

ACOUSTIC CHARACTERISTICS FOR EFFECTIVE AMBULANCE SIRENS

Carl Q. Howard, Aaron J. Maddern and Elefterios P. Privopoulos

School of Mechanical Engineering, The University of Adelaide, Adelaide, South Australia

Ambulances involved in collisions with motorists at intersections result in a number of negative outcomes including the inability to respond to the assigned emergency task, injury of people, and sometimes the loss of an operational appliance. The warning siren is perhaps the only non-visible device to alerting motorists approaching intersections of a converging ambulance. Acoustic measurements were conducted on several commercial-off-the-shelf sirens, a motor vehicle, and an ambulance, to characterise the noise transmission system. Tests were conducted in order to provide recommendations to improve the audibility and effectiveness of the warning signal. It is recommended that ambulance operators install sirens that broadcast sideways to the ambulance; that broadcast low frequencies so that the siren sound can penetrate into vehicle cabins; and that have signals with short repetition periods to convey high perceived-urgency.

INTRODUCTION

Emergency vehicles are regularly driven using warning lights and sirens to alert motorists and pedestrians of its approach, with the expectation that the motorist or pedestrian will clear the path for the emergency vehicle. The flashing lights on the emergency vehicle are only effective if the motorist has already directly sighted the lights on the vehicle or from a reflection. The warning sirens on an emergency vehicle are the only means that a motorist or pedestrian is alerted to its approach, without having sighted the vehicle, and hence this warning mechanism is important for the prevention of collisions.

A common factor in many collision incidents is that the motorist was not alerted, or did not recognise, the approach of an emergency vehicle [1]. This is where the warning siren on the emergency vehicle is pivotal in the prevention of collisions with motorists.

A study of insurance claims over a 2 year period (2003-2004) in the United States against emergency medical service agencies showed that the most frequent claims were for emergency vehicle crashes and patient handling mishaps [2]. Statistics indicate that most accidents between emergency vehicles and motorists occur at intersections [3-7]. A counter example is from a study conducted in Houston Texas USA which indicated that most collisions between emergency vehicles and motorist *did not* occur at intersections, and for those collisions that *did* occur at intersections there was no correlation with the severity of the collision [8].

There is an elevated risk of collision and injury when ambulances respond rapidly to emergency call-outs that require the use of lights and sirens, and several papers address the question of whether there is a decrease in travel time to the job site or transport of a patient to a hospital [9-12], and whether there is significant benefit for patient outcomes. The reported statistics indicate that there is only a small decrease in response time for transport in urban areas. Care must be taken when considering the applicability of the results to other cities where road networks, road rules, and driver education standards differ.

In the metropolitan area of South Australia, where this study was undertaken, there are several collisions between ambulances and motorists that occur each year at intersections resulting in vehicles being ‘written-off’ and are replaced at substantial cost. The goal of the investigations was to provide recommendations to improve the audibility of sirens on ambulances to approaching motorists at intersections, with the intention of reducing the number of collisions between vehicles.

FAVOURABLE SIREN CHARACTERISTICS

De Lorenzo and Eilers [13] describe the favourable characteristics for sirens. They note a US Department of Transport report that suggested that “...over a siren’s effective frequency range, the average signal attenuation (through closed-windowed automobile bodies combined with typical masking noise) resulted in a maximal siren effective distance of siren penetration of only 8 to 12 m at urban intersections.” For a vehicle travelling at 50km/hr, this distance would be covered in less than 1.15 seconds, which is insufficient to prevent a collision. The problem is further exacerbated as road users tend to overestimate the distance from noise sources by a factor of two [14], thus causing drivers to assume they have more time to respond. The favourable siren characteristics include: sufficiently loud, wide frequency spectrum (1kHz-4kHz) to overcome ‘masking’ noise, rapid rise in pitch, rapid cycling time. The work conducted here provides additional details about the favourable acoustic characteristics for sirens including findings from psychoacoustic studies and experiments.

Catchpole and McKeown [15] provide a good overview of the favourable characteristics for ambulance sirens that are similar to the recommendations by De Lorenzo and Eilers [13]. They conducted several acoustic measurements and field trials to evaluate the performance of two siren types, a ‘Wail’ and ‘Yelp’ siren and a ‘Localiser’ siren, mounted under the wheel arch and another behind the radiator grill. The wail type of siren sweeps non-linearly between 800-1700Hz with a sweep

period of 4.92s [16]. The yelp siren has identical bandwidth to the wail with an increased sweep period of 0.32s [16]. The ‘Localiser’ siren emits a tonal sweep between 500-1800 Hz with a period of 0.384s, and emits a burst of white noise for 0.256s, every 0.128s, centred at the highest portion of the sweep frequency (see Fig 3. in Ref.[16]), with the highest sound pressure level emitted at 4kHz (see Fig 3 in Ref. [15]). Their conclusion was that a grill-mounted ‘Localiser’ siren sound had better penetration into vehicles and hence had a better effective range than the standard ‘wail’ and ‘yelp’ siren. This result is surprising considering that the Localiser siren has a peak sound pressure level at 4kHz, where most modern vehicle cabins provide high sound transmission loss, and hence is unlikely to be audible above background noise levels in the vehicle. The experimental results presented here quantify these characteristics and show that a better method of achieving sound penetration into vehicles is for the siren to emit low-frequency sound, where a vehicle cabin has poor transmission loss properties, resulting in higher interior noise levels.

NOISE CONTROL FACTORS

Noise transmissions problems can be analysed as three inter-related components: (1) the noise source, (2) the transmission path, and (3) the receiver, and each are described below.

Noise source factors

The siren on an emergency vehicle should be capable of alerting nearby motorists so that they clear the path for it. There are several acoustic characteristics that must be considered:

- Adequate amplitude emitted by the siren.
- Directivity (sound radiation pattern) of the siren loudspeaker. This factor is related to the mounting location of the siren and whether there is an effective reflective ‘backing plane’ to aid in the radiation of sound.
- Ensuring that the radiated sound pressure level from the siren is not altered due to the added pressure placed on the diaphragm of the siren due to the forward motion of the vehicle.

Transmission path factors

The transmission path is from the siren to the receiver. The factors that should be considered are the:

- Attenuation of broadband noise due to distance, which decreases by a factor of 6dB per doubling of distance from a point source [17]. Attenuation of tonal noise, which is used in sirens, has constructive and destructive interference caused by the reflection from the ground and is more complicated to predict.
- Attenuation of the noise source due to the acoustic transmission loss of the vehicle cabin.
- Diffraction and reflection of the warning sound around vehicles and buildings.

Receiver factors

The receivers in this system include motorists, pedestrians, emergency personnel, patients, and housing residents. Some of the factors to be considered for the receiver can also be attributed to the characteristics of the noise source. For example, the waveform generated by the siren should be

perceived by the receiver as urgent. The factors for the receiver that need to be considered include:

- ‘Masking’ of the siren noise by background noise such as car audio, engine, passengers speaking, fans, and wind noise.
- Localisation of the siren warning signal, such that a person can determine the direction and movement of the noise source.
- Psychoacoustic factors such the correct interpretation of the sound as a warning signal, and the perceived urgency of the noise.
- Limiting the noise exposure to emergency workers to siren noise to prevent hearing loss [18, 19].
- Limiting the interior noise levels inside the ambulance to prevent communication difficulties with crew and radio communications. It is common practice for ambulance crews to switch off the siren when conducting radio communications, during which time there is an elevated risk of a collision.
- An awareness that the emergency transport of patients has been shown to increase their stress levels [20-22] leading to elevated heart rates and blood pressure which is medically undesirable for cardiac and stroke patients.
- Appropriate use of sirens to prevent community annoyance, particularly at night.
- Sufficient time for a motorist to hear and react to the warning signal.
- Awareness of standards that place limits on the noise level and directivity of sirens [23].

Intrusiveness

Robinson et al. [24] commented that many researchers that conduct detection threshold tests to explore the masking curves for human hearing will ask the listener to indicate if they can hear a target tone when a customised masking background noise is played concurrently, where the listener is waiting to hear the target noise (for example see Refs [25-27]). However, a motorist is pre-occupied with a ‘foreground’ driving task and is not expecting to hear the noise from a siren.

Fidell [28] conducted tests on 24 drivers in driving simulator to examine their reaction time to an emergency siren. Later, Fidell and Teffetellar [29] examined the intrusiveness of a sound on a group of subjects that were playing computer games. In both experiments it was found that the sound level required for the subjects to reliably detect the test sounds was ‘considerably’ higher than if they were not engaged in the distracting foreground task. In the driving simulator tests, the required sound pressure level of the siren was around 10dB higher than if the subjects were not driving.

The ability to notice a warning sound when preoccupied with a primary task can be explained by considering the ‘spare capacity’ of a human mind to monitor unexpected stimuli [30]. The ‘spare capacity’ of an aviation pilot engaged in the foreground task of flying a plane is important if there is a need to deal with alarms, and this topic has been the focus of a great deal of research.

Localisation

One of the main methods that humans use to determine the direction and movement of a sound source is from the slight difference in the arrival time of sound at the ears on the left and right side of the head, called the inter-aural time difference (ITD).

It has been demonstrated that a driver within a vehicle with closed windows has greater difficulty identifying the correct direction of the source of an ambulance siren, compared to if the person was not within a vehicle [14,31,32]. A vehicle enclosure obstructs the direct path of siren noise and redistributes the acoustic energy over the surface of the vehicle, re-radiating into the enclosed space, which has the effect of altering the apparent direction of an external sound source.

Sounds that are easier to localise have the characteristics of a broad frequency range and uniform sound power density [33]. A siren sound has been designed to improve localisation called ‘The Localiser’ [33] that is a combination of a traditional ‘yelp’ with white noise components [16]. This siren sound was evaluated in a driving simulator and also in road trials [34] and motorists were better to identify the direction of the siren signal. However field testing involving the use of the Localiser siren by Catchpole and McKeown [15] indicated that the “... sound pattern was not as easily recognised as a more traditional emergency vehicle siren.”

Withington [32] suggested that the reason why many sirens are ineffective is because “... the frequency content of the siren sounds is so poor” to enable localisation. Common warning signals comprise single frequencies that change frequency and amplitude over time, and it has been shown that humans have difficulty in identifying the correct location of the source of pure tones [35,36].

Although the ability for motorists to correctly identify the source direction of a warning signal is important, a precursor is that the motorist has heard the warning signal. It will be shown in the following section that the combined effects of limited siren output, a compromised sound radiation pattern, high noise reduction of a vehicle cabin and background noise means that the siren signal will often be ‘masked’.

Catchpole and McKeown measured the Localiser siren radiating into *free-field* at a distance of 11m (Fig 3. [15]) and showed that the highest sound pressure level was between 3kHz-5kHz, and suggested that it would be more likely to be detected than the ‘wail’ and ‘yelp’ sirens. However, modern vehicles are acoustically designed to have high transmission loss above 1kHz, and hence will significantly attenuate high-frequency siren noise compared to low frequency noise.

EXPERIMENTAL TESTING

Measurement of siren loudspeaker directivity

Acoustic directivity measurements of a siren were conducted to measure the variation in the off-axis radiated sound compared to the on-axis sound levels. Two siren loudspeakers that are used in the South Australian ambulance fleet were individually tested using a white-noise source. The tests were conducted in an anechoic chamber with a reflecting ground plane, and a backing plane behind the loudspeaker.

The measurements were taken at 0, 30, 45, 60, and 90 degrees from the axis of the siren, at a distance of 1.8m, which is in the acoustic ‘far-field’ at the acoustic wavelengths of interest.

Figure 1 shows the difference between the measured total sound pressure level and the maximum total sound pressure level for one of the sirens, which was directly in front of the speaker at 0 degrees, which shows the attenuation of the sound level with angle.

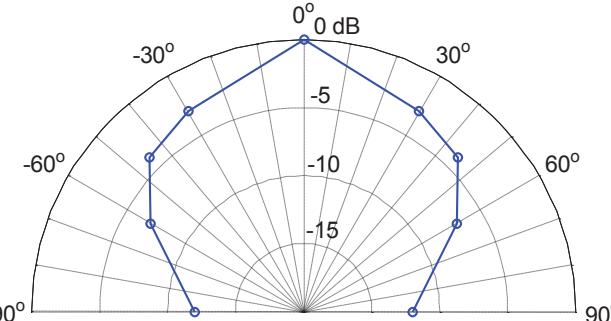


Figure 1: Measured directivity of a siren, displayed as difference from on-axis sound pressure level.

The results for the test on the second siren displayed a nearly identical radiation pattern as the first siren. The results show that there is significantly less (12dB) sound radiated at 90 degrees to the axis of the siren. This would be subjectively interpreted as less than half as loud (p85 Ref. [17]). This is an important finding as collisions between ambulance vehicles and motorists occur when transiting four road intersections, where the warning signal should be projected to the side of the ambulance. For example, when an ambulance approaches a four-way intersection where they are approaching a stop light, there is usually cross-wise vehicular traffic movement. Ambulances will stop before entering the intersections to ensure that vehicles on the cross-wise roads have stopped. Unfortunately, some vehicles do not stop and collide with the ambulance attempting to cross the intersection. Hence, it is recommended that ambulance vehicle operators install additional siren loudspeakers that project sound transverse to motion of the ambulance, or sirens that provide consistent sound radiation over +/- 90 degrees from the axis of the siren.

Sound power measurements of sirens

Most literature quote Sound Pressure Levels (SPLs) for sirens measured at a distance from the siren. However, these values are dependent on the measurement distance and mounting location of the siren. An alternative method used to characterise sound sources is the measured radiated acoustic power, which is independent of measurement distance and mounting location.

Experiments were conducted to measure the total acoustic sound power the systems listed in Table 1.

The Rumbler unit is intended to be installed as a complement to a primary audio warning system. The Rumbler unit obtains the input audio signal from the output of the primary warning system amplifier, then frequency shifts, low-pass filters, amplifies and broadcasts by sub-woofer loudspeakers.

Table 1: Configuration of sirens for sound power measurements.

Hazard Systems	Signals: generated by Hazard Systems unit: ‘wail’ and ‘yelp’. Amplifier: Hazard Systems. Sirens: 2 – Hazard Systems siren model 810-011.
Federal Signal Rumbler	Signals: ‘wail’ and ‘yelp’ generated by Hazard Systems unit that the Rumbler frequency shifts and low pass filters. Amplifier: Federal Signal Rumbler Sirens: 2 – Federal Signal Rumbler, sub-woofers.
European	Signals: generated by European Unit: Police (France), Gendarmerie (France), Pompiers (France), UMH (France), Ambulance (France), Polizia (Italy), Ambulanza/Vigili del Fuoco (Italy), 2 Ton Police (Norway), 3 Ton Fire Brigade (Norway), Feuerwehr (Fire Brigade) (Germany), Rettungsdienst (Emergency Service) (Germany), Polizei (Germany), Pistensignal (Runway Signal) (Germany), Fire Brigade (UK). Amplifier: European Unit. Sirens: 2 – Hazard Systems horn type.

The sound power measurements were conducted in an acoustic reverberation chamber using the ‘absolute method’ [17], a traversing calibrated Brüel and Kjaer microphone, and a Larson Davis 2900 spectrum analyser. The results of the one-third octave band sound power measurements are shown in Figure 2, and show that the sirens exhibit similar sound power levels, and broadcast a similar frequency range. The frequency range of the ‘Rumbler’ siren is distinguishable, emitting between 125Hz-500Hz. This result is important as it will be shown that low-frequency sound can better penetrate a vehicle cabin than high-frequency noise.

Figure 3 shows the A-weighted total sound power of the sirens. The ‘Rumbler’ siren has a lower A-weighted total sound power than the other siren types, as it emits noise in a lower frequency band compared to the other sirens where the A-weighting reduces the contribution. However this is not necessarily detrimental, as it is the perceived loudness of the sound at the *receiver* that is the important characteristic, which is also dependent on the transmission loss of the vehicle cabin, and in the frequency range of the Rumbler siren vehicle cabins have poor transmission loss, which can lead to a higher interior noise level compared to the emission of a high frequency siren noise.

Noise reduction of a passenger vehicle

The purpose of conducting this experiment was to quantify the noise reduction of a typical passenger vehicle. The vehicle tested was a 2005 Mitsubishi Magna station wagon. The test was conducted by placing a microphone at the driver’s seat position. Two large loudspeaker enclosures that emitted white noise were positioned in front of the vehicle, at the rear of the vehicle and to the driver’s side of the vehicle, at a distance of 4.2m from the microphone in each case. The doors and windows on the vehicle were closed for the tests. The sound pressure levels at the driver’s position were recorded and subtracted from the sound pressure level at the microphone when the vehicle was absent. The difference between these two

levels represents the noise reduction of the vehicle.

The results from the experimental testing are shown in Figure 4 and show the expected trend of poor noise reduction at low frequencies, and high attenuation at high frequencies.

Catchpole and McKeown [15] recommended adding high-frequency content “... would improve vehicle penetration...”, however as shown in Figure 4 there is high noise reduction at high frequencies. Hence it is unlikely that the addition of high frequency content in sirens will improve vehicle penetration.

The frequency ranges of the Hazard Systems ‘wail’ and ‘yelp’, and Rumbler sirens, that broadcasted frequency shifted and low-pass filtered versions of the ‘wail’ and ‘yelp’ signals, are highlighted in Figure 4, and shows that the standard sirens operate in the range where the car exhibits high noise reduction and the Rumbler operates where there is less noise reduction. Hence, installation of a siren that emits low-frequency content will have greater vehicle penetration than the same amplitude at higher frequencies. Non-acousticians will be familiar with this effect from the pass-by noise of car audio systems with sub-woofer loudspeakers.

Masking by background noise

The siren noise that is received by the driver of a vehicle must be sufficiently loud to be detected. There are many sources of noise that can mask siren noise such as road traffic, car audio, air-conditioning and ventilation fans [37].

Corliss and Jones [38] have investigated the issue of siren noise penetrating vehicles and the minimum levels that a person can hear a tonal siren noise in the presence of background noise, called the masked threshold levels. They suggest that the sound pressure level of an emergency siren should be about 72dB re 20µPa for quiet interior conditions, and with an assumed 30dB of attenuation provided by a closed car, it must have a level of excess 100dB outside the car.

Robinson and Casali [39] describe two methods used for the prediction of the detectability of a siren in the presence of background noise, namely the ‘The Critical Band Method’ and the international standard ‘ISO 7731-1986: Danger signals for work places -- Auditory danger signals’ [40]. The critical band method is based on the physiology of the human ear [41,42]. These methods are used to calculate *masked thresholds*, which basically provide a conservative estimate of the sound levels needed for a signal to be detected, from measured levels of a background noise. In general, a signal is less affected by masking if it is relatively complex in nature and has a relatively large contrast with the background noise. It is stated that signal levels 6-10 dB above the masked thresholds will ensure 100% detectability, and that signal levels approximately 15 dB above the masked thresholds are recommended for ensuring rapid response from the listener.

Robinson and Casali [39] recommend characteristics for auditory danger signals in the context of a workplace. However many of these recommendations are applicable to ambulance sirens warning motorists. Some of the relevant recommendations include:

- The signal should exceed the masked threshold by at least 15 dB above masked threshold across the entire spectrum where possible.

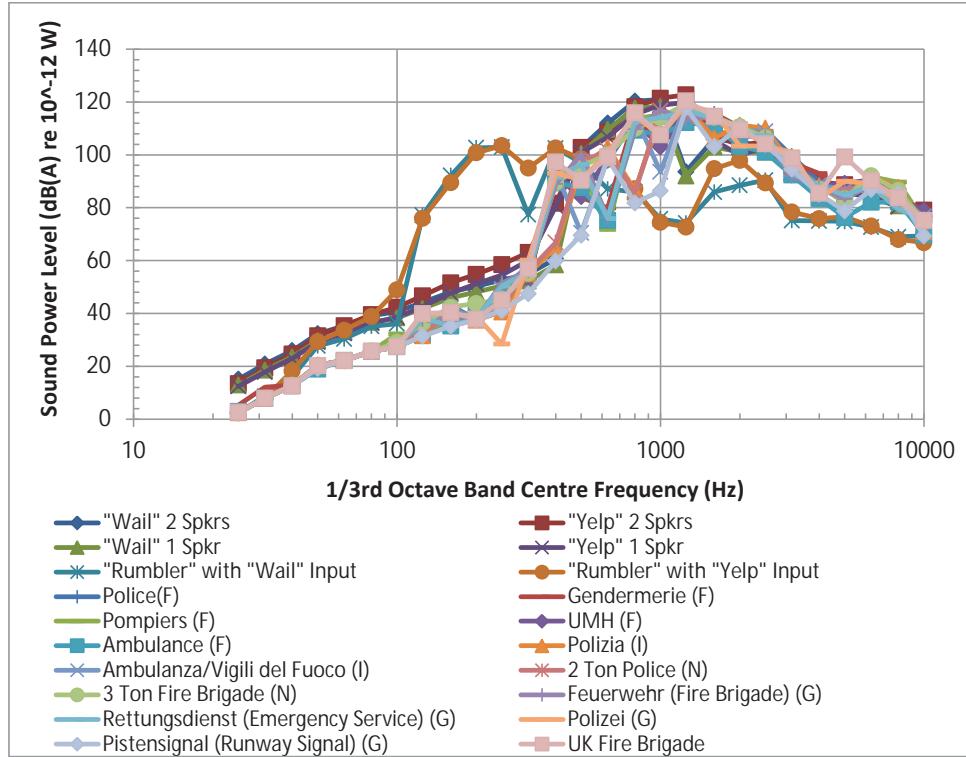


Figure 2: Sound power levels (A-weighted) of all sirens.

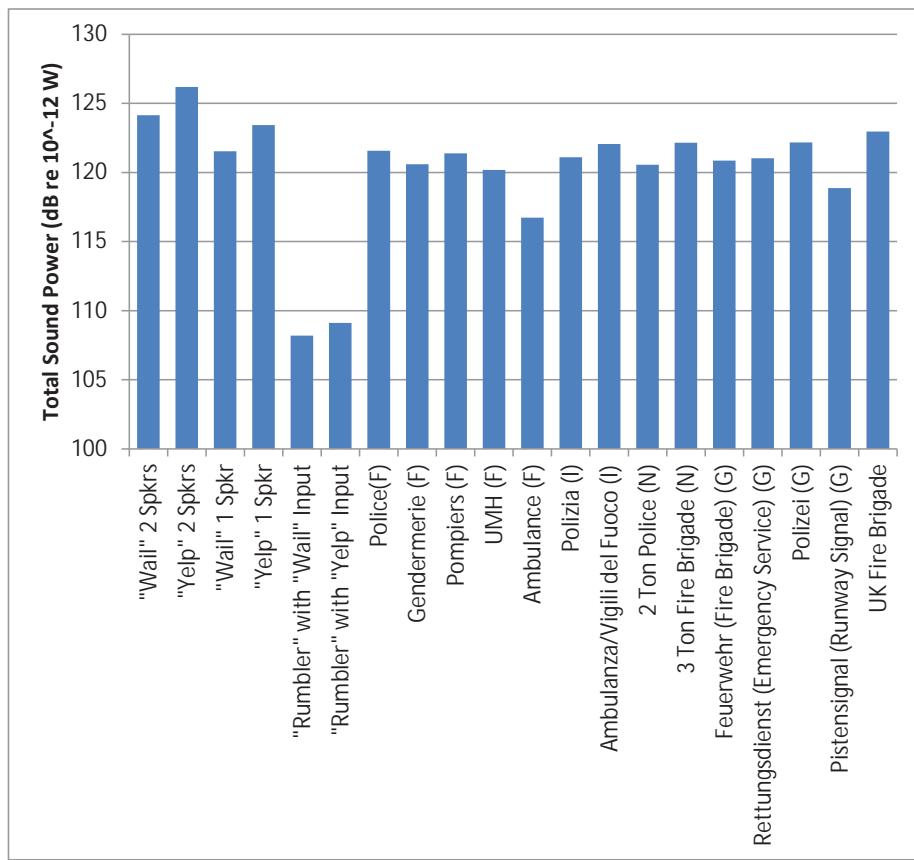


Figure 3: Total A-Weighted sound power levels of all siren

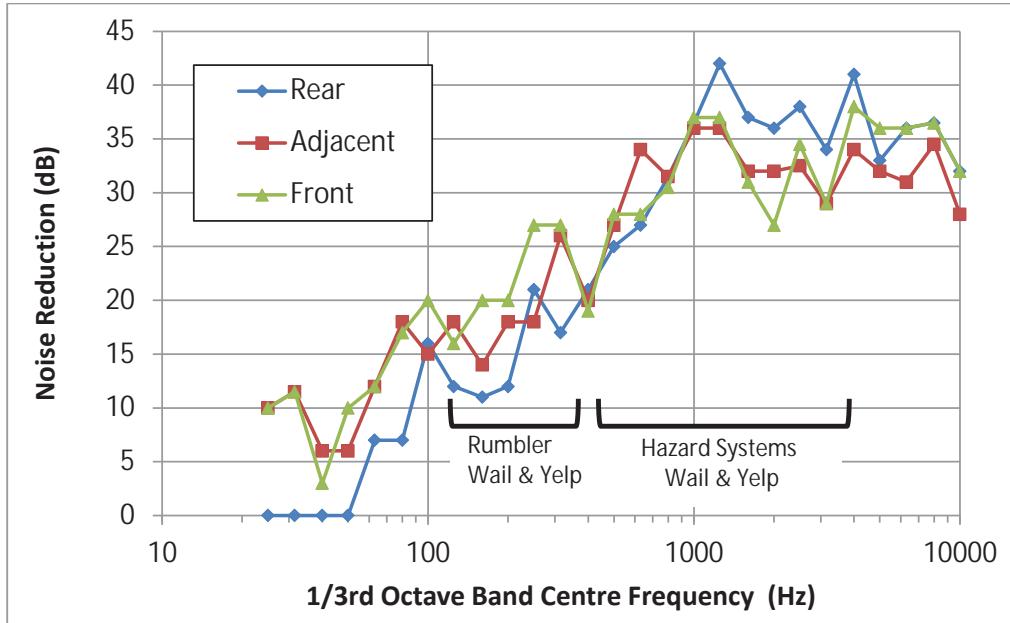


Figure 4: Noise reduction of an average passenger vehicle

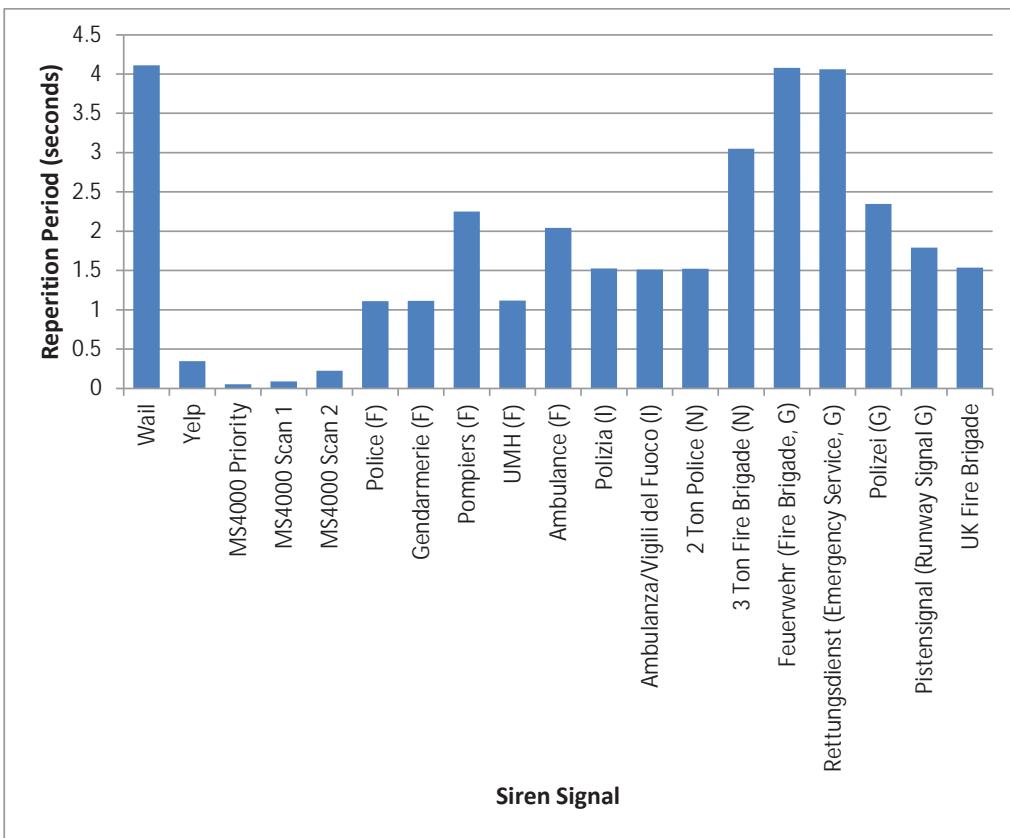


Figure 5: Repetition period of siren signals.

- Frequencies higher than 3000Hz are not recommended as subjects with noise-induced hearing loss are more likely to be disadvantaged by not being able to detect such signals.
- Complex signals with harmonic components with a fundamental frequency below 1000 Hz should be used.
- Signals below 1000Hz should be used for outdoor alarms as such low frequencies are less affected by atmospheric absorption and are more effective in regards to diffraction around barriers, such as vehicles and buildings.

The last recommendation to use low frequency sirens is consistent with the recommendation by Mortimer [43], to use low frequency horns on trains to enhance sound propagation and penetration into vehicles.

The requirements for sirens are described in the standard 'ISO 7731-2003: Ergonomics - Danger signals for public and work areas - Auditory danger signals' [44], in regards to masking as:

- The siren signal should exceed the masked threshold by at least 13dB in one or more 1/3 octave bands.
- A-weighted sound pressure level of the signal should be at least 15dB greater than that of the background noise.

Perceived urgency

The term 'Perceived Urgency' is used to describe the urgency inherent in a warning signal, and is a product of its acoustic characteristics. Hellier and Edworthy [45] conducted human jury testing of various sounds to evaluate perceived urgency where parameters such as pitch, speed, rate of repetition, inharmonicity and length were altered. Their investigations showed (and confirmed by other researchers [46-47]) that a sound source that repeats quickly was the most important parameter affecting perceived urgency: the shorter the repetition of the sound source, the higher the perceived urgency.

To determine the perceived urgency of the sirens examined in the work presented here, the repetition period of the sirens were measured using the audio editing software Audacity, and the results are shown in Figure 5.

The results show that the 'wail' siren, which is used widely in Australian ambulance fleets, has one of the longest repetition periods of the signals examined. The 'yelp' siren has a faster repetition period than the 'wail' siren and should convey a higher degree of perceived urgency.

The Federal Signal 'MS 4000 Priority' siren exhibited the shortest repetition period, and is likely to convey the highest perceived urgency of the sirens tested. The situations that require conveying a high degree of urgency include approaching intersections, clearing vehicles ahead in the same lane, and lane changing into oncoming traffic, and therefore it is recommended that the 'Priority' signal be broadcast at appropriate situations.

Passenger vehicle background noise masked threshold calculation

Experiments were conducted to measure typical background noise levels inside a moving vehicle. The results were used calculate the masked threshold levels using the critical band method [39]. The one-third octave-band average sound pressure levels (L_{eq} 30 seconds) were recorded using a Larson Davis 2900 sound level meter. The microphone was calibrated

before conducting the measurements. The measurements were conducted in a 2005 Mitsubishi Station Wagon, driving through the central business district of Adelaide. All measurements were taken in the front passenger seat of the vehicle at ear height. The test cases are listed in Table 2.

Table 2: Driving field-test cases.

Test No.	Radio	Windows	Overall SPL [dBA]
1	Off	Closed	58
2	Off	Open	66
3	On	Closed	78

Figure 6 shows the one-third octave band masked thresholds using the Critical Band Method [39]. It is observed, that the sound pressure levels with radio turned on exhibited the highest levels for most of the measured frequency range. The second highest levels occurred while driving with the windows open, and the lowest levels were with the windows closed.

Figure 7 shows the masked threshold level for the test with the windows closed and the radio turned on, compared with the predicted in-car sound pressure levels from a wail and Rumbler siren located 20m from the car. The results indicate that it would be difficult to hear the wail siren, and that the Rumbler siren might just be audible. These results are consistent with Ref [37] that stating that the average siren attenuation, through closed-windows and typical masking noise, resulted in an effective distance of siren penetration of only 8-12 m at urban intersections, which is an insufficient distance to alert road users to safely clear the path.

Additional locations for sirens

It is common for sirens to be mounted at the front of an ambulance beneath the front grill or bumper and point forwards. As noted previously, that most collisions between emergency vehicles and motorists occur at intersections [3-7], there is a need to broadcast the warning signal transverse to the ambulance. Two potential locations for installing sirens are shown in Figure 8: in both front wheel arches and on the light bar on the roof on both passenger and driver sides. Measurements were conducted of the Sound Pressure Level at the driver's position when the 'wail' siren was operational at the three locations shown in Figure 8, and the results are listed in Table 3.

Table 3: Total A-weighted siren sound pressure levels that can be expected within cabin according to different mounting locations

Position	Total Sound Pressure Level (dBA, re 20μPa)
Current Position on Front Bumper	71
Roof Location	79
Front Wheel Arch	72

The results indicate that mounting the siren on the light bar on the roof increases the interior sound pressure level at the driver's ear by about 8dB, which would be clearly perceptible. Although this level of 79dBA is below the recommended

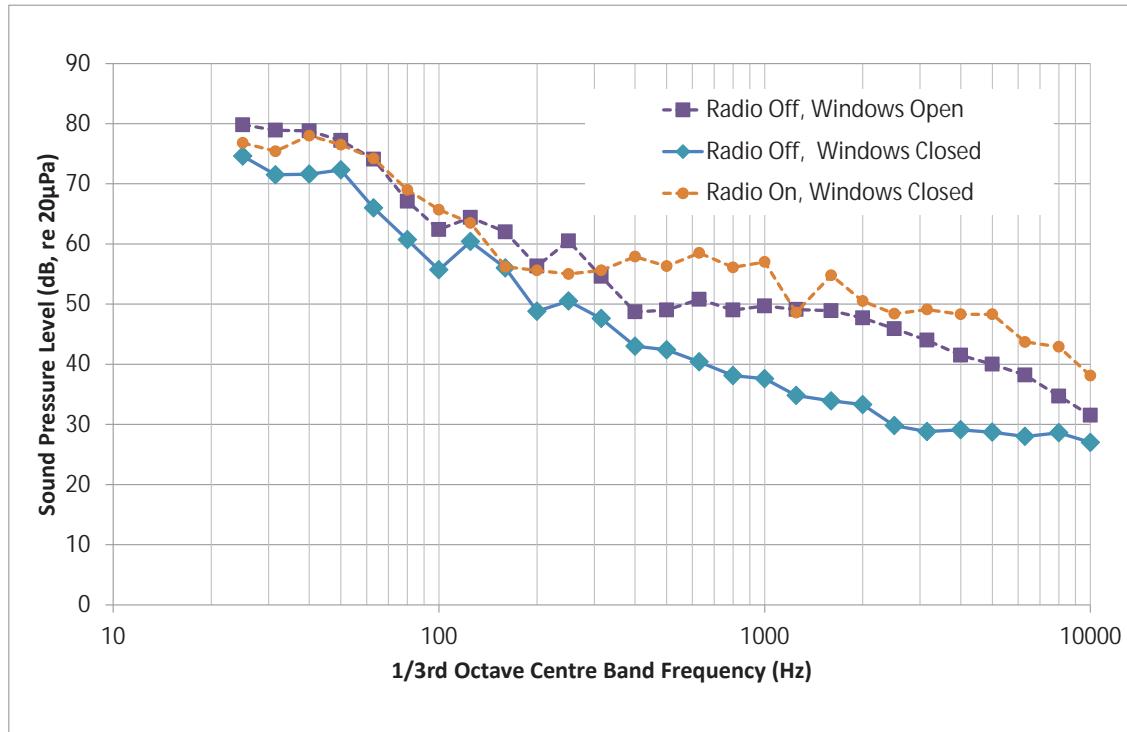


Figure 6: Masked thresholds while driving for three test cases, using L_{eq} levels over 30 seconds.

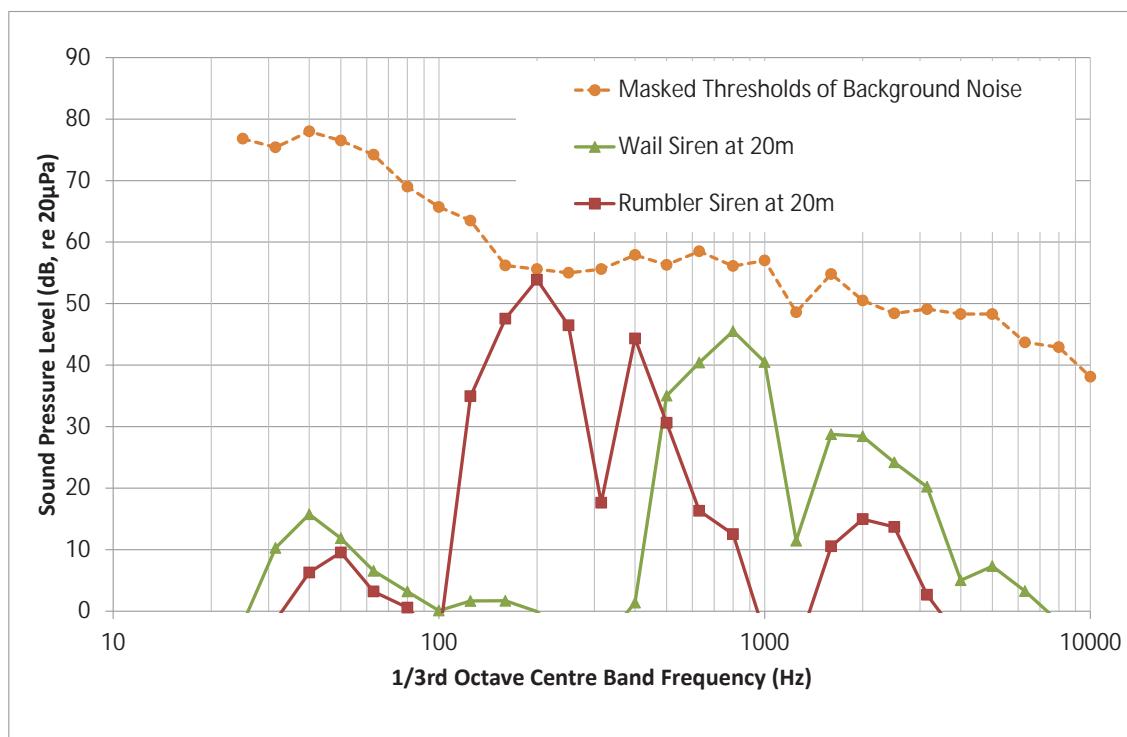


Figure 7: Masked threshold Sound Pressure Levels when driving with the radio on and windows closed, and the predicted vehicle interior SPLs from the Wail and Rumbler sirens.

Occupational Health and Safety guidelines of 85dBA (8-hours), paramedic crews currently have communications difficulties and hence it would not be advisable to install additional sirens on the roof. However installation of additional sirens in the wheel arch only increased the interior noise levels by about 1dB, which is subjectively unperceivable [17].



Figure 8: Potential mounting locations for sirens.

SUMMARY

The study conducted here considered several factors and the summary of the findings are described below.

Intrusiveness

Researchers have found that the human response to an auditory alarm depends on psychoacoustics and whether a subject is occupied with a foreground task. Studies indicate that the amplitude of a warning signal to attract attention needs to be 10dB higher if the subject is involved in a foreground task compared to when the subject is waiting for the signal. This result is applicable to warning driving motorists of an approaching emergency vehicle.

Localisation

Previous studies have shown that when motorists are able to correctly identify the source direction and movement of a warning signal, that they are correctly able to take evasive manoeuvres. Warning signals with high or broadband content improve the Localisation of warning signals. However, it was found that these hybrid signals are not widely recognisable as warning signals [15]. In addition, modern vehicles are designed to provide good “acoustic comfort” to passengers, and one of the key metrics that is minimised is the A-weighted sound pressure level [48,49]. As a consequence, vehicle cabins provide good sound transmission loss in the mid- to high-frequency ranges (1-8kHz), which unfortunately corresponds to the frequency range required to improve the localisation of a warning signal. Also, a vehicle with closed windows has an enclosed semi-reverberant sound field that blurs the direct-path of an external warning signal, which will decrease the ability of a motorist to correctly identify the direction of a sound source.

Directivity

Measurements of the acoustic directivity of a siren used on a fleet of ambulances that showed that there was about

a 12dB decrease in sound level at 90 degrees to the axis of the siren, compared to the on-axis sound level. The Society of Automotive Engineers standard for emergency sirens [23] and the California Code of Regulations [50] only provide recommendations for sound levels of sirens within +/- 50 degrees of the axis of the siren. The recommendation from the work conducted here is that emergency vehicles should be fitted with sirens that project a warning signal transverse to the ambulance direction, in order to improve the audibility of the siren to converging vehicles. Alternatively, sirens that have a consistent sound radiation pattern over +/- 90 degrees from the axis of the siren are also suitable.

Sound power

The sound power of several sirens was measured in an acoustic reverberation chamber and they had similar levels. The frequency range was also similar, with the notable exception of the Rumbler siren that is designed to emit low-frequency sound. Although simply increasing the sound power output from sirens well above the masked threshold levels would improve their detection rate, standards exist that prescribe maximum sound pressure level limits and many sirens are designed to operate close to these limits. Currently there is no opportunity to increase the output sound power from sirens, and other methods must be employed to improve the detectability of a siren.

Noise reduction

Modern vehicles are designed to have a comfortable acoustic environment, and as a result of the materials used they provide high sound transmission loss above 1kHz. It was found that the noise reduction of a passenger vehicle is greater than 30dB above 1kHz, and hence warning signals with high-frequency content are significantly attenuated. Vehicles exhibit only moderate noise reduction around 100Hz and hence warning signals with low-frequency content have greater penetration into vehicles compared to high-frequency warning signals. Hence it is recommended that emergency vehicle operators consider using a combination of low-frequency and their current warning signals.

Masking noise

Experiments were conducted to estimate the background noise level in a typical passenger vehicle for three conditions. Driving with the windows closed and a radio playing music at moderate level resulted in the highest background noise levels, with the vehicle cabin providing the highest noise reduction. Research has indicated that the critical band method is a useful tool for predicting the required amplitude of a signal to be detected. However this estimated level must be increased as motorists are engaged in a foreground task and are not expecting a warning signal.

Perceived urgency

The acoustic characteristic of a signal that has the greatest influence in conveying the importance of an alarm is the period of repetition. Several warning signals were examined and it was found that the Federal Signal ‘MS 4000 Priority’ had the shortest period and hence conveys a high degree of urgency.

Mounting locations

Although many emergency vehicles have sirens that face

forwards, it is important to ensure that the acoustic radiation pattern of the siren adequately broadcasts transverse to the motion of the vehicle, to ensure that converging motorists can hear the warning signal. Mounting additional sirens near the front wheel arches and facing transverse to the vehicle can improve the radiated sound field.

CONCLUSIONS

The desirable acoustic qualities for warning signals broadcast by emergency vehicles result from a system of noise transmission, psychoacoustics, standards, and practicalities. The selection of an effective warning signal involves many competing factors that ultimately requires making compromises.

REFERENCES

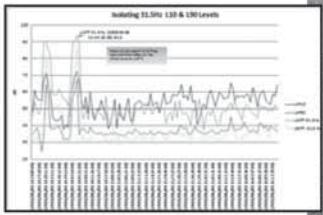
- [1] C.E. Saunders and C.J. Heye, "Ambulance collisions in an urban environment", *Prehospital Disaster Medicine*, **9**(2), 118-124 (1994)
- [2] H.E. Wang, R.J. Fairbanks, M.N. Shah, B.N. Abo, and D.M. Yealy, "Tort Claims and Adverse Events in Emergency Medical Services", *Annals of Emergency Medicine*, **52**(3), 256-262 (2008)
- [3] A.M. Ray and D.F. Kupas, "Comparison of Rural and Urban Ambulance Crashes in Pennsylvania", *Annals of Emergency Medicine*, **46**(3), 113-113 (2005)
- [4] A.M. Ray and D.F. Kupas, "Comparison of Crashes Involving Ambulances with Those of Similar-Sized Vehicles", *Prehospital Emergency Care*, **9**(4), 412-415 (2005)
- [5] C.B. Custalow and C.S. Gravitz, "Emergency medical vehicle collisions and potential for preventive intervention", *Prehospital Emergency Care*, **8**(2), 175-184 (2004)
- [6] C.A. Kahn, R.G. Pirrallo and E.M. Kuhn, "Characteristics of fatal ambulance crashes in the United States : An 11-year retrospective analysis", *Prehospital Emergency Care*, **5**(3), 261-269 (2001)
- [7] D.E. Slattery and A. Silver, "The Hazards of Providing Care in Emergency Vehicles: An Opportunity for Reform", *Prehospital Emergency Care*, **13**(3), 388-397 (2009)
- [8] W.A. Biggers and B.S. Zachariah, "Emergency medical vehicle collisions in an urban system", *Prehospital Disaster Medicine*, **11**(3), 195-201 (1996)
- [9] R.C. Hunt, L.H. Brown, E.S. Cabinum, T.W. Whitley, N.H. Prasad, C.F. Owens Jr, C.E. Mayo Jr, "Is ambulance transport time with lights and siren faster than that without?", *Annals of Emergency Medicine*, **25**(4), 507-511 (1995)
- [10] J. Ho and B. Casey, "Time Saved With Use of Emergency Warning Lights and Sirens During Response to Requests for Emergency Medical Aid in an Urban Environment", *Annals of Emergency Medicine*, **32**(5), 585-588 (1998)
- [11] B.S. Zachariah, P.E. Pepe, D.E. Persse, and P.A. Curka, "The effect of warning lights and sirens on EMS response intervals (abstract)," *Annals of Emergency Medicine*, **23**(3), 637-637 (1994)
- [12] J. Ho and M. Lindquist, "Time saved with the use of emergency warning lights and siren while responding to requests for emergency medical aid in a rural environment", *Prehospital Emergency Care*, **5**(2), 159-162 (2001)
- [13] R.A. De Lorenzo and M.A. Eilers, "A review of emergency warning systems", *Annals of Emergency Medicine*, **20**(12), 1331-1335 (1991)
- [14] T. Caelli and D. Porter, "On difficulties in localizing ambulance sirens", *Human Factors*, **22**(6), 719-724 (1980)
- [15] K. Catchpole and D. McKeown, "A framework for the design of ambulance sirens", *Ergonomics*, **50**(8), 1287-1301 (2007)
- [16] R.S. Sherratt, "Results of a DSP based adaptive cancellation filter system for the chirp, pulsar and localiser sirens", *IEEE Nordic Signal Processing Symposium*, 2000.
- [17] D.A. Bies and C.H. Hansen, *Engineering Noise Control*, 4th ed., Spon Press, New York, USA (2009).
- [18] D.W. Johnson, R.J. Hammond, and R.E. Sherman, "Hearing in an ambulance paramedic population", *Annals of Emergency Medicine*, **9**(11), 557-561 (1980)
- [19] P.E. Pepe, J. Jerger, R.H. Miller, and S. Jerger, "Accelerated hearing loss in urban emergency medical services firefighters", *Annals of Emergency Medicine*, **14**(5), 438-442 (1985)
- [20] U. Weber, A. Reitinger, R. Szusz, C. Hellmich, B. Steinlechner, H. Hager, B. Mora, M. Selzer, M. Hiesmayr and A. Kober, "Emergency ambulance transport induces stress in patients with acute coronary syndrome", *Emergency Medicine Journal*, **26**(7), 524-528 (2009)
- [21] U. Weber, A. Reitinger, T. Erdeii, C. Hellmich, B. Steinlechner, H. Hager, M. Selzer, M. Hiesmayr, A. Rajek, A., "Effects of high-urgency ambulance transportation on pro-B-type natriuretic peptide levels in patients with heart failure", *The American Journal of Emergency Medicine*, **28**(5), 568-576 (2010)
- [22] K. Witzel, "Effects of Emergency Ambulance Transportation on Heart Rate, BloodPressure, Corticotropin, and Cortisol", *Annals of Emergency Medicine*, **33**(5), 598-599 (1999)
- [23] Society of Automotive Engineers Standard, "SAE J1849:2002 Emergency Vehicle Sirens" (2008)
- [24] G.S. Robinson, S. E. Lee, and J. G. Casali, "Auditory Warnings and Displays: Issues Relating to Design and Selection", in *International Encyclopedia of Ergonomics and Human Factors*, 1st Ed., CRC Press (2001), pp. 791-794
- [25] W.R. Garner, "Auditory Thresholds of Short Tones as a Function of Repetition Rates", *Journal of the Acoustical Society of America*, **19**(4), 600-608 (1947)
- [26] R.V. Shannon, "Two-tone unmasking and suppression in a forward-masking situation", *Journal of the Acoustical Society of America*, **59**(6), 1460-1470 (1976)
- [27] A.A. Saoji and D.A. Eddins, "Spectral modulation masking patterns reveal tuning to spectral envelope frequency", *Journal of the Acoustical Society of America*, **122**(2), 1004-1013 (2007)
- [28] S. Fidell, "Effectiveness of auditory warning signals for emergency vehicles", *Human Factors*, **20**(1), 19-26 (1978)
- [29] S. Fidell and S. Teffeteller, "Scaling the annoyance of intrusive sounds", *Journal of Sound and Vibration*, **78**(2), 291-298 (1981)
- [30] P.A. Wilkins, "Assessing the Effectiveness of Auditory Warnings," *British Journal of Audiology*, **15**(4), 263-274 (1981)
- [31] R.C. Potter and H.S. Pei, "How well can audible warning devices of emergency vehicles be localized by the driver of an automobile? (Abstract)," *The Journal of the Acoustical Society of America*, **59**(S1), S16-S16 (1976)
- [32] D.J. Withington, "Localisable Alarms," in *Human factors in auditory warnings*, (Ashgate, England 1999), pp. 33-40
- [33] D.J. Withington and A.C. Chapman, "Where's that siren?", *Science and Public Affairs*, **2**, 59-61 (1996)
- [34] D.J. Withington and S.E. Paterson, "Safer Sirens," *Fire Engineers Journal*, **48**, 6-10, (1998)
- [35] J. Blauert, *Spatial Hearing*. MIT Press, Cambridge, USA, 1997.
- [36] F.L. Wightman and D.J. Kistler, "Sound Localisation," in *Human Psychophysics* (Springer-Verlag, 1993)

- [37] S.C Skeiber, R.L Manson, and R.C Potter, "Effectiveness of Audible Warning Devices on Emergency Vehicles," *Sound Vibration*, **12**, 14-22 (1978)
- [38] E.L. Corliss and F.E. Jones, "Method for Estimating the Audibility and Effective Loudness of Sirens and Speech in Automobiles," *Journal of the Acoustical Society of America*, **60**(5), 1126-1131 (1976)
- [39] J.G. Robinson and G.S. Casali, "Speech Communications and Signal Detection in Noise," in *The Noise Manual*, 5th edition, ed. ed. E.H. Berger, L.H. Royster, J.D. Royster, D.P. Driscoll, M. Layne, (American Industrial Hygiene Association Press, Virginia, USA, 2003), pp. 567-600
- [40] International Standards Organisation, "ISO 7731:1986: Danger signals for work places - Auditory danger signals" (1986)
- [41] H. Fastl and E. Zwicker, *Psychoacoustics: Facts and Models*, 3rd edition, ed. T.S. Huang, T. Kohonen and M.R. Schroeder, Springer, New York (2007)
- [42] H. Fletcher, "Auditory Patterns", *Reviews of Modern Physics*, **12**(1), 47-65 (1940)
- [43] R.G. Mortimer, "Oh! Say, can you hear that train coming to the crossing?" in *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting*, 898-902 (1994)
- [44] International Standards Organisation, "ISO 7731:2003: Ergonomics -- Danger signals for public and work areas -- Auditory danger signals" (2003)
- [45] E. Hellier and J. Edworthy, "On using psychophysical techniques to achieve urgency mapping in auditory warnings", *Applied Ergonomics*, **30**(2), 167-171 (1999)
- [46] C. Suied, P. Susini, and S. McAdams, "Evaluating Warning Sound Urgency With Reaction Times", *Journal of Experimental Psychology: Applied*, **14**(3), 201-212 (2008)
- [47] A. Guillaume, L. Pellieux, V. Chastres and C. Drake, "Judging the Urgency of Nonvocal Auditory Warning Signals: Perceptual and Cognitive Processes", *Journal of Experimental Psychology: Applied*, **9**(3), 196-212 (2009)
- [48] H. Onusic and M.M. Hage, "Parameters used for acoustic qualification/quantification of automotive vehicles", *International Journal of Vehicle Design*, **37**(1), 81-98 (2005)
- [49] F. Rossi, A. Nicolini, and M. Filipponi, "An Index for Motor Vehicle Passengers Acoustical Comfort", in *Internoise 2003: The 32nd International Congress and Exposition on Noise Control Engineering*, Seogwipo, Korea, p. N833 (2003)
- [50] Barclays Official California Code of Regulations, "Title 13. Motor Vehicles, Division 2. Department of the California Highway Patrol, Chapter 4. Special Equipment, Article 8. Sirens" (2010)

Noise Loggers



Remote access



1/1 & 1/3 Real-Time Loggers

Norsonic



Nor-277 Tapping Machine

- Remote Operation
- Battery & Mains
- Low weight
- Compact

Sound Meters & Analysers



Low Cost Real-Time 1/1 & 1/3

Nor-136
OHS
Vibration



Nor-140
Analyser



BELCUR PTY. LTD.

Ph: 07 3820 2488 : 0418 491 409
belcur@optusnet.com.au
www.norsonic.com
93 Cumberland Drive, Alex Hills, Qld 4161