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Low Frequency Noise from Transportation Sources

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ABSTRACT

Low frequency noise (LFN) is common as background noise in urban environments and as an emission from many artificial sources: road vehicles, aircraft, industrial machinery, artillery and mining explosions, and air movement machinery including wind turbines, compressors, and indoor ventilation and air conditioning units (Tempest, 1976; Leventhall, 1988 from St Pierre and Maguire [1]). LFN may also produce vibrations and rattles as secondary effects. The effects of LFN are of particular concern because of its pervasiveness due to numerous sources, efficient propagation and reduced efficacy of many structures (dwellings, walls, and hearing protection) in attenuating LFN compared with other noise.

Current transportation noise impact assessments are usually based on broadband A-weighted noise indicators. Over the past 50 years, the A-weighted sound pressure level (dB(A)) has become the major measurement descriptor used in noise assessment. This is despite the fact that many studies have shown that the use of the A-weighting curve underestimates the role that LFN plays in loudness perception, annoyance, and speech intelligibility. The de-emphasizing of LFN content by A-weighting can also lead to an underestimation of the exposure risk of some physical and psychological effects that have been associated with low frequency noise.

As a result of this reliance on dB(A) measurements, there is a lack of importance placed on minimizing LFN impacts. A more complete picture and better correlation with annoyance and health effects may result from indicators that include temporal aspects and frequency character. This paper presents an overview of some examples of low frequency indicators applied to transportation sources.

INTRODUCTION

Low frequency noise (LFN) is common as background noise in urban environments and as an emission from many artificial sources: road vehicles, aircraft, industrial machinery, artillery and mining explosions, and air movement machinery including wind turbines, compressors, and indoor ventilation and air conditioning units (Tempest, 1976; Leventhall, 1988 from St Pierre and Maguire [1]. LFN may also produce vibrations and rattles as secondary effects. The effects of LFN are of particular concern because of its pervasiveness due to numerous sources, efficient propagation and reduced efficacy of many structures (dwellings, walls, and hearing protection) in attenuating LFN compared with other noise. Current transportation noise impact assessments are usually based on broadband A-weighted noise indicators. Over the past 50 years, the A-weighted sound pressure level (dB(A)) has become the major measurement descriptor used in noise assessment. This is despite the fact that many studies have shown that the use of the A-weighting curve underestimates the role that LFN plays in loudness perception, annoyance, and speech intelligibility. The de-emphasizing of LFN content by A-weighting can also lead to an underestimation of the exposure risk of some physical and psychological effects that have been associated with low frequency noise.

As a result of this reliance on dB(A) measurements, there is a lack of importance placed on minimizing LFN impacts. A more complete picture and better correlation with annoyance and health effects may result from indicators that include temporal aspects and frequency character.

EFFECTS OF LOW FREQUENCY NOISE

For those who are sensitive to low frequency sound the effects can be dramatic. Complainants often describe the noise as:

- Pressure in the ears
- Affecting the whole body
- Sounding like a large, idling engine
- Coming from far away
- Arising in quiet rural or suburban environments
- Often close to inaudibility and heard by a minority of people
- Typically audible indoors and not outdoors
- More audible at night than during the day
- Having a throbbing and rumbly characteristic

Also, research relating to the effects of low frequency noise, including increased fatigue, reduced memory efficiency and increased risk of high blood pressure and heart ailments, were analyzed. The results showed a need to develop and utilize other measures of sound that more accurately represent the potential risk to humans. Kjellberg and Goldstein in St Pierre and Maguire [1] showed that dB(A) measurements can underestimate loudness by as much as 14 dB when the noise primarily consists of low frequency components (below 400 Hz). In reviewing studies comparing annoyance to dB(A) measurements, Leventhall [2] points out that dB(A) underestimates annoyance for frequencies below about 200 Hz. Brambilla et al from St Pierre and Maguire [1] when analyzing the noise produced by a skid steer loader, concluded “from the results obtained the A-weighted L_{Aeq} appears to not be adequately correlated with the perception of the noise at the operator’s seat in an earth moving machine, as it does not properly take into account the distribution of sound energy in the frequency, predominantly in the low-medium frequency range (40-315 Hz).” Finally, in surveying research into low frequency noise, Alves-Pereira et al from St Pierre and Maguire [1] concludes that “it is invalid to compare acoustical environments based on dB level measurements because, despite comparable dB level measurements, the distribution of the acoustic energy over the low frequency spectra can be substantially distinct.

MEASURING AND REGULATING LOW FREQUENCY NOISE

When prominent low-frequency noise components are present, noise measurements based on A-weighting are inappropriate. A-weighting has the effect of reducing measured levels of low and very high frequencies, but has less filtering effect on most mid-range sound frequencies where speech and communication are important.

Many jurisdictions measure both dB(A) and dB(C), and take the following steps (or something similar) to determine whether or not there is a low frequency noise problem:

Step 1: Determine difference (Δ) between dB(C) and dB(A).

The difference between dB(C) and dB(A) provides crude information about the presence of low frequency components in noise. Research suggests that when the difference (Δ) is great enough that further investigation or action related to the presence of low frequency noise is warranted.

- In Germany, $\Delta > 20$ dB is used as an initial indication of the presence of low frequency noise, and the need to conduct further investigations. (Leventhall, 2003 [2])
- If $\Delta > 10$ dB the World Health Organization (1999) [3] recommends that a frequency analysis of the noise be performed
- Kjellberg and co-workers (1997) [4] have suggested that when $\Delta > 15$ dB, an addition of 6 dB to the measured A-weighted level is a simple procedure for addressing the annoyance.

Step 2: Conduct frequency analysis of low frequency noise and compare to criteria.

There are numerous methods for determining the significance of low frequency noise. Over the past 25 years, many European countries (Sweden, the Netherlands, Germany, Denmark and Poland) have developed national criteria for environmental low frequency noise. According to Leventhall (2003) [2], the move to develop criteria was driven by specific problems, "particularly gas turbine installations, which radiate high levels of low frequency noise from their discharge." Low frequency threshold curves for the European countries mentioned above are shown in Figure 1.

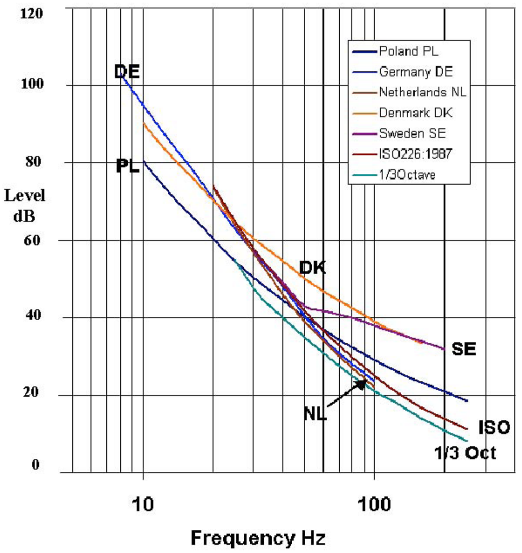

Figure 1. Low frequency threshold curves for various European countries Source: (Leventhall Powerpoint)

In Sweden and Germany, low frequency noise may be considered a nuisance if its level exceeds a criterion in any third-octave band. In the United States, a standard for low frequency noise from wind turbines has been developed for the U.S. Department of Energy. (Kelley, 1987) [5] Also, some counties in northern Michigan have developed ordinances that reference low frequency noise as separate to other noise issues. Denmark has taken an entirely different approach. Queensland in their draft Ecoaccess Guideline ‘*Assessment of Low Frequency Noise*’ 2010 [6] has applied a combination of the German and Danish guidelines.

LOW FREQUENCY NOISE SOURCES AND IMPACTS

Low frequency noise and infrasound are produced by machinery, both rotational and reciprocating, and all forms of transport and turbulence. Typical sources include pumps, compressors, diesel engines, aircraft and fans.

Combustion turbines are capable of producing high levels of low frequency noise generated by the exhaust gas.

Burners can emit broadband low frequency flame roar.

Structure borne noise, originating in vibration, is also of low frequency, as is neighbourhood noise heard through a wall, since the wall attenuates higher frequencies more than lower frequencies.

Low frequency noise can be noise or vibration from traffic or from industries, totally or partly transmitted through the ground as vibration and re-radiated from the floor or the walls in the dwelling.

Low frequency noise creates a large potential for community annoyance. It is most often experienced inside of homes and buildings where resonance amplifies the sound. It is a general observation that indoor noise is perceived as more "low-frequency-like" than the same noise heard out of doors. (Torben Poulsen,and Frank Rysgaard, 2002 [7]).

Also, low frequency noise can be a factor at much greater distances than audible noise sources. A case study in Northern Carolina near a wind turbine documented low frequency noise problems at residences located more than 1/2 mile from the turbine. (SERI, 1995 [8]).

The firing rate of many diesel engines is usually below 100 Hz, so categories of road vehicle noise can be regarded as low frequency. Similar considerations can be made for engines or compressors in industries or co-production plants.

Further analysis in this paper is based on the frequency content of LFN from motor vehicles close to the source and at distant receptor locations, the particularly annoying character of engine brake noise and the low frequency indicators applied to transportation sources by various countries.

MOTOR VEHICLE EMISSIONS

Netherlands

In the Netherlands many complaints about LFN from traffic are reported. When specific complaints are mentioned then these relate to accelerating and stationary conditions.

Specific sources include:

- Exhaust systems
- City buses
- Motorcycles; and
- Heavy traffic

An example of a city bus is given where complaints were investigated from residents living close to bus stops and at traffic lights.

The bus company had received a number of complaints about the introduction of a new bus model and an investigation was commenced.

Measurements were taken on two different types of bus (old and a newer version). Both were correctly approved according to the R51 drive by test. The new model emitted more low frequency noise: slightly during R51 acceleration and stand still and significantly during pulling away from stand still in the 50-70 Hz range. As a result the manufacturer was requested to optimize the exhaust system and the bus company introduced ‘bus stop’ noise criteria for all newly purchased buses.

Exhausts normally emit the firing frequency and higher harmonics.

In this case: A 6 cylinder 4 stroke line engine at 500 rpm has a firing frequency = 500/60 * 6 / 2 = 25 Hz with higher harmonics: 50 Hz, 75 Hz and so on.

A V8 engine produces four exhaust pulses per revolution, a V6 or straight six produces three, and a four cylinder produces two. At 2,200 rpm, which is a typical highway cruising speed, a V8 engine is spinning at 37 times a second and is producing a frequency of 148 Hz. Such low frequency tones can also easily penetrate the passenger compartment and create harmonics in the entire exhaust system, resulting in a droning, moaning or booming noise.

Germany

In considering vehicle noise regulations and sound filtering via weighting networks it was observed that:

“Vehicle test results are generally in the range of 70-80 phon and measured in dB(A). However, if dB(A) is used for noise levels of 70-80 phon, the influence of low frequencies is underestimated as low frequencies are filtered out. The question was raised as to the justification for the use of dB(A) in vehicle noise certification tests”.

Australia [9]

A sound power level survey was conducted during 2010 of vehicles on Queensland, Australia roads to produce a database of vehicle sound power levels categorised on vehicle classification, speed, pavement surface type and driving conditions. The purpose of this study was to compare the local vehicle sound power levels with similar surveys conducted in Europe in application of the Nordic and Harmonoise prediction methods.

The sound power level of individual vehicles in-situ traffic was measured generally following the Nordtest Method 109 (NT ACOU 109).

The L_{eq} and L_{max} in 1/3 octave bands from 20Hz to 20kHz of an individual vehicle was measured with a known microphone distance and were recorded directly into a spreadsheet database with details of the vehicle classification and speed for each of the different pavement surface types investigated.

The final L_w using the Nordtest method for each 1/3 octave band was the highest L_w obtained from the 0.2m and 4.0m microphones.

The spread of sound power level across the assessed vehicle categories was compared with the mean Harmonoise sound power level from 80km/hr to 110km/hr.

Comparisons were made only with Harmonoise major classifications as follows: Category 1 = Light (eg cars), Category 2 = Medium (eg. trucks and buses) and Category 3 = Heavy (eg. trucks and buses).

With category 1 vehicles the notable features was the relatively larger variability in the 80Hz and 100Hz 1/3 octave bands which was attributed to faulty or modified exhausts (based on site observations).

Queensland’s mean sound power levels in terms of overall, dB(A) and overall – dB(A) as well as the sound pressure levels at predominant 1/3rd octave bands for various vehicle categories are illustrated in Table 1.

Category	Description of vehicle	Overall dB	A^+ dB	Δ dB(C)-dB(A)	1/3rd octave band centre frequency & level (dB)
1	Light	108	106	2	100 @1000 Hz
2	Medium	113	110	3	103 @ 800/1000 Hz
3	Heavy	120	115	5	110 @ 80 Hz (tonal)

Table 1: Queensland mean sound power levels and 1/3rd octave band centre frequencies for various vehicle categories

In all three vehicle categories, the influence of the exhaust system was clearly observable, in particular for category 3 vehicles. The largest variability in heavy vehicles is in the 80Hz band, and the mean for Queensland was found to be significantly higher than the mean for Harmonoise.

The initial summary of the observations were:

1. Queensland vehicle sound power levels generally follow the same spectral characteristic trends as the Harmonoise calculated sound power levels.

2. Exhaust noise in Queensland tends to dominate the 80Hz 1/3 octave band whereas it dominates the 63Hz 1/3 octave band in the Harmonoise method.

Transportation Noise Reference Book [10]

Chapter 12 [11] from the reference book considers the generation and propagation of low frequency noise and ground borne vibration from traffic.

Hollingsworth and Gilbert [12] predicted low frequency noise from traffic streams. They used the indicator L_{Aeq} (15 min)(40-125 Hz) to predict the LFN from a mixed traffic stream at a height of 1.2m and reference distance 10m from nearside kerb.

At this distance:

LAeq (15 min)(40-125 Hz) = 53.0+9.43 log (Q1 + 10Q_{MCV} + 40Q_{HCV})+ gradient correction

where: LAeq (40-125Hz) = energy equivalent level over frequency range stated. This covers effects of chest resonance and floor vibrations.

Q1 = total hourly vehicle flow , veh/hr

Q_{MCV} = flow of meduim commercial vehicles , veh/hr

Q_{HCV} = flow of heavy commercial vehicles , veh/hr

Typical values for LAeq (15 min)(40-125 Hz) for four different hourly vehicle flows, 60 % medium, 5 % heavy commercial vehicles and 3 ranges of gradient correction are shown in Table 2.

Total vehicle flow, veh/hr	200	1000	1750	2200
Gradient, 0-3%	85	92	94	95
Gradient, 3-4%	86	93	95	96
Gradient, 5-6%	87	93	96	97

Table 2: LAeq (15 min)(40-125 Hz) for different vehicle flows, % vehicle mix and gradients

Classification of vehicles:

a) Includes motor bikes (all types), cars (all types), light commercial vehicles (car-based vans and/or two axle commercial vehicles) with unladen vehicle weight<=3000kg

b) Meduim vehicles (commercial vehicles with two axles and unladen vehicle weight>3000kg, including all buses and coaches

c) Heavy vehicles (all commercial vehicles where the number of axles>=3)

MOTOR VEHICLES IMMISSIONS

Netherlands [13]

The increase in power ratings and dimensions of cars, trucks and other equipment makes low-frequency noise an increasing concern. In van den Berg's paper [13] the impact of low-frequency noise or the share of low-frequency in noises from various sources on human health and well being was investigated.

For annoyance, however the influence of low frequency content has been well studied. Most of these studies come from studies of the effects of heavy artillery. The main finding is that the relation between rating level and effect improves substantially if the difference between A-weighted and C-weighted levels are taken into account. Preliminary results for road traffic indicate that this is also valid in this area. The current best estimate for an adjusted low-frequency level is based on the difference between C-weighted and A-weighted levels, in the general form:

$$L_{LF,adj} = L_A + \alpha^*(L_C - L_A)^*(L_A - \beta)$$

where $L_{LF,adj}$ = adjusted low-frequency level, L_A = the A-weighted level and L_C = C-weighted level and α and β are empirical correction factors. The best estimate for α=0.015 and β= 47.

Table 3 shows the low frequency adjustment Δ L_{LF} for various L_C-L_A differences.

L_C	L_A	L_C-L_A	$L_{LF,ADJ}$	Δ L_{LF}
115	90	25	106.1	16
105	85	20	96.4	11.4
95	80	15	87.4	7.4
85	75	10	79.2	4.2
75	70	5	71.7	1.7

Table 3: Low frequency adjustment Δ L_{LF} for various L_C-L_A differences

The large scale study showed that for many sources large differences between A-weighted and C-weighted levels do occur in practice. Table 4 shows typical results for different sources.

Difference between A-weighted SEL and C-weighted SEL for different sources in dB		
Source	**Average**	**Maximum**
Rail traffic	5.3	15
Road traffic	7.1	15
Aircraft	9.1	13
Industry	13.2	24
Ships	13.8	21

Table 4. Differences between A-weighted SEL and C-weighted SEL for different transport sources

These results are based on outside measurements. As houses attenuate higher frequencies much beter than lower frequencies, the differences inside may be 5-15 dB higher.

The conclusions arrived at by van den Berg were that low frequency sound can have far reaching biological consequences which scientists are just beginning to understand. In view of this the precautionary principle demands that at least further increase of low frequency should be limited. Relatively simple methods are available.

Germany [14]

There was minimal road traffic prior to 1990 in villages near the border of the former German Democratic Republic. As a result no by-pass roads were built, but after the reunification of Germany the situation changed dramatically in some villages. One example is Barbis, Bad Lauterberg, near the Harz Mountains. Heavy goods traffic from the Hanover region to the Halle-Bitterfeld industrial area flows day and night through the narrow streets. On average every 2 minutes during the night, a heavy truck passes by the houses within a distance of 1-3 m. Complaints from the community were referred to the Federal Environmental Agency for investigation and a pilot study was planned to investigate potential health effects.

Figure 2. Heavy vehicle traversing rural area entering village Source: (Cedric 2006)

About 40 families living in the vicinity of street B 243 and after an additional invitation 10 families from a quiet village agreed to cooperate.

Medical checks were made of 56 children aged 7 - 10 and they and their mothers completed questionnaires. The main purpose of this study was to test the hypothesis that noise generally causes more cortisol increases in the first half of the night, because some of the exposed persons reacted with cortisol decreases in the second half of the night. The children lived either at a busy road with 24 h truck traffic or in quiet areas. At the side of the road the noise level was registered during five nights. In the bedrooms representative measurements of the short-term maximum sound pressure level (L_{Amax} and L_{Cmax}) and of the frequency spectrum were taken. During the night on average every 2 minutes a truck with L_{Amax} > 80 dB(A) passed by the houses.

The indoor levels of the higher exposed half of the children were L_{Amax} = 33-52 dB(A) and 55-78dB(C) with a range of Δ = 22 to 26 dB. The frequency spectrum had its maximum below 100 Hz.

The study indicated that a limitation to L_{Amax} < 45 dB(A) as suggested by WHO (2000) [3] does not protect against awakening due to low frequency truck noise. It is necessary, therefore, to develop safer limits for low frequency night-time noise.

During the field phase the sound pressure level was recorded as 4sec mean levels (L_{Aeq}) and maximum level (L_{Fmax}, time constant "fast") for five days and nights. In the noise exposed sleeping rooms of the participating children representative short term measurements of the indoor L_{Fmax} of passing trucks were carried out with frequency weightings "A" and "C".

Results

The maximum free field sound pressure level of trucks passing by reached 90 dB(A) at a distance of 3m from the roadside kerb and at a distance of 8 m from the nearest house. The mean level at night (10 pm till 6 am) varied between 65 and 70 dB(A) and resulted in an average of 67.1 ± 1.7 dB(A). The number of passing lorries with L_{Fmax} > 80 dB(A) was found to be 220 ± 72.

Most of the highly exposed houses were fitted with special sound insulating windows. Nevertheless the low frequency noise of passing trucks could be clearly heard. A third octave spectrum of the mean L_{Fmax} and the L_{Aeq} was taken in one of the highest exposed rooms. The mean L_{Fmax} amounted to 78 dB(C) and 53 dB(A) with Δ = 25 dB. The mean indoor L_{Fmax} varied between 55 and 78 dB(C) and 26 and 53 dB(A) with Δ

= 29 dB and Δ = 25 dB respectively in the higher exposed group.

Netherlands [15]

In the Netherlands, transport activities from roadways, airports and railways are major noise sources. The resulting noise levels have a severe impact on the environmental quality. Noise from roadway traffic causes the highest rate of annoyance: 29% of the Dutch population above the age of sixteen are severely annoyed by this source.

Because complaints due to LF noise are often difficult to resolve, these complaints take up a disproportionate amount of time. To address this, RIVM has modelled and mapped the LF noise from motorways. The research program aimed at extending knowledge on noise exposure from the usual A-weighted noise exposure indicator (L_{den}) to other noise indicators such as background noise levels and low frequency (LF) noise.

After modelling LF noise, RIVM used two methods to evaluate the scope of the LF noise exposure, namely the guidelines proposed by the Dutch Association for Noise Annoyance (NSG) [16] and a method based on the difference between C-weighted and A-weighted noise levels.

NSG guideline [16]

In the NSG guideline the reference values are based on the hearing threshold for a group of 50 to 60 year old people, of which 10% are just able to hear the sound.

In order to objectively evaluate the complaint, the sound levels of the frequencies in the defined region are compared to the reference values. If these reference values are exceeded, it is assumed that the complaint is objectively attributable to a LF source.

C-A method

In order to apply the NSG method, the sound pressure levels in dB had to be assessed for each of the 1/3 octave bands. Since measuring noise for specific frequencies requires specialized equipment, RIVM proposed to assess the LF content in the total spectrum of the noise by assessing the difference between average C-weighted and A-weighted values.

Noise Maps

Using traffic data from the Dutch motorways, LF noise maps for the major motorways were set up according to the two methods outlined above. All calculated outdoor levels were converted to indoor levels before testing, using the isolation from Table 5 [17].

Frequency (Hz)	**20**	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**
Reference (dB)	74	62	55	46	39	33	27	22
Assumed isolation (dB)	8	9	10	11	12	13	14	16

Table 5. Reference threshold values (NSG) for LFN assessment and assumed isolation

Isolation is based on the sound isolation characteristics of 4mm glass. All indoor levels were calculated for average night-time exposure from 23:00 to 07:00 hours. In order to apply the NSG assessment, the RIVM model was used to calculate the noise exposure for single octave band frequencies. For the low frequency region, this means that calculations for the 31.5 Hz, 63 Hz and 125 Hz octave bands were made. The noise exposure levels were subsequently weighted with the isolation values from Table 5. Taking the maximum of the three weighted levels resulted in a measure of low frequency noise exposure caused by road traffic.

For the C-A weighting method, the RIVM model was applied to calculate C-weighted and A-weighted noise exposure for the entire frequency range. The result of the subtraction of the two exposure levels (Δ) revealed the low frequency characteristic of the noise exposure.

The noise map of the ‘Randstad’ region for the dwellings where the NSG guideline was applied demonstrated exceedences up to 15 dB (classified as high). The noise map for the same area using the C-A method gave exceedences as high as 28 dB and as low as 10 dB.

When observing the entire noise map for both methods, two problem areas emerge where the noise exposure contains unusually high levels in the lower frequencies. These turned out to be areas behind noise barriers, and motorways with a large amount of heavy vehicle traffic.

Table 6 shows the number of households situated in areas where the limits proposed by the NSG were exceeded, or where C-A weighted noise levels exceeded 15 or 20 dB. As can be seen, the number of households where these limits were exceeded can be substantial. Table 6 shows that the frequency of 125 Hz is important when looking at the number of exposed households.

Guideline	**Number of households (min)**	**Percentage of total (%)**
NSG guideline 63 Hz	3.0	43
NSG guideline 125 Hz	5.6	79
NSG guideline 63 or 125 Hz	5.6	79
C-A >= 15 dB	4.2	59
C-A >= 20 dB	0.64	9

Table 6. Number and percentage of households exceeding two guidelines for LF noise in Dutch study

Almost 80% of households in the Netherlands showed a LF noise exposure exceeding the NSG guideline. In the Randstad this guideline was exceeded almost everywhere. From the results it seems that the frequency of 125 Hz is the determining factor in the amount of exposure. However, in more than half of those households the limit for 63 Hz was also exceeded.

Other Noise Evaluation Methods [18] [19]

In looking to alternative methods of evaluating sound, one needs look no further than the original 1936 sound level meter standard. In that standard, the B-weighting scale was introduced and since has drifted into obscurity, even though its inclusion in sound level meters is still required to meet full ANSI S1.4 – 1983 standards. Several studies have shown that the B-weighting scale correlates much better to subjective responses than the A-weighting scale, most likely because it is based on the 70 phon equal loudness curve which is more applicable to most typical transport noise events.

Aarts from St Pierre and Maguire [1] compared dBA, dBB, dBC and dBD and both ISO 532 loudness measurements to subjective responses using pink noise. The surprising result was that dBB correlated best to the subjective response with the Zwicker loudness method (ISO 532B) close behind. Only dBD (which was originally devised for aircraft fly over noise) performed worse than dBA. In every case tested, the dBA measurement underestimated the subjective loudness. It was stated that it is unfortunate that the B-weighting filter is no longer used or studied.

Recently, Schomer [18] has devised a method of noise assessment that uses the same equal loudness contours (ISO 226, 1987) used for the A- and B- weighting scale. However, he uses these contours dynamically based on the overall sound level present. As a result, the weighting filter is adjusted based on the overall level to the closest approximation to the correct equal loudness contour. In his first comparison, Schomer showed that this method, called the loudness-level-weighted equivalent level (LL-LEQ), provided a better assessment of various transportation noises than A-weighted measurements [18].

In a later study, Schomer compared LL-SEQ to the ISO 532b loudness measurement and found them to be very well correlated and in some cases, especially with impulsive noise, there is a benefit to using the LL-SEQ method [19]. Compared with A-weighting, loudness level weighting better orders and assesses transportation noise sources, and it better assesses sounds with strong low frequency content. Once again, the technology is readily available to incorporate this type of dynamic filter into sound level meters.

Engine Brake Noise – Draft Regulatory Impact Statement developed in Australia [20]

Engine brake noise is the greatest source of community complaint against the heavy vehicle industry in Australia. Not only does it adversely affect a large part of the population in all areas of the country, but it also has the potential to adversely affect heavy vehicle productivity because of demands for curfews and other restrictions arising from affected populations.

Figure 3. Jakes exhaust brake muffler fitted to a large truck

Source: (Cedric 2007)

Engine brake noise is generally low frequency (i.e. less than 200 Hz). Understanding the nature of low frequency noise is important in properly addressing engine brake noise, recognising that customary approaches to traffic noise: constructing roadside noise barriers or sound proofing houses, do not adequately address the low frequency characteristics of engine brakes.

One method of controlling engine brake noise is to fit a Jakes muffler as shown in Figure 3.

An in-service engine brake noise standard that will target excessively annoying engine brakes has been developed using the research undertaken in Australia.

The National Transport Commission (NTC) has addressed the situation by undertaking research to determine the feasibility of a regulatory solution to engine brake noise.

A critical part of the problem is that there is no internationally accepted measure of engine brake noise. The characteristic 'bark' of an engine brake is the source of most complaints. However, the standard A-weighted scale will not identify the annoying pulses or variations in noise that people often find more annoying than the decibel level alone as the pitch (or frequency) of the sound also contributes to the sensation of loudness of the sound.

NTC commissioned Sonus Pty Ltd [22] to investigate a means of detecting noisy engine brakes via a roadside test using robust methodology.

Sonus found that there are few reports in the literature that go beyond using a traditional maximum noise level to describe engine brake noise and that traditional maximum noise measurements do not identify the annoyance of engine brakes. Sonus found that the modulation of engine brake noise at low frequencies was the cause of annoyance and an assessment of the modulation characteristics of the waveform was necessary. Figure 4 shows an engine brake noise trace. It clearly shows many 'up and down' movements referred to as 'modulation'.

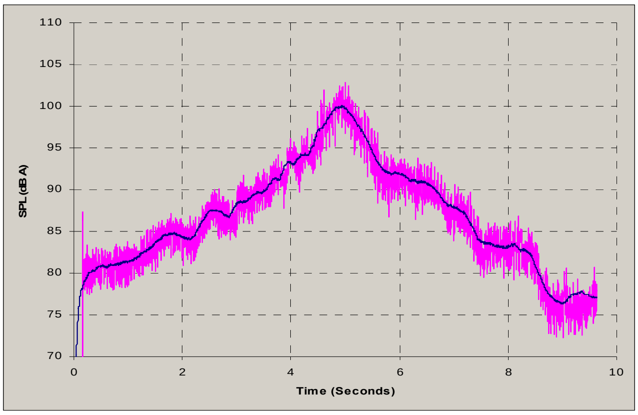

Figure 4. An Engine Brake Noise Trace Showing Modulation Characteristics Source: (NRTC 2003 [20])

Sonus took about 600 roadside measurements of engine brake events. From there investigations Sonus recommended a 'Rise and Fall' criterion for the identification of excessive heavy vehicle engine brake noise within a traffic stream. The 'Rise and Fall' criterion specified that the noise should not exceed a minimum of three modulations of 3 dBA over a 0.5 second period with each modulation exceeding 80 dBA.

In addition, the overall maximum instantaneous L_{Amax} for excessively noisy engine brakes is not to exceed 95 dB(A) at a reference distance of 7.5m.

Subsequently, at the request of the NTC, Acoustic Technologies [21] conducted further investigations, with a view to establishing a criterion that could not only reliably identify an excessively noisy engine brake but a criterion which could be readily adopted using existing instrumentation and certification procedures.

Acoustic Technologies evaluated 96 recordings against the Sonus 'Rise and Fall' method as well as a range of other algorithms namely:

- root mean square (RMS);
- tonal; and
- harmonic content.

It was concluded that RMS of the modulation characteristic was best at distinguishing the level of annoyance of a noise event. The RMS algorithm also has other advantages in terms of repeatability, certification and the availability of software and instruments.

The identification of the modulation characteristic as a way to identify engine brake noise annoyance is supported by previous studies commissioned by Austroads from Vipac. Vipac Report No. 34950-2, 1991[22] references a 1981 Vipac study [23] which concluded that:

- A-weighted peak engine brake noise level was not an adequate predictor for assessing the changes in noise emission due to brake operation; and
- the annoyance due to engine compression brakes was the result of a change in the spectral characteristic of the noise emission rather than due to an increase in the overall A-weighted peak noise level.

Following the Sonus work and the later Acoustic Technologies investigations, it was clear that while modulation is the key, there were at least two ways of capturing modulation and identifying a quantifiable measure of the degree of annoyance of the 'bark' associated with engine brake:

1. By measuring the RMS of the modulation characteristic (Acoustic Technologies); and
2. By measuring the number and amplitude of rises and falls of the noise over a certain period (Sonus)

COMPARISON WITH AUSTRALIAN STANDARD AS3657

Australian Standard AS3657: *Acoustics - Expression of the subjective magnitude of a sound or noise*, provides methods for expressing the subjective magnitude of a sound as a single number. The Standard takes account of the frequency spectrum of the sound and is identical to the internationally accepted method of assessing the annoyance a sound would be likely to create.

The calculations for AS3657 are too complex to allow routine analysis of engine brake noise, but AS3657 provides a benchmark to compare with the candidate algorithms.

CONCLUSIONS

A literature search of research carried out by various countries on LFN from motor vehicles has revealed that the major frequency content of motor vehicle emission in terms of one third octave bands is in the range of 63 Hz to 125 Hz depending on vehicle speed and engine size. A lower frequency peak of 16 Hz has been identified from the firing rate of a pair of cylinders from a V8, 8 litre, four stroke diesel configuration [10].

The Netherlands has seen the value of producing LFN maps in addition to the traditional A-weighted approach. Modelling in the Netherlands study [15] using the C-A method indicated that areas behind noise barriers and motorways with a large amount of heavy vehicle traffic show high C-A levels. This may indicate that these areas are exposed to noise with a strong low frequency charactistics.

This C-A level approach appears to be popular in establishing low frequency content. Recently the Z-weighting is being proposed to replace C-weighting [6] for low frequency industrial noise immission and there is no reason why Z-A could not be used for transportation noise sources. Recent research seems to suggest an application of two equal loudness contours (A- and B- weighting) (dynamically based on the overall sound pressure level) and Zwickers method for loudness determination although this is a laborious process. There is even a suggestion that the loudness of transportation sources can be best represented by the phased out B weighting than the A-weighting due to its resemblance to the 70 phon contour more representative of the level and frequency of transportation noise sources.

LFN auditory threshold curves in one third octave bands have also been successfully applied for indoor spaces after correcting outdoor measurements for sound transmission loss through building facades.

The German study [14] indicated that a limitation to $L_{Amax} <$ 45 dB(A) as suggested by WHO (2000) [3] does not protect against awakening due to low frequency truck noise.

There has been extensive research undertaken to identify the characteristic 'bark' of engine brakes. The 'bark' can be clearly seen as modulation when engine brake noise is recorded and graphed. There are two methods of measuring the modulation of the waveform and both offer potential as a means of identifying engine brake noise annoyance. Relying on traditional A-weighted measurements will not capture the modulation nor would it offer the potential to distinguish engine brakes from other traffic noise.

The technology is available, especially with digital methods, to use much more complex filters and calculations in the measurement of low frequency sound, and studies have shown that these methods yield results that are more useful. However, until the acoustic community begins to seriously question the use of A-weighting measurements, more accurate measurements will continue to be ignored by both engineers and manufacturers.

In order to provide policy makers with the best information regarding noise exposure, a thorough knowledge of the various types of noise exposure and a better understanding of the relation between exposure and effects is needed. In particular, the present knowledge of the influence of time and spectral characteristics of the noise on human perception should be improved.

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