APPLICATION OF SIGNAL DETECTION THEORY TO ALARM AUDIBILITY IN A LOCOMOTIVE CABIN ENVIRONMENT

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Abstract

The diversity of design criteria for the audibility of safety-critical alarms is illustrated through a review of design standards across a range of industry applications. Several of these design criteria have been tested on sound pressure level samples of audible alarms in locomotive cabins in a recent study commissioned by Queensland Rail. Noise sampling was conducted under a wide range of locomotive operating conditions and for a wide range of alarm types. All-pass frequency and single-band types of design criteria were in some situations found to give unreliable predictions of audibility. The Queensland Rail study suggested that all-pass type criteria have the potential to lead to excessively loud alarm designs. An alternative audibility index based on the band-width adjusted root-sum-of-squared band signal/noise ratios has been found to give consistent predictions of audibility. This Detectability Index, *d'*, offers a metric that can be readily calibrated through field testing. The index is able to achieve a consistent approach to audibility across diverse background noise conditions without leading to excessive alarm levels that may compromise function by inducing startle reactions or by generating unnecessary annoyance.

Introduction

There are many diverse applications involving the design of alarm systems which need to be audible in variable background noise environments. Common examples include alarms for drivers in locomotive cabins, signalised pedestrian crossings, level railroad crossings and reversing beepers on earthmoving machinery. In all of these situations appropriate design for audibility may mean more than just the alarm being clearly noticed. In many instances, alarms need to be effective yet not excessive, to avoid startling the people that alarms are intended for, to avoid hearing damage and, in some cases, simply to minimise annoyance.

An ideal design criterion for alarm audibility should therefore be robust enough to accurately reflect the audibility of an alarm for the intended receiver over the range of background noise environments in which it will operate. An optimum alarm design criterion should lead to the design of alarms that are effective but not excessive.

This paper describes a recent investigation that was conducted to establish an effective and robust design criterion for alarm audibility in a locomotive cabin environment characterised by a wide range of load-dependent background noise levels as well as intermittent tonal noise events such as wheel squeal. The outcomes of the study however can be adapted to a much wider range of applications.

General Audibility Concepts

The audibility of an alarm signal depends on its frequency and sound pressure level in relation to the hearing threshold of the listener at the same frequency. In the presence of background noise such as locomotive cabin noise, the threshold of audibility is elevated to a so-called *"masked threshold"*, when a higher alarm signal level is needed for audibility at a given frequency.

This masked threshold provides a lower bound of interest for desirable levels of alarm signals within a locomotive cabin. In addition, the alarm signal should be *"noticeable"* not just audible.

Simply put, an alarm signal must stand out against the prevailing background noise level at a level sufficient enough to gain the attention of human operators concentrating on tasks other than listening for that (unexpected) signal.

Increasing the alarm signal level however has the potential to cause a *"startle"* reaction. Very loud noise has the potential to distort human hearing and may in fact reduce signal audibility and recognition. It has been documented [1,2] that in lieu of taking the intended action, overloaded human operators will occasionally resort to a canceling response in order to remove an intrusive warning signal. In a similar vein, the abrupt onset and offset of an intense alarm signal can produce a startle reaction characterized by transitory general muscle tension in the listener causing a temporary disruption of cognitive thought. As a result, it is generally agreed that alarm signals should be arresting yet not startling.

To account for these effects, standards and guidelines typically recommend that an upper limit be placed on the level of auditory signals such as alarms to reduce their intrusiveness and hence to avoid both hearing damage to operators and the startle phenomenon described above.

Design Standards for the Audibility of Alarm Signals

The following selection of design guidelines illustrates the range of audibility indices utilised to design alarm signals across a range of different applications and ambient background noise environments.

UK Ministry Of Defence, (Interim) Defence Standard 00-25 (Part 8) – 1989, "Human Factors for Designers of Equipment - Part 8: Auditory Information"

The above UK standard [1] gives the following hierarchy of audibility criteria, such that if any one of the criteria (in order) is satisfied, the remaining criteria become optional.

- The overall A-weighted sound level of the signal shall be at least 15 dBA above that of the noise, and shall be at least 65 dBA.
- The sound level of the signal shall be at least 15 dB greater than that of the noise in at least one octave band. Preferably the maximum octave band level of the signal shall be in a different band from that of the noise.
- The sound level of the signal shall exceed that of the noise by at least 15 dB in at least one, and preferably three, one-third octave bands.
- The temporal distribution of signal energy shall be distinct from that of the background noise. The pulse frequency of a signal shall not be identical with any periodic fluctuation in the background noise level.

FHWA-RD-94-087, Technical Report UMTRI-93-21 (1994), "Suggested Human Factors Design Guidelines for Driver Information Systems"

This report [2] involved research jointly funded by the US Federal Highway Administration and the National Highway Traffic Safety Administration and included general design principles and guidelines in relation to auditory displays for hazard warning systems. The following recommendations were made:

- Auditory tones should be about 15 dB above the masked threshold, but no more than 115 dB absolute level.
- Non-speech auditory tones have the potential to produce startle at levels 15 dB to 25 dB above masked threshold.
- To create distinguishable sounds, two or more of the following parameters should be varied: (1) spectral content, (2) pulse duration, (3) pulse shape, and (4) temporal pattern.

MIL-STD-1472F (1999) US Department of Defense, "Design Standard Criteria – Human Engineering"

This standard [3] established general human engineering criteria for design and development of military systems, equipment and facilities. The following criteria are used:

- A signal-to-noise ratio of at least 10 dB shall be provided in at least one octave band between 200 Hz and 5,000 Hz at the operating position of the intended receiver.
- Signal to noise ratios can be greater as long as the levels do not exceed 115 dB at the ear of the listener.
- Attention and avoidance of startle reaction. Signals with high alerting capacity should be provided when the system or equipment requires the operator to concentrate attention. Such signals shall not, however, be so startling as to preclude appropriate responses or interfere with other functions by holding attention away from other critical signals. To minimize startle reactions, the increase in sound level during any 0.5 sec period should be not greater than 30 dB. In addition, the first 0.2 sec of a signal should not be presented at maximum intensity, use square topped waveforms, or present abruptly rising waveforms.

Transport Research Laboratory Report PA 3721/01 (February 2002), "Design Guidelines for Safety of In-Vehicle Information Systems"

The following TRL recommendations [4] were made in relation to the audibility of In-Vehicle Information Systems (IVIS), including alarm signals:

- It should be possible to hear the signal of interest under all driving conditions at a level that will not startle the user.
- The volume of auditory output should be adjustable over a reasonable range, in most circumstances between 50 dBA and 90 dBA would be suitable; higher than 90 dBA should be avoided.
- Broadband sound should be presented at an appropriate volume; usually this can be achieved if the signal exceeds the ambient noise by 15 dBA or more. However, to avoid a startle response, the signal should not exceed ambient noise by more than 25 dBA. The signal level is a matter of balancing the listener comfort against message audibility.
- Auditory information should always lie within the range of human hearing, ie 200 Hz to 8000 Hz, but it is recommended in practice that it should lie between 500 Hz and 4000 Hz.

- In relation to the audibility of speech, the system should be able to cope with background noise and should not be influenced by it, a signal to noise ratio (SNR) of around 5 dBA should be sufficient to ensure audibility – refer also ISO/CD 15006 (1996).

US National Fire Alarm Code, NFPA 72 (2002), National Fire Protection Association

The above standard [5] gives the following performance guideline in relation to the audibility of fire alarms in residential buildings:

- The overall A-weighted sound level of the signal shall be at least 15 dBA above the average ambient sound level, or 5 dBA above the maximum sound level having a duration of at least 60 seconds, or a sound level of at least 75 dBA, whichever is greater, measured at pillow level in the occupiable area.
- The overall A-weighted sound level of the alarm signal system shall not exceed 120 dBA anywhere in the occupiable area.
- In summary, current design criteria for alarm audibility require the attainment of a certain signal to noise ratio in a specified band-width, preferably with a signal that has dominant frequencies that differ from dominant frequencies of the background. The bandwidth varies from all-pass to one-third octave (or unspecified), and frequency weighting may be either 'A' or linear. The minimum signal to noise ratio varies as much as 10 dB for a given bandwidth.

Audibility Indices Derived from Signal Detection Theory

Signal detection theory is increasingly being utilised to evaluate the audibility of signals (including alarms) in a diverse variety of applications. For example, the U.S. Department of Transport [6] demonstrated the use of a detectability index, *d'*, for the audibility of railroad horns at level crossings. Harris Miller Miller & Hanson Inc [7] used the same detectability index to evaluate the audibility of aircraft over-flight noise in an environmental noise annoyance context. Algorithms covering common signal detection indices are summarised below.

Detectability Index, d'

The Detectability Index, *d'*, is a measure used to quantify the audibility of a signal. The value of *d'* in a single frequency band (Bi) is given by:

$$d'_{Bi} = \eta \,.\, \{ S/N \} \,.\, \sqrt{B_W} \qquad (1)$$

In the above, η is an *"efficiency of hearing"* term (maximum 0.4 at around 1000 Hz), S is the signal energy, N is the background noise energy, B_W is the bandwidth of the frequency band in Hertz.

The overall *d'* value or d'_{total} is the root-sum-of-squares of the individual frequency band d'_{Bi} values:

$$d'_{total} = \sqrt{\Sigma\, (d'_{Bi})^2} \qquad (2)$$

Detectability Level, D'L

The overall d'_{total} level is often expressed as the Detectability Level, "D'L", which can be computed as $10 \log_{10} (d'_{total})$ and expressed in decibels (dB).

Noticeability Level, n'L

The Noticeability Level, "n'L" related to the Detectability Level can be computed as $10 \log_{10} (n')$, where n' is given by the ratio $d'/d'_{noticeable}$.

The Noticeability Level (of a signal) is the degree to which an observer who is engaged in an activity other than actively listening for acoustic events will notice an (otherwise audible) signal. Laboratory tests by Sneddon et al [8] suggest that signals become noticeable to participants otherwise engaged in another task at a Detectability Level D'L of 7 dB.

Queensland Rail Locomotive Cabin Alarm Noise Study

Measurements of sound pressure levels associated with locomotive engine noise, rolling and windage noise and alarm noise where conducted within a range of locomotive cabins for Queensland Rail [9]. Alarm signals were sampled while locomotives were at idle and with windows closed, to minimise masking effects of engine, windage and rolling noise on the alarm samples. Samples were then obtained of cabin noise for engine, rolling noise and windage effects over the full range of locomotive load conditions.

All measurements were conducted as "fast" response, A-weighted one-third octave-band statistics, and A-weighted all-pass levels. Background cabin noise levels were sampled using the L_{Aeq} parameter. Alarm levels were measured as L_{Amax} spectra based on the maximum instantaneous all-pass level. The sampling period ranged from 15 seconds to 20 seconds for samples of engine noise, to 1 second to 2 seconds to capture transient alarm signals. Subjectively, all alarm signals were clearly audible at the driver position.

The audibility of alarm signals was then examined primarily in the context of full load background cabin noise levels. Three audibility indices were applied to each test signal/noise scenario of interest to evaluate the consistency of these audibility indices across a range of alarm signals and cabin noise environments:-

- *All-pass signal/noise ratio*: this is simply the A-weighted decibel background noise level subtracted from the A-weighted decibel signal level.
- *Maximum one-third octave signal/noise ratio*: this is the maximum difference in any one-third octave band between the signal level and the background level – expressed in decibels.
- *Detectability level (D'L)*: this is the root-sum-of-squares of the band signal/noise ratios, expressed in decibels (refer previous section for definition of the index). This has been evaluated between 160 Hz and 10 kHz to capture the frequency range of the sampled alarm spectra.

Sample Results

Sample graphs from the Queensland Rail study are provided in Figures 1 to 3 showing each of the audibility indices for the range of noise scenarios tested.

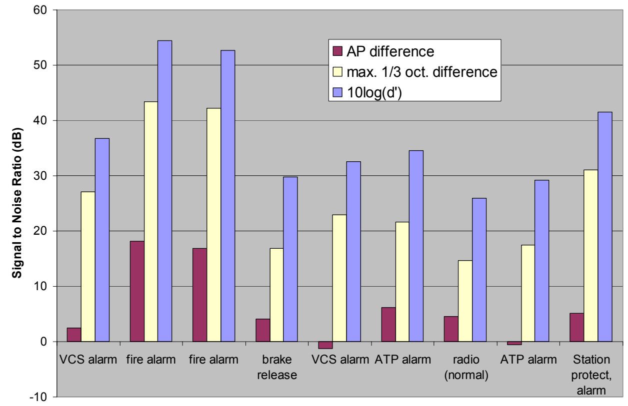

Figure 1. Comparison of Audibility Indices Locomotive A, Windows Closed.

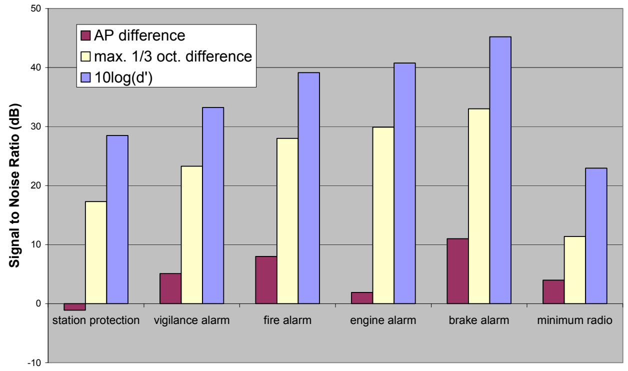

Figure 2. Comparison of Audibility Indices Locomotive B, Windows Closed.

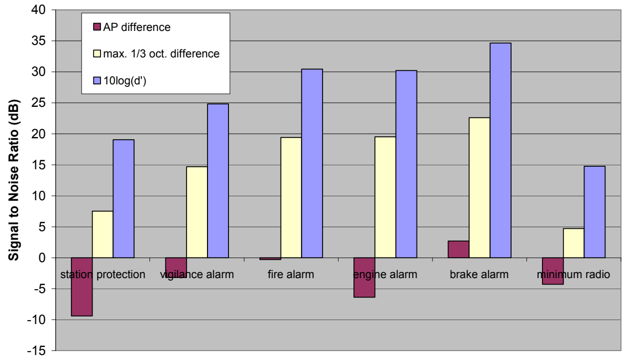

Figure 3. Comparison of Audibility Indices Locomotive B, Windows Open.

Discussion

The graphs of the alternative audibility indices shown in the previous section suggest that the all-pass A-weighted signal/noise ratio index is a poor indicator of audibility. This is best illustrated in Figure 3, where the all-pass index could be interpreted as indicating that many of the signals would likely be inaudible above the relevant background noise. With regard to the all-pass index, the all-pass signal is well below the all-pass background, and nearly all signals would fail an overall 10 dB signal-to-noise requirement.

However, subjectively this was clearly not the case. In some instances a 15 dBA criterion applied to the all-pass signal-to-noise ratio would require alarm levels to be as much as 25 dB higher to maintain audibility under all operational conditions, eg with windows open.

For the one-third octave signal/noise index the alarms fairly consistently result in an index of 15 dB or more. A 15 dB signal-to-noise ratio is recommended in a number of design standards, sometimes with an explicit one-third octave bandwidth, but often with no specified band-width. A 15 dB criterion level for this index accords reasonably well with subjective observations of audibility during the locomotive cabin noise testing.

In general, the Detectability Level, D’L, is consistent across different alarm types but with higher numerical values (about 10 dB higher) compared to the straightforward one-third octave band index. This is to be expected as the D’L index combines the detectability of the signal in all frequency bands where the signal exceeds the background, but in effect, ignores the background where it exceeds the signal, and similarly, ignores the signal where it coincides with a peak in the background noise spectrum. In effect, the Detectability Index, *d’*, algorithm simultaneously checks that the signal is sufficiently higher than the background noise level and has significantly different spectral characteristics to the background noise spectrum.

The Detectability Index, *d’*, has the advantage of being a consistent index for a full range of signal spectra, encompassing the other two indices at either signal “extreme” (ie either tonal or broadband). For single tonal signals, *d’* converges to the straightforward one-third octave band index. For broadband signals, *d’* converges to the straightforward overall all-pass A-weighted signal/noise index. However, the detectability index *d’* also provides meaningful information for more complex intermediate structured signal spectra, such as where more than one tone is present or where the signal information is spread amongst many frequencies. The Detectability Index, *d’*, also provides a way to evaluate the effect on audibility of a constant signal spectrum when the background noise spectrum is altered.

It can be argued that the complexity of audibility indices has evolved with the sophistication that is available in instrumentation for sound pressure level measurements. Early all-pass instruments led to all-pass criteria with adjustment factors. Readily available octave-filter sets led to octave-band based design criteria and so on with one-third octave filters.

The Detectability Index, *d'*, allows analysis of audibility based on any filtering bandwidth and thus is adaptable to a range of instrument sophistications.

Conclusions

In the recent Queensland Rail study, the all-pass A-weighted signal/noise index was found to be a poor indicator of alarm signal and 2-way radio audibility, particularly for tonal alarms. The adoption of this type of index for the design of alarms would likely yield excessively loud alarms.

A 15 dB criterion level for the one-third octave signal/noise index accords reasonably well with subjective observations of audibility during testing. A criterion level of 15 dB for this index is recommended for tonal alarms. However, this type of criterion may not be suitable for alarms with harmonics and for modulating alarms.

Based on the audibility of both tonal and broadband in-cabin signals measured to date, it is suggested that a Detectability Level, D'L, of 25 dB be assessed further as a suitable criterion for achieving audibility of a wide range of narrow-band and broad-band noise as well as of intermediate spectral composition.

It is further concluded that the Detectability Index, *d'*, provides a rational basis for testing the effect of alterations to the background noise spectrum on the audibility of a signal of interest.

Acknowledgements

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References

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