate of change.

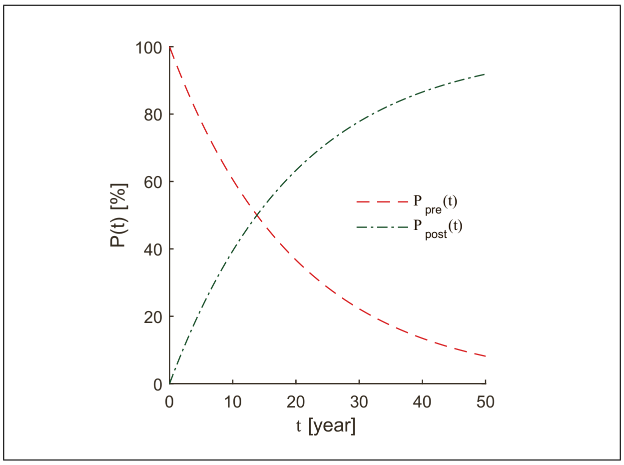

Figure 6. (Colour online) Example of change of resident type over time, when mobility rate is equal to 10% per year.

scribed above. The literature offers only a few systematic analyses or quantitative answers to questions about how promptly and closely annoyance prevalence rates track changes in transportation noise exposure (cf. [27, 28, 29, 30, 31]). Questions about the time constants of aircraft noise annoyance include "How long does it take for community annoyance to become fully aroused by a novel noise exposure situation?", "How much time must pass with stable operations before annoyance prevalence rates diminish?", "How much do short-term changes in annoyance prevalence rates overshoot or undershoot changes in exposure?", and in general, "How much and for how long do annoyance prevalence rates vary from asymptotic values as aircraft operations vary?"

Not all changes in annoyance prevalence rates are necessarily due to changes in noise exposure. As formally recognized by CTL analysis, attitudinal changes can affect annoyance prevalence rates as well. For example, feelings of helplessness and lack of control have been found to increase individual annoyance. A belief that people are not being treated fairly can also increase annoyance prevalence rates ([32, 33, 34] *inter alia*).

The community (rather than the individual) was selected as the unit of analysis for calculating CTL values in the belief that many factors affecting annoyance are similar for all residents of a community, but may differ widely between different communities. When a sudden change in airport operations occurs, it affects all residents, so the community's tolerance for aircraft noise change. A modicum of evidence [18, 30] suggests that an individual's elevated annoyance due to a sudden change does not subside over time: once highly annoyed, always highly annoyed.

However, community populations are not static over time. Some residents leave neighborhoods, while others arrive. Community size and composition may vary for noise exposure-related reasons, but also due to changes in land use, economic, and other social conditions. National census bureaus provide information on local migration. In 2010, ten percent of US households expressed a desire to move, and about half of these cited 'neighborhood conditions' as the main reason for their desire to change residence. In 2014, 12% of the US population actually did move to a new location (US Department of Commerce, 2015). Similar data from Norway show that in 2014, 15% of the population relocated to a new residence. The percentage of households which change residence annually ranges between 2% and 15% for all OECD countries [35].

The quantitative effects of population mobility on the stability of CTL values in airport neighborhoods can be assessed with the aid of a simple modeling exercise. Population mobility creates two categories of residents within communities: those who were present prior to a large operational change at an airport (pre-change residents), and those who moved in afterward (post-change residents). The first group decreases as a percentage of a community's population over time, while the second group grows at a similar but opposite rate

For a fixed total community size over time, the percentage of pre-change residents (P_{pre}) can be calculated recursively from the yearly mobility percentage rate (r_{m}) and the time (t) passed since the change.

$$P_{\text{pre}}(t) = \frac{100\% - r_{\text{m}}}{100\%} P_{\text{pre}}(t-1). \tag{3}$$

The percentage of post change residents at time t ($P_{\text{post}}(t)$) is then equal to

$$P_{\text{post}}(t) = 100\% - P_{\text{pre}}(t). \tag{4}$$

Figure 6 shows the change of resident type in the time following a change, at an assumed mobility rate of 10% per year.

Assuming that an operational change has permanently decreased the tolerance for aircraft noise of pre-change residents, while post-change residents have average tolerance for aircraft noise (or possibly even self-select for greater than average tolerance), the community's average

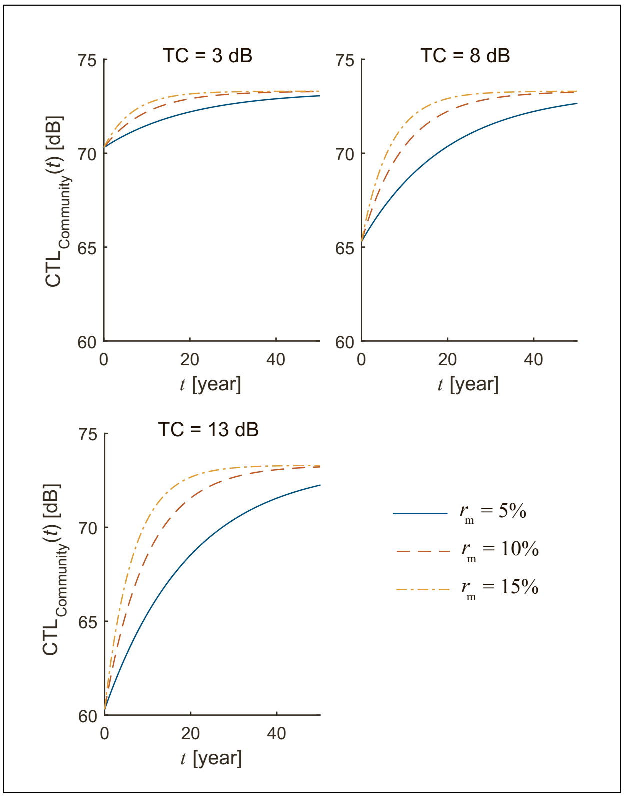

Figure 7. (Colour online) Examples of recovery in CTL values for a range of mobility rates and changes in tolerance for aircraft noise.

CTL over time ($\mathrm{CTL}_{\mathrm{Community}}(t)$) becomes a weighted average of CTL scores for each respective group of residents ($\mathrm{CTL}_{\mathrm{pre}}$ and $\mathrm{CTL}_{\mathrm{post}}$).

$$\mathrm{CTL}_{\mathrm{Community}}(t) = \frac{P_{\mathrm{pre}}(t)\mathrm{CTL}_{\mathrm{pre}} + P_{\mathrm{post}}(t)\mathrm{CTL}_{\mathrm{post}}}{100\%}. \quad (5)$$

Figure 7 shows the change of a community's CTL over time for different mobility rates and for different change in tolerance (TC), assuming that new residents are of average tolerance for noise exposure. Higher rates of mobility and smaller differences in tolerance of pre- and post-change residents lead to shorter recovery times, but the effects of a change in aircraft noise annoyance will generally take decades to disappear if only normal mobility of residents is considered. This is consistent with findings that recovery from excess reaction (overshoot) to noise changes is very slow [30].

Straightforward modeling of the effects of self-selection of neighborhood residents on the basis of tolerance for aircraft noise exposure provides some insights into potential effects of population changes on the temporal stability of annoyance prevalence rates and CTL values.

The model can be altered to take into account additional effects. The current modeling exercise suggests that following hypotheses merit testing in potential longitudinal studies:

- If residents who are highly annoyed by aircraft noise exposure are more likely to leave a neighborhood following an increase in aircraft noise exposure, $\mathrm{CTL}_{\mathrm{pre}}$ will increase over time, accelerating the increase of $\mathrm{CTL}_{\mathrm{Community}}$. The rate at which people move in and out of the community (r_{m}) may not be directly affected by a step change in the airport operations, but the selection of people who actually move may change.
- Similarly, if a step change in operations motivates residents to leave a community, which directly affects r_{m}, P_{pre} will decrease at a greater rate. Again, the increase of $\mathrm{CTL}_{\mathrm{Community}}$ over time will be quicker. This enhanced "recovery" of $\mathrm{CTL}_{\mathrm{Community}}$ may well depend on the size of the step increase in noise. It seems plausible that community residents who are highly annoyed by noise are more likely to leave a neighborhood in the aftermath of an increase in noise exposure, but data to support this assumption is inconclusive [36, 37]. In one aircraft noise study in Norway (NOR-311, 1989), respondents were asked about plans or desire to move. Among those (only about 1%) who had plans to move out of the community in the near future, none listed aircraft noise as the main reason. Gelderblom *et al.* [26] found that about 25% of the residents expressed plans or desires to move, but only 25% of these (about 6% of the total community) were highly annoyed by aircraft noise. About 40% of those wanting to move cited "noise" as their primary reason for moving, even though only half of them considered themselves highly annoyed.
- If residents who choose to move into a noise-exposed neighborhood are more tolerant of aircraft noise, the $\mathrm{CTL}_{\mathrm{post}}$ will be above average. If so, the community as a whole will eventually exhibit greater than average tolerance of noise exposure.

8. Conclusions

No evidence was found for a large enough temporal trend in aircraft noise-induced annoyance prevalence rates to justify updating existing exposure-response curves. The airports included in the current analysis were classified as low or high rate of change. Residents living near LRC airports experience relatively stable noise conditions and only incremental changes in the airport operations. Residents at HRC airports experience major changes in operational patterns, and/or controversial plans for anticipated changes, often accompanied by airport/community conflicts. Without this distinction between LRC and HRC airports, annoyance prevalence rates appear to have increased since the 1960s for the same noise exposure values. This observation is misleading, however, due to the temporal distribution of 'high rate of change' surveys. All but two surveys conducted before 1995 were conducted in communities with relative stable aircraft noise exposure and stable airport operations. In contrast, about half of the studies conducted after 1995 were conducted in communities at high rates of change airports. No significant increase or decrease over time in annoyance due to aircraft noise was observed when the rate of change of airport operations was taken into account.

The average annoyance response from HRC surveys indicated 9 dB ±6 dB less tolerance for aircraft noise compared with communities near LRC airports. The average annoyance response in airport communities with relatively stable operating conditions (LRC airport communities) was very similar to the mean CTL value for 43 aircraft noise surveys initially analyzed by Fidell *et al.* [1]. The exposure-response curve associated with this CTL value is almost identical to the exposure-response curve recommended by the European Union [8].

Incompleteness of available data, especially for studies completed decades ago, complicates classifying airport communities into LRC and HRC categories. The analysis of data is based on (and therefore sensitive to) the likely imperfection of the chosen categorization. However, the existence of a difference between CTL values for the two types of airports is robust. Even if nearly a quarter of the studies are misclassified, that tolerance for aircraft noise exposure is significantly lower at HRC airports than at LRC airports.

Although over-reaction caused by a major change in airport operations may be permanent and stable on an individual level, CTL values can eventually revert to pre-change levels due to migration of residential populations. Depending on the rate at which people move into and out of the community and the initial change in CTL, the effect of the change may persist for a decade or more.

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