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A COMPARISON BETWEEN THE USE OF LOUDNESS LEVEL WEIGHTING AND LOUDNESS MEASURES TO ASSESS ENVIRONMENTAL NOISE FROM COMBINED SOURCES

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ABSTRACT
Currently, most countries use some form of the A-weighted equivalent level (ALEQ) to assess most noises. Many adjustments have been suggested to provide a method whereby all noise can be assessed using ALEQ. Schomer [1] has suggested the used of equal-loudness-level contours [2] as a dynamic filter to be used in place of the A-weighting filter. He showed that loudness-level-weighted sound exposure level (LLSEL) and loudness-level-weighted equivalent level can be used to assess environmental noise without most of the adjustments required when using A-weighting. This paper compares the LLSEL with two methods based on loudness calculations using ISO 532b [3]. It shows that in terms of correlation with subjective judgments, the LLSEL formulation performs much better than do loudness calculations. In general, this result is true for both individual and combined sources.

1 - INTRODUCTION
Currently there is a need to assess the urban/suburban noise environment using a single, all encompassing method. Most countries use some form of the A-weighted equivalent level to assess most noises. Some have suggested that adjustments, possibly functions of level, be added to various noise source levels such that the resulting numerical levels provide for a correctly combined resulting metric when compared with community response. In principle, the LEQ or DNL for any transportation noise source is calculated from the A-weighted sound exposure levels of the individual vehicle passbys. Each train passby, each truck passby, and each plane flyby contributes some amount of sound energy to the time-period total. So, a priori, there is no inherent reason to expect any adjustment to be a function of the DNL. In fact, numerous regulatory jurisdictions, national and international standards, and journal papers have suggested such SEL-based adjustments.

Schomer [1] has suggested the use of equal-loudness-level contours [2] as a dynamic filter in place of the A-weighting filter. This new method provides a filter that changes with both sound level and frequency. Schomer showed that loudness-level-weighted sound exposure (LLSEL) and loudness-level-weighted equivalent level (LL-LEQ) can be used to assess environmental noise with most of the adjustments required when using A-weighting−especially for transportation noise sources. That is, compared to A-weighting, using Schomer's method, one can better assess a combined noise environment−without the need for any adjustments. The "adjustments" are inherent in the method and "operate" on each single event.

Some have asked why the general concepts of loudness were not used in the Schomer paper as some experiments have shown that loudness calculations can provide better rankings across sounds than does ASEL. To answer this question, this paper compares the LLSEL with two methods based on loudness calculations using ISO 532b. It shows that in terms of correlation with subjective judgments, the LLSEL formulation performs much better than do the loudness calculations based on ISO 532b. In general, this result is true for both individual and combined sources.

2 - A REVIEW OF THE LOUDNESS-LEVEL WEIGHTING METHODOLOGY

Equal-loudness-level contours are given in functional form in ISO 226 [3]. The functions in ISO 226 correspond to one-third-octave-band center frequencies from 20 Hz to 12500 Hz. Each one-third-octave-band sound pressure level (SPL) is assigned the phon level that corresponds to that frequency and level. For example, a one-third-octave-band SPL of 82 dB in the 125 Hz band would be assigned a value of 80 phon since it corresponds to a phon level of 80. Similarly, a one-third-octave-band level of 82 dB in the 31,5 Hz band would be assigned a value of 51 phon.
The overall phon level is calculated from this set of one-third-octave-band phon levels by summation on an energy basis. The frequency-summed phon level, L_{Lj}, at time t_j, is given by:

$$L_{Lj} = 10\log\left\langle \sum_{\mathrm{i}} 10^{(\mathrm{L_{Li}}/10)} \right\rangle \quad (1)$$

where L_{Li} is the phon level corresponding to the ith one-third-octave band.
The equal-loudness level contours show that the ear is less sensitive to noise at frequencies below 500 Hz and that the curves tend to converge with decreasing frequency. There are also temporal characteristics to hearing. Short-duration sounds are not perceived to be as loud as long-duration sounds. To be perceived with full loudness, sound must be present for a duration that is longer than the integration time of the ear. There is some general agreement that the integration time of the ear lies between 25 ms and 250 ms. Thus, level variations that occur over times that are long compared to about 100 ms will be perceived by the auditory system as varying in loudness. But the hearing process will not perceive level variations that occur over times that are short compared to 50 ms. That is to say, short-duration variations are integrated.
The above suggests that if the concept of energy-summation is to be retained, then the overall time- and frequency-summed phon level for an event such as an airplane flyby should be the (energy) sum of a time-series of frequency-summed phon levels. In the loudness-level-weighting procedure, the *fast*-integration time is used to provide an approximation to the integration time of the ear. That is, the output of a one-third-octave-band spectrum analyzer is set to *fast*-integration time and summed over time and frequency. As a practical matter, the output should be sampled sufficiently fast compared to 125 ms (*fast*-integration time)−say every 100 ms. This time-series of 100 ms, one-third-octave-band spectra is used to calculate the overall time- and frequency-summed phon level, L_L, that is given by:

$$L_L = 10\log\left\langle \sum_j \sum_i 10^{(L_{Lij}/10)} \right\rangle \quad (2)$$

where L_{Lij} is the phon level corresponding to the ith one-third-octave band during the jth time sample. The quantity calculated by (2), L_L, has been designated as the loudness-level weighted sound exposure level (LLSEL). It is similar to the A-weighted sound exposure level (ASEL) except that instead of using a filter (A-weighting) that varies only with frequency, LLSEL uses a dynamic filter that varies with both SPL and frequency. Moreover, the time series that is used to calculate LLSEL, is time weighted and sampled to compare roughly to the integration of sound by the ear. Note, additionally, one can calculate the loudness-level-weighted equivalent level (LL-LEQ) in an analogous fashion to the way one calculates A-weighted equivalent level.

3 - DATA ANALYSIS

3.1 - Equal-loudness-level contour data and corresponding community response data

Schomer calculated the LLSEL for a variety of sources and conditions and compared these with the known human response to these sounds. Specifically, Schomer evaluated road traffic at a variety of sites and in a variety of situations, aircraft taking off and landing, helicopter flybys, trains, and four sources of gunfire. These were compared with community responses garnered from a variety of sources.
In this analysis, the physical parameter of interest is the difference between the LLSEL and the ASEL for various noise events. For example, the literature suggests that aircraft noise is perhaps 5 dB more annoying than road traffic noise for the same A-weighted sound level. Suppose that the difference, Δ_R, between LLSEL and ASEL for motor vehicles is, on average, 10 dB, and that the Δ_A for aircraft flybys is, on average, 15 dB. Then the 5-dB adjustment that is required when using A-weighting is automatically

incorporated in the physical measurements if one uses LLSEL, because the difference between Δ_A and Δ_R is 5 dB.

3.2 - ISO 532b loudness data

For the above data analysis using the equal-loudness-level contours, a fast-time-weighted one-third-octave-band spectrum was sampled every 100 ms for each event. For the ISO 532b analysis, the loudness in sones and phons has been calculated using the ISO standard for each 100 ms one-third-octave-band spectrum. Two analyses have been performed, one based on sones and one based on phons. For the phone analysis, the 100 ms phon samples for each event have been summed on an energy basis to form the ISO 532b loudness (in phons) exposure level (LPZEL). Table 1 contains the results for the analysis using LPZEL.

For the sone analysis, the sones for every 100 ms sample for each event have been summed to form the total "sone-seconds" for that event. These total-sone-second values have been converted to a decibel like number by taking 10 times the logarithm base 10 of the total-sone-seconds. These are represented herein by the symbol LSZEL. As a further variant, the decibel conversion was performed using 10 times the logarithm base 2. However, the correlation between the base 2 and base 10 conversions is so high that only the base 10 conversion is further considered. Table 1 also contains the results when LSZEL is used.

Location	**Source**	**Subjective Response**			**LLSEL**	**LPZEL**	**LSZEL**
		Re Road Traffic (dB)			Inherent Correction re 5.0 dB−+12 dB for gunfire	Inherent Correction re 14.5 dB−+12 dB for gunfire	Inherent Correction re 76.0 dB−+12 dB for gunfire
		Base Case	**Alternate 1**	**Alternate 2**			
Munster	35 mm gun	16	16	16	14.8	14.6	4.4
APG	25 mm gun	16	16	16	15.8	15.3	9.5
APG	M-16 rifle	12	12	12	12.1	14.7	20.8
Munster	G-3 rifle	8	8	8	8.2	12.6	12.7
APG	Low Helicopter	6	12	7	5.8	5.0	13.7
APG	High Helicopter	6	12	7	4.5	5.6	13.8
Seattle	Airplane-takeoff	4	10	5	2.9	0.9	3.3
Seattle	Airplane-landing	4	10	5	1.0	0.6	1.9
Munster	Vehicles	0	0	0	0.7	4.0	7.3
Champaign	Street vehicles	0	0	0	1.6	4.3	4.7
APG	V1, V2, and V3	0	0	0	1.1	-1.1	6.6
APG	V4	0	0	0	2.1	-0.5	3.9

Location	**Source**	**Subjective Response** Re Road Traffic (dB)			**LLSEL** Inherent Correction re 5.0 dB−+12 dB for gunfire	**LPZEL** Inherent Correction re 14.5 dB−+12 dB for gunfire	**LSZEL** Inherent Correction re 76.0 dB−+12 dB for gunfire
		Base Case	**Alternate 1**	**Alternate 2**			
Tacoma	Freeway (noisy road surface)	0	0	0	0.5	3.0	-1.6
Tacoma	Freeway (noisy road surface, noisy trucks)	4	5	5	3.0	3.3	-4.2
Champaign	Freeway-trucks	0	0	0	-1.0	3.1	3.9
Champaign	Freeway-trucks	0	0	0	-2.2	-3.8	-1.3
Champaign	Freeway-autos	0	0	0	-3.1	-12.1	-19.5
APG	Train-electric-fast	-1	-5	-5	-0.5	2.9	2.3
APG	Train-electric-slowing	0	-5	-5	1.6	5.4	3.6
APG	Train-diesel-slow	4	5	5	3.0	5.0	9.2

Table 1: Summary of alternative subjective responses and corresponding calculation.

4 - DISCUSSION

Basic Results

Table 1 summarizes the results. It contains the community response adjustments relative to road traffic (including the two alternatives), and the physical data for the difference between the measure indicated and A-weighting relative to road traffic and including, in each case, the 12 dB adjustment for the gunfire sources. Figures 1a, 1b, and 1c plot the measures in Table 1 compared with the base case response values for LLSEL, LPZEL, and LSZEL, respectively. Each figure contains the equation fit to the line and the R-squared value. Clearly, LLSEL does the best job of correlating with these community response judgments.

However, one may suggest that the above analyses depend on the response judgments chosen. Therefore, alternative community response alternatives were hypothesized (Table 1) that exhibit somewhat larger adjustments for aircraft and trains. Table 2 contains the linear-fit equation parameters and R-squared values for each response alternative and each calculation method. For each case, LLSEL correlates much better with the response data than does either of the methods based on ISO 532b.

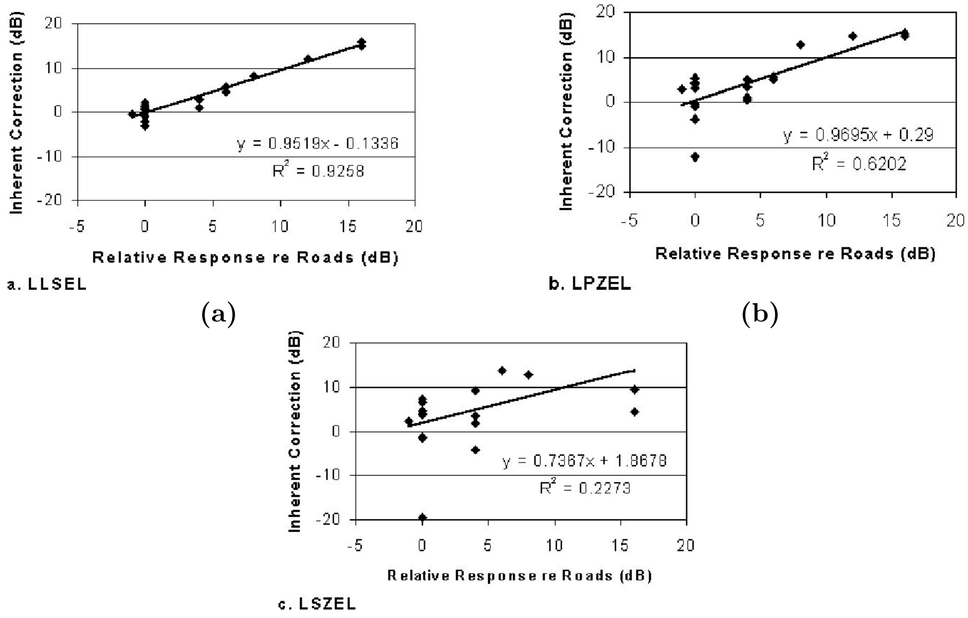

Figure 1: Correlation between subjective judgments and the calculation indicated.

CASE	CALCULATION	Y = K x + B		R^2
		K	B	
Base Case	LLSEL	0.9519	-0.1336	0.9258
	LPZEL	0.9695	0.2900	0.6202
	LSZEL	0.7367	1.8678	0.2273
Alternate 1	LLSEL	0.6404	0.5526	0.6514
	LPZEL	0.5905	1.2853	0.3576
	LSZEL	0.5842	1.9738	0.2222
Alternate 2	LLSEL	0.8005	0.5844	0.8160
	LPZEL	0.7693	1.1963	0.4867
	LSZEL	0.6273	2.3941	0.2054

Table 2: Linear-fit equation parameters and R-squared values for each response alternative and each calculation method.

5 - CONCLUSIONS

Loudness-level-weighted sound exposure level (LLSEL) and loudness-level-weighted equivalent level (LL-LEQ) can be used to assess environmental noise. Compared with A-weighting, loudness-level weighting better orders and assesses transportation noise sources, and with the addition of a 12-dB adjustment, loudness-level weighting better orders and assesses highly impulsive sounds.

The LLSEL does a significantly better job of assessing combined noise sources as compared with the methods based on the loudness calculations using ISO 532b examined herein. For any set of response judgments, the correlation with LLSEL is always much higher. Further, for just assessing gunfire or highway traffic alone, there is a clear benefit to the use of LLSEL over the methods based on the loudness calculations using ISO 532b. For trains or urban road traffic alone, no method is clearly better. However, when urban and highway traffic are combined together, LLSEL appears to be superior. For aircraft, the LLSEL and the LFZEL measures are better than the LSZEL measure.

Since Type 1, hand-held one-third-octave-band instruments are readily available at relatively low costs, it would be inexpensive to implement LLSEL and LL-LEQ capabilities in these hand-held instruments. Thus, significant improvements can be made to the measurement and assessment of environmental noise without resorting to the large number of adjustments that are required when assessing sound using the A-weighting.

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