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SOUND LEVELS FOR THE BRITISH RAIL INDUCTIVE LOOP WARNING SYSTEM

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INTRODUCTION

British Rail Research has developed an Inductive Loop Warning System (ILWS) to give advanced warning of approaching trains to track maintenance gangs. The ILWS uses existing track and signalling circuits to detect the presence of trains. To convey this information to the maintenance gang each section of track, about 1 km in length, is enclosed within a permanently installed inductive loop which radiates electromagnetic signals. These signals are picked up by a "Portable Warning Issuing Device" or PWID carried by the "ILWS Warden" and cause the PWID to generate one of a set of warning sounds through a built-in loudspeaker. To make the system failsafe, if no trains are detected the PWID issues a "safetone" every two to three seconds. This gives the Warden confidence that the system is working and that he will hear any danger warning. The warning sounds are described more fully in the following paper [1].

The ILWS Warden must warn his colleagues and ensure the track is clear whenever a train is detected or whenever it is unsafe to work. The Warden must therefore stand close enough to the rest of the gang to warn them and consequently will be exposed to noise from the work in hand. On occasions, within designated distances of various plant or machinery where noise levels are high, the Warden will be required to wear earmuffs. In which case the warning sounds will be produced by earphones in the muffs.

Setting the warning sound levels for this application is critical. Because of the need for the safetone a warning sound may be present for, say 15-20% of the working day: the warnings must be loud enough to be heard reliably, but must not contribute any more than necessary to the Warden's noise exposure. This paper describes how levels were chosen for design purposes.

GUIDELINES FOR WARNING SOUND LEVELS

A warning sound must be loud enough to be heard reliably, identified and acted upon, but not so loud that it causes startle, interferes with communication or disrupts thinking. In practice, in noise, these conditions are met if the main frequency components of the warning are between 15 and 25 dB above the masked threshold imposed by the background noise [2]. In the quiet, a warning sound should not be allowed to fall below 65-70 dB(A) at the ear, even if it is more than 25 dB above the masked threshold, or it will seem insignificant or unimportant. The first stage in specifying warning sound levels is therefore to analyse the background noise so that masked thresholds can be predicted.

THE TRACKSIDE NOISE ENVIRONMENT

The ILWS will be used in many different situations. A single person inspecting track may experience little noise. At work sites the noise levels will be higher and will vary from site to site and from moment to moment, depending on the vehicles, plant, machines and tools in use. Noise levels will also be higher in enclosed spaces, especially tunnels.

To enable an assessment of the background noise at work sites, British Rail identified several common noise sources or classes of noise source. These included vehicles, such as dumper trucks and stationary trains, plant and machinery such as generators and compressors, and tools ranging from shovels to power saws and pneumatic hammers. Calibrated tape recordings were made at various distances from the sources and at typical positions at which an ILWS Warden might stand. Recordings were also made of trains passing at speeds of up to 200 km/h (125 mph).

CALCULATION OF MASKED THRESHOLDS AND APPROPRIATE WARNING SOUND LEVELS

The recordings were analysed to obtain the A-weighted level and spectrum of each noise using an FFT analyzer (Bruel & Kjaer 2032). The spectra, with a frequency span up to 6.4 kHz and a resolution of 8 Hz, were transferred to a desk top computer (Hewlett-Packard 216) and stored on disc. The masked threshold for tonal signals heard in each noise was subsequently calculated from the spectrum using a computer program written for this purpose [3].

The program calculates a masked threshold as a function of frequency by modelling the auditory filtering processes of the ear. Threshold at any frequency is determined by calculating the shape of the auditory filter centred on that frequency, weighting the noise spectrum by the filter shape, and integrating the noise power within the filter passband. The signal-to-noise ratio at threshold is then applied to give the predicted threshold sound pressure level. The auditory filter shapes used are Patterson et al's rounded exponential (roex) models [4] with bandwidths related to their centre frequency using the data of Moore and Glasberg [5].

The program has been validated by a direct comparison of measured and predicted thresholds in various helicopter noise fields, aircraft being the original field of application [3]. Thresholds predicted from noise levels measured with miniature microphones at the ears of ten subjects were compared with masked thresholds determined by Bekesy audiometry at frequencies between 100 Hz and 4 kHz. A high correlation was obtained between mean measured and mean predicted thresholds as summarised in Figure 1.

For the ILWS study, spectra were obtained and masked thresholds predicted for forty five different background noise recordings. Some typical examples are shown in Figure 2. Note that each spectrum (lower line) is plotted as a spectral density with the ordinate showing dB re 400×10^{-12} Pa^2/Hz while the threshold curve (upper, smoother line) is a sound pressure level in dB re 20 μPa. The two curves are plotted together with the same numerical scale so that they can be compared conveniently.

Most of the masked threshold curves predicted for the various noise sources were fairly flat in the frequency range from 500 Hz to 3 kHz, the range which will contain most of the frequency components of a warning sound. Thus there would be no advantage in emphasizing any particular frequency band in the PWID output. The flatness of the curves is purely fortuitous and should not be assumed to apply in other situations; for example it is not the case on many aircraft flight decks.

The flatness of the threshold curves enables us to reduce each to a single value, ie the average sound pressure level between 500 Hz and 3 kHz, without over-generalising. This considerable simplifies the specification of the optimum sound level for the warnings. Table 1 summarises the sound levels and thresholds for a few of the noise sources considered. The minimum and maximum sound levels for warning sound tonal components in each noise were obtained by adding 15 and 25 dB respectively to the sound level at threshold in accordance with Patterson's guidelines.

An examination of the data for all noise sources, including those shown in Table 1, suggests that if a warning sound level were chosen to be numerically equal to the A-weighted background noise level, it would, with few exceptions, coincide roughly with the minimum level recommended in Patterson's guidelines. An assumption has been made here that two or three main tonal components will reach the minimum level given in the table and that the overall warning level will be 3-5 dB above the level of components. For example, the A-weighted level of a rail saw at 2 metres is 84 dB(A); the recommended minimum level for warning components in that noise is 81 dB. A warning sound in which two main components reach this level would have a level of approximately 84 dB(unweighted). Thus as a rough rule of thumb, if the background noise level is N dB(A) then the optimum range of level for a warning sound would be N dB to N+10 dB. In this particular application there is a requirement to minimise the noise exposure of the Warden and consequently a warning sound level towards the minimum of the range would be chosen.

Table 1 also shows that the minimum recommended sound level in some noises exceeds the maximum recommended for other noises, indicating that no single sound level can be used under all conditions.

SETTING WARNING SOUND LEVELS IN A VARYING BACKGROUND NOISE.

In specifying warning sound levels from the PWID, British Rail's policy on hearing protection must be considered: hearing protection must be worn in levels exceeding 85 dB(A). The PWID will be equipped with a pair of earmuffs for use when the noise level exceeds 85 dB(A), and these will incorporate earphones through which the warnings will be presented. The PWID loudspeaker is therefore the primary warning sound source in noise levels up to about 85 dB(A), while the noise excluding earphones will be the primary source in levels above 85 dB(A). For convenience, a single muff will also be provided which the Warden can hold to one ear during short bursts of noise, such as the passage of trains.

Sound levels from the PWID loudspeaker

A warning sound from the PWID loudspeaker should be suitable for use in noise levels up to 85 dB(A). Using the approximate rule of thumb that the warning sound level should be numerically equal to the A-weighted noise level, a level of 85 dB must be produced by the PWID loudspeaker in 85dB(A). This sound level would be satisfactory for background noise levels between about 75 and 85 dB(A). For background levels progressively below 75 dB(A) this warning sound level would become increasingly unsuitable, at first irritating, then annoying and ultimately aversive. When used in quiet conditions a PWID output of about 65 dB would be appropriate. The PWID loudspeaker must therefore cover a range from about 65 dB to about 85 dB. This could be achieved satisfactorily by either:-

i) a continuously variable manual volume control allowing 65-85 dB output,

ii) a continuously variable automatic volume control,
or

iii) switched levels of 65dB, 75dB and 85dB.

Considering each in turn, the manual volume control has disadvantages if noise is continuously changing as various machines stop and start at different distances. Either the warden must continuously fiddle with the control, or more likely, he will just set a fairly high level, turning it up when necessary but not bothering to turn it down during lulls. This may be safe but is not ideal.

The second possibility, the automatic volume control is ideal from the human factors viewpoint, but the practical implementation should not be underestimated. Firstly a microphone must be incorporated to measure background noise levels. The microphone must be proof against dampness, cold and other extremes of weather. It must be positioned and shielded to minimise wind noise, preferably assisted by a low frequency roll-off to prevent the wind noise overloading the level detecting circuitry. The microphone must also be robust, insensitive to knocks and bumps and sited so it cannot be covered up accidentally in normal use. Also the level measuring circuit should not detect the warning sounds -- this is probably most easily achieved by sampling the background level during the gaps designed into the warnings' temporal patterns, though these gaps may be shortened by reverberation in tunnels. Satisfactory attack and release time constants to cope with abrupt changes in background noise level must also be found.

The third possibility is not as ideal as the automatic volume control ergonomically, but is less complex and little development work would be required. It would be more likely to be used as intended than the manual continuously variable control. In practice the 'low' setting would be used in quiet situations, while the medium and high would be used in the presence of plant and machinery. Under blustery conditions the warden would be able to choose his level to suit local conditions (wind noise around the head and ears can be significant) whilst the PWID itself would not be susceptible to wind noise.

With all the above options the reduction in warning sound level from the maximum in quieter backgrounds is not only important in optimising the warning sound's efficacy and acceptability, but also serves to minimise the warden's noise exposure and increase the PWID's battery life. The noise levels recommended above do not preclude a 10 dB boost for the first cycle of a warning sound if that sound is more urgent than its predecessor. Although listeners find it difficult to estimate absolute signal levels especially in varying noise, they will notice changes in signal level. Thus signal level is not in itself a good indication of the urgency of a warning, but changes in level can be.

<u>Sound levels from the PWID headset</u>

The PWID headset would be worn when noise levels exceed roughly 85 dB(A). The maximum noise level from plant and machinery on the tapes supplied was 101 dB(A) from a pneumatic hammer at 2 metres. The highest level from a train passing, at a distance no closer than 5 metres, was roughly 112 dB(A). This level was produced by a 100 mph train on corrugated track. The PWID headset and the single muff held to the ear therefore need to be able to generate warning sounds at the ear to overcome noise of 85-115 dB(A) measured outside the muff. A good earmuff will have a mean sound attenuation of 35 dB or more at frequencies between 1 kHz and 3 kHz in laboratory tests to British or ISO standards. Communication headsets with built in earphones are commercially available and those designed for noisy environments such as helicopters can match these attenuations, albeit at a higher weight due to the built in transducers. But the standard deviations of a headset or earmuff's attenuation can be 3-4 dB even in a laboratory. In industrial situations where muffs may not be carefully fitted, or may be used with safety spectacles or hard hats which prevent an optimum seal, the attenuation achieved may be only 25 dB.

Assuming that a headset will reduce sounds at the ear by 25 dB(A) at best, external background noise levels of 85-115 dB(A) will be reduced to 60-90 dB(A) at the ear. Plant and machinery noise would rarely exceed 80 dB(A) at the ear; passing trains would produce up to 90 dB(A) under a well designed headset.

Again no single level of warning sound is ideal to cover that range of background levels. The range of background levels at the ear when the headset is worn is similar to the range of levels when the headset is not needed and not worn. The options for coping with a range of levels when the headset is producing warning sounds are similar to those with the loudspeaker producing the sounds. Assuming that the warning sound level should be numerically equal to the A-weighted level at the ear, the possibilities are:-

- i) a manual volume control from 70-90 dB approximately,
- ii) an automatic volume control, or
- iii) a three position switch giving 70, 80, or 90 dB at the ear, approximately.

The assumption that a warning sound level set to be numerically equal to the A-weighted background noise level would fall at the minimum of the recommended range of warning sound levels cannot necessarily be assumed for the headset. The approximate levels quoted in this section are current best estimates but are subject to further assessment.

Tunnels and partially enclosed spaces

No recordings were available of noise sources in tunnels or cuttings. Close to machinery where direct sound will dominate the reverberant field the worst case noises may be little affected. Generally, though, machinery noise levels will be greater in the tunnel than they would have been in open air.
Under reverberant conditions the ILWS warden might choose to wear the PWID headset in levels below 85 dB(A) as the temporal patterns of the warning sounds might be more distinct through the headset than from the loudspeaker.
Without recordings of noise sources in tunnels more specific comments cannot be made.

CONCLUSIONS

Based on a detailed analysis of background noise and on published guidelines for warning sounds, but in advance of practical trials, the following conclusions were drawn:-

(i) The optimum frequency characteristic for the system is flat over the range from 500 to 3000 Hz.

(ii) Background noise levels experienced by the ILWS Warden will range from quiet up to about 100 dB(A) in the presence of plant and machinery, and up to about 112 dB(A) in the worst case from fast trains on corrugated track.

(iii) In noise levels below about 65 dB(A) the warning sounds should should have a level of about 65-70 dB.

(iv) In noise levels above 65 dB(A) the warning level in dB is optimum when roughly numerically equal to the background level in dB(A) (both measured at the Warden's head or ear position).

(v) To cope with background noise levels up to 85 dB(A) the PWID loudspeaker will need to produce levels between 65 and 85 dB SPL at the warden's head.

(v) A single warning sound level for all background noise levels would be unsatisfactory. A form of manual or automatic volume control will be needed.

(vi) In background levels above 85 dB(A) the ILWS Warden will wear earmuffs. Background levels under the muff are likely to be between 70 and 90 dB(A) and optimum warning sound levels from earphones in the muffs will vary between about 70 and 90 dB SPL. A form of manual or automatic volume control will be needed for the earphone output.

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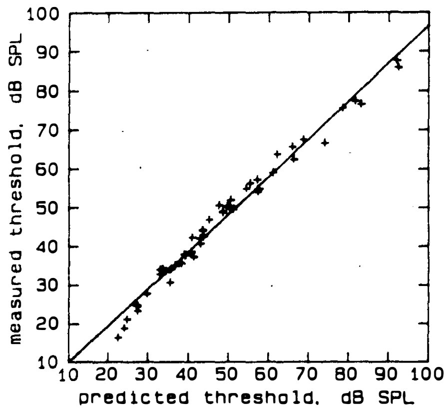
TABLE 1

Recommended warning levels in the vicinity of various noise sources (extract)

Noise source	Distance m	Noise level dB(A)	Average threshold (0.5 - 3 kHz) dB SPL	Appropriate range for main warning sound tonal components dB SPL
Rail saw	2	84	66	81 - 91
	5	78	60	75 - 85 *
Lighting generator	2	94	77	92 -102
	5	87	69	84 - 94 *
Rail disc cutter	5	95	77	92 -102 *
	10	90	72	87 - 97
Pneumatic hammer	2	101	82	97 -107
	5	97	77	92 -102 *
Shovelling ballast	2	82	65	80 - 90 *
Chainsaw	5	93	76	91 -101 *
	10	86	69	84 - 94
Permaquip packer	2	91	75	90 -100
	5	85	68	83 - 93 *
Track relaying machine	3	83	64	79 - 89 *
	10	75	55	70 - 80
Tamping machine	3	95	76	91 -101 *
	10	87	68	83 - 93
Electric loco + Mk 2 stock, 100 mph	2	104	89	104 -114
	10	100	84	99 -109
	25	94	78	93 -103
Electric loco + Mk 2 stock, 100 mph on corrugated track	5	112	95	110 -120
Idling Class 31 loco	2	79	60	75 - 85
Stationary Class 47	5	77	57	72 - 82
Mk 3 Stock, 100 mph jointed track	2	110	92	107 -117

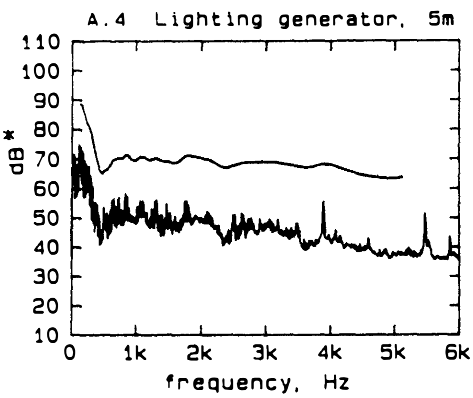
* indicates typical combinations of noise source and distance for an ILWS Warden



Each data point is a mean for ten subjects, at a test frequency between 100 Hz and 4 kHz, in one of three different noise spectra.

N = 51 points
y = 0.966x + 0.102
r = 0.990
std error of estimate = 2.42 dB

Figure 1 Mean predicted and mean measured thresholds compared.



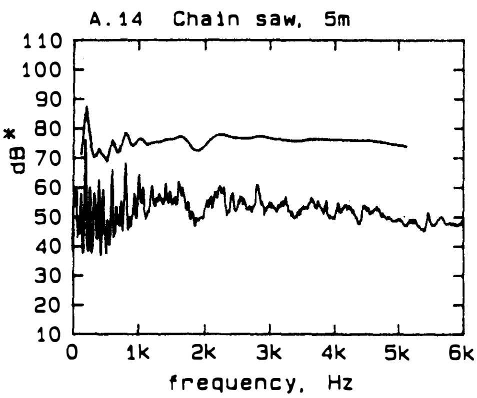


Figure 2 Examples of background noise spectra and predicted masked thresholds.
* See text for explanation.