Emergency Vehicle Auditory Warning Signals: Physical and Psychoacoustic Considerations

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ABSTRACT

This paper presents the results of research into the effectiveness of auditory warning signals for emergency vehicles. Recommendations are provided to improve the effectiveness of warning sirens to alert motor vehicle drivers. Physical and psychoacoustic issues are explored, along with consideration of various mounting locations for siren loudspeakers.

INTRODUCTION

There are a number of collisions with emergency vehicles and public road users every year which result in high annual cost due to the replacement of emergency vehicles, injury to specialist staff, general public, and service inefficiency. A contributing factor to these collisions is that drivers are unaware of an approaching emergency vehicle, particularly at intersections.

A key issue is the audibility of the warning siren on emergency vehicles approaching intersections. Simply increasing the loudness of the sirens is not an option as most are operated at the maximum levels permitted under the relevant standards. In addition there are concerns with noise induced hearing loss for ambulance drivers.

This paper describes the literature review, outcomes from experimental testing, and recommendations to improve the audibility of warning sirens.

PREVIOUS WORK

The most complete previous study into optimising the effectiveness of auditory warning signals was conducted for the application of alarms in civil aviation (Patterson & Mayfield, 1990). Guidelines on the design of auditory warnings are based on this study, and key issues are identified to be *localisation*, *perceived urgency*, and *masking* due to background noise (Robinson and Casali, 2003).

A localisable sound source has characteristics such that its direction can be accurately detected by a listener. The broader the range of frequencies in the sound, and the more uniform the power density, the more localisable the sound (Catchpole & McKeown, 2007). A siren's localisation ability can be improved to within 5˚ if designed properly (Makous & Middlebrooks, 1990).

Perceived urgency is the level of urgency that a listener perceives the sound and is dependent on the characteristics of the sound. The impression that a person gets when hearing a warning signal is called perceived urgency, which is a psychoacoustic property (Hellier & Edworthy, 1999). Among other factors, the largest contributing factor to perceived urgency is the speed of the signal (Catchpole et al., 2004).

Masking is the effect of the reduction of the loudness of a sound due to background noise (Robinson and Casali, 2003). This is a major consideration in analysing the audibility of sirens, as road users typically experience significant background noise due to traffic, and music playing within the vehicles.

KEY FACTORS

The problem under consideration can be classified into physical and psychoacoustic factors as listed in Table 1.

Table 1: Key Factors

Physical Factors	Psychoacoustic Factors
Noise reduction of a passenger vehicle	Perceived urgency
Attenuation due to distance	Localisation
Directivity of a siren loudspeaker	Masking
Effects of wind on loudspeaker	
Shadowing due to vehicles/barriers on road	

All of the key factors were explored through testing, research and theoretical analyses.

Noise Reduction of a Passenger Vehicle

An experiment was conducted to measure the average noise reduction of a passenger vehicle from three directions, to simulate the situation of an approaching emergency vehicle. The experiment consisted of measuring the noise reduction of the vehicle due to a noise source placed at the rear, side and front of the vehicle. Sound pressure level (SPL) measurements at $1/3^{rd}$ octave centre band frequencies were measured inside and outside the vehicle cabin. Figure 1 shows the average noise reduction for a passenger vehicle for the three directions in 1/3rd octave frequency bands.

The results exhibited the expect trend for an enclosure where the noise reduction is poor at low frequencies and increases with frequency at about 20dB per decade. The important feature to note is that low frequency sound is more effective in penetrating the vehicle than high frequency sound.

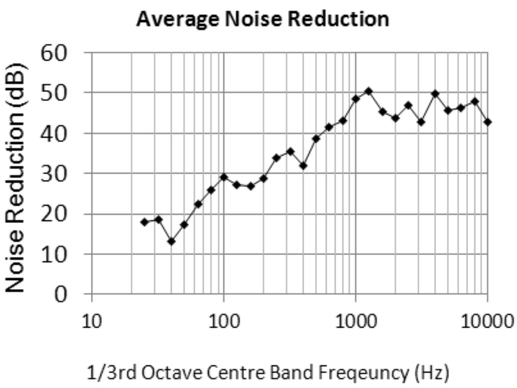

Figure 1: Average noise reduction values for a passenger vehicle

Experiments were conducted to measure the sound power level of several commercially available sirens. The tests were conducted using the "absolute method" (Bies and Hansen, 2009) in an acoustic reverberation chamber at The University of Adelaide using a traversing microphone and a Larson Davis LD2900 sound level meter. Figure 2 shows the sound power levels in 1/3 octave bands of the siren called the "Rumbler", manufactured by Federal Signal, that generates a low frequency sweep, and a "Wail" warning siren used extensively throughout Australia. The "Wail" siren emits sound in the frequency range from 500Hz to 1600Hz, whereas the "Rumbler" siren emits sound from around 125Hz to 400Hz.

Comparison of the results for the vehicle cabin noise reduction in Figure 1 and the siren Sound Power Levels in Figure 2 indicate that the "Rumbler" siren is better able to penetrate into a vehicle cabin compared to the siren emitting a "Wail" signal.

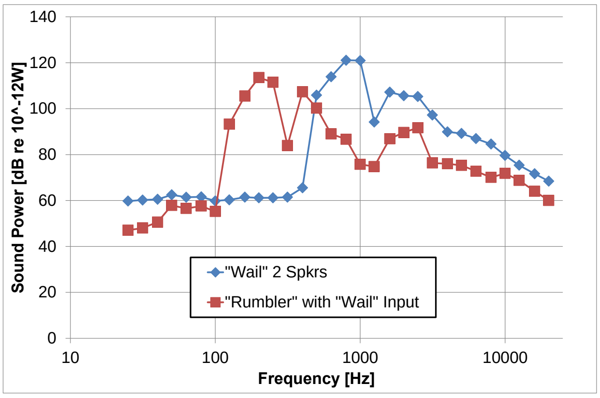

Figure 2: Sound power levels of the "Rumbler" and "Wail" sirens.

Attenuation Due to Distance

A siren can be modelled as a radiating point source that attenuates at approximately 6dB per doubling of distance. The equation used to model the attenuation of sound is given by (Bies & Hansen, 2009):

$$L_P = L_W - 10\log(4\pi r^2) + DI \qquad (1)$$

where L_p is the sound pressure level (dB re 20µPa) for a given distance, L_W is the sound power level (dB re 10^{-12}W), r is the radius (m) away from the source and DI is the directivity index. A directivity index of 6 was used (Bies & Hansen, 2009). It should be noted that siren's sound pressure levels are significantly attenuated due to distance from the emergency vehicle to the listener.

Directivity of a Siren Loudspeaker

The directivity of a typical siren loudspeaker was measured in order to assess the expected SPLs perpendicular to the axis of the siren. The off-axis sound levels for a siren are important when an emergency vehicle is approaching an intersection where incoming vehicles must be alerted.

The directivity of the siren loudspeaker was measured in an anechoic chamber. A white noise source was played through the siren loudspeaker and SPLs were measured at a distance of 1.8m from the speaker various angles as shown in Figure 3, where 0° is directly in front and 90° is perpendicular to the direction of the speaker. Figure 3 shows the overall SPLs in 1/3 octave bands.

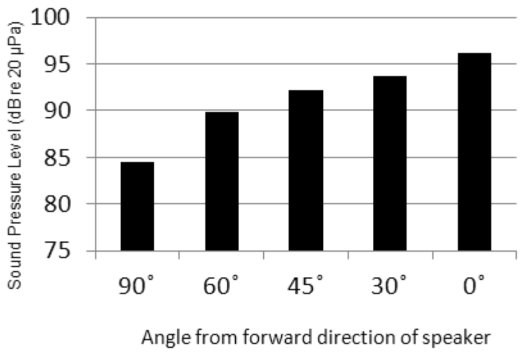

Figure 3: Total SPL for respective directions

The results indicate an 11dB reduction in SPL between the on-axis and perpendicular directions, which would be subjectively perceived as "half as loud" (Bies & Hansen, 2009). Due to the directional behaviour of the speaker, it is recommended that a second pair of speakers be installed on emergency vehicles, directed sideways and activated when approaching intersections.

Effects of Back Pressure on a Siren Loudspeaker

Emergency vehicles often travel at speeds of 60-80km/h with sirens active and there is a potential that the sound radiated from the siren could be reduced due to the back-pressure acting upon the siren loudspeaker diaphragm. Tests were conducted that involved placing the siren loudspeaker in a wind tunnel, with wind speeds of 60 & 80km/h, and measuring the SPLs. The SPLs from the wind-loaded siren were compared to no-wind conditions and it was found that the wind loading did not degrade the radiated SPLs. The siren loudspeaker was dismantled and found to have a pressure compensating design with ports connecting the front to the rear of the speaker. Hence, the design of the siren cabinet is self-compensating for wind loading.

Shadowing due to Vehicles/Barriers on the Road

Sound waves are reflected and absorbed by barriers which for the purpose of this study primarily include any vehicles between road users and the siren loudspeaker. Shadowing is the result of this and causes the region behind the barrier to have decreased sound pressure levels. Low frequency signals, i.e.

below 1000Hz, are more effective at refracting around barriers (Robinson and Casali, 2003).

Perceived Urgency

Perceived urgency is a psychoacoustic factor that is dependent on the characteristics of the sound. It is the degree of urgency which a listener judges the sound to be, and is a factor in listener reaction times. The factor that has the greatest influence on perceived urgency is the repetition period of the signal: a rapidly repeating signal is perceived to be more urgent than a slowly repeating signal. (Catchpole et al., 2004). The repetition period of a number of siren signals used in Australia and Europe were measured and it was found that the “MS4000 Priority” signal had the shortest repetition period, as listed in Table 2.

Table 2: Period of siren signals.

Siren Signals	Period (s)
Wail	4.11
Yelp	0.35
MS4000 Priority	0.05
MS4000 Scan 1	0.09
MS4000 Scan 2	0.23
Police (F)	1.11
Gendarmerie (F)	1.12
Pompiers (F)	2.25
UMH (F)	1.12
Ambulance (F)	2.04
Polizia (I)	1.53
Ambulanza/Vigili del Fuoco (I)	1.51
2 Ton Police (N)	1.52
3 Ton Fire Brigade (N)	3.05
Feuerwehr (Fire Brigade, G)	4.08
Rettungsdienst (Emergency Service, G)	4.06
Polizei (G)	2.35
Pistensignal (Runway Signal G)	1.79
UK Fire Brigade	1.54

Based on these results, it is suggested that the "MS4000 Priority" should be used when it is desired to project a high degree of perceived urgency, for hazardous situations such as when approaching intersections, or when a quick response time is desired.

Localisation

A localisable sound source has characteristics such that its direction can be accurately detected by a listener. It is desirable that the direction of a warning sound source can be accurately localised so that road users are able to identify the direction of an approaching emergency vehicle. The broader the frequency range of the sound, and the more uniform the power density, the more localisable the sound (Catchpole & McKeown, 2007).

The frequency ranges of most of the siren signals tested are similar, approximately 800Hz-2kHz. In order to increase the localisation of a warning signal it is desirable to increase the frequency range. A white noise source has the most effective localisation characteristics due to its frequency range and uniform power density.

One method of improving the localisation of the standard warning "wail" and "yelp" sirens on emergency vehicles is to increase the high-frequency components of the warning signal. However as automotive cabins have good transmission loss at high-frequencies, this is unlikely to result in improving the localisation as the signals will be masked, as described in the following section. In addition 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.

Masking

Masking is the effect of the reduction of perceived loudness of a sound due to background noise and can be calculated using the “Critical Band Method” (Robinson and Casali, 2003).

Figure 4 shows the masked threshold levels inside a vehicle due to background noise levels when driving, and the expected sound pressure levels of the "wail" siren signal experienced in a passenger vehicle after attenuation due to distance of 20m and the typical noise reduction of a passenger vehicle (shown in Figure 1). The background noise levels inside the vehicle were measured while driving at approximately 50kph in the Adelaide CBD, windows closed and radio playing at a comfortable volume, and are listed in Table 3.

Table 3: Sound pressure levels while driving in car.

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

The masked thresholds for this background noise are shown as the line with the cross markers. In order to elicit a rapid response from listeners it is required the level of a warning signal should be 15dB above masked thresholds (Robinson and Casali, 2003). The results show that this guideline is not met, and that a siren is quite ineffective at a distance of 20m. This result is consistent with the findings from a US Department of Transportation study that an auditory warning signal, after attenuation due to distance, vehicle noise reduction, and taking masking noise into account, is only effective for up to 8-12 metres at urban intersections (Skeiber et al., 1978).

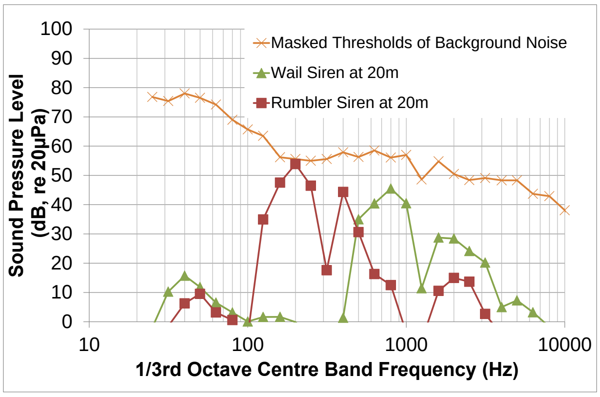

Figure 4: In vehicle siren SPL compared to masked thresholds of background noise

However, it must be kept in mind that predictive masked threshold calculation methods are conservative (Robinson and Casali, 2003), and that siren signals that consist of a wide frequency range, and where the frequency sweeps from low to high, (typical of most sirens, and characteristic of the "wail" and "yelp"), are detectable at lower signal-to-noise ratio. It should be that the Critical Band theory described in Andersen

2003, applies to third-octave band-limited random noise, and that reduced masking would occur with narrow-band signals. Another conservative factor was that the background noise was time averaged, thus it is likely at particular points in time the background levels will reach lower values for particular frequency bands, therefore increasing the opportunity for the siren signal to be audible.

The addition of a siren that emits low frequency sound to emergency vehicles will assist in combating this issue, particularly in regards to vehicle penetration.

SUMMARY

Recommendations that have been made based on findings are displayed in Table 4.

Table 4: Recommendations based on key issues identified

Key Issues	Recommendations
Perceived Urgency	Use "MS 4000 Priority" at intersections
Localisation	Install Federal Signal's "Rumbler" siren
Siren Speaker Directivity	Install extra speakers directed towards sides of emergency vehicle, for activation at intersections
Siren back pressure due to wind	Current typical siren loudspeaker is insensitive
Shadowing by vehicles	Install Federal Signal's "Rumbler" siren
Vehicle Noise Reduction	Install Federal Signal's "Rumbler" siren
Masking	Install Federal Signal's "Rumbler" siren

Noise Reduction of a Passenger Vehicle

The results of the noise reduction experimental testing of a passenger vehicle indicated that low frequency signals have greater vehicle penetrability. It is therefore recommended that part of a warning signal incorporates a lower frequency signal. Such a siren that is commercially available is the “Rumbler” siren available from Federal Signal.

Directivity of a Siren Loudspeaker

Experimental testing showed that the current typical siren loudspeaker although it meets the recommended standards for sirens, has reduced sound levels perpendicular to the axis of the siren. A hazard of a collision exists when an emergency vehicle and another motor vehicle converge at an intersection. There are several collisions incidents of this scenario that occur each year. To address this hazard at intersections, an effective auditory warning signal can be broadcast to motorists approaching the intersection by installing additional loudspeakers directed towards the sides of the emergency vehicle.

Effects of Back Pressure on a Siren Loudspeaker

The current siren loudspeaker design compensates for back-pressure caused by forward motion of the emergency vehicle. Experimental tests in a wind tunnel confirmed that the back-pressure on the siren did not reduce the radiated sound.

Shadowing due to Vehicles/Barriers on the Road

In consideration of the effects of signal shadowing due to barriers such as road vehicles, and buildings, suggested that signals with frequencies below 1000Hz are recommended (Robinson and Casali, 2003).

Perceived Urgency

The characteristic that has the greatest influence on the perceived urgency of a signal is its repetition period. The “MS4000 Priority” signal from Federal Signal had the shortest repetition period and hence conveyed the highest perceived urgency. It is recommended that this signal be used in situations where a high level of perceived urgency is desired to be projected, such as when approaching intersections.

Localisation

The ability for listeners to accurately judge the direction of the sound source can be improved. This can be achieved by broadening the range of frequencies of the warning signal.

Masking

The most effective way to combat the effects of masking is to make the signal more complex, and to broaden the frequency content, in order to improve the chances of signal levels being significantly above masked thresholds at as many instants in time as possible. It is recommended that to reduce the effects of masking that a low frequency siren is installed, such as the "Rumbler".

Mounting Options

A recommendation was made to install additional sire speakers directed towards the sides of the vehicle for the purpose of improving the projection of the warning signal to drivers approaching from a perpendicular direction, such as at an intersection. Mounting the siren loudspeakers on the roof of the emergency vehicle, or an overhead lightbar, would reduce the effects of shadowing due to other vehicles. However, measurements of the in-cabin sound levels for this configuration resulted in an 8dB increase, which is undesirable. An alternative location for the sirens is around the front wheel arches, which resulted in an increase in the SPL at the driver's position of less than 2dB, which is subjectively unperceivable.

CONCLUSIONS

There are many factors to consider when broadcasting an effective warning signal from an emergency vehicle to motorists. Standards exist (Barclays 2010, SAE J1849:2002) that limit the maximum output sound levels from sirens, and modern motor vehicles provide good noise reduction in the frequency range of standard "wail" and "yelp" sirens. This paper has described some of the issues and provided practical recommendations to address them.

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