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Safer Sirens

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The data from both the laboratory and field trials indicate that if fire engines are fitted with sirens that produce optimally alerting and localizable sounds, they can be made safer, both for their occupants and for other road users, and they will be able to travel more swiftly to and from emergencies as necessary.

1 INTRODUCTION

An every-day occurrence for the majority of drivers is the sound of an emergency vehicle siren, whether from an ambulance, police car or fire appliance. When the emergency siren is heard, drivers look all around trying to determine from which direction the sounds are coming. The visual cue is required because the sound alone gives no clue as to which direction the vehicle is coming from. The driver is not able to make appropriate avoiding action until the emergency vehicle is seen, which is often too late to allow a clear path to be created for the emergency vehicle. This uncertainty regarding the direction of approach costs lives. Any improvement in the sound quality of the siren, which enables road users to take earlier and more appropriate evading action, will both reduce the journey time and enhance the safety for other road users, pedestrians and drivers alike, and the emergency vehicles attending emergencies.

The psychoacoustic requirements for a sound to be localized with any degree of accuracy are not incorporated into the sound patterns of existing sirens. Indeed, it is recognised that the emergency vehicle siren is "an extremely limited auditory warning device"[1]. Auditory localization, i.e. our ability to pinpoint the direction of a sound source, is achieved by extremely complex processing in the brain. Identifying the direction of a sound source is, in fact, one of the most complicated tasks our brain performs without us being aware of it. Nevertheless, accurate sound localization is possible given the right sound in the first instance, and we are capable of determining the position of a sound source to an accuracy of 5^{o}. We hear sounds over a huge frequency range of about 20 Hz to 20,000 Hz, although this range diminishes as we age. It has long been recognised that localizing a sound source requires a vast amount of neural processing [3]. Only certain types of sounds are inherently localizable and the crucial component is that they contain a large spectrum of frequencies, i.e. broadband noise. Pure tones, simple tone combinations or narrowband noise cannot be localized. To understand why this is the case the cues given by sound, that the brain can access, must be considered.

There are three main types of information that allow the brain to localize sound. The first two are known as binaural cues because they make use of the fact that we have two ears, separated by the width of our head. A sound which emanates from either side of the midline will arrive first at the car closest to it and will also be loudest at the car closest to it. At low frequencies the brain accesses differences in the time of arrival of the sound between the ears, and at higher frequencies the salient cue is the loudness/intensity difference between the sound at each car. The use of these two types of cue is known as the “duplex” theory and was proposed by Lord Raleigh as long ago as 1877.

For single frequencies these cues are, however, spatially ambiguous. The inherent ambiguity has been described as the "cone of confusion" and this arises due to the fact that for any given frequency there are numerous spatial positions that generate identical timing/intensity differences and these can be graphically represented in the form of a cone, the apex of which is at the level of the external ear. The cone of confusion is the main reason that we cannot localize pure tones [4,5].

The final main piece of information processed by the brain regarding sound localization is called the head-related transfer function (HRTF) [6]. The HRTF refers to the effect the external car has on sound. As a result of passing over the bumps or convolutions of the pinna, the sound is modified such that some frequencies are attenuated and others are amplified. Although there are certain generalities in the way the sound is modified by the pinnae, the HRTF of anyone person is unique to that individual. The role of the HRTF is particularly important when we are trying to determine whether a sound is immediately in front of, or straight behind, us. In this instance the timing and intensity differences are negligible and there is consequently very little information available to the central nervous system on which to base a decision of "in front" or "behind'.

So, to locate the direction of a sound source the larger the frequency content, to overcome the ambiguities inherent to single tone sounds, the better the accuracy. For a sound to be localizable it must contain as much of the audible frequency range (20 - 20,000 Hz) as possible. Existing sirens operate only over a tiny portion of our hearing range, just 500- 1,800 Hz (Figure 1a). It is, therefore, hardly surprising that they cause such difficulty when trying to pinpoint the direction of approach.

In addition to being localizable, emergency vehicle sirens should also be "alerting", in other words, attract the listener's attention. Although it is generally assumed that existing sirens are alerting, this may, in part, be due to familiarity and learned association of emergency vehicles with the existing sounds. The scientific literature on what makes a sound alerting indicates that existing siren patterns don't even possess this characteristic in an optimum form [7]. localizable phases which were combined to produce a composite signal.

The data gathered from the simulator trials showed conclusively the poor localization characteristics of existing sirens. All the currently available sirens were associated with exceedingly poor front/back accuracy: participants had difficulty identifying whether the sound emanated from the front or rear of the car, to the extent that they were wrong more often than not (Figure 3). It is worth noting that if participants just guessed front or back, in theory they would have been correct 50% of the time. In contrast, with the newly-created sound-patterns from Sound Alert Ltd., the corresponding judgements were made correctly most of the time (Figure 3). Improvement was also evident in left/right accuracy (Figure 4).

The new sounds consist of rapid frequency sweeps, and associated with each train of frequency sweeps is a burst of broadband noise (Figure 5 and see also Figure 1B).

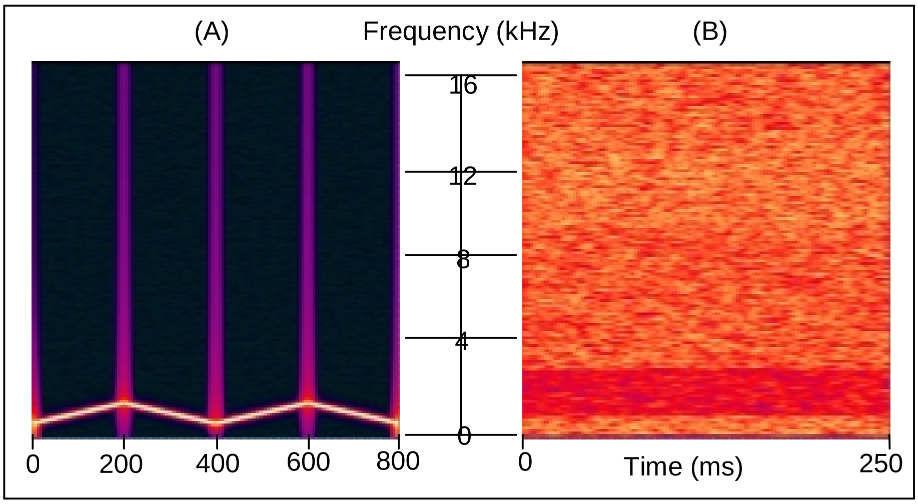

Figure 1: Spectrogram of the frequency content of an existing “yelp” siren (A) and the broadband noise used in the Localizer siren (B).

2 LABORATORY-BASED RESEARCH

The initial task to start the process of improving emergency vehicle sirens was a laboratory-based study to a) quantify the accuracy possible with existing sirens and b) experiment with scientifically engineered sounds which should be more localizable.

Four existing sirens were tested; "hilo", "Pulsar", "wail" and "yelp". In addition to the existing sirens a range of new sound patterns was tested. The new sound patterns contained alerting and

The aggregate pattern optimises both the alerting and localizing features of a sound configuration, and there is a range of sound patterns covered by this description thus allowing a choice of sounds for the emergency services.

The next stage in the development of the new sirens was to take the sound patterns which had worked so well in the laboratory and subject them to field trials.

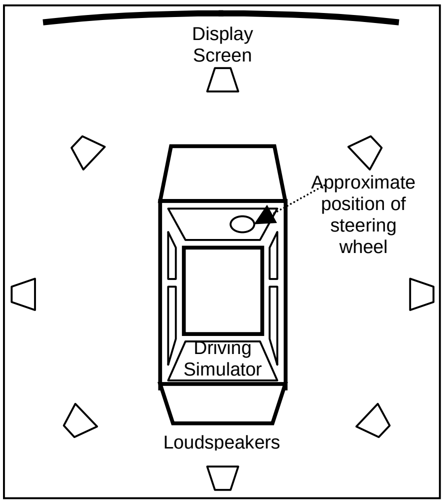

Figure 2: Layout of the speakers in respect to the driving simulator for the laboratory-based research

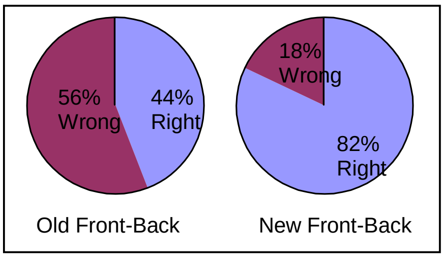

Figure 3: Pie charts showing the % of particular responses which judged correctly whether the sound was played from the front or rear of the car, using the old siren (left) and using the new sound patterns (right).

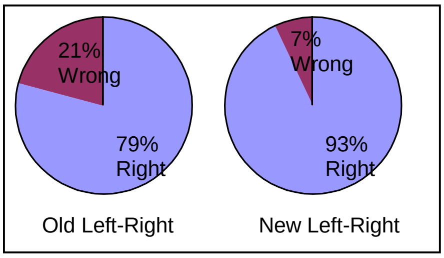

Figure 4: Pie charts showing the % of particular responses that were accurate to $\pm 22.5^{o}$ of sound coming from the left or right of the car, using the old siren (left) and using the new siren sounds (right).

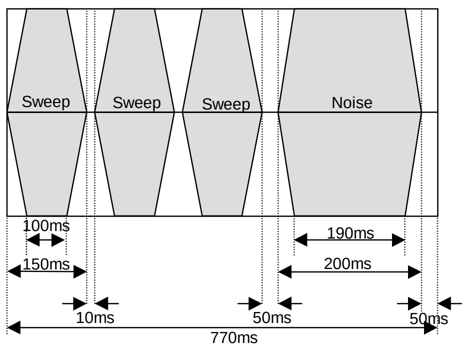

Figure 5: Diagrammatic representation of the sound pattern incorporated in the Localizer siren.

3 FIELD TRIALS

The purpose of the analysis used on this part of the project was to investigate whether the new auditory warning system affected the efficacy of the emergency vehicle in its progress through traffic.

The aim of the analysis was to monitor both the existing auditory warning system and the new auditory warning system in operation on actual emergency journeys using video-recording apparatus. This video footage provided an objective record of the interrelationship between the emergency vehicles and the other road users. The collected data could then be arranged into generalised road user responses towards the emergency vehicle. This standardised code of behaviour provides an accurate classification of typical driving behaviour which was used as a template for comparing the effect of both auditory warning systems through traffic.

For each type of behaviour the cumulation of number of occurrences for each behaviour was recorded which allowed numerically driven forms of statistical analysis to be performed. This technique is capable of identifying differences in overall performances between the existing and new auditory warning systems.

The choice of a methodological approach using anthropometric style evaluation though the use of video analysis is being used by a growing amount of technical disciplines. Increasingly qualitative observation techniques are being married to computer software and video analysis techniques in order to understand complex systems [8]. The validity of combining analysis using observational techniques with objective technical apparatus such as video recording equipment is a valid form of behavioural analysis.

The presence of an onboard observer was valuable as the observer had the advantage of understanding the context within which the data were gathered originally. Thus, the coding was more sensitive to the experience of the emergency crews. Translating the video data into a coding system which can be processed numerically allows a reliable comparison of the effectiveness of auditory warning systems. Carlson et al comment that, “observational techniques...is most often a prerequisite to the appropriate application of quantitative methods” [9]. Thus, the chosen analysis has relevance, reliability and validity.

Data for the analysis were gathered from a 3 month trial at Leicestershire Fire and Rescue Service (LFRS) during the period mid October ‘96 - January ‘97. The data were collected using video-recording equipment installed on a fire appliance and accurate notes were taken by a researcher who shadowed the emergency journeys. The fire appliance was fitted with both old (yelp/wail and 2-tone) and new (3 different versions of the “localizer”) siren systems.

On S302 Fire Appliance, video recordings of every emergency journey during the trial period were taken whilst using either the old or the new siren. The video data formed an accurate record of the oncoming road traffic which the fire crews experienced on a day to day basis.

Data gathered from journeys using the old siren were used to identify typical road user responses. Through rigorous video analysis of the video footage typical road user responses was coded to give the frequency rate that these behaviours occurred.

Thus, a comparison of the old and new siren video footage highlighted any difference in the responses to the old Vs new siren sounds.

Precise notes on each emergency journey were also taken by the on board researcher. Factors such as weather conditions, appliance position, duration of journey and type of emergency were considered as potential variables relevant to the emergency journey (table 1).

1.route of journey	6.miles
2.watch	7.weather condition
3.officer in charge	8.light
4.time mobile	9.appliance position
5.journey duration	10.siren type

Table 1: Information recorded by researcher.

After viewing the extensive video footage from LFRS, fifty emergency journeys using the old and new siren were analysed.

Ten variables were highlighted as relevant to the experience of both the fire crews and road users during an emergency situation. These appear in table 2. Table 3 shows an example of how an analysed journey was scored.

For each emergency journey all ten variables were observed. This profile of individual emergency journeys illustrated the frequency of typical driver behaviour. Every time a variable occurred it was recorded and a total produced. An example of a page of the master spreadsheet is given in table 4.

- Congestion - *The amount of vehicles present during each emergency journey.*
- Vehicles passed - *The amount of vehicles which the appliance actually passed.*
- Move / Indicate - *The number of times when the road users indicated while manoeuvring.*
- Move only - *The number of times road users move without indicating.*
- Lane Changes - *The number of times the appliance had to change lanes or drive on the wrong side of the road.*
- Junction / stop - *The number of times the appliance was forced to stop at a junction or traffic light.*
- Appliance stuck - *The number of times the appliance was forced to come to halt at any point during the emergency journey.*
- Vehicle break / slow - *The number of time road users either slow in confusion or break abruptly.*
- Cross junction - *The number of times road users speed across junctions and crossings.*

Table 2: Variable description.

The conditions recorded by the researcher (table 1) were analysed so that factors, such as length of journey time and distance travelled, were normalised for the old and new siren systems. Therefore, all the conditions in table 1 were filtered out as dependant variables in the analysis. Thus, the analysis of the emergency journeys was investigated with the knowledge that the only important variable factor is the type of siren system.

type of siren	congestion	vehicles passed	moved / indicate	move only	lane changes	junction / stop	appliance stuck	vehicle break/slow	cross junction
Old	57	47	5	4	2	7	2	2	3

Table 3: An example of how a typical journey was scored.

type of siren	congestion	vehicles passed	moved / indicate	move only	lane changes	junction / stop	appliance stuck	vehicle break/slow	cross junction
Old	57	47	5	4	2	7	2	2	3
Old	127	113	10	12	4	6	2	19	1
Old	87	82	7	9	2	9	2	7	0
Old	56	35	2	4	1	4	1	7	0
Old	19	16	1	11	3	7	0	7	1
Old	19	13	0	0	0	4	0	3	1
Old	72	58	2	5	1	6	0	8	3
Old	54	31	4	1	0	1	0	8	2
Old	56	36	5	0	0	3	0	6	2
Old	67	52	5	6	2	9	1	9	0
Old	78	61	7	5	1	1	0	23	0
Old	81	79	8	3	0	5	1	12	1

type of siren	congestion	vehicles passed	moved / indicate	move only	lane changes	junction / stop	appliance stuck	vehicle break/slow	cross junction
New	46	41	10	3	8	1	0	18	0
New	40	24	3	1	7	3	0	16	2
New	48	37	4	3	4	2	2	10	1
New	24	14	13	2	2	7	4	34	0
New	37	31	7	3	5	3	1	12	1
New	43	6	0	0	0	0	2	2	3
New	34	26	2	1	4	2	5	12	0
New	41	29	5	5	2	2	1	8	1
New	23	19	2	4	2	1	1	4	2
New	21	9	2	1	1	1	2	1	0
New	53	21	4	2	1	1	1	3	0

Table 4: An example of a page taken from the master spreadsheet showing typical driving behaviour of road users.

4 FIELD TRIAL RESULTS

From the video footage of the LFRS field trials a profile of the driver behaviour was extracted. The comparison between variables from the old and new siren did indicate a number of differences in performance.

The results indicated notable differences for the following variables:

- Variable **Move only** results: New siren = 30.4% vs Old siren = 69.6%
  More road users failed to indicate their intended direction of travel when the fire appliance was using the old siren.
- Variable **Junction Stop** results: New siren = 19.3% vs Old siren = 79.7%
  The results showed that the fire appliance was forced to stop at junctions four times more often with the old siren.
- Variable **Lane Changes** results: (New siren = 27.4% vs Old siren = 72.6%)
  Inappropriate road user responses force the appliance to change lanes on the emergency journey. With the old siren this happened three times more often.

The results are depicted in graphical form in Figure 3 with the variable move only described as fail / indicate.

5 DISCUSSION

The variables lane changes, junction/stop and move only are areas where noticeable differences where found whilst using the new siren. These improvements highlight the road users ability to localize sound more accurately with the new siren.

Road users were able to clearly make appropriate avoiding action and had more decision time when the new siren was on the approaching vehicle. The road users failing to indicate when manoeuvring highlights clearly the lack of decision time, and the overall panic, which road users experience in response to an approaching emergency vehicle utilising the old siren.

The ability of the road user to determine the direction of the emergency vehicle can be identified by the lower amount of lane changes made by the emergency vehicles. The appliance is also stopped at junction far fewer times while using the new siren which highlights the lack of disruption which the appliance experienced whilst using the new siren.

The differences in performance between the old and new siren indicated by these features clearly validate the new auditory warning system's ability to allow road users to determine the direction of the oncoming emergency vehicle, resulting in greater safety for both the emergency crews and road users.

The fire service field trial produced very similar results to those previously obtained from trials with the ambulance services in West Yorkshire and London. Most notably road-users reacted quicker, resulting in more appropriate, well signalled manoeuvres. For example, the incidence of drivers who did not indicate their planned direction of movement was two and a half times more common with the old siren compared with the new in the fire service trials (see Figure 6). Furthermore, as a consequence of the better reactions by other road-users fire appliance journey times were cut by as much as 8.5% . The emergency vehicle drivers, in both services, found the new siren disconcerting to drive with at first, due to the reduced noise levels of the new siren compared to the old inside the cab. However, by the end of the trials the majority of drivers had become accustomed to the lower noise levels. Research has shown that high noise levels in the cab should be avoided for many reasons. It is well documented, for instance, that loud noise levels affects drivers' ability to perform complex tasks (such as driving) [10].

In summary, the data from both the laboratory and field trials indicate that if fire engines are fitted with sirens that produce optimally alerting and localizable sounds, they can be made safer, both for their occupants and for other road users, and they will be able to travel more swiftly to and from emergencies as necessary.

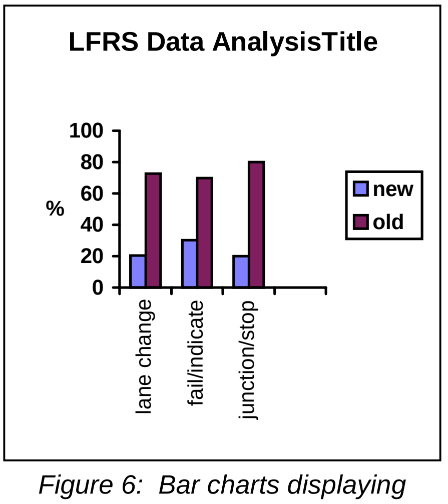

Figure 6: Bar charts displaying the data analysis from the on-board video camera recordings with a fire appliance.

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