Comparison of different vehicle backup-alarm types with regards to worker safety

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INTRODUCTION

Audible backup alarms installed on mobile equipment are used to warn or alert nearby workers. Still, accidents and fatalities involving vehicles in reverse are reported every year (Murray et al. 2007; NIOSH 2004; Blouin 2005). Two important factors may affect the effectiveness of backup alarms on workers safety (Laroche 1995). Firstly, the uniformity of the sound field behind the vehicle is not guaranteed, in particular for tonal alarms. Secondly, spatial localization of the alarm can be a problem, particularly for workers wearing hearing protectors. Additionally, the noise generated by such devices will propagate and, quite often, be a source of nuisance for residents living in close proximity. In recent years, a new type of vehicle backup-alarm has been drawing increasingly more interest from many industrial sectors. The new alarm, based on the use of broadband noise instead of the typical tonal ("beep") signal, is deemed to reduce environmental noise annoyance close to industrial settings and construction sites and to be more efficient for spatial localization and uniform noise propagation behind vehicles. While conceptually appealing, few published and peer-reviewed scientific studies have demonstrated the advantages and disadvantages of such an alarm to ensure worker safety, particularly in comparison to existing technologies (Burgess & McCarty 2009; Homer 2008; Withington 2004). This two-part study was intended to compare three types of backup alarms: the standard tonal signal, a multi-tone signal and the broadband noise technology. The first part, performed in the field, focused on objective measurements of the sound propagation behind vehicles for various vehicles and terrain configurations. The second part, performed in a laboratory environment, was centered on the measurement of various psychoacoustic metrics (hearing threshold, loudness, and perceived urgency), as well as the study of spatial localization tasks. The paper presents the methods used for the "field" and "laboratory" parts. Results illustrating some of the findings, both from the field and from the psychoacoustic standpoint, are finally presented.

METHODS

Sound field behind vehicles

Three backup alarms were tested in this study: i) a standard tonal alarm from Grote (Grote Industries Inc. 2011); ii) a broadband alarm from Brigade (Brigade Electronics 2011) and; iii) a custom-made multi-tone alarm. The multi-tone was proposed by Laroche (1995) as an improvement over the conventional tonal alarm. It was included in this study for comparison with the two other types of signal. The frequency content of the three alarms is illustrated in Figure 1. The sound pressure levels (SPL), measured at approximately 1 m in front of the alarms, are shown as a function of frequency. The multi-tone alarm consists of three major tones located between 1,000 and 1,300 Hz, contrarily to the standard tonal alarm where the acoustic energy is concen-

trated around 1,250 Hz. For the broadband alarm, the energy is distributed over a larger frequency span, most of the energy being found in the 700-4,000 Hz range.

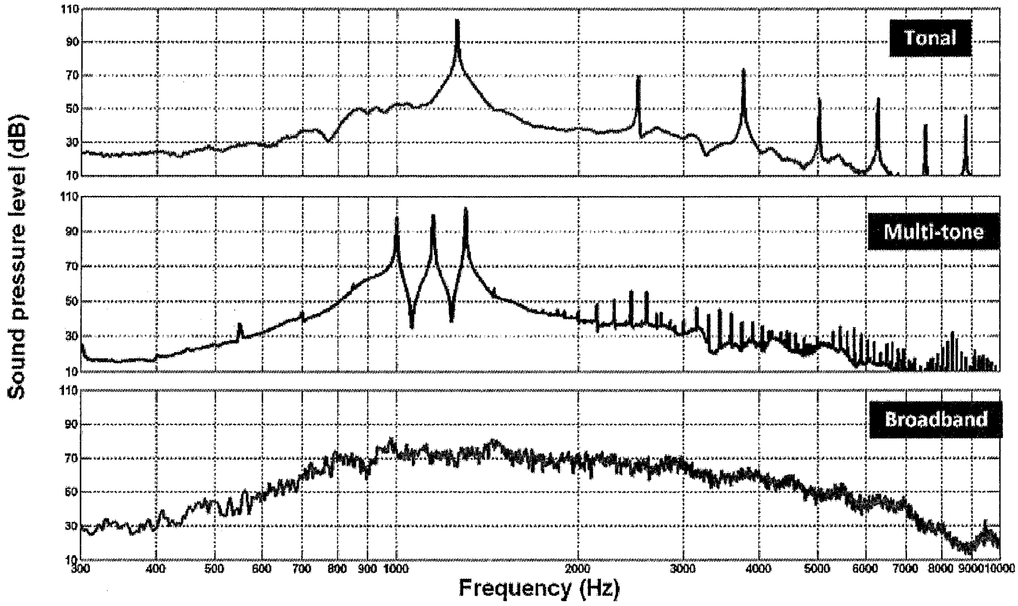

Figure 1: Frequency content of the three alarms tested

Tests were performed at three different locations: a sawmill site, a limestone and a quicklime plant. All had different terrain configurations (hard soil or gravel & dirt). To study the sound propagation behind vehicles, a test method inspired from the ISO 9533 standard (1989) was developed. The ISO 9533 procedure was adapted and enhanced to be able to produce, in addition to what is required by the standard, contour maps of the sound field behind the vehicles for the different alarms. BSWA type 1 ½-inch microphones were used in conjunction with an Edirol audio recorder and National Instruments/Labview acquisition system for sound pressure measurements. For the positioning of the alarms on the vehicle, two mounting scenarios were considered: i) a "realistic" one, which consisted of using the alarm as installed on the vehicle (the alarms were off-centered in all three cases tested,) and; ii) an "ideal" one where the alarm was centered, unobstructed and facing outward.

Two sets of measurements were performed for each alarm. In the first set, alarm level adjustments were performed by measuring the sound pressure levels at the seven microphones positions specified in the ISO standard (see Figure 2(a)). The alarm level was then manually adjusted so that a difference equal to or greater than 0 dB (signal-to-noise ratio S/N≥0dB) was obtained at all measurement points between the sound levels generated when the vehicle was operating at high idle without alarm present and those prevailing when the reverse alarm was activated and the truck operated at low idle. For a given vehicle/terrain, the procedure was repeated for each alarm. It allowed examining if one alarm type would require higher levels than the others to maintain the desired S/N≥0 dB at all microphones. A reference microphone was located at a center position 1 meter behind the vehicle to monitor alarm levels.

In a second step, a microphone was mounted to a pole and digital audio recordings were performed while the alarm was activated by moving the microphone slowly along 9 axes and 2 curvilinear arches behind the vehicle (see Figure 2(b)). The alarm levels were set at the values found during the first set of measurements and the vehicle engine was stopped. A post-processing scheme was developed under MATLAB to obtain sound pressure levels along the various lines. Subsequently, an interpolation algorithm was used to produce sound pressure level maps behind the vehicle when the alarm is activated. Such procedure was used to investigate the uniformity of the sound field generated by each alarm.

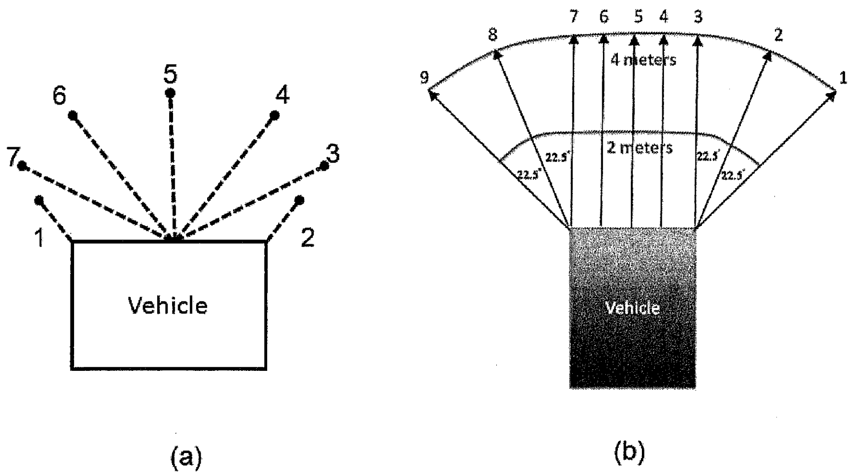

Figure 2: (a) Position of the microphones for the alarm level adjustment; (b) Illustration of the scanning lines for sound mapping measurements

Psychoacoustic measures

Twenty-four subjects with normal hearing (hearing thresholds ≤ 25 dB HL from 250 to 8,000 Hz) took part in laboratory measures of psychoacoustic metrics (detection thresholds, equal loudness judgments and perceived urgency ratings) and spatial localization tasks, both with and without hearing protection devices, in four background noises measured in the field and played back in a noise simulation room. The noises are characterized by various global sound pressure levels (Noise 1 = 81 dBA, Noise 2 = 83 dBA, Noise 3 = 86 dBA, and Noise 4 = 89 dBA) and cover a range of spectra, as illustrated in Figure 3. Half of the sample used Peltor Optime 95 (NRR = 21 dB) earmuff-style hearing protection devices (HPDs), while the rest wore EAR UltraFit earplugs (NRR = 25 dB). In this paper, preliminary results on 16 participants are presented.

Prior to testing, subjects were familiarized with the signals and tasks to be performed. All alarms were played through a single loudspeaker placed 1 meter in front of the subjects, whereas five additional loudspeakers around the subject and one subwoofer were used to create a diffuse noise field.

For threshold measurements, defined as the presentation level at which one can correctly detect 50 % of the presented stimulus, an adaptive method was utilized. Using a tablet PC and a software specifically designed for this study, subjects were required to adjust (using 2-dB steps) the level of each alarm up and down until they were barely audible. Testing was performed twice in each of 5 conditions (quiet + 4 background noises), firstly in open-ear conditions and then with HPDs.

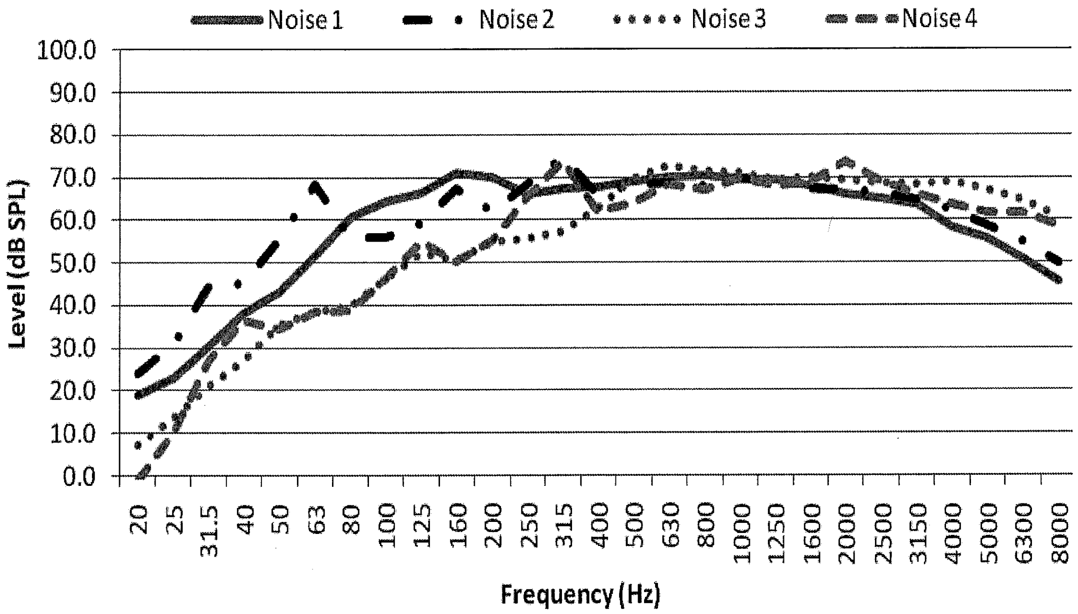

Figure 3: Normalized spectra at 80 dBA for the four background noises used in the study

For equal-loudness measurements, the tonal alarm presented at S/N ratio = 0 dB served as the reference alarm. In each of the four noises, participants were required to adjust the sound pressure level of the broadband and multi-tonal signals until they were perceived to be as equally loud as the reference alarm.

Equal loudness does not guarantee that the signals will be perceived by workers as relaying equivalent information about an urgent situation. To investigate the degree of urgency evoked by the different signals, the three backup alarms were randomly presented at three different S/N ratios (-6 dB, 0 dB and +6 dB) while subjects had to rate alarm urgency on a scale of 0 to 100, with a rating of 0 indicating that the alarm was heard but evoked no sense of urgency and 100 being most urgent. Nine urgency ratings (3 alarms x 3 S/N ratios) were performed in each of the 4 background noises, with and without HPD.

Finally, the ability to judge the direction of backup alarm incidence was assessed through a source-identification task in the horizontal plane using a set of 12 loudspeakers arrayed uniformly over a 180° localization arc. Subjects were seated in the center of the localization arc, at a distance of 1 meter from each loudspeaker. Three spatial configurations were tested, with the loudspeaker arc placed at the back of the subjects (to quantify left-right confusions) and to their right and left sides (to quantify front-back confusions). The alarm signals were adjusted to simulate increasing sound pressure levels associated with a vehicle reversing at a speed of 4.4 m/s (10 mph). Testing was performed in one of the selected background noises (Noise 2) at S/N ratios gradually increasing from -6 to 0 dB over 3 seconds, simulating the sound pressure levels at a worker's position as the vehicle is backing up. Following familiarization, a given alarm signal was randomly presented twice from each of the loudspeakers (for a total of 24 trials) and subjects were required to verbally identify the loudspeaker thought to have emitted the sound. Overall, the task consisted of 216 alarm presentations (24 trials X 3 testing conditions X 3 alarms). Testing was repeated with HPDs.

RESULTS

Alarm level adjustment per ISO 9533

Results obtained for the "S/N≥0 dB" procedure are summarized in Table 1. For each alarm and each site, the mean and standard deviation of the S/N ratio is presented as well as the sound pressure levels at the reference microphone. It is observed that higher levels had to be used for the tonal alarm compared to the multi-tone and broadband ones. Also, higher mean S/N and standard deviations are obtained for the tonal alarm, suggesting more sound level variations for this design.

Table 1: Mean (standard deviation) values of the signal-to-noise ratio (expressed in dB) over the 7 microphone locations & sound pressure levels (in dB(A)) at the 1m reference microphone (alarm position: "ideal" mounting).

	Site 1		Site 2		Site 3	
	Mean (std)	Level @ 1m	Mean (std)	Level @ 1m	Mean (std)	Level @ 1m
Tonal	6.9 (4,2)	107.2	8.0 (5.9)	112.0	3.2 (2.3)	106.0
Multi-tone	3.9 (2,3)	99.4	5.4 (4.0)	105.2	4.9 (3.1)	102.8
Broadband	1.9 (1.2)	99.3	3.1 (2.9)	104.9	1.0 (0.7)	102.1

Sound pressure level maps

Maps of the sound pressure levels behind the vehicle are presented in Figure 4 for one of the site (alarms positioned in the "ideal" mounting scenario). Variation of the alarm level on the order of 10 dB within a short range of ~1 meter can be observed for the tonal alarm due to the effect of acoustic interferences. Not surprisingly, this interference effect is quite pronounced when only one strong tonal component dominates. However, it tends to be smoothed out considerably when adding two additional tonal components to the signal, as is the case for the multi-tone alarm. Finally, a relatively uniform sound field was obtained for broadband alarm.

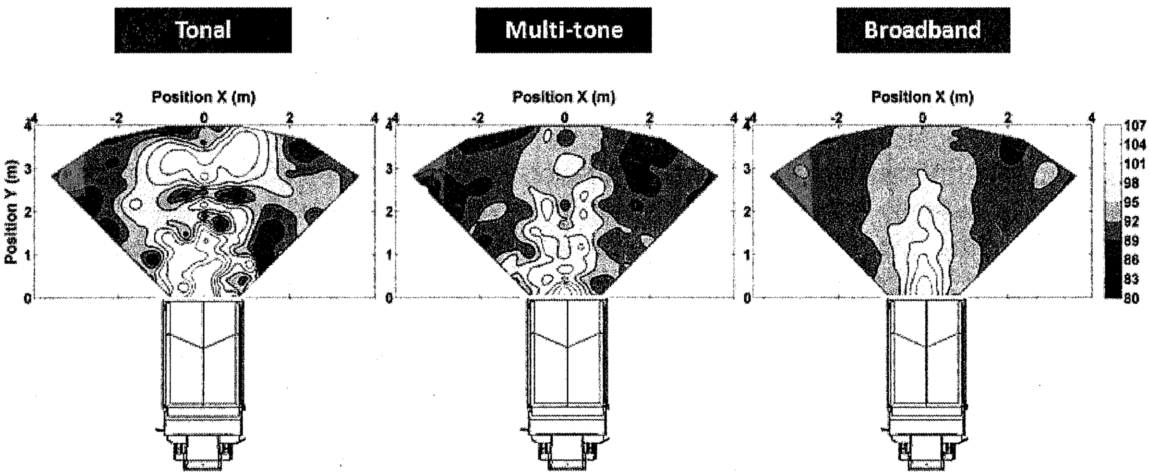

Figure 4: Sound pressure levels behind the vehicle (expressed in dB(A)) for one of the site and for the alarms in the "ideal" mounting position

Results on psychoacoustic measures and localization data

Preliminary data obtained on 16 of the 24 subjects are presented here for measures of detection, perceived urgency and sound localization. Due to space constraints, only results from the two commercial alarms (tonal, broadband) are presented.

Detection results are expressed as the mean S/N ratio at threshold in Figure 5. As can be seen, the average S/N ratio at threshold is relatively constant across the four noises for the tonal alarm, whereas it seems to depend on the type of noise when a broadband signal is used, being somewhat similar in Noises 1 and 2 and higher in Noises 3 and 4. With greater energy in the high-frequency region, Noises 3 and 4 appear to have a larger masking effect on the broadband signal (which extends into the high frequencies) than on the tonal alarm (whose energy is centered around 1250 Hz) as shown in Figures 1 and 3. In this frequency range, all noise spectra are relatively identical, potentially yielding similar masking effects on the tonal signal, which could explain uniform thresholds for this signal across the noises.

With HPDs, similar trends are observed but thresholds are improved by about 0-2 dB for the broadband signal and 3-4 dB for the tonal alarm. Lower S/N ratios for detection could be attributed to narrower auditory filters and associated decrease in masking effect when testing is performed at lower background noise levels under HPDs, relative to unprotected conditions. Average thresholds in Noise 1 are very similar for both alarms when unprotected, while a difference of 4 dB favoring the tonal alarm is found with HPDs. In Noise 2, protected and unprotected thresholds are very similar for both alarms. In Noises 3 and 4, threshold differences of 4 dB and 6-7 dB favoring the tonal alarm are noted in the unprotected and protected conditions, respectively.

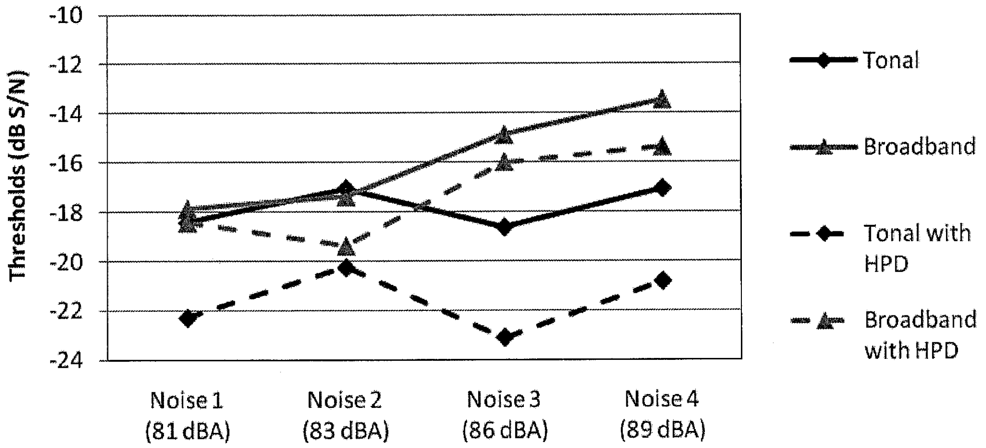

Figure 5. Average detection thresholds for the tonal and broadband alarms obtained in four background noises with 16 individuals with normal hearing

Average ratings of perceived urgency for the tonal and broadband alarms are reported for two noises (Noises 1 and 3) at three S/N ratios (-6 dB, 0 dB and +6 dB) in Figure 6. As expected, the degree of urgency conveyed increases with the S/N ratio in a constant noise. Results also vary according to the noise, alarm and listening condition. At the highest S/N ratio (+6 dB S/N) in unprotected conditions, the broadband alarm was rated either equally urgent or more urgent than the tonal alarm, with a 10-point maximum difference in ratings on a 100-point scale. A different trend is noted with HPDs, where the broadband signal is being rated equally or less urgent than the tonal alarm (10-point maximum difference). At this S/N ratio, urgency ratings drop for both alarms when HPDs are worn relative to unprotected conditions, with larger drops noted for the broadband signal (15-30 points) than the tonal alarm (5-12 points).

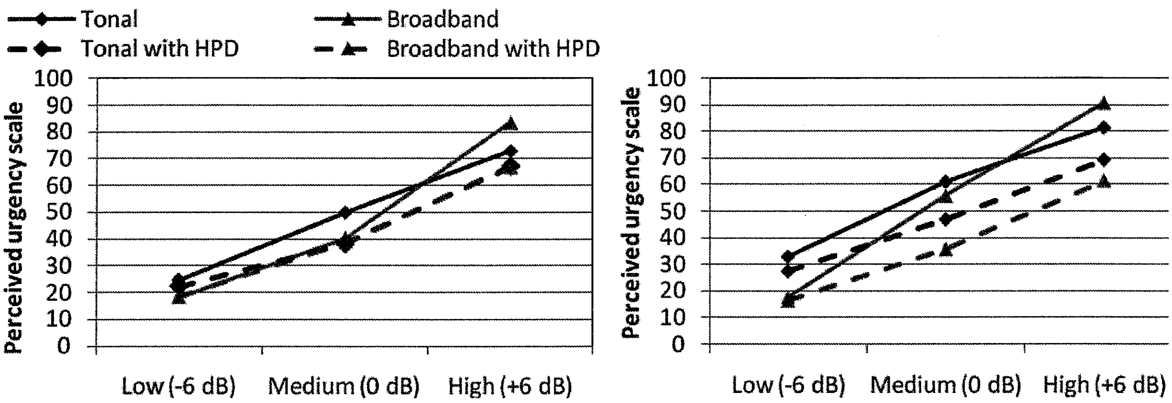

Figure 6: Average perceived urgency ratings at various S/N presentation levels obtained with 16 individuals with normal hearing (left panel = Noise 1; right panel = Noise 3)

The average number of left/right and front/back sound localization errors is shown in Figure 7 for tonal and broadband alarms, with and without HPD. A left/right or front/back error occurs when a loudspeaker position within a 90° quadrant is confused with a position in the other 90° quadrant. As expected, the number of errors is greater for the side conditions (front/back judgement) of the localization arc, where localization cues rely heavily on spectral information, than for the condition at the back (left/right judgement), where binaural cues such as interaural time and level differences are used to localize sound. This is noted for both the unprotected condition and when HPDs are used. The number of right/left and front/back errors also increases for both alarms when HPDs are worn, particularly when localization relies on spectral information (front/back dimension).

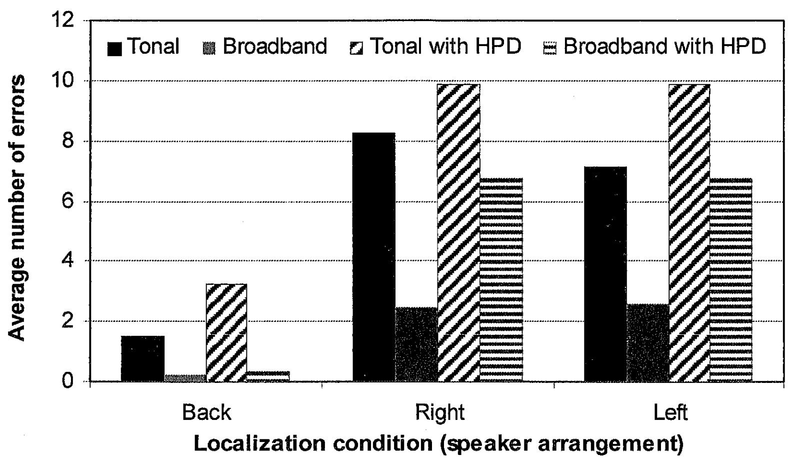

Figure 7: Average number of localization errors obtained with 16 individuals with normal hearing in Noise 2. In the back and side conditions, errors consist of Left/Right and Front/Back confusions, respectively

Preliminary results indicate that HPDs can hinder sound localization for both alarms, especially for the front/back judgements in the side conditions. Unprotected, subjects seem to perform better with the broadband alarm. Such effect of the alarm type is particularly evident in the side conditions. The broadband alarm also appears to be easier to localize than the tonal alarm under protected listening conditions. Further data collection and analyses will reveal whether these obervations reach statistical significance.

CONCLUSIONS

A sampling of acoustic measurements and psychoacoustic data on three backup alarms is presented in this paper. Alarms with a broad frequency content appear to present some advantages over conventional single-tone alarms, including: 1) a more uniform sound propagation pattern behind heavy vehicles; 2) lower sound pressure levels to meet the requirements set forth in ISO 9533; 3) higher urgency ratings at high S/N ratios without protection devices and; 4) better sound localization performance. However, some disadvantages were also noted. Firstly, higher S/N ratios are required for detection of the broadband alarm, at least in noises rich in high-frequency content. Secondly, detection thresholds and urgency ratings appear to be more severely affected by the use of HPDs for the broadband alarm than the tonal alarm.

The preliminary findings and general trends above must be interpreted with caution. Additional data on a greater number of subjects and more comprehensive analyses are required to draw firm conclusions from such findings. Results need to be more thoroughly analyzed form a work safety standpoint, taking into consideration other factors such as environmental annoyance, habituation and familiarity of the alarms.

ACKNOWLEDGMENTS

The authors would like to thank the Institut de Recherche Robert Sauvé en Santé et Sécurité du Travail (IRSST) for its financal support.

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Intelligibility of speech corrupted by nonlinear distortion

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INTRODUCTION

Attempts to predict the intelligibility of speech transmitted by a communication system have led to numerous models (see, for example, ANSI 1997; IEC 2003; Christiansen et al. 2010; Elhilali et al. 2003; Kates & Arehart 2005; Payton & Braida 1999; Steeneken & Houtgast 2002a; Yu et al. 2010). Of these, the speech intelligibility index (SII) (ANSI 1997) and the speech transmission index (STI) (IEC 2003) have received most attention. Both provide an index of intelligibility from 0 to 1 based on the speech signal-to-noise ratio in discrete frequency bands. The frequency bands of the SII were originally chosen to reflect the psychoacoustic masking of test sounds by noise (critical bands). The method was later standardized with the speech spectrum alternatively broken down into fewer, broader frequency bands for convenience of calculation (one-third octave, and octave bands from 125 Hz to 8 kHz). The test signals are those naturally occurring in the communication system (i.e., speech and noise, the levels of which need to be separately determined). The STI focuses on the temporal modulation of speech sounds and adopted octave bands as the basis for calculating the modulation spectrum (Steeneken & Houtgast 2002b). It replaced speech by a probe signal to ensure that the modulation could be determined in each modulation frequency band, which have frequencies from 0.63 to 12.5 Hz in the international standard.

In modern communication systems the speech signal is often corrupted by the signal processing and electronic circuitry, as well as by noise, which in some circumstances introduces audible distortion and may degrade intelligibility. The SII and STI have been shown to predict speech intelligibility for a range of conditions in which speech understanding is impeded by continuous noise, but fail when the speech signal is corrupted by nonlinear distortion such as center clipping. In these circumstances the performance of the SII has been improved by calculating the speech signal-to-'noise' (or distortion) ratio from the coherence, which needs to be determined for different amplitude ranges of the speech signal in order to assess the intelligibility (Kates & Arehart 2005). We have explored replacing the test signal of the STI by speech and adjusting the metric for the coherence between the original and corrupted speech, as a means for determining when the observed modulations are due to speech rather than 'noise' (Payton & Braida 1999; Goldsworthy & Greenberg 2004). Also, the contributions to intelligibility from speech information in nearby frequency bands is known not to be independent, and so cannot be simply summed as in some models (e.g., ANSI 1997), resulting in the need to estimate inter-band redundancy (Steeneken & Houtgast 1999; Brammer et al. 2010).

In this paper we briefly describe our models and their application to speech-spectrum shaped noise and center clipping. The latter occurs when a signal within a communication channel rapidly changes polarity from a non-zero value. An example is given