Proceedings of the Institute of Acoustics

AUDITORY WARNINGS FOR THE BRITISH RAIL INDUCTIVE LOOP WARNING SYSTEM

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INTRODUCTION

A set of warning sounds has been produced for the Inductive Loop Warning System (ILWS) being developed by British Rail to give advanced warning of approaching trains to track maintenance workers. The manually operated warning system currently employed by BR (referred to as the PeeWee) was reviewed with regard to the guidelines for auditory warning sounds suggested by Patterson [1]. The spectral characteristics were found to be broadly suitable.

The ILWS uses a total of four warning sounds. In order of urgency they are Alarm, Reminder Warning, Qualified Safetone and Safetone. Four new sounds were produced from the original PeeWee sound to preserve the general association between sound and function. This paper reports the stages by which the warning sounds have been designed, the assessment of the PeeWee and its modification.

ANALYSIS OF EXISTING WARNING SOUNDS

Terminology: When describing auditory warnings we use the following three terms:

1. Pulse: An acoustic waveform that carries the distinctive warning sound quality. It is the basic building block of a warning sound and is usually between 100 and 500 ms in duration.
2. Burst: A set of pulses with a distinctive melody and rhythm (between 1 and 3 sec in duration).
3. Warning Sound: A sequence of bursts that indicate a specific warning state.

The Existing Warning Device: The PeeWee sounder emits half-second pulses of a complex wave, and the pitch of the pulses sweeps upwards in frequency from approximately 500 to 1000 Hz. The device has two states -- Alarm and Safetone. The former is signalled by a continuous sequence of half-second pulses, the latter by individual pulses separated by 2-second gaps. The Alarm and Safetone are in regular use and are familiar to track maintenance workers.

The new ILWS will have four states with the addition of a Reminder Warning and Qualified Safetone. British Rail Research (BRR) produced experimental Reminder Warnings and Qualified Safetones to demonstrate the feasibility of adding two extra sounds. These experimental sounds were evaluated alongside the standard sounds, though they have not been used on the railway network and have not been heard by track maintenance gangs. Thus the four existing warnings, in order of urgency are:

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Alarm (A): a stream of continuous pulses (Standard PeeWee).

Reminder Warning (RW): repeated bursts of a double and single pulses (Experimental).

Qualified Safetone (QST): repeated bursts of a 3-level pulse cycle (Experimental).

Safetone (ST): a single pulse repeated with 2-sec gaps (Standard PeeWee).

The existing signals were assessed against the requirements of each of these three versions. BRR provided the APU with a PeeWee sounder and a cassette tape recording of a different PeeWee. Specimen warning sounds were generated from both of the above sources.

Overall Sound Levels

The level that the current PeeWee device operates at, when continuously sounding, is approximately 100 dB at a distance of 2 metres from the unit [2]. The level of the experimental Reminder Warning is about 6 dB lower than the Alarm. The Qualified Safetone operates at three different levels. The levels cycle between 0, 6 and 12 dB lower than the Alarm. A level of 100 dB at 2 metres is not only aversive but also potentially damaging if the listener is subjected to prolonged periods of exposure to the sound. Any personnel monitoring the device will, by design of the current system, be exposed for long periods to the PeeWee sounder. Consequently, the new system (as detailed below) reduces the level whenever possible, taking note of the recommended levels. These recommended levels are based upon analyses of the background noise environment [3] and upon Patterson's guidelines [1] for warning sound levels. The fixed, Alarm, level from the PeeWee loudspeaker is from 10 to 35 dB higher than the recommended levels which vary depending on the local background noise.

The level of the experimental Reminder Warning was 6 dB below the level of the Alarm. Also the experimental Qualified Safetone was distinguished from the Safetone in that the level of the former varied while the level of the latter was constant from pulse to pulse. In the construction of warning sounds, it is not advisable to use level as the sole means of distinguishing two warning sounds. When the demands on operator attention are high, changes in level as large as 12 dB may go unnoticed and so level differences should not be used as the sole means of distinguishing warning sounds. Variations in level within a group of pulses can be used as a means of reinforcing distinctiveness where variations in other parameters exist, e.g. spectrum, rhythm, and pitch, but they should not be used as the sole distinction between states.

Temporal Characteristics

For the Alarm sound, the repetition rate of the PeeWee is 2 Hz. The individual pulses have a duration of approximately 500 ms. They have very abrupt, almost instantaneous, onsets but slower offsets of some 50 ms. The Alarm consists of a stream of continuous pulses. There is a disadvantage with continuous warnings in that they inhibit inter-personal communication. Even if there are relatively few occasions when trackside crew need to

communicate with each other, the option to do so should still be available. The need to communicate is likely to be the highest when the Alarm is sounding and there is no need for a continuous warning sound. It only makes the warning more aversive.

Equivalent continuous sound level, Leq, is the notional steady A-weighted level that would produce the same A-weighted sound energy over a stated amount of time as the real time-varying sound. Thus the Leq for a given work period will be higher for continuous sounds than for intermittent sounds. So to minimise Leq, one should reduce the total duration of warning sounds, and the sound pulses within the warning wherever possible. Since a reduction of 20% in the duration of a signal reduces the Leq of a signal by only 1 dB and a halving in the duration is necessary to reduce its Leq by 3 dB there is often little to be gained, especially since background noise also contributes to the ambient Leq. However, these reductions in duration will have the advantage of reducing the annoyance caused by the warnings and may give worthwhile extensions to the battery life of portable equipment.

The Reminder Warning has two pulses in immediate succession with a combined duration of 960 ms. After a delay of 500 ms, a single 500 ms pulse is then played. After a further delay of 980 ms, the whole cycle is repeated. The duration of the complete burst, in this case the cycle time of the warning, is 2.94 seconds. The intermittent nature of the Reminder Warning (a double pulse followed by a single pulse) makes it distinctive, and its intermittency permits a brief verbal command between bursts. The lightly syncopated rhythm helps to distinguish it from other competing warnings that might occasionally be found in the working environment, and so broadly speaking, it has a good temporal pattern.

The Qualified Safetone is a variant of the standard PeeWee Safetone. It consists of individual pulses played at the same rate as the those of the Safetone, but differentiated by level; pulses are presented in groups of three in which the second is some 6 dB lower, and the third, 12 to 13 dB lower than the first. This cycle is repeated on a continuous basis, and the total cycle time of this warning is 7.8 seconds. Although the Safetone and Qualified Safetone are temporally distinct from the Alarm and the Reminder Warning, they have the same temporal pattern, and are distinguished solely by differences in sound pressure level. A distracted operator might well miss the change from one state to another. The cycle time is also rather long in that up to 8 seconds is needed to distinguish these two warnings if level information is overlooked. The Safetone consists of single 500 ms pulses with 2.1 seconds silence between each, making a cycle time of 2.6 seconds.

Summary: The duration of the pulses in all of the proposed warnings is longer than necessary. A listener only requires a pulse in the region of 100 ms to perceive the sound quality, and the longer the pulse the lower the level of urgency that can be conveyed by pulse rate. The onsets of the pulses are too abrupt especially for non-urgent warnings; the offsets acceptably slow (around 50 ms). A pulse with a slower onset would be less aversive and less likely to evoke a startle reaction.

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Assessment of Spectral Characteristics

The PeeWee emits waves that sweep up in frequency from around 500 to 1000 Hz. Figure 1 shows the spectrum of the APU PeeWee at the start of the sweep when the frequency is low. It can be seen that the sound is broadband and complex, with a concentration of energy in the 400 to 4000 Hz region. Although BRR describe the PeeWee as emitting square waves, it was found on analysis that the waves are far from square. The spectrum of a true square wave contains odd harmonics only. The spectra of samples taken at the start and end of the pulse showed as much energy at the even harmonics at the odd harmonics. The high frequency wave sweeps upwards in frequency from 540 to 1140 Hz, which is slightly more that one octave. The low frequency wave is approximately one semitone lower in frequency throughout the sweep.

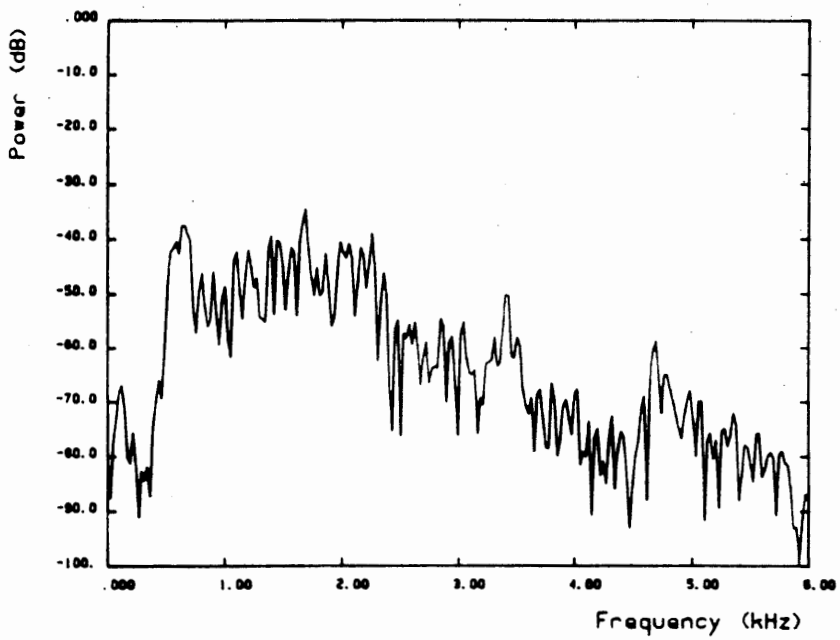

Figure 1. PeeWee Spectrum

In summary, the raucous PeeWee sound is a good attention getter. It has harmonics throughout the spectrum and this, together with the fact that it has a wide frequency sweep, renders it resistant to masking by all but the very loudest, steady-state noises. The discordant nature of the sound is appropriate for a warning which is used to signal danger. A warning used outdoors should be distinct from other warning sounds likely to be encountered. While the PeeWee is reasonably distinct from many other warning sounds such as train horns, car horns, fire bells, and fire sirens, it does bear some similarity to certain ambulance sirens which also employ rising

frequency sweeps. The main disadvantages of using the existing sounds in a new system are that a single acoustic building block, the half-second, upward gliding double wave, is used in the construction of all four warnings, and the same pulse is used to signal both danger and safety. Only timing and sound pressure level are used to distinguish the different members of the existing warning set. Modifications to overcome these disadvantages are described in the next section.

MODIFICATION OF THE EXISTING WARNING SOUNDS AND DESIGN OF NEW SOUNDS

The warning set that was ultimately agreed by APU and BRR for the ILWS was developed through a process of refinement over a period of several months. Broadly speaking, APU would generate sets of prototype (or demonstration) sounds and send them to BRR on tape. BRR would then assess the sounds and obtain reactions and comments from a range of BRR personnel. Subsequently, BRR and APU would meet and modify the preferred prototypes. Eventually this iterative process converged on the final set of four warning sounds shown in Figure 3, and approved by the ILWS Project Team. The following subsections present a brief review of that refinement process.

The First Prototype Warning Set

The first set of prototype warnings were primarily intended to demonstrate the variety of sounds that could be generated from the original PeeWee sound, and the distinctive temporal patterns that APU were likely to recommend for the warnings in the ASAD system. The desire of BRR to reduce Leq as much as possible for reasons of safety was taken into account in all of warning sets produced. Each warning sound was designed with the reduction of pulse and burst duration in mind.

The tape consisted of 12 warning sounds (three examples of each of the four states: A, RW, QST and ST). The bursts of pulses that identify the individual warnings are summarised schematically in Figure 2; the abscissa is time, the ordinate is pitch, and with a little practice, the schematics can be read like music. The Qualified Safetone and the Safetone were always built on the single 'square' wave in order to keep the perceived urgency of these warnings down to the appropriate level.

BRR then provided comments and suggestions on these initial prototype warnings. We began the refinement process by assembling a new warning set composed of the Alarm, Reminder, Qualified Safetone and Safetone that obtained the most favourable reaction. The preferred warnings were A1, RW1, QST3 and ST1. Then we used the comments from BRR personnel to improve the warnings. To establish if the warnings were distinguishable in a tunnel working environment BRR had tested each warning in reverberant conditions. This constraint alone resulted in the redesign of some of the warning sounds described below. With regard to Alarms, version A1 was preferred; both A2 and A3 were thought to let the listener down at the end. This was interpreted to mean that they were not sufficiently urgent. For the Reminder Warnings, RW1 was preferred over RW2 and RW3. It was, however, perceived to be too urgent despite the downward pitch contour. Although,

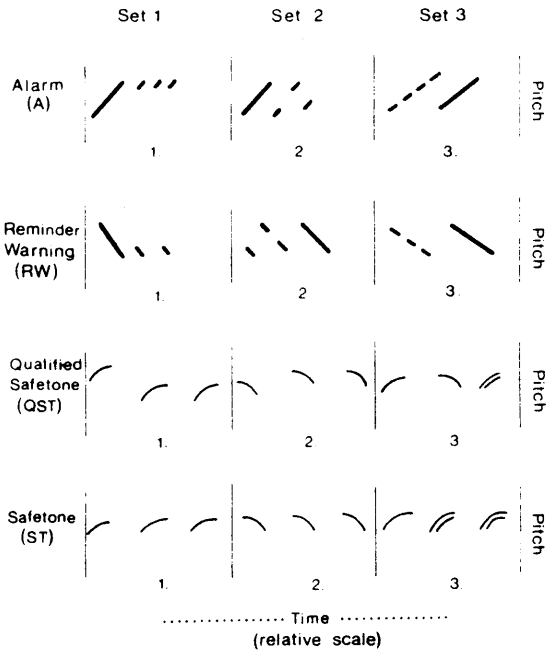

Figure 2. Prototype Auditory Warnings

the Reminder Warning is very important, it was felt that it should be distinguishable from the Alarm in terms of its perceived urgency. With regard to the Qualified Safetone, QST3 was preferred. QST1 was considered to be too close in character to the preferred Safetone (ST1). QST2 was not favoured because the falling pitch contour was not sufficient to distinguish it from ST1, the preferred Safetone. This left QST3 proved to be a good partner for ST1 in reverberant conditions. (The distinction between QST3 and its corresponding Safetone, ST3, had disappeared when BRR had tested them under such conditions). Finally, the Safetone, ST1, was universally preferred. This was almost identical to the original Safetone but with its pulse duration substantially reduced (from 500 to 330 ms).

Warnings A1, RW1, QST3 and ST1 were then modified to produce the second set of prototype warnings. The Alarm was increased in urgency by shortening the silent gaps between the last three pulses; this had the additional effect of making the sound more syncopated and thus more distinctive. The Reminder Warning retained its general downward pitch movement, but an additional short pulse was added at the beginning of the burst to make it more distinct and less urgent then the Alarm. The Qualified Safetone, QST3, had its final "double square-wave" pulse removed from the burst. The Safetone, ST1, was left unchanged for the second prototype set.

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The Final and Recommended Set of Auditory Warning Sounds

The second set was presented by the ILWS project team to representatives of all BR regions. Reactions gained from this, plus further comments from BRR who once again tested the sounds in reverberant conditions were used to produce this final set of warning sounds at APU. These are schematically illustrated in Figure 3. The Safetone was considered to be adequate and went forward unmodified. The Qualified Safetone had its second pulse moved (in time) away from the first pulse. In reverberant conditions reproduced by BRR there had been a merging of the first two pulses in a burst of four pulses. The Alarm was felt by BRR to be (initially) insufficiently urgent. The second prototype Alarm, which employed a cycle of three bursts of successively increasing pitch, was reduced to a cycle of two bursts. The remaining bursts still differed in pitch, however, but were perceived by all to be more urgent.

Finally, the Reminder Warning was thought to be too complex in its second version and possibly too close to the Alarm in temporal structure. The direction of the burst was changed so that the general pitch movement was downward. The long downward sweep of the second pulse was further segmented to add further syncopation and distinctiveness. The final two pulses were repeated and tagged on to the end of the burst creating a slight

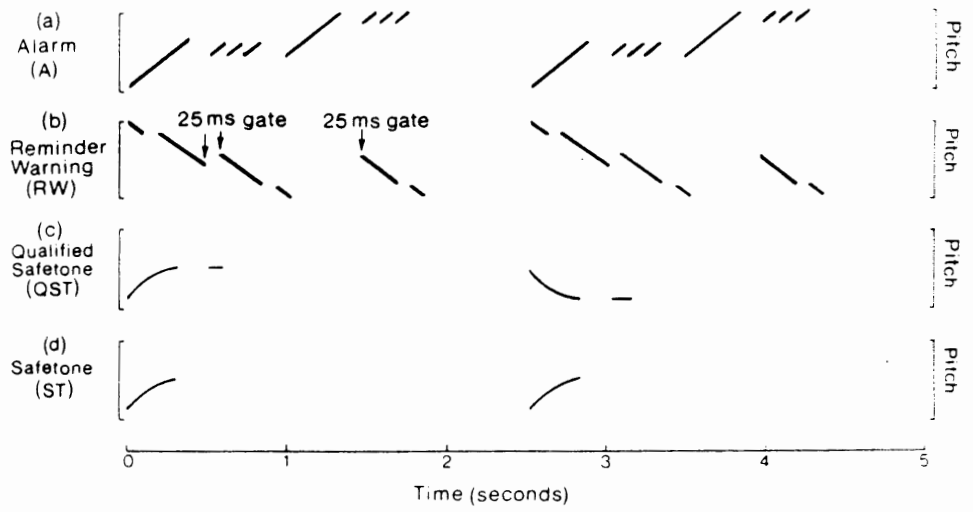

Figure 3. Recommended Warning Set

echo effect. All the warnings in the final recommended set have repetition rates of 2.5 seconds.

DISCRIMINABILITY TRIALS OF THE WARNING SOUNDS

It is important that trackside workers are able to learn the warning sounds and recognise any member of the set without hesitation. Since the recommended set of warning sounds all have similar or identical spectra a confusion test was performed in order to assess the warnings for discriminability. Ten BR trackside maintenance staff from the Cambridge area took part. The experiment was structured as a self-paced learning programme comprising two test sessions spaced one week apart. Subjects were required to identify the four warning sounds after a preliminary learning presentation. All the sounds were presented at the same relative levels as in the final demonstration tape, the Alarm being measured at approximately 86 dB SPL through the headset.

With only four sounds to learn subjects quickly attained perfect performance on a single trial. In order to establish that correct identification on one trial was not a chance occurrence three consecutive perfect trials had to be completed before the learning session was terminated. Audiometry was performed on subjects between learning sessions. This achieved the dual purpose of testing the acuity of each subject's hearing, and providing a suitable gap between learning sessions so that retention could also be tested. Confusion analyses were performed on three learning and two retention trials. The analysis is extremely sensitive but only revealed one confusion with a probability of occurrence of less than 5%. This happened on the second learning session between the Alarm and Reminder Warning but did not occur in any subsequent session. It is very unlikely that track maintenance personnel would confuse any of these warnings.

The recommended final set of prototype warnings (Figure 3) has been approved by British Rail. They are to be incorporated into a prototype warning device and subsequently tested in field trials.

ACKNOWLEDGEMENTS

We would like to thank British Rail for their support of this research, and in particular, the Physics Group at British Rail Research, Derby.

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