

Broadband Sound

The safer and noiseless* back-up alarm

A Brigade white paper
March 2009

**Webster's dictionary definition of 'Noise': "any sound that is undesired or interferes with one's hearing of something".
The sound from a correctly selected and installed broadband alarm is heard only in the hazard area - where it is meant to be heard.*



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Introduction

This paper sets out both the safety and the environmental benefits of broadband sound as applied to back-up alarms. The rationale for its adoption as standard fit on trucks, fork-trucks and mobile plant is self-evident.

During Summer 2007 a company suffered fatalities in two separate back-up accidents. In each case the truck and mobile plant involved were equipped with fully functional and compliant tonal back-up alarms. The findings were that each victim had “tuned out” the tonal alarms. The appropriate response to a back-up alarm follows recognition of its being a danger signal. Response failure indicates that the signal was filtered out as irrelevant background noise or a sub-conscious assumption that the sound originated from a truck backing up elsewhere. This effect is emphasized with tones which travel a greater distance than broadband sound.

Evaluation of back-up alarms and scientific research confirm that broadband sound is very effective at indicating the location of a sound source. In 2002 the American Council for the Blind called for the use of locatable sound saying current tonal alarms “serve more to disorientate people who are blind and visually impaired than to assist them”¹.

“Noise seriously harms human health and interferes with people’s daily activities at school, at work, at home and during leisure time”. “Calling noise a nuisance is like calling smog an inconvenience” and “noise must be considered a hazard to the health of people everywhere” are frequently quoted comments by Dr. William H. Stewart, former Surgeon General of the USA.

In comparison to the conventional tonal (narrowband) back-up alarm, an equally loud (phons) broadband back-up alarm is just as effective at alerting a listener to the presence of a reversing vehicle but, by contrast, is little heard outside the danger area. This eliminates noise nuisance complaints and the risk of the alarm being ignored due to “over-familiarity”².

Whilst specific circumstances may dictate the retro-fit of broadband back-up alarms, this paper presents the general case for their adoption as part of a managed process.

Whilst this paper is directed specifically at back-up alarms, it’s information applies to all types of travel alarm.



¹ American Council for the Blind resolution ACB 2002-22.

² New York State – Department of Health Case Report 03NY036; "Often people who work regularly near back-up beepers become accustomed to their sound and become desensitized to them as warning signals." <http://www.health.state.ny.us/environmental/investigations/face/03ny036.htm>

Safety – Fitness for Function

A comparative chart of the relative effectiveness in normal working environments between tonal alarms and broadband sound alarms:

| Tonal and broadband alarm effectiveness compared | | | |
|--|--------------------------------------|---|-----------------|
| | Factors | Tonal | Broadband Sound |
| Safety | Recognition: | | |
| | Loudness / Audibility | <i>An alarm with appropriate loudness should be installed</i> | |
| | Is sound an effective danger warning | Depends | Yes |
| | Is the danger relevant | Depends | Yes |
| | Response | Unreliable | Good |
| | Hard of hearing - audibility | Risky | Good |
| | Cause confusion | Likely | Unlikely |
| Environmental | Strident | Yes | No |
| | Noise complaints | Yes | No |
| Health | Risk of hearing damage & stress | Greater | Lower |

Figure 1

Every measure of a back-up alarm's fitness-for-function (see Figure 1 above) shows that a broadband signal provides a superior warning to a tonal signal in terms of safety, of health and of the environment.

Safety – Fault Tree Analysis

A "fault tree analysis" is a useful tool for reviewing possible causes of an accident, see copy below. In the UK, for example, a coroner may reach one of three decisions: Death by natural causes; Accidental Death (where neither the deceased nor a third party were a cause of the fatality) or Unlawful Killing. In the fault tree below, the "causes" in red relate to the back-up alarm and in each case the risk is greater when the alarm is tonal. A full "fault tree analysis" is at Annex A.

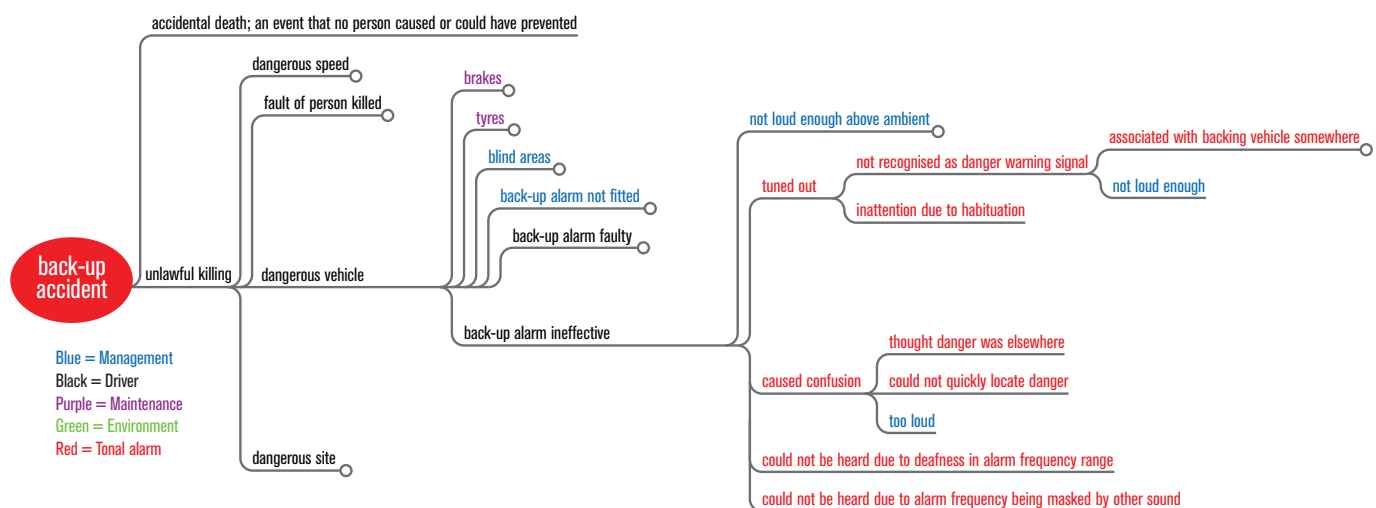


Figure 2

Safety – Key Factors

Back-up alarms are fitted to improve safety. Their function is to alert anyone who may be in the hazard zone that the vehicle is backing-up so that the hazard is recognized and appropriate action is taken to move out of harm's way. The warning signal needs to be heard in all parts of the hazard area. The hazard area is the area where a person is either in, or could move into, the travel path of the backing vehicle. The alarm sound is unnecessary outside this zone and sideways sound "spillage" is unwanted sound.

Back-up alarm model selection should be to maximize safety within the hazard zone. To this end it should fulfil two criteria:

1. Recognition.

- a. Audibility.** The alarm must be audible enough to alert someone pre-occupied by a task. ISO-7731 defines the audibility³ required for danger signals. ISO-7731, written for tonal alarms, recommends more than one tone for an alarm to be effective⁴.
- b. Is the sound a danger warning?** The primary requirement for a back-up alarm's warning signal is a sound pattern which makes the signal unambiguous⁵. SAE J994's definition is for the pattern to be 0.8KHz to 1.8KHz, with the length of the on and off periods being within 20% of each other⁶.
- c. Is the danger relevant?** If the sound has a high false alarm rate it will not be associated with danger. Low false alarm rates improve safety and worker/public acceptance. "False alarms negatively impact safety"⁷. False alarms become associated with a vehicle backing-up elsewhere.

- 2. Response.** The alarm should demand immediate response by those in the hazard area. Faster response occurs when the sound source direction (and identification thereby of the backing vehicle) is instantly locatable.

Cross References:

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Continued.....

³ ISO 7731, 4.2.2 Audibility

⁴ ISO 7731, 6.3 Special Characteristics

⁵ ISO 11429, 4.2

⁶ SAE J994, Section 6.2; "Cyclic Pulsation Rate and Duty Cycle"

⁷ www.grc.nasa.gov/WWW/RT/2005/RI/RIS-hunter.html

Other Factors:

| | | |
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General

The hazard warning signal should be such that people in the reception area hear and react to the signal as intended. Hearing impaired persons and wearers of safety helmets, ear defenders etc require special care to be taken. The characteristics of the signal should be relevant to the situation⁸.

Audibility

An acoustic warning signal “shall be clearly audible. The effective masked threshold of audibility shall be distinctly exceeded. If relevant, the possibility of hearing loss in the recipient population may be assessed and taken into account.” If ear-defenders are worn, their levels of attenuation shall be known and considered in the assessment.⁹ SPL (decibels) and Loudness (phons) are not the same. (See glossary.)

Recognition - General

The primary requirement for a warning signal is that its message is clear and unambiguous and is recognised under the environmental conditions¹⁰.

Locatable Sound

The American Council for the Blind reported at their 2002 annual Conference in Houston, Texas, that conventional alarms serve more to confuse blind people than to assist them and called for the use instead of locatable sound.

Instant location of a sound-source is a part of nature’s survival mechanism. An animal in imminent danger of attack promptly locates the sound of the stalking predator by naturally occurring “broadband” sounds such as the crack of a breaking twig or the rustle of leaves, which accurately reveals the approach direction of the danger, triggering instant flight in the opposite direction.

In locating a sound source, three parts of the frequency spectrum are heard simultaneously, as a single sound:

1. Low Frequencies. With low frequencies (about 1.5 KHz and below) the brain can process the time difference between the sounds arrival at one ear then the other. This is known as the Interaural Time Difference (ITD)¹¹. These leave a ‘cone of confusion’ as illustrated in Figure 3. (Sources on the surface of the cone have the same time delay between the two ears.)

⁸ ISO 7731, 4.1

⁹ ISO 7731, 4.2.2.1

¹⁰ ISO 11429, 4.2

¹¹ Human Localisation, Binaural cues <http://www.isvr.soton.ac.uk/FDAG/VAP/html/localisation.html>

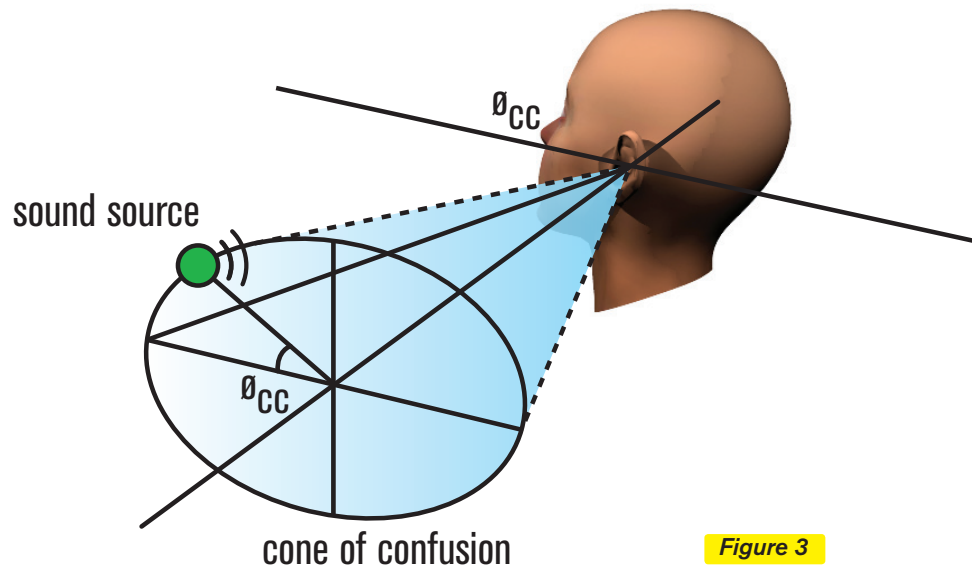


Figure 3

2. Mid Frequencies. At mid frequencies (3KHz up to 5KHz¹²) the brain senses the intensity difference of the sound at each ear, i.e. the brain determines that the ear receiving greater sound intensity is closest to the source. With this frequency range we can determine if the sound is to the left or right. This is known as the Interaural Level Difference (ILD) or Interaural Intensity Difference (IID)¹³.

3. Higher Frequencies. Due to our outer ear shape and body shape, higher frequencies (5KHz and above) are modified before entering the ear canal. This is an individual response and is the high frequency end of the Head Related Transfer Function (HRTF). This phenomenon becomes significant when the wavelength of the sound is similar to or shorter than the dimension of the outer ear. It's use is a learned skill and assists front/rear sound source location.

Using a selection of each of these frequency ranges the brain locates the direction of the sound source. With broadband sound the accuracy of instant locatability is around 5 degrees.

Tonal alarms often create confusion in the work place. The location of a tonal sound source is unreliable and takes precious time. (See section – Tonal Alarms Cause Confusion on page 11.)

Sound Confined to Hazard Area

Broadband sound is localised within the hazard area. This has two main benefits:

1. It eliminates noise nuisance and complaints from those outside the hazard area who do not need to hear the warnings.
2. Tonal alarms which are heard well away from the hazard zone become "meaningless"¹⁴ which leads to their being disregarded, even in a hazard zone. A broadband alarm is normally heard only in a hazard zone and consequently is respected as a genuine warning.

¹² Various sources give above between 1.5 kHz and 3 kHz.

¹³ http://en.wikipedia.org/wiki/Sound_localization

¹⁴ Toyota Industrial Equipment booklet; 00698-20036-04 06TMH35158; with reference to tonal alarms - "Pedestrians become habituated to the alarm and ignore it, as it constantly sounds a meaningless warning."

How is this achieved?

1. Lower SPL Figure 4 illustrates a tonal alarm and a broadband alarm each 100dBA. The tonal alarm concentrates all its energy into one narrow frequency band. The broadband alarm spreads its energy over a wide frequency range, typically at levels about 10dB lower than the tonal alarm, though the total sound energy is similar for both.

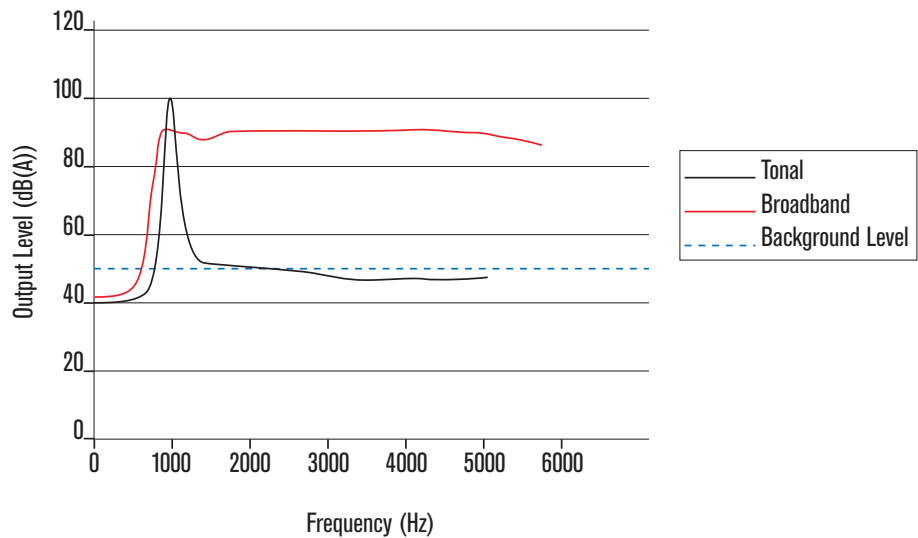


Figure 4

2. Dissipation off-axis. Whereas a tonal alarm is largely omni-directional, broadband sound is focused into the hazard area. The schematic Figure 5 below, recorded by Hanson Aggregates¹⁵, is typical of several studies reviewing broadband SPL reduction off rear axis. Whilst there is negligible sound dissipation in the hazard area, there is significant reduction (typically around 10 dBA at 90 degrees to the side of the vehicle) outside the hazard area. The inherent directivity of an alarm measured in the absence of any reflecting surfaces will be different from the directivity of an alarm when mounted on a vehicle. E.g. a 102 dBA broadband alarm in an open space shows 8 dBA reduction at 90 degrees but on a vehicle might show 13 dBA or greater reduction.

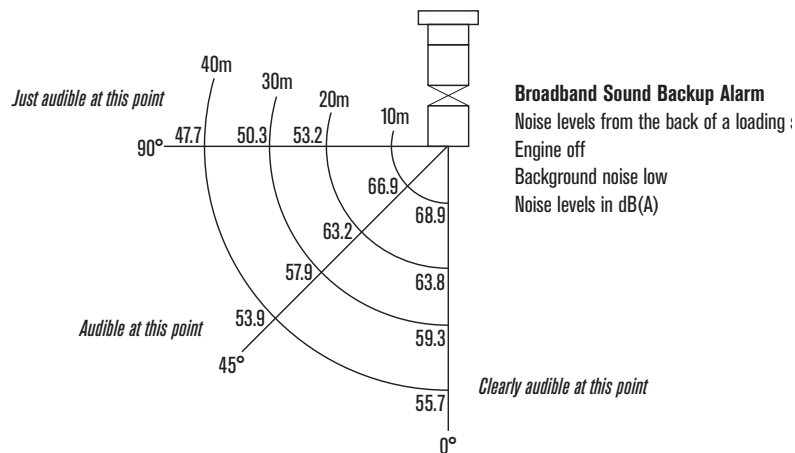


Figure 5

3. Lower dBA rating. Scientific analysis has revealed that a broadband back-up alarm is equally effective at 5dBA lower SPL than a conventional tonal alarm^{16 17}. Consider the measurement of loudness as detailed in Figure 6. from ISO-226:2003. A contour dips into a region of more sensitive hearing. The dip around 3,000Hz is due to resonance in the ear canal, which increases the sound input to the ear. Figure 6. shows typical broadband (red box) and tonal (blue line) alarm SPLs. In the range of around 1kHz to 4kHz, tonal alarms operate at the frequency that is least audible to the human ear; whilst broadband alarms include the regions of the ear's enhanced sensitivity and are subjectively louder than a tonal alarm of the same total SPL. A tonal alarm requires about 5dB higher SPL for equal loudness to a broadband alarm. Conversely, a broadband alarm provides the same loudness at 5dB less than a tonal alarm.

¹⁵ Tom Hill, Environmental Manager, Hanson Aggregates, Whatley Quarry; drawing dated 15 July 2002

¹⁶ Martin Lever, HS&E Manager RMC (Cemex); verified results of 150 subjects at South East Quarries Liaison Safety Day 2003.

¹⁷ UK Health & Safety Executive report "Improving the safety of workers" Contract Research Report 358/2001.

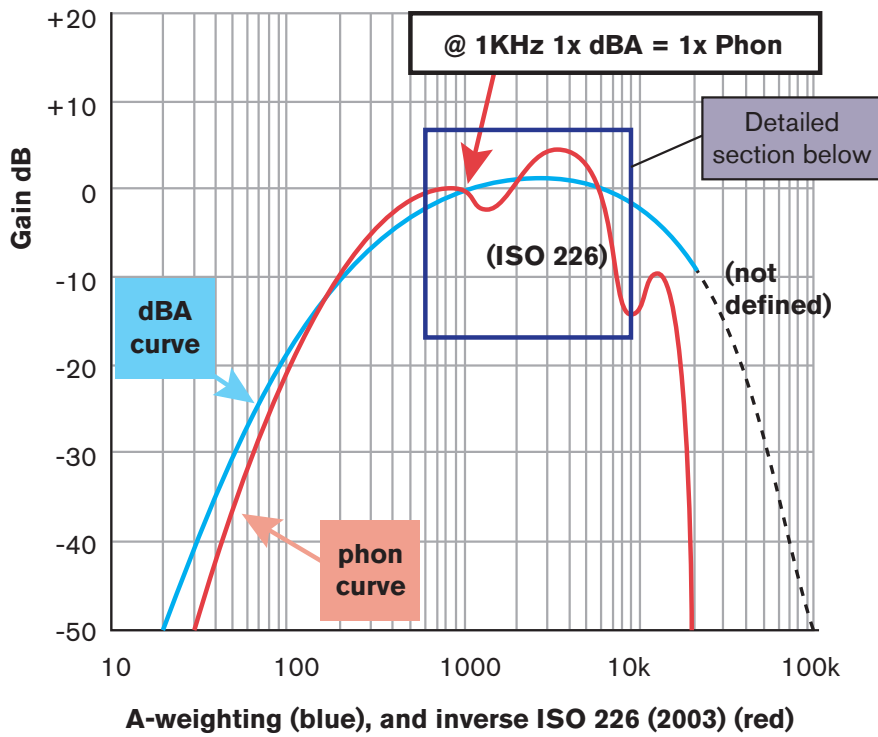


Figure 6

Net Effect

Aggregating these three factors reveals broadband sound's full potential as a noise-abater. A doubling of distance from sound-source gives a 6dB reduction in SPL. The higher frequencies in broadband sound attenuate more rapidly with distance.

In Figure 7, the components of the broadband alarm are typically 10dB closer to the background noise than the tonal alarm. As distance from the alarms increases the SPLs reduce until the broadband sound fades into background whilst the tonal sound remains typically 10dB higher. The broadband SPL drops off more rapidly than the tonal SPL because the higher frequencies attenuate faster.

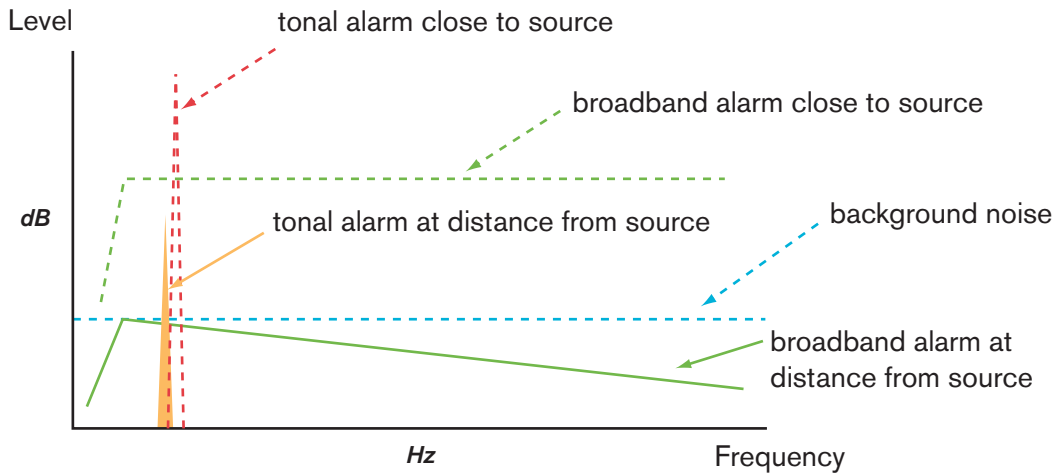


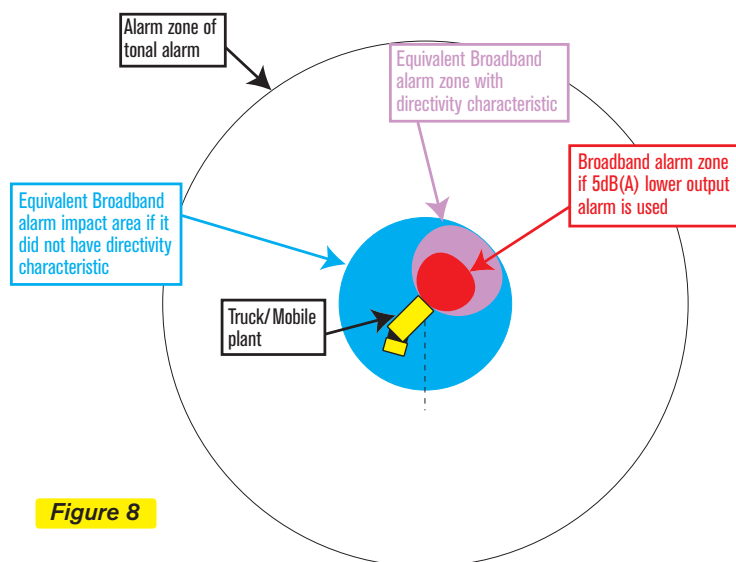
Figure 7

Additionally, as the sound level of the broadband alarm is typically 5 dB lower for equal loudness this could lead to a 15 dBA difference. This is illustrated in Figure 8.

Net Effect - Illustration

Illustration of equally SPL rated tonal and broadband alarms range of audibility i.e. ranges at which the broadband alarm sound blends in to background noise (blue circle), whilst the tonal alarm (outer circle) is still above background.

1. Black Outer Circle. Alarm zone of a tonal alarm.
2. Blue disc. Alarm zone of a broadband alarm with the same over-all SPL as a tonal alarm (without directivity characteristic included). Assuming that the tonal alarm is 10dB above background noise, the area covered by the broadband alarm is about 10% of that of the tonal alarm.
3. Mauve disc. Alarm zone of broadband alarm with directivity characteristic included. This area is less than half that of the blue disc.
4. Red Area. Alarm zone of broadband alarm with 5dBA lower output than tonal alarm. This area is smaller than the mauve area because as distance from the broadband sound source increases it's SPL drops to background level whilst the tonal alarm sound remains around 15dB above background.



False Alarm

A false alarm is an alarm heard outside the hazard zone. "False alarms are of no use to anyone, serving only to increase noise levels. Over time they become less effective as people sub-consciously match their response level to the false alarm rate"¹⁸. For example, alarms which are genuine for 90% of the time produce response rates close to 100%, whereas alarms which are genuine only 10% of the time will trigger a response rate of only 10%. False alarms are costly both in terms of annoyance and of performance¹⁹.

False alarm rates for tonal alarms are unacceptably high.

Resonance

A tonal alarm can resonate with truck (or other metal) panels. This resonance increases noise levels, sound-source confusion, environmental noise nuisance and loss of respect as an alarm.

The level of increase can be startling, 5 dBA²⁰ for a garbage truck and over 20 dBA²¹ on a fork truck working near metal panels.

¹⁸ Bliss et al, 1995.

¹⁹ Edworthy Judy, Hellier Elizabeth; Auditory warnings in noisy environments

²⁰ Geoff Leventhall: Noise Measurements on Garbage Truck and Back-Up Alarms

²¹ Tony Gardner: Ibstock Bricks Lodge Lane Factory noise exposure study 2004

Tonal Alarms Cause Confusion

Whilst a broadband sound source is locatable, of concern is sound-source confusion caused by tonal alarms.

This problem results from the acoustical phenomenon of standing waves. A typical tonal back-up alarm has a frequency around 1.25 kHz with a wavelength about 11 inches. When radiating a tone, its speaker oscillates at a constant rate (frequency) to produce the sound. It compresses the air in front of the speaker, then it rarefies the air; these compressions and rarefactions similarly affect the ear-drum and so we hear the sound. When a tonal alarm “beeps” these compressions and rarefactions are sensed by the ear either directly or via one or more reflections. When the distance between two paths of the alarm sound travel is a multiple of the alarm wavelength then the compressions combine and intensify and for a good reflection this can increase the sound pressure by up to 3dBA (See Figure 9 below). Similarly, if the path difference is $\frac{1}{2}$ the wavelength, the compression and rarefaction can cancel each other out in the case of a good reflection and no sound is heard! “Reflections of these sound waves on the ground or diffraction by the sides of vehicles have the effect of reducing or even cancelling them before reaching the listener. Within spaces of less than a few inches, Laroche and Lefebvre found variations in sound pressure level (on construction sites) of more than 15 dB²² behind vehicles.”²³

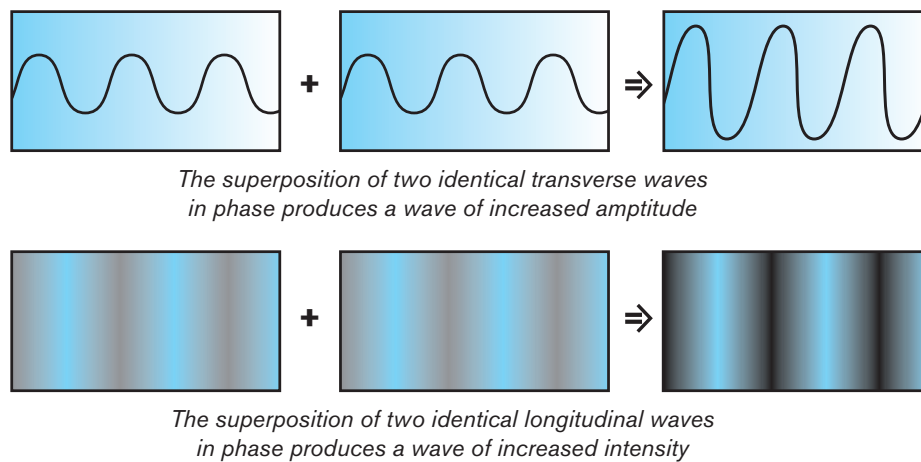


Figure 9

Whilst a tonal back-up alarm’s narrow frequency band does not enable sensing of the subtle intensity difference required to locate a sound source²⁴, there are often much larger intensity differences due to reflections. The listener assumes the greater SPL in one ear is due to its being closer to the sound source but it can be due to standing wave pressure differences.

What’s more; as the listener’s head turns towards the assumed sound source the SPL varies in these few centimetres unconnected with sound source direction – compounding the confusion. This is not possible with a broadband alarm because it’s wide frequency band has wavelengths varying from under 2 inches to over 17 inches. While a frequency analysis will show intensity variations due to standing waves, the over-all SPL remains constant.

²² Laroche, C., and L. Lefebvre: Determination of optimal acoustic features for reverse alarms: Field measurements and the design of a sound propagation model. *Ergonomics* 41:1203–1221 (1998).

²³ Alice H Suter: Construction Noise: Exposure, Effects, and the Potential for Remediation; A Review and Analysis - *AIHA Journal* (63) November/December 2002. This Suter paper can be accessed on <http://www.cdc.gov/elcosh/docs/d0100/d000054/d000054.html>

²⁴ See section “Locatable Sound, 2. Mid Frequencies.

Audibility Through Ear Defenders (Ear Protection)

Low frequencies more readily penetrate solid objects. When loud music is played in a building or in a car with windows and doors shut, it is the low frequency boom-boom noise that is heard. Low frequencies can travel through the body and be heard through ear defenders. Fog horns use low frequencies because they travel long distances, round corners and penetrate solid objects such as windows, walls etc.

Ear-defenders are better at attenuating some frequencies than others. A broadband alarm with its wide range of low frequencies is more likely to be audible through ear-defenders than a tonal alarm.

Reduced Risk of Alarm Sound Being Masked

Tonal travel alarms are easily masked by similar frequency background noise. A broad frequency band eliminates this risk.

Rapid Sound Dissipation

Broadband sound's wide frequency spectrum enables lower over-all SPL for the same loudness. While it's low frequencies travel further they are more benign. The less tolerable high frequencies are more readily absorbed by air and ground and as a result the over-all SPL reduces more rapidly with distance from source.

Less Irritating

Tonal alarms are strident and irritating. Broadband alarms are environmentally "friendly". (See Technical Stuff; Psychoacoustics & Tonal Aspect sections).

End to Intentional Disconnects

Increased hazards and repair costs result from sabotage of tonal alarms. Broadband alarms are rarely, if ever, sabotaged.

Hard of Hearing – Better Recognition

The cochlea (inner ear) is a long 'string' of receptors, akin to a ticker tape. Each receptor receives within a narrow frequency band. Hearing impairment is restricted to those receptors which are damaged. Figure 10 below shows a case where the damaged receptor frequencies align with the tonal alarm's frequencies. As a result the tonal alarm is unheard. Conversely, all the other frequencies of the broadband alarm are heard.

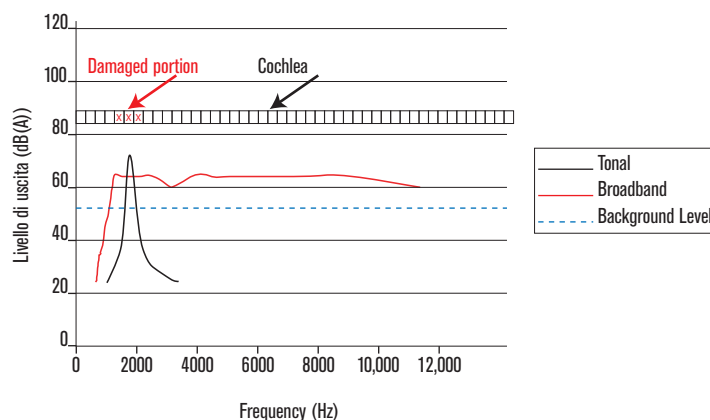


Figure 10

Reduced Risk of Hearing Damage

High lower-frequency content for a similar tonal SPL reduces the risk of hearing damage.

Reduce Heart Risk due to 'Startle'

ISO-7731 states; "Reactions due to fright (e.g. more than 30dB in 0.5 seconds) may be caused by using too high a sound-pressure level." These can delay, or even prevent escape from danger due to 'freezing'".

The risk of shock/startle is unlikely using broadband alarms with their lower SPLs and multi-frequency band width.

Technical Stuff

Equal SPL measurements and Spectral analysis

A reading of sound pressure on an SPL meter (as per ANSI S1.4 or IEC 60651) – specification for sound level meters) will 'average' the sound pressure in each frequency band and present a consolidated single figure output - weighted as per the settings on the meter.

It is the industry norm to measure SPL using the 'A'-weighting dBA which adjusts the measured SPL to the response of the human ear.

The graph at Figure 11 below shows the SPLs which might be expected from a tonal alarm (when centered on 1250Hz) and a broadband alarm. By definition, the frequency content of broadband sound is vastly larger than for tonal, but is at a lower SPL. These SPLs can be read using a sound meter (and filter set) as per ANSI S1.4 & S1.11 (or IEC 60651 & 61260) set to the one third octave range.

Although the broadband sound spectrum shows lower SPLs in each one third octave band the added effect of these is equal to the tonal travel alarm - 100dBA at 1m.

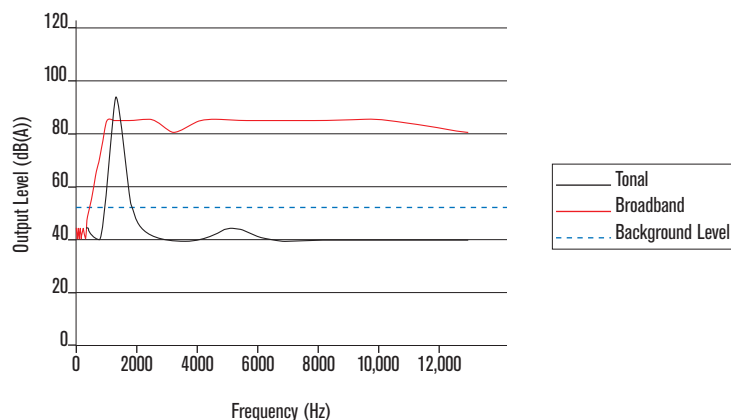


Figure 11

Sound versus Distance

In a free field (open 3D spherical space) sound dissipates from a point source according to the inverse square law. The reduction in dB compared with 1m from sound source is calculated as:-

$$SPL=20 \log \left[\frac{1}{r} \right]$$

where 'r' is the distance of the listener from the source. This results in the well known 6dB drop for each doubling of distance from the source. However, most sound sources are not 'ideal point sources' and hence have less than ideal sound distribution in every direction.

The rate of sound-absorption depends on numerous other features including frequency content. Air absorbs sound faster (i.e. more rapidly per doubling of distance) in the higher frequency ranges. Atmospheric conditions (humidity, temperature, wind direction and speed etc.) all affect the speed of sound. The rate of sound absorption by physical structures between source and listener (buildings, fences, trees etc) is also frequency dependent.

Psychoacoustics

Perception of sound is highly subjective. Music to one person is noise to another. Sensitivity is greater and sounds therefore seem louder in the 1KHz to 4KHz band (this forms the basis for the 'A' weighting system). Tonal alarm noise is intrusive to all ears even in high ambient noise levels.

Tonal Aspect

The 'Tonal' aspect is important enough for the Federal Aviation Administration to have made provision for the presence of "tones" in aircraft noise in the Federal Regulation for Noise Standards on Aircraft. (Title 15 - Aeronautics and Space, Chapter 1, part 36.803 - Noise evaluation and calculation). The FAA "penalizes" tonal content by nearly 7dBA. In other words aircraft noise containing tones is considered to be equally annoying as a 7dBA louder noise without tones.

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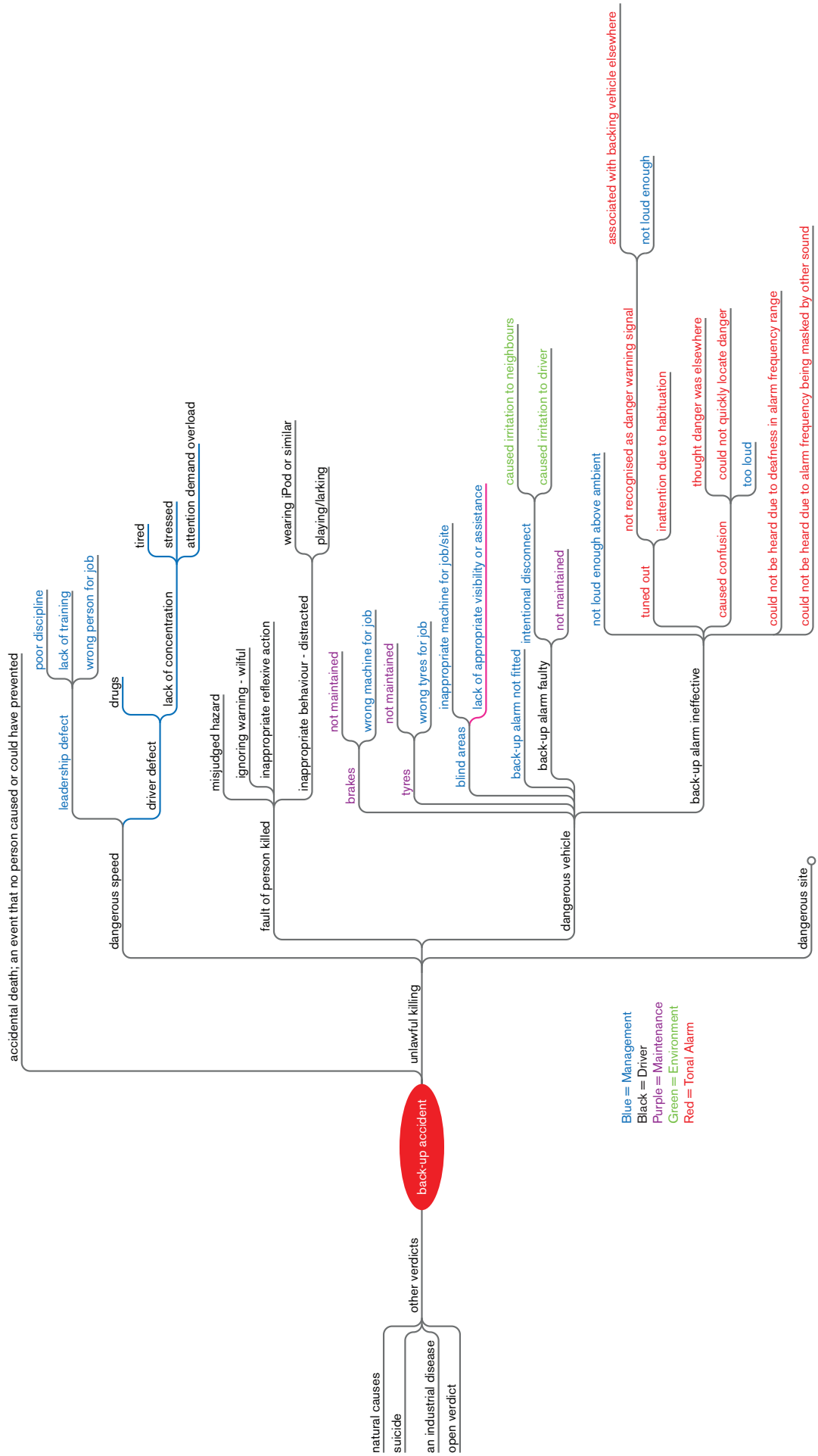
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Annex A - Fault Tree Analysis



Glossary

| | |
|------------------------|--|
| Loudness | A sound's perceived loudness (phons) is a non-linear varying function of its SPL and frequency (see fig.6). |
| SPL | Sound pressure level measured in decibels. Not to be confused with Loudness. |
| Decibel (dB) | <p>The decibel is a logarithmic scale used to denote a change in the relative strength of an acoustic wave. It is a standard unit for expressing the ratio between sound-pressure and a reference pressure.</p> <p>An increase of 10dB is an approximate doubling of perceived loudness. The decibel is not an absolute measure but indicates the relationship or ratio between two sound pressures.</p> |
| dBA | SPL weighted to the 'A' scale. |
| Frequency | Measure of the number of times per second a sonic vibration repeats itself, expressed in Hertz (Hz). High frequency sounds attenuate quickly, travelling short distances, low frequency sounds attenuate slowly, and travel far (e.g. fog horns). |
| Attenuation | Reduction of SPL over distance. |
| Tonal sound | Sound whose pressure varies sinusoidally with time. Also referred to as a discrete tone such as that produced by a tuning fork when struck lightly. High tone is high frequency, low tone is low frequency. |
| Broadband sound | <i>Sometimes known colloquially as "white sound".</i> Sound whose acoustic energy is distributed over a very wide frequency range. The spectrum is largely smooth and continuous save at the extremes. |
| Phon | Measure of perceived loudness. |
| Locatability | Degree of accuracy of a sound-source's directional location by a listener. |
| Localisation | Confinement a sound-pattern within, or restriction to, a locality. |
| Directivity | Measure of how a source radiates sound in different directions. |

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