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Directional Sound for Long Distance Auditory Warnings from a Highway Construction Work Zone

Final Report

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Directional sound can be used as a warning signal to denote that failure to follow an indicated action could result in serious accidents. In some applications such as to alert a vehicle that is likely to intrude into a highway construction work zone, long distance auditory warnings are necessary. In such cases, directed sound could be utilized to warn the specific vehicle without disturbing other vehicles on the highway. This report reviews the currently available scientific technologies that can potentially be used to develop a long distance auditory warning system for highway work zone applications. Of these, ultrasound based parameter arrays and time delay controlled arrays of compact ordinary speakers are taken up for detailed analysis and experimental evaluation. An ultrasound based parametric array is the most appropriate technology for generating highly directional sound. However, if cost, installation, maintenance, and price are considered, the most suitable technology is found to be arrays of flat panel loudspeakers with time delay control. Such a system can be used to generate directional sound effectively for long distance auditory warnings.

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Table of Contents

List of Tables

List of Figures

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Executive Summary

Directional sound can be used as a warning signal to denote that failure to follow an indicated action could result in serious accidents. In some applications such as to alert a vehicle that is likely to intrude into a highway construction work zone, long distance auditory warnings are necessary. In such cases, directed sound could be utilized to warn the specific vehicle without disturbing other vehicles on the highway. This report reviews the currently available scientific technologies that can potentially be used to develop a long distance auditory warning system for highway work zone applications. Of these, ultrasound based parameter arrays and time delay controlled arrays of compact ordinary speakers are taken up for detailed analysis and experimental evaluation. An ultrasound based parametric array is the most appropriate technology for generating highly directional sound. However, if cost, installation, maintenance, and price are considered, the most suitable technology is found to be arrays of flat panel loudspeakers with time delay control. Such a system can be used to generate directional sound effectively for long distance auditory warnings. This project shows that an annular pattern of flat panel speakers can provide directed sound along a highway lane with no real-time control of time delay necessary. Hence, an extremely inexpensive and portable system can be obtained with components consisting of compact flat panel speakers, a battery, power supply, and inexpensive electronics. In terms of performance, the developed system can provide a difference in sound level of 6 dB or higher between adjacent lanes at all frequencies in the range of 2- 4 kHz at distances up to 40 meters from the location of the warning system.

1. Introduction

An auditory warning can be used to signal danger. For example, it can be used to convey a warning that failure to follow an indicated action could result in a serious accident on the highway. An available loudspeaker which can generate high sound pressure levels and send sound over long distances is an emergency siren, whether from an ambulance, police car, or fire appliance. The sound pressure level generated from this loudspeaker is more than 100 dB and the sound can travel more than 100 meters.

However, the sound from an emergency siren is ambiguous. Listeners cannot tell easily where the sound is coming from [5]. When an emergency siren is heard, people need to look around, trying to determine from which direction the sounds are coming. The visual cue is required because the audio gives no clue as to which direction the sound is coming from. Listeners cannot keep away from action until the sound source is seen. It may be too late to act for avoiding danger when they eventually find the direction of the sound source. Moreover, the auditory warning which spreads in every direction alerts not only the people in danger but also causes a disturbance to many other vehicles on the highway. Drivers on safe vehicle may be disturbed and make wrong decisions which cause an accident. An example of this situation is shown in Figure 1. If a general emergency siren is used to alert a vehicle which is coming into a construction zone, the emergency siren can generate sound which spreads to lanes which are not under construction. The sound may bother drivers in these lanes and can potentially cause drivers to make wrong decisions. Also, road users and workers working in the construction zone may continue to be in danger. In brief, there is a trade-off in auditory warnings between false alarms and necessity to prevent intrusion.

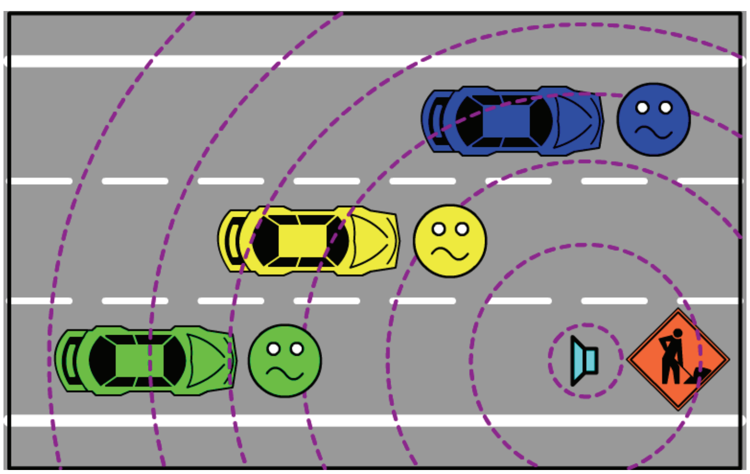


Figure 1 Emergency siren alerts not only people in danger but also people who are safe

Thus, researchers have been trying to improve auditory warnings. Withington [4] suggests that many alarms are difficult to localize because the frequency content of the siren sounds is so poor. Typically emergency siren sounds are emitted over the frequency range 500 Hz - 1.8 kHz, far too narrow a frequency range for localization. He has developed an improved loudspeaker by adding a pulse of broadband sound. His experiments in which the pulse was interspersed throughout traditional siren sounds showed conclusively important improvements in localization compared with traditional siren sounds.

Even though the traditional siren with a pulse of broadband sound can be located, the sound from it still spreads and bothers people whom we do not want to alert. Only localization of sound source is not enough to provide desired auditory warning. Ideally, the desired auditory warning should be limited to a target group without disturbing other vehicles nearby. Ideally, the sound should be a low indistinct murmur that suddenly comes up only when the vehicle enters a danger zone. Consequently, devices for focusing sound have been developed by several researchers. Currently, there are three possible technologies which can be used for developing long distance auditory warnings. They are reflector-based loudspeakers, ultrasound based parametric array or hypersonic sound, and time delay controlled arrays of flat panel loudspeakers. However, these technologies are normally used for short distance applications. Therefore, this paper will develop and evaluate these technologies for long distance auditory warnings.

The specific scenario being considered in this case is a work zone with a flag operator, such as the one shown in Figure 2 below:

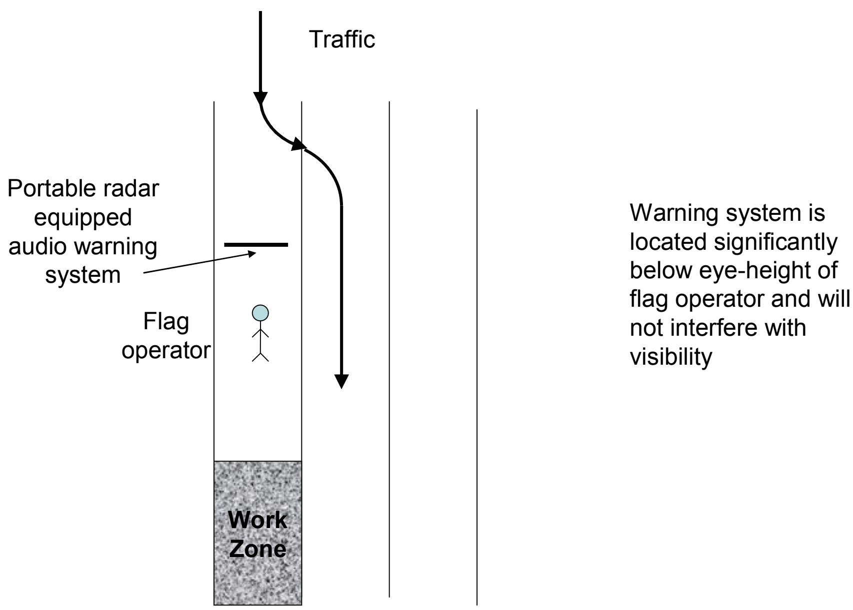


Figure 2 Work zone with flag operator scenario

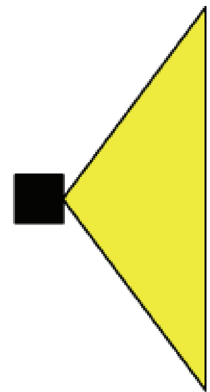
According to sources at Mn/DOT, in the work zone scenario above, some drivers do not notice the presence of the flag operator or of the signs indicating a construction zone and necessity to change lanes. Cell phones, computers, people reading books, eating, elderly drivers etc. are examples of problems noticed by flag operators when vehicles enter a work zone, missing all the work zone signs that are supposed to alert them to road work ahead. Approximately 1000 fatalities and over 50,000 injuries occur nationwide every year due to work zone intrusions.

The overall goal of this project is to develop and evaluate an audio alert system for work zones that provides warnings both to the potentially violating vehicle and to the flag operator in the work zone so as to ensure their safety. Specifically, the developed audio warning system should provide audio warnings to the potentially intruding vehicle without affecting other nearby vehicles on the highway.

2. Review of Available Technologies for Auditory Warnings

2.1 Normal Loudspeaker

(a) Normal loudspeakers



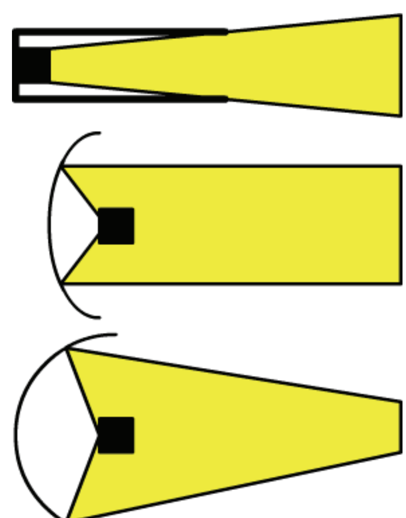
(b) Sound Projection

Figure 3 Normal loudspeaker

Normal loudspeakers project a 90 degree or greater than 90 degree cone of sound [19]. This is obviously much too wide for focused long distance auditory warning applications. One can at least take advantage of the proximity law that states that sound pressure level increases by 6 dB every time speaker to listener distance is halved. By locating the speaker as close as possible to the listener's head, sound pressure level can be decreased, thereby decreasing the sound level in the spillover area. Even though its price is inexpensive, if auditory warning is applied for an application as shown in Figure 2, normal loudspeakers do not work well for this application.

2.2 Reflector-Based Loudspeaker

(a) Brown Innovations Localizer



(b) Sound Projects

Figure 4 Reflector-based loudspeaker

The concept of reflector-based loudspeakers is using a reflector to change and focus the direction of sound. These loudspeakers take advantage of the acoustical properties of 3-dimensional curved surfaces. The specific properties of these loudspeakers vary with the exact type of reflector. Loudspeakers with reflectors, such as hemispherical reflectors, parabolic reflectors and hybrid domes, can be used to generate stereo effects and directional sound within a defined listening zone.

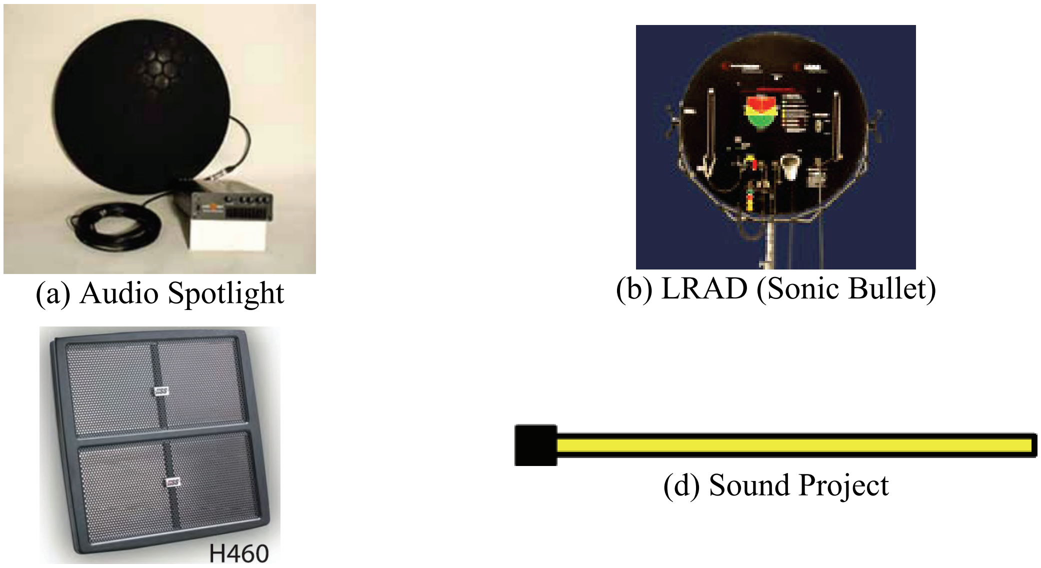
However, this approach has disadvantages. First, the beaming effect is less effective at lower frequencies, and the frequency response within the working bandwidth tends to be irregular because dishes of different sizes and shapes reflect some frequencies less effectively than others. Second, they are less effective at greater distances. At greater distance the sound losses its direction and spreads in every direction. Lastly, even though reflector-based systems are the simplest to set up and maintain, the reflector cost is high and the reflector size is also large.

A good reflector-based loudspeaker for long distance auditory warnings may be provided by Meyer Sound. Meyer Sound's SB-1 is a hybrid transducer design, working as both a parabolic reflector and a direct radiator. Frequency response is given as 500 Hz to 15 kHz, with a 10 degree (-6 dB) coverage pattern and maximum SPL of 110 dB, at more than 300 ft (91.4 meters). The size of SB-1 dish is 54 inches (1.4 meters) in diameter and weight is 293 lb (133 kg). The list price of it is about $16,710.

Figure 5 Meyer sound SB-1

There are other companies providing reflector-based loudspeaker. For example, Hemispherical Reflectors are provided by Brown Innovations and Hybrid Domes are provided by Sound Tube Entertainment. Even though their products are significantly cheaper than Meyer Sound's products, their products are not suitable for long distance auditory warnings. These products are designed for short range operation (less than 30 feet (9.1 meters)). In addition, their reflector size is more than 30 inches (0.8 meters) in diameter.

2.3 Parametric Array or Hypersonic Sound



(a) Audio Spotlight

(b) LRAD (Sonic Bullet)

(c) Hypersonic Sound

(d) Sound Project

Figure 6 Parametric array or hypersonic sound

Modulation of Ultrasonic Sound has been developed since early 1960s under the name "Parametric Array". The Journal of the Acoustical Society of America has published several papers about Parametric Array. These loudspeakers have been successfully developed for short distance applications by Holosonics Research Lab., American Technology Corporation (ATC), and Sennheiser Electronic, a German audio company. Parametric Array has another familiar name "Hypersonic Sound" because researchers at ATC who were developing these loudspeakers did not know the phrase "Parametric Array".

Sound from ultrasound is the situations when modulated ultrasound can make its carried signal audible without needing a receiver set [9]. This happens when the modulated ultrasound passes through anything which behaves nonlinearly and thus acts intentionally or unintentionally as a demodulator. These loudspeakers can be made to project a very narrow beam of modulated ultrasound that is powerful enough (100 to 110 dB) to change the speed of sound in the air that it passes through. The air within the beam behaves nonlinearly and extracts the modulation signal from the ultrasound, resulting in sound that can be heard only along the path of the beam, or that appears to radiate from any surface that the beam strikes. The practical effect of this technology is that a beam of sound can be projected over a long distance to be heard only in a small well-defined area. A listener outside the beam hears nothing. This effect cannot be achieved with normal loudspeakers, because sound at audible frequencies cannot be focused into such a narrow beam.

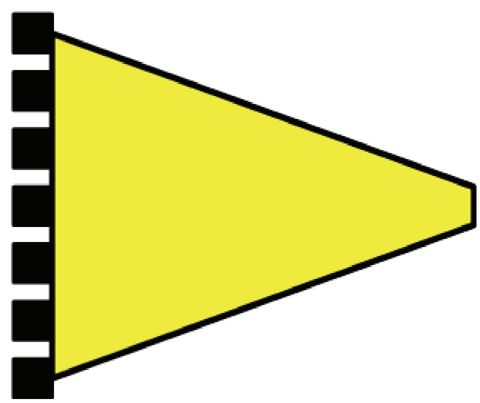
Parametric Array is the most suitable technology for short distance auditory warnings. These loudspeakers can alert only target people in desired direction without disturbing others. However, a parametric array is very difficult to apply for long distance auditory warnings. Almost no published paper shows the results of sound at long distances. However, ATC claims to apply this technology successfully for long distance auditory warnings. A commercial product developed by ATC is called Long Range Acoustic Device (LRAD). (The technology behind LRAD is confidential.)

LRAD was originally intended to be used by American warships to warn incoming vessels approaching without permission, and some reports claim that this is now a "non-lethal weapon". According to the manufacturer's specifications, the device weighs 45 pounds (20 kg) and can emit sound in a 30° beam (only at high frequency, 2.5kHz) from a device 33 inches (83 cm) in diameter. At maximum volume, it can emit a warning tone that is 146 dBSPL (1000 W/m²) at 1 meter, a level that is capable of permanently damaging hearing, and higher than the normal human threshold of pain (120 – 140 dB). The design range extends to 984 feet (300 metres) maximum usable range. At 300 meters, the warning tone (measured) is less than 90 dB. The warning tone is a high-pitched shrill tone similar to that of a smoke detector.

However, the list price of LRAD is very expensive ($23,000 - $35,000). The price of loudspeakers from Audio Spotlight and Hypersonic Sound is much cheaper than LRAD. Their price is about $1,000-5,000. Nevertheless, they are not designed to be long distance auditory warnings like LRAD. They are designed for applications like exhibits in museums or retail stores which require only a short range of less than 5 meters.

2.4 Arrays of Multiple Loudspeakers

(a) Digitally Steerable Array Systems



(b)Sound Project

Figure 7 Arrays of multiple loudspeakers

This technology uses arrays of ordinary multiple loudspeakers [8,10,16,17], with the signal to loudspeakers delayed by varying amounts to achieve what is popularly known as “beam steering.” A steered array, strictly controlling the launch time from each element, causes all elements to act together in concert at the target location whereas at any other location sounds arrive out of step with each other. The most common application of the principle involves linear arrays, a technique that allows the sound to be focused to varying degrees in the plane perpendicular to the array. (It also allows the coverage to be shifted up or down relative to the axis of the array.) By varying the design of the array and the timing of the speakers, different patterns and focal lengths may be obtained.

Arrays of multiple loudspeakers are an inexpensive solution for making long distance auditory warnings. Arrays of multiple loudspeakers can be made from cheap normal loudspeakers. The price of a system could be less than $100. However, unlike an ultrasound based system, an ordinary multi-speaker array does not only deliver sound to just the intended target zone. It also delivers some lower levels of sound to unintended zones.

There are many companies selling products with this technology, such as Renkus-Heinz, Brown Innovations, or Dakota Audio [19]. The size and price of arrays of multiple loudspeakers varies, depending on the type of application. Also, most products are designed for applications like entertainment and exhibition and hence work over only short distances in providing directed audio.

2.5 Comparison of Directed Sound Technologies

The appropriate device for long distance auditory warnings should create directional sound that will alert only people in a target area. It should be small and light, so it can be easily moved to a required construction zone on the highway. In addition, it should be cheap and easily to install and maintain. Table 1 compares characteristic of loudspeakers from each of the directed sound technologies.

Table 1 Comparison of directed sound technologies

	Directional Sound	**Size**	**Weight**	**Install and Maintenance**	**Price**	**Overall Appropriateness**
Normal Loudspeakers	Poor	Small	Light	Easy	Cheap	Poor
Reflector-based	Fair	Large	Heavy	Difficult	Expensive	Fair
Parametric Array (LARD)	Excellent	Medium	Medium	Difficult	Expensive	Good
Arrays of Multiple Loudspeakers	Good	Large	Light	Easy	Cheap	Good

Table 1 shows that parametric array and arrays of multiple loudspeakers are the most appropriate technology for the application. Parametric Array can provide highly directional sound and its size is not large. Likewise, arrays of multiple loudspeakers are cheap and easy to install and maintain. Therefore, the rest of paper will focus on parametric array and arrays of multiple loudspeakers and evaluate these technologies for the highway construction zone application.

3. Ultrasound Based Parametric Array or Hypersonic Sound

A parametric array uses the nonlinearity of the air to create audible sound from inaudible ultrasound [6]. It exploits an effect known as *self-demodulation* to create extremely directive, beamlike wide-band acoustical source. Self-demodulation occurs when nonlinearities of a compressible nonlinear medium, such as water or air, cause high frequency (ultrasound) wave components to interact. The interaction produces an output which contains both of the original signals f_1 and f_2, plus the sum of the two original signals, the difference of the two original signals, and a set of harmonics as shown in Figure 8. This phenomenon was first analyzed by Westervelt [14]. He has derived an inhomogeneous wave equation which is satisfied by the sound pressure of secondary waves produced by the nonlinear interaction. Then, Berktay's analysis [2] shows a collimated primary wave consisting of an AM modulated wave and a secondary wave of pressure.

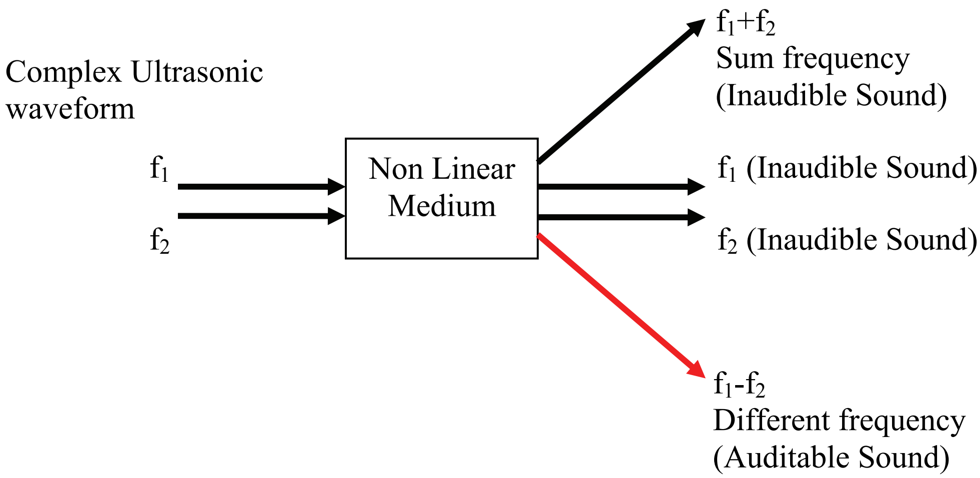


Figure 8 Self-demodulation, nonlinear interaction

The simple principle of self-demodulation can be presented below.
A carrier wave (ultrasound, $\omega_c/2\pi \geq 20\,\text{kHz}$) is modeled as:

$$V(t) = A\cos(\omega_c t + \varphi) \qquad (1)$$

where $\omega_c/2\pi$ is carrier frequency (Hz). A and φ are arbitrary constants that represent the carrier amplitude and initial phase of carrier wave. They may be set as 1 and 0, respectively.
An audio signal ($20\text{ Hz} \leq \omega_m/2\pi \leq 20\,\text{kHz}$) is modeled as:

$$m(t) = M\cos(\omega_m t + \varphi_m) \qquad (2)$$

where $\omega_m/2\pi$ is signal frequency (Hz). M and φ_m are arbitrary constants that represent the carrier amplitude and initial phase of audio signal. It is generally assumed that $\omega_m \ll \omega_c$.
Then amplitude modulation is created by forming the product:

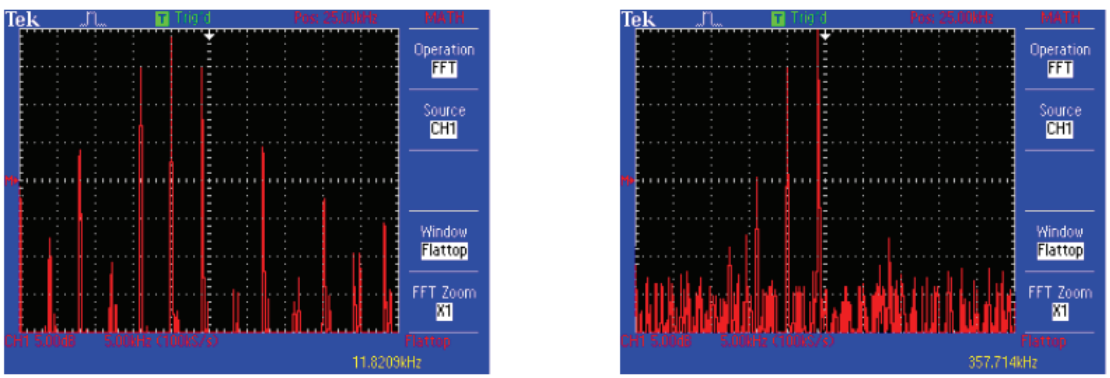
$$S(t) = A\left[1 + m(t)\right]\cos(\omega_c t)$$
$$S(t) = A\left[1 + M\cos(\omega_m t + \varphi_m)\right]\cos(\omega_c t) \qquad (3)$$

After a bit of math manipulation, it can be shown to be the same as

$$S(t) = A\cos(\omega_c t) + \frac{A}{2}a_m \cos((\omega_c + \omega_m)t + \varphi_m) + \frac{A}{2}a_m \cos((\omega_c - \omega_m)t + \varphi_m) \qquad 4$$

where $A\cos(\omega_c t)$ is carrier wave which is unaffected by the modulation. $\omega_c + \omega_m$ is upper sideband. $\omega_c - \omega_m$ is lower sideband.

After amplitude modulation, when the signal is sent through the loudspeaker, the product signal is mainly composed of three frequencies, ω_c, $\omega_c + \omega_m$, and $\omega_c - \omega_m$. When the product signal is examined by spectral analysis, the power spectra of frequencies, ω_c (f_1) and $\omega_c + \omega_m$ (f_2), are obviously noticeable as shown in Figure 9b. The power spectra of the frequency $\omega_c - \omega_m$ is smaller than that of the frequency ω_c and $\omega_c + \omega_m$. ([1,9,13] suggests to reduce distortion of the sound coursing by $\omega_c - \omega_m$ by using single sideband amplitude modulation instead of double sideband amplitude modulation.) Then, only frequencies ω_c and $\omega_c + \omega_m$ may be considered. When two sound waves of different frequency approach listener, the alternating constructive and destructive interference causes the sound to be alternatively soft and loud (Beat Phenomenon). The beat frequency is equal to the absolute value of the difference in frequency of the two waves, $(\omega_c + \omega_m) - \omega_c$. (The frequency $\omega_c - \omega_m$ and ω_c is also possible to cause the beat.) Thus, listener can hear the sound of frequency, $(\omega_c + \omega_m) - \omega_c$, because $(\omega_c + \omega_m) - \omega_c$ or ω_m is an audio signal.



TDS 2022 - 11:38:56 AM 7/23/2008

(a) Input to loudspeaker

TDS 2022 - 11:59:02 AM 7/23/2008

(b) Output from loudspeaker

Figure 9 Spectrum of input and output signal

The characteristics of the self-demodulated wave also depend on many parameters of the primary waves. Firstly, the directivity of the self-demodulated wave is increased when the parametric array length and the transducer surface are increased. The parametric array length is related to the primary wave frequency (dissipation of the wave and shock formation distance) and to the sound pressure level of the primary waves (shock formation distance). Next, the level of the self-demodulated wave depends on the sound pressure level of the primary waves, the transducer surface and the amplitude of the envelope function, which is related to the modulation rate.

Another important characteristic of the self-demodulated wave is the distortion rate. This can be reduced by decreasing the modulation rate: if the envelope function is $f = 1 + m\cos(\Omega t)$, then the demodulated wave is proportional to $m\cos(\Omega t)$ and the distortion is proportional to $m^2\cos(2\Omega t)$. So with a small modulation rate, m, we have very small distortion but also a small demodulated wave. The distortion may also be reduced by pre-processing the signal. The basic block diagram of parametric array is shown in Figure 10. The block diagram of parametric array with distortion corrected is shown in Figure 11.

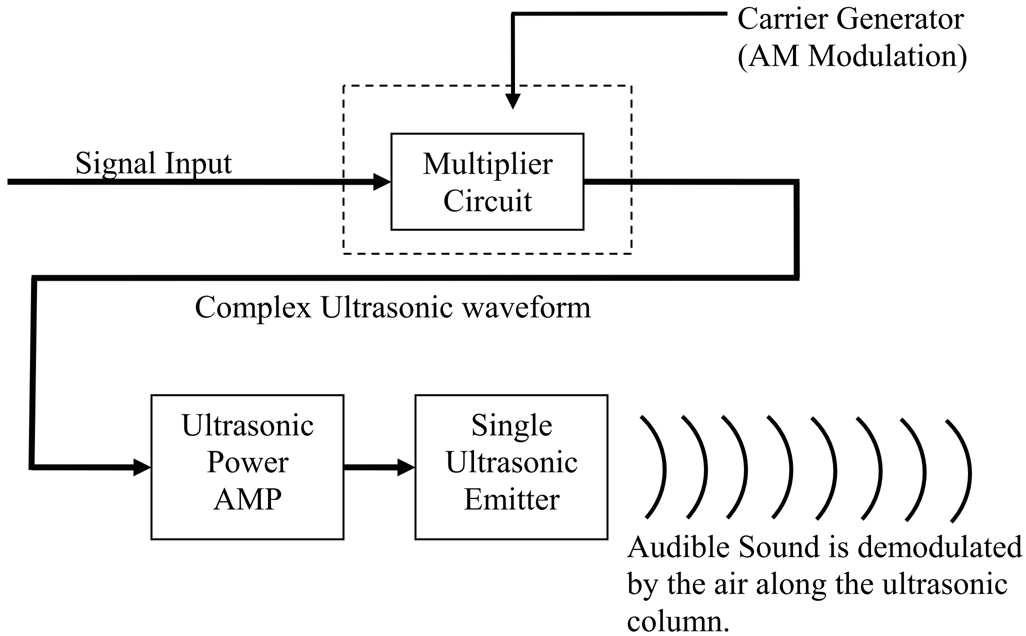


Figure 10 Basic block diagram of parametric array

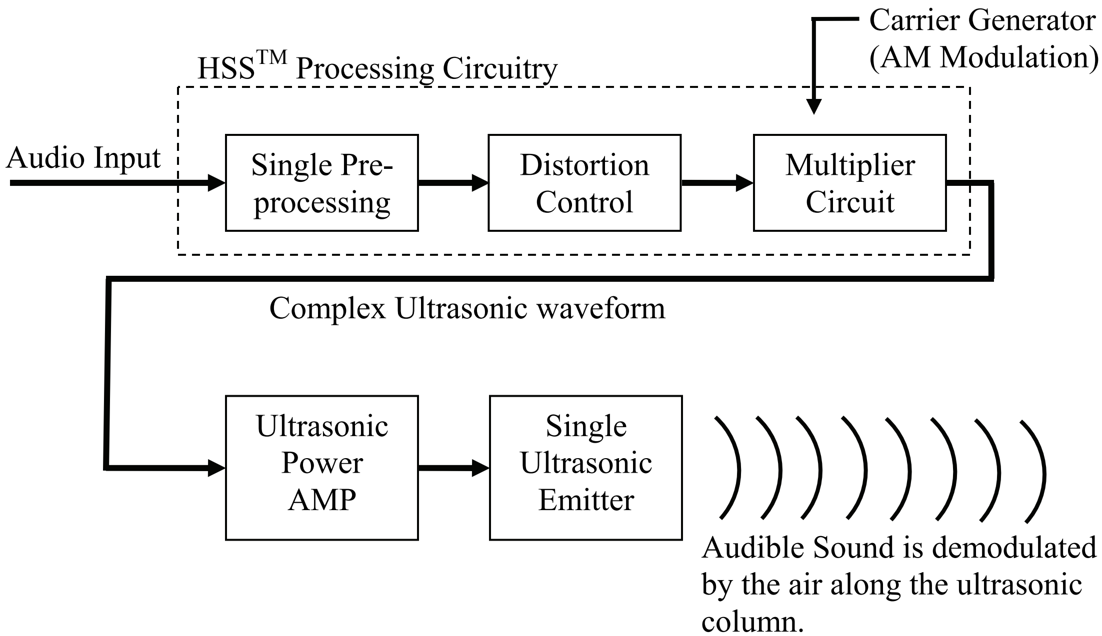


Figure 11 Block diagram parametric array with distrotion corrected by ATC

Because we are concerned only with creating a warning sound, the distortion does not need to be reduced. The pre-processing and distortion control do not need to be included in the system. Also, large modulation rate, m , should be used to increase the amplitude of secondary wave in our application.

4. Problems and Solutions with Parametric Array Systems

Although the principle of a Parametric Array seems simple, there are significant problems in developing a system due to issues with hardware, the ultrasonic emitter and the power amplifier.

The performance of the system is limited by ultrasonic emitters. An ultrasonic transducer with a working frequency 30 – 50 kHz is adequate. However, a multi-ultrasonic-transducer is required for the system because only one unit of transducer cannot provide the desired sound pressure level. The systems that have been developed using ultrasonic transducer need to use typically more than 300 units of transducers. Thus, these systems are expensive. An example of this system is shown in Figure 13 [12].

Figure 12 Ultrasonic transducer

Figure 13 Multi-ultrasonic-transducer [12]

To reduce cost of emitters ATC suggests using Monolithic film ultrasonic transducers, based on a polyvinylidene diflouride Film (PVDF film). However, the resonant frequency of monolithic film ultrasonic transducers is very low.

Figure 14 Monolithic film ultrasonic transducers

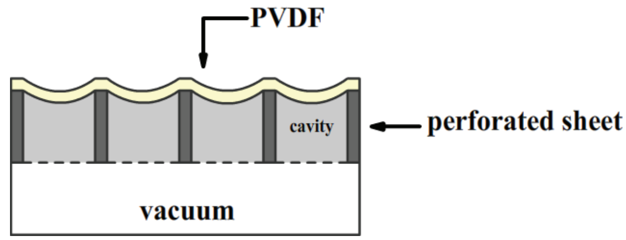


Figure 15 PVDF transducer

For the simplest implementations to increase the resonant frequency, one takes a sheet of PVDF and lays it over a metal perforated plate [1,9] as shown in Figure 15. Then apply vacuum to one side of the plate to create an array of PVDF diaphragms, each with the diameter of the hole under it, which are under uniform tension and can be driven in parallel. When the diameter of the hole decreases, the vibrating surface decreases and so the resonance frequencies increase. When the vacuum quality increases, the membrane tension increases, as do the resonance frequencies [1].

The power amplifier is also an important part of the system. To obtain a high sound pressure level the gain need to be large. Moreover, the bandwidth needs to be in the designed range. Most of the audio amplifiers are not suitable for parametric array system because their bandwidths are low, 20-30000 Hz. Also, amplifiers of radio frequency are not suitable. Their bandwidths are higher than 1 MHz. The suitable amplifiers should have bandwidth 40 kHz – 1 MHz. However, it is not easy to find an inexpensive amplifier which has this bandwidth. The amplifiers may need to be specifically designed for the parametric array system.

5. Experimental Results with Parametric Arrays

The objective of the experiments conducted in this project are to evaluate the directionality of sound and the levels of sound that can be created by using ultrasound based parameter arrays. Figure 16 shows the parametric array system which is explored in laboratory at University of Minnesota. The system uses PDVF film size 24 x 11 inches and 52 um thickness. The amplifier is Sound Storm Laboratories Force Amplifier, model 2F1200 (600 Watts/channel). Its bandwidth is 9Hz-50 kHz and its gain is about 10. With carrier frequency 20, 30, 40 kHz and signal frequency 2.5 kHz, this system can give directional sound up to 15 meters and sound pressure level about 68 dB.

The sound pressure is measured by sound level meter, Quest Electronics Model 2700 Digital Sound Level Meter. Its range is 35 to 140 dB and its resolution is 0.1 dB.

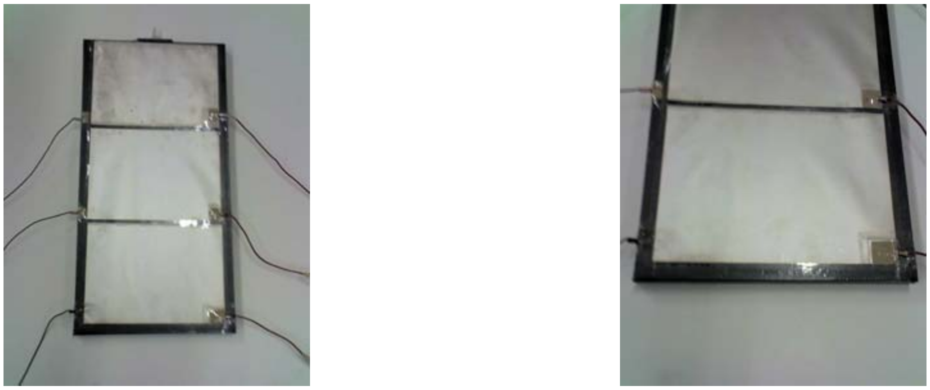


Figure 16 Loudspeaker of parametric array system

The measurement positions of experiment are shown in Figure 17. The sound pressure is measured along the center line of PDVF film and the lines which are away from the center line 0.5 meters and 1 meter. Also, the sound pressure is measured at the red spot as shown in the figure. At each red spot, the sound pressure is measured by sound level meter 4 times. The first, second, and third experiment uses the carrier frequency 20 kHz, 30 kHz, and 40 kHz, respectively.

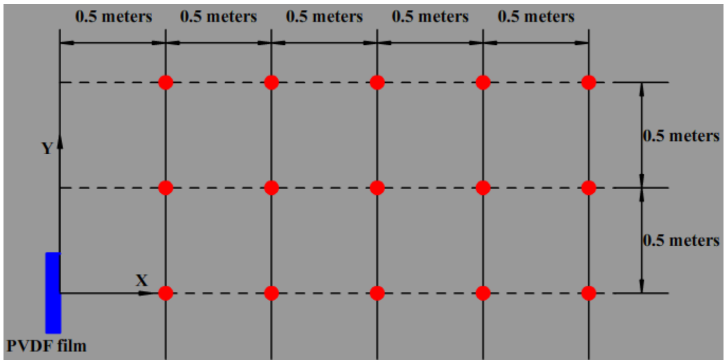


Figure 17 The measurement set up of parametric array

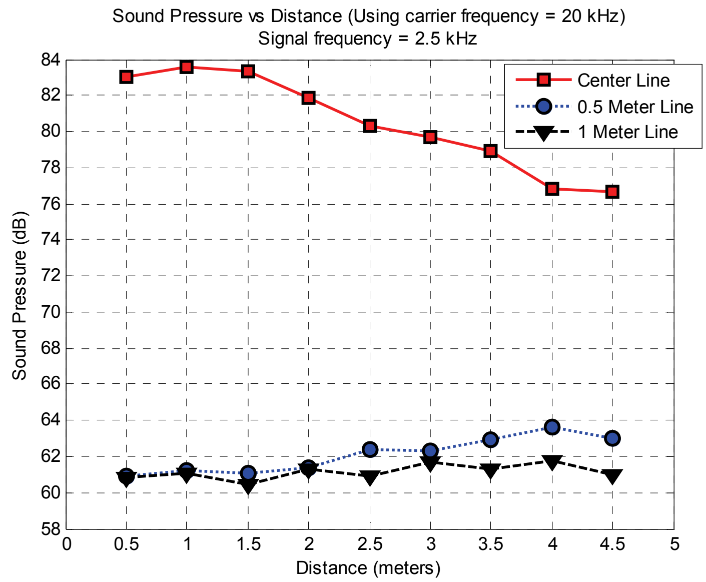


Figure 18 Sound pressure when carrier frequency 20 kHz

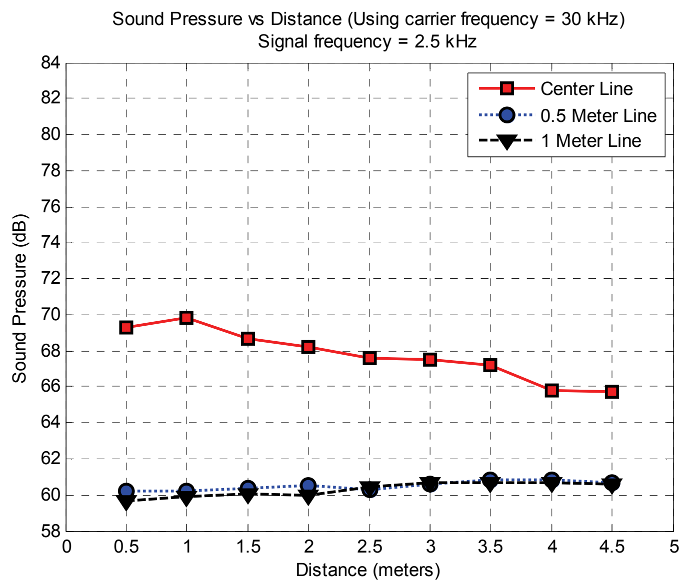


Figure 19 Sound pressure when carrier frequency 30 kHz

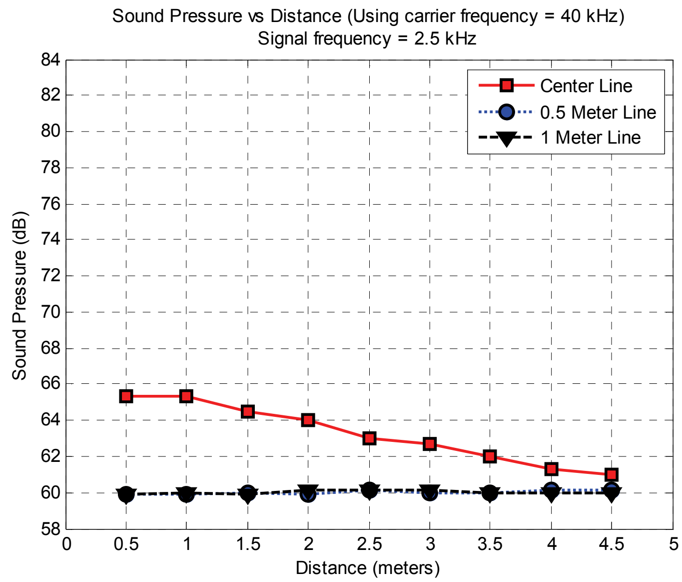


Figure 20 Sound pressure when carrier frequency 40 kHz

Figure 18, 19, and 20 show that the sound from parametric array is highly directional sound. Sound pressure level is high only the center line or in front of the loudspeaker. Sound pressures level on the 0.5 meters line and 1 meter line are almost not changed or close to sound pressure level of background noise, 59.8 dB. This means listeners can hear the sound only when they stand in front of the loudspeaker.

Figure 18, 19, and 20 also show that when the carrier frequency is increased, the difference between the sound pressure level on 0.5 and 1 meters line and the sound pressure level of background noise is decreased. This means the sound is more directional when the carrier frequency is increased. However, the sound pressure level on the center line is decreased when the carrier frequency is increased.

This system is not successful at transmitting sound for long distances. It is believed that the confidential LRAD project uses carrier frequency more than 100 kHz and a very high gain power amplifier. When carrier frequency is increased, the sound is more directional but the sound pressure level is decreased. Thus it requires a high gain power amplifier.

In summary, the directional sound of parametric array depends on carrier frequency. A higher carrier frequency gives highly directional sound but low sound pressure level. Lower carrier frequency gives low directional sound but high sound pressure level. It is believe that the LRAD product uses a carrier frequency of more than 100 kHz and very high gain power amplifier to obtain both highly directional sound and high sound pressure level. (An amplifier which has bandwidth more than 100 kHz is very expensive.). The minmum cost of a LRAD system is over $23,000.

6. Time Delay Control with Arrays of Flat Panel Speakers

The idea behind using arrays of multiple ordinary loudspeakers with time delay control is relatively simple. The location where the sound waves from multiple loudspeakers are in phase is called a point of *constructive interference*. The sound at this location is loud (high sound pressure). Likewise, the location where the sound waves from multiple loudspeakers are out of phase is called a point of *destructive interference.* The sound at this location is weak (low sound pressure). Therefore, with this principle, the loud sound can be generated at specific locations from weak sound sources, using multiple loudspeakers.

It is possible to make the sound loud at only a desired location or in a desired direction. (The directional sound is not perfect like it could be from a Parametric Array. There is lower levels of sound outside of the desired area.) Each signal from each loudspeaker is delayed such that they arrive at the desired location at the same time (in phase). When applied correctly to arrays of multiple loudspeakers, these signals will be added up at the desired location. This theoretically works because there will be perfect constructive interference in the desired location or direction and destructive interference elsewhere. Consider the arrangement of speakers as shown in Figure 21. The equation for calculating the delays in the near field is [10]:

$$D_i = \frac{(L_{\max} - L_i)}{V} \qquad 5$$

where V is speed of sound (m/s), the length from a focus to the i-th speaker is L_i. The maximum of L_i is $L_{\max}$, D_i is the delay.

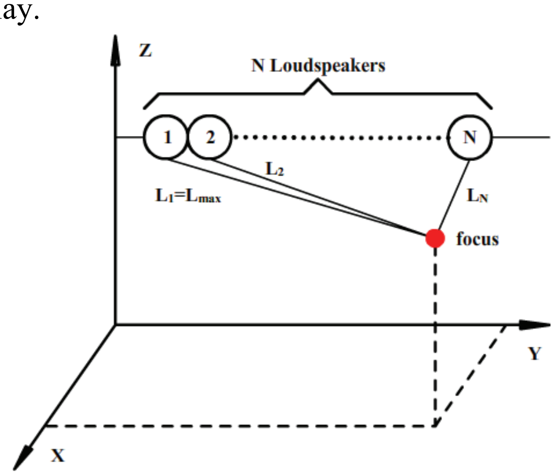


Figure 21 Arrays of multiple loudspeakers

In the following, an expression for sound pressure is described. The point at which the sound pressure is requested is $C(x, y, z)$, the distance from C to each speaker is R_i, the frequency is ω. The synthetic wave Q_c at point C is shown by the following expressions. A_c is the amplitude of the synthetic wave at point C, and α is the phase difference.

$$Q_c(t) = \sum_{i=1}^{N} \frac{L_i}{R_i} \sin\omega\left(t + \frac{L_i - R_i - L_{\max}}{V}\right) = A_c \sin(\omega t + \alpha) \qquad 6$$

$$B_c = \sum_{i=1}^{N} \frac{L_i}{R_i} \sin\left(\frac{L_i - R_i - L_{\max}}{V} \right) \quad 7$$

$$C_c = \sum_{i=1}^{N} \frac{L_i}{R_i} \cos\left(\frac{L_i - R_i - L_{\max}}{V} \right) \quad 8$$

$$A_c = \sqrt{B_c^2 + C_c^2} \quad 9$$

$$\alpha = \arctan\left(\frac{B_c}{C_c} \right) \quad 10$$

In general, the amplitude becomes smaller in proportion to the distance. In this simulation, a standard acoustic pressure was assumed to be amplitude at the focus (A_f). The amplitude of the synthetic wave at the focus is A_f . In these simulations, sound pressure at point C (SPLC) is shown by the following expressions.

$$S_{PLC} = 20 \log\left(\frac{A_c}{A_f} \right) \quad 11$$

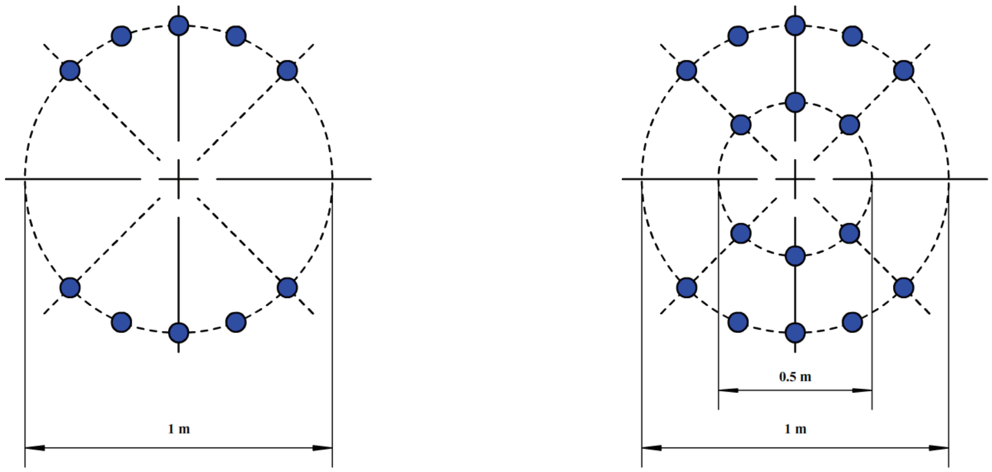
So, the sound pressure at the focus is necessarily 0 dB.

For far field, the delay is equal to the dot product of the speaker position with the unit direction vector divided by the speed of sound all subtracting the minimum delay of all the elements,

$$D_i = \frac{S_i \cdot r}{V - D_{\min}} \quad 12$$

where S_i is the speaker position, r is the unit vector in the observation direction, V is the speed of sound, and $D_{\min}$ is the minimum of all the delays of all the elements.

However, if an application needs only directional sound in a particular direction (not at a particular point), then multiple loudspeakers can be placed on an annular array pattern without requirement for time delay control. Such an arrays of multiple loudspeakers can generate directional sound which has the loudest sound along the axis perpendicular to the annular plane. This is because the sound from each loudspeaker will arrive along the axis at the same time. The example of this array pattern is shown in Figure 22.



(a) (b)

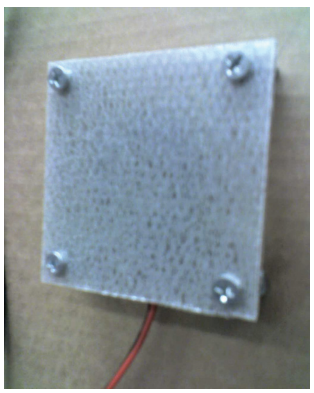
Figure 22 Annular array pattern

The example of a double annular array pattern is shown in Figure 22b. These patterns do not have loudspeakers lying on the horizontal axis. This pattern makes the sound pressure much more different between the axis perpendicular to the annular plane and the side axis on the horizontal plane.

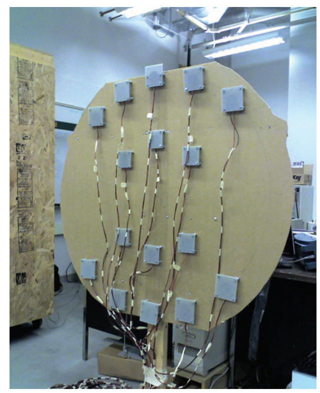
7. Experimental Results with Flat Panel Speakers

The objective of the experiments conducted in this project is to show that an annular array pattern of multiple loudspeakers can generate highly directional sound. The experiment uses the annular array patterns shown in Figures 22a and 22b.

The size of the loudspeaker array of multiple loudspeakers ued in the experiments is 3.5 x 3.5 inches for outer circle and 3 x 3 inches for inner circle. The speaker impedance of each loudspeaker is 4 ohms. The power amplifier for each loudspeaker is LEGACY series II, model LA 160 (75 Watt/channel). A photograph of the array of multiple loudspeakers is shown in Figure 23b.



(a) Loudspeaker



(b) array of multiple loudspeakers

Figure 23 Array of multiple loudspeakers

The normal loudspeaker used to compare the performance with the array is a 6 inches full range acoustic suspension speaker (Realistic No. 40-1285c). Its speaker impedance is 8 ohms. The power amplifier for normal loudspeaker is Sound Storm Laboratories Force Amplifier, model 2F1200 (600 Watts/channel).

The sound pressure is measured by a sound level meter, Quest Electronics Model 2700 Digital Sound Level Meter. Its range is 35 to 140 dB and its resolution is 0.1 dB.

The experimental set up is shown in Figure 24. Because the application of directional sound can apply for the case as shown in Figure 1, it needs to measure the sound pressure along the center line of the first highway lane and the sound pressure along the lines which are away from the center line 6 feet and 12 feet (the center line of the second lane). (Note: the highway lane width is 12 feet.) Thus, the sound pressure is measured at the red spot as shown in the figure. At each red spot, the sound pressure is measured by sound level meter at least 10 times. The first experiment uses a normal loudspeaker. The second and last experiments use the array pattern shown in Figure 22a and Figure 22b, respectively.
(Note: The background noise at the experiment set is 59.8 dB.)

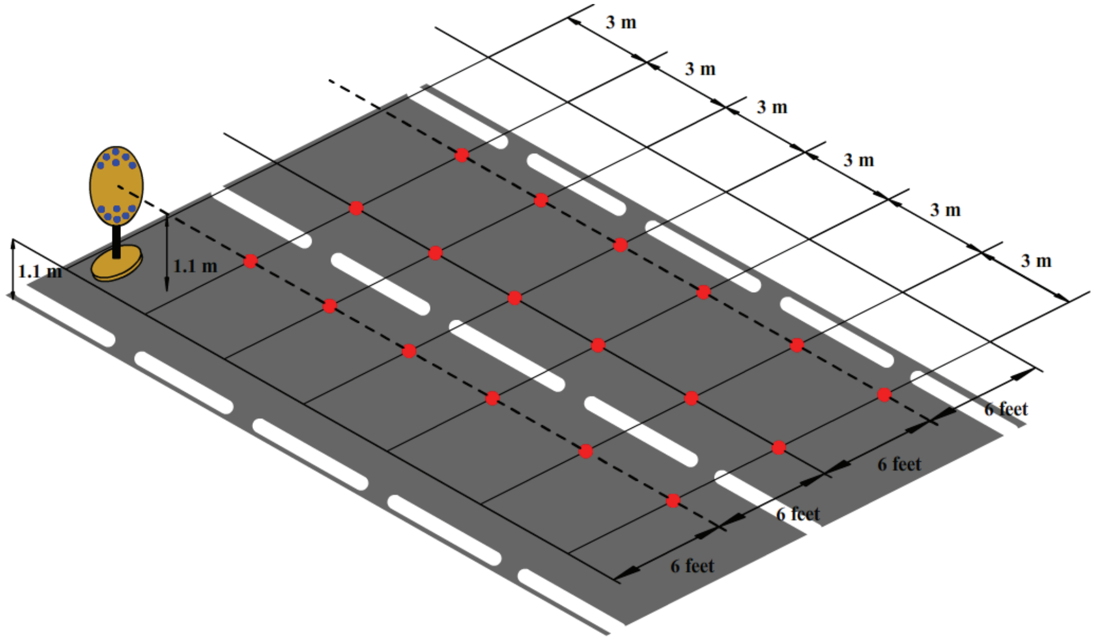


Figure 24 The experiment set up for array of multiple loudspeakers and normal loudspeaker

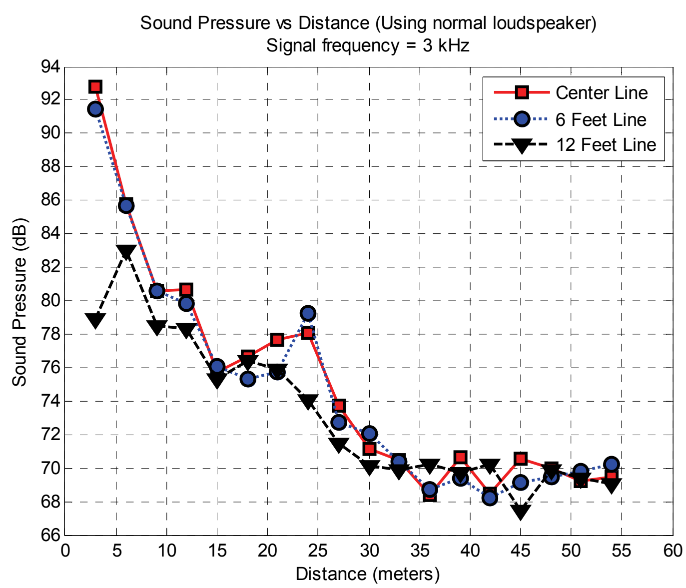


Figure 25 Sound pressure of normal loudspeaker

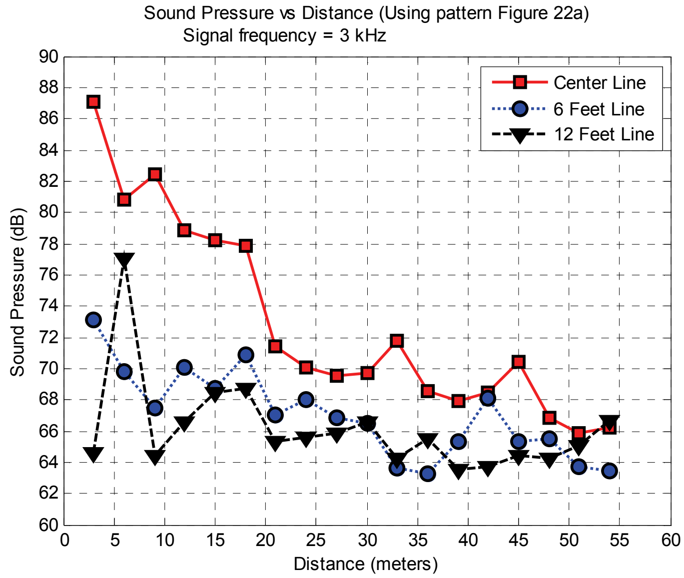


Figure 26 Array of multiple loudspeakers (Figure 22a) with frequency 3 kHz

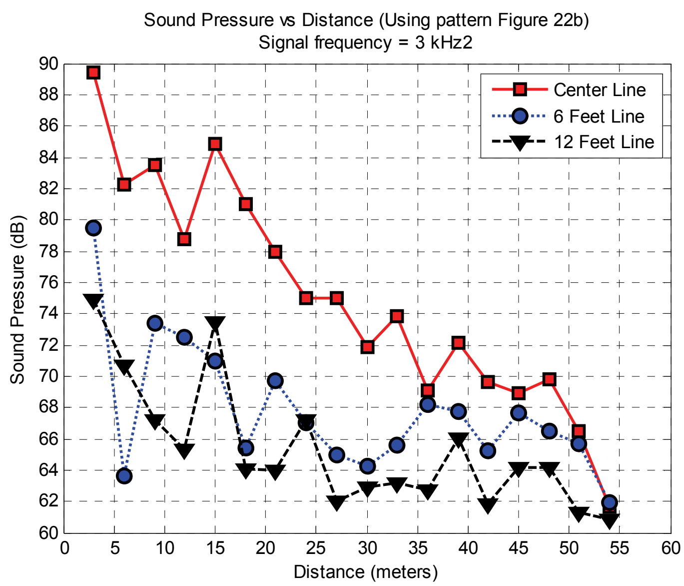


Figure 27 Arrays of muliple loudspeakers (Figure 21b) with frequency 3 kHz

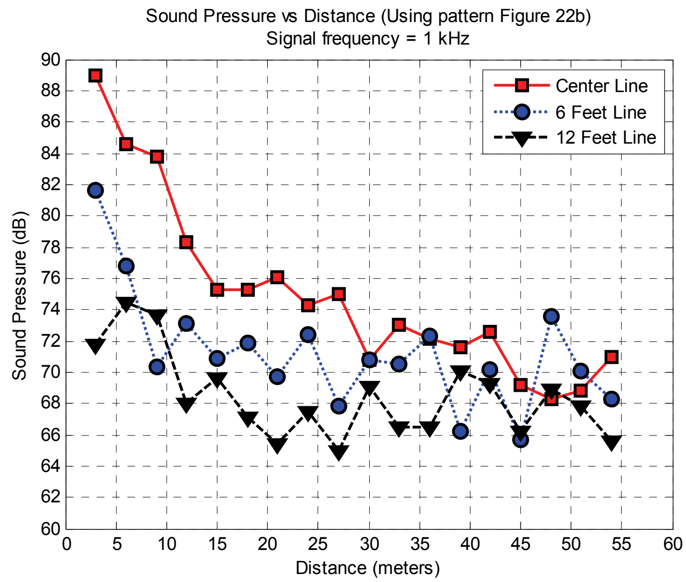


Figure 28 Arrays of multiple loudspeakers (Figure 21b) with frequency 1 kHz

Figure 24 shows that the normal loudspeaker cannot generate directional sound. There is very little difference of sound pressure level between the center line of the first and second lane. Moreover, the difference of sound pressure level exists up to about 10 meters from the normal loudspeaker. After a distance of more than 10 meters, the difference of sound pressure level is almost non-existent.

Figures 25 and 26 show that there is a significant difference in the performance between a normal loudspeaker and arrays of multiple loudspeakers. Arrays of multiple loudspeakers can be used to generate directional sound. For the single annular array pattern with frequency 3 kHz, the sound difference between the center line and 12 feet line is more than about 5 dB up to 25 meters. Likewise, for the two annular array patterns with frequency 3 kHz, the sound difference is more than 6 dB at distances up to 40 meters.

Figure 27 shows the two annular array patterns with frequency 1 kHz, the sound difference is smaller than those with frequency 3 kHz. This means the sound with high frequency is more directional than that with low frequency. Moreover, it is observed that when the signal frequency is changed, the sound pressure level is not the same even though the signal amplitudes are the same.

With this principle, it is possible to increase the difference of sound pressure between the first and second lanes on a highway. Adding more loudspeakers on the annular array pattern and adding more annular arrays can further increase the difference of sound pressure. However, adding more loudspeakers increases the size and cost of the system.

8. Traffic Auditory Warning System

The previous experiments show that arrays of ordinary multiple loudspeakers are an appropriate system for long distance auditory warning. Such a system is inexpensive and easy to install and maintain. This section will show results when the system is actually used for warning a vehicle on traffic. The sound pressure level in these experiments is measured inside a car.

The experiment is set up at the mechanical engineering parking lot of the University of Minnesota. The parking lot size is about 60x36 meters. The space is enough to simulate two-lane traffic. The experiment uses an annular array pattern is shown in 21b and the power amplifier for each loudspeaker is LEGACY series II, model LA 160 (75 Watt/channel).

The sound pressure is measured by sound level meter, Quest Electronics Model 2700 Digital Sound Level Meter. Its range is 35 to 140 dB and its resolution is 0.1 dB.

The measurement set up is shown in Figure 28. The sound pressure level is measured along the center line of the first lane and the second lane. (The distance between the first lane and second lane is 12 feet.) Thus, the sound pressure level is measured at the red spot as shown in the figure. At each red spot, the sound pressure is measured by sound level meter at least 4 times inside the car, Mazda Protégé ES 1999.
(Note: The background noise outside the car is 59 dB. The background noise inside the car is 51.5 dB.)

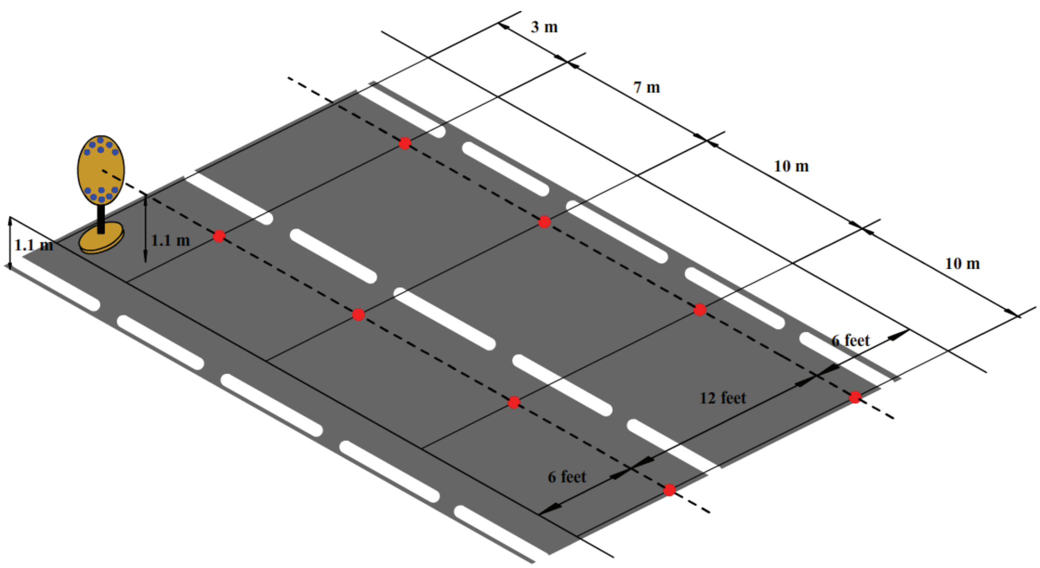


Figure 29 The measurement set up for traffic auditory warning

Most vehicles have sound insulation to reduce cabin noise levels and provide a more enjoyable driving experience. Thus, the auditory warning should be of adequately high pressure level, so that a driver and passengers can hear the sound. For example, the sound pressure level from a car horn is found to be 116 dB when measured at a distance of 3 meters from the horn. When the sound pressure level is measured inside a car, it is found to be only about 76 dB. Also, the sound pressure level from a siren is 120 dB measured outside at 3 meters. The sound pressure level inside a car is about 74 dB. (Note: the background noise inside a car is 51.5 dB) In short, the sound level should be at least 115 dB outside the car, so a driver and passengers inside a car can hear the sound.

The sound pressure level from arrays of multiple loudspeakers is increased up to 115 dB at distance 3 meters from sound source. Then audio measurements are collected as described. The result is shown in Figures 29, 30, 31, 32 and 33.

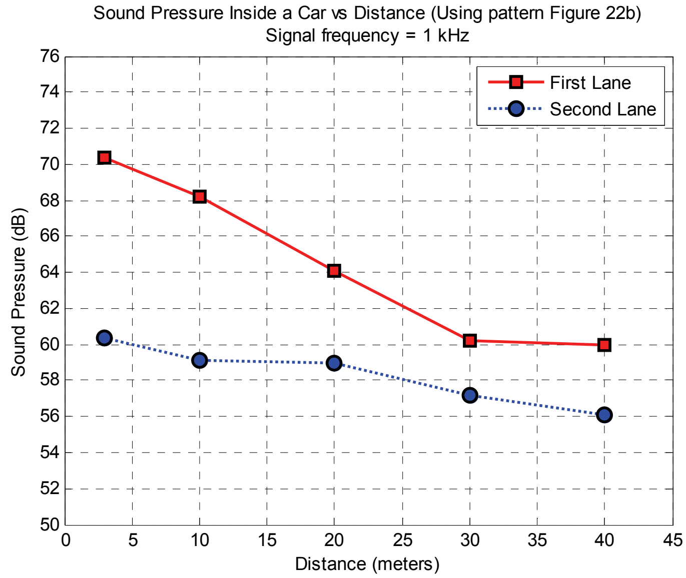


Figure 30 Sound pressure inside a car with frequency 1 kHz

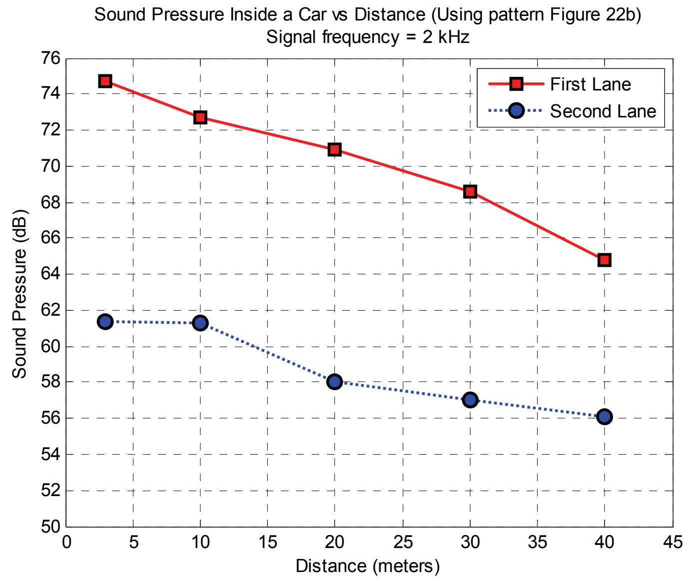


Figure 31 Sound pressure inside a car with frequency 2 kHz

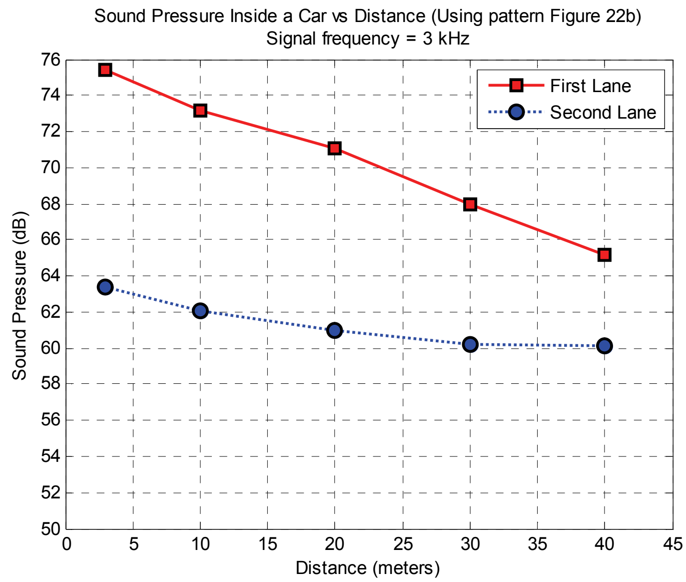


Figure 32 Sound pressure inside a car with frequency 3 kHz

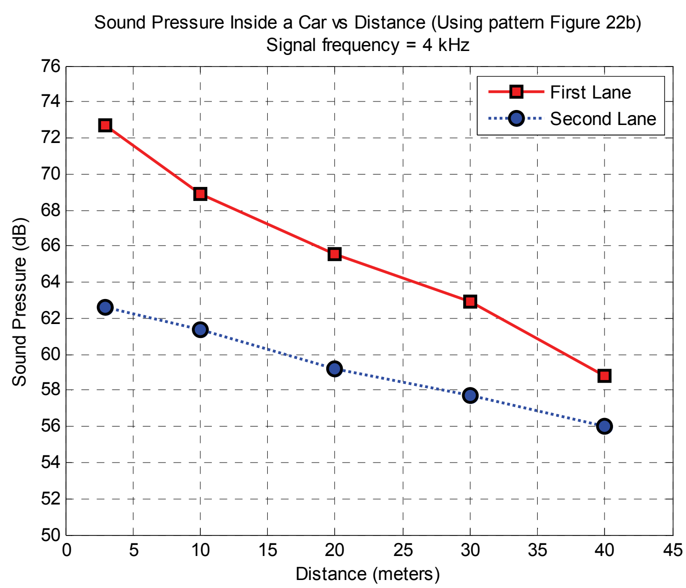


Figure 33 Sound pressure inside a car with frequency 4 kHz

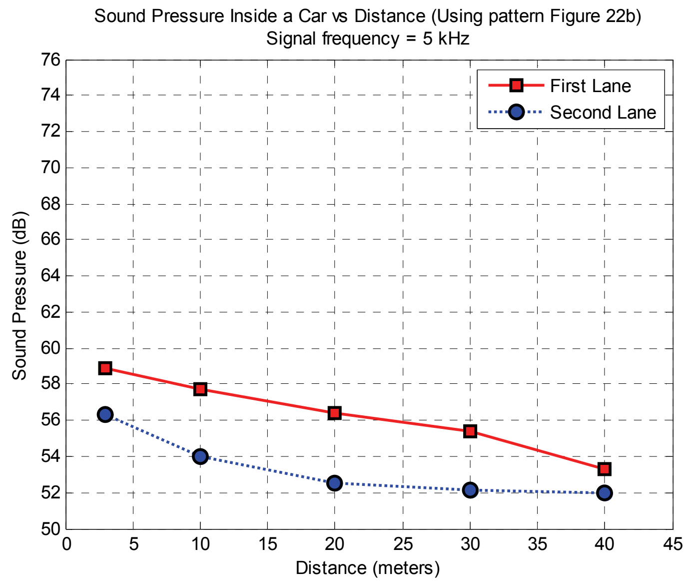


Figure 34 Sound pressure inside a car with frequency 5 kHz

Figures 31 and 32 show that an array of multiple loudspeakers can still generate directional sound, even though the sound level is measured inside a car. For a frequency 1 kHz, the sound difference between the first lane and the second lane is more than about 5 dB up to 20 meters. For the frequency 2 kHz, the sound difference is more than 8 dB up to 40 meters. For the frequency 3 kHz, the sound difference is more than 6 dB up to 30 meters. For the frequency of 4 kHz, the sound difference is more than 5 dB up to 30 meters. However, for the frequency of 5 kHz, there is very little difference of sound pressure level between the first lane and second lane. This is because vehicle insulation in most cars is designed to stop high frequency sound. (Increasing the frequency narrows the sound direction, but the overall sound pressure inside the car is decreased.) A good frequency range for auditory warning is between 2 and 3 kHz.

When applying this system for traffic auditory warning, using only a pure tone or one frequency may be not efficient. This is because the sound from a high pure tone frequency is very annoying to listeners. Also, a sound with more frequencies can be more ear-catching to the driver. Thus, the auditory warning sound should be composed of at least 3 different frequencies. The suggested frequencies for auditory warning are 2, 3, and 4 kHz. A frequency of more than 5 kHz is not recommended because most of vehicle insulation is designed to cancel high frequency sound and sound higher than 5 kHz is found to be effectively absorbed by insulation from our experiments.

The sound signal may be generated by using 2 kHz for 0.5 seconds, then changing to 3 kHz for 0.5 seconds, then changing to 4 kHz for 0.5 seconds, and then changing back to 2 kHz. With this example, the sound will be more ear-catching and also not annoying to listeners outside the car. Another combination of frequencies is also possible. However, it is not recommended to use a smoothly swept signal with frequency from 2 to 4 kHz. The sound will not be directional sound in the case of swept frequency because when the frequency is smoothly changed, close frequencies are found to interfere with each other. Then, the directional sound is not as effectively generated.

Moreover, amplitude of the signal is important. The sound level should be at least 115 dB at 3 meters from the speaker outside the car, so a driver and passengers inside a car can hear the sound. Thus, signal amplitude needs to be adjusted until the array of multiple loudspeakers can generate the sound pressure at the designed level. Each frequency needs a different signal amplitude to generate the sound pressure at the same level.

With the above result, arrays of multiple loudspeakers can be used as a traffic auditory warning system. The system can generate high pressure sound level in the first highway lane and low pressure sound level in the adjacent highway lane. With this system, the directional sound can be used to alarm only a target group or zone and not bother undesirable vehicles on the highway.

9. Field Implementation Preliminary Design

This project completed the investigation of technologies and designs that allow the development of a directed audio warning system. Although the prototype developed is not suitable for field deployment it was perfect for experimentation and it allowed for a number of demonstrations to transportation professionals. Based on their recommendations the following functional specifications for a field deployable device are defined.

According to the Minnesota flagging Handbook Figure 35 and Table 2 outline the distances of interest in a flagging operation. Based on this work zone outline we recognize three primary locations where the audio warning device can be deployed. The first location is away from the flagger between him/her and the advance flagger sign. The second location is at the flagger location while a third possible location is on a work zone vehicle located inside the work zone. The latter is the least desirable when a flagger is in place since he/she will be in the path of the sound waves but can be used instead of a flagger.

Table 2 Flagging operation work zone distances

Posted Speed Limit Prior to Work Starting (mph)	Advance Warning Sign Spacing (feet) **(A)**	Channelizing Device Spacing (feet) **(G)**	Buffer Space (feet) **(B)**	Decision Sight Distance (feet) **(D)**
0 - 30	250	25	85	550
35 - 40	325	25	170	700
45 - 50	600	50	280	900
55	750	50	335	1200
60 - 65	1000	50	485	1400
70 - 75	1200	50	670	1600

In addition to the location of the device, its deployment characteristics are influenced by the driver reaction time and vehicle stopping distance characteristics. Table 3 provided by the National Safety Council's Defensive Driving Course for Professional Truck Drivers discusses the above for different driving speeds. Passenger vehicle values are smaller.

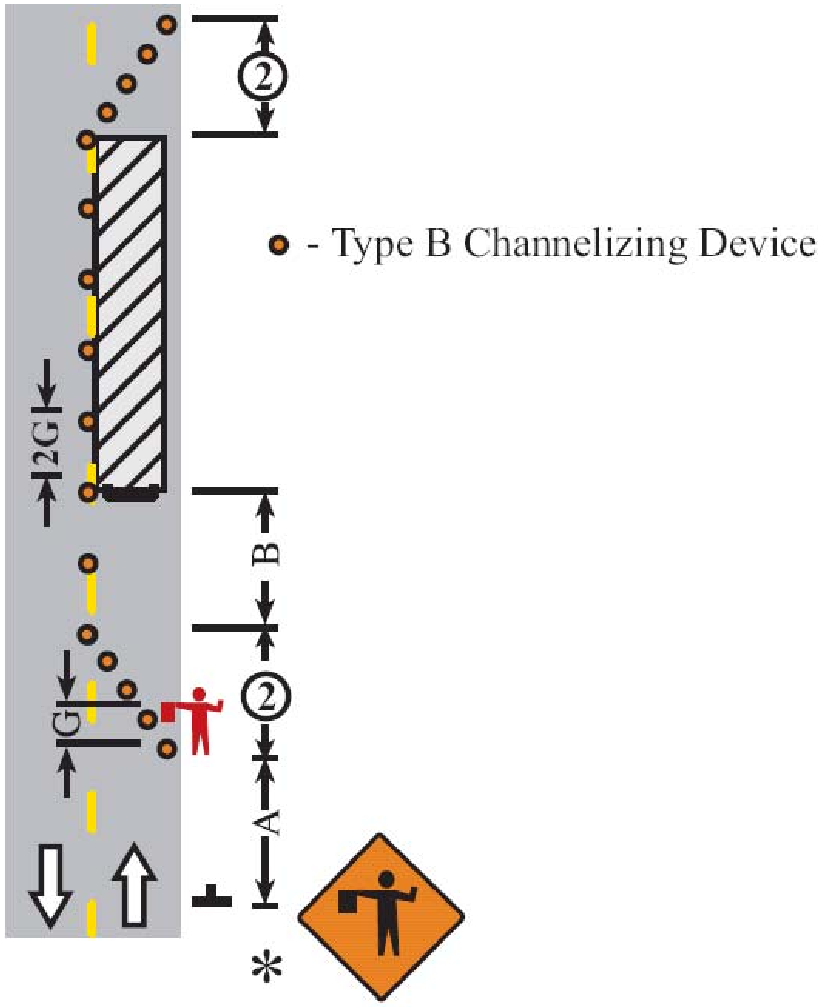


Figure 35 Flagger location for a lane closure

Table 3 Stopping distances required for trucks

Speed	Reaction/Braking Distance	Total Stopping Distance
30 mph	33' / 67'	100'
40 mph	44' / 125'	169'
55 mph	60' / 275'	335'
60 mph	66' / 360'	426'
65 mph	71' / 454'	525'

What Table 3 dictates is that the directed audio warning device needs to be effective inside a truck at a minimum distance of 100 feet for low speed roads and around 500 feet for high speed roads. Based on the experimental results presented for the prototype device we believe that the device can be effective on work zones with speeds up to 40 mph when located at or near the flagger while it must have a forward deployment at least 250 feet away for speeds higher than 55 mph.

For the device to produce the necessary audio level to be effective inside a vehicle more than one commercial amplifier is required and in extent power from batteries. At its current state the prototype consumes less than 12 amps power while in operation. One dry cell 12 volt battery will be sufficient for hundreds activation cycles. Considering the size and weight of the amplifiers and battery the entire system can be on a small hand pulled cart. The cart can serve as the base for the stop – slow sign required for all flag operators. The speakers can be mounded on branches extending out of the main body of the stop – slow sign. It is important to note that for the device to generate 100dB sound at 200 feet the source must produce sound in the range of 140dB or more. This is a dangerous sound level for the operator to be near at therefore provisions must be taken to soundproof the side and rear area of the device as well as provide the flagger with ear protection.

If the device is not to be located near the flagger but it will be located before or after in the travel lane and it can be mounted on a standard drum or weighted channelizer (Figure 36).

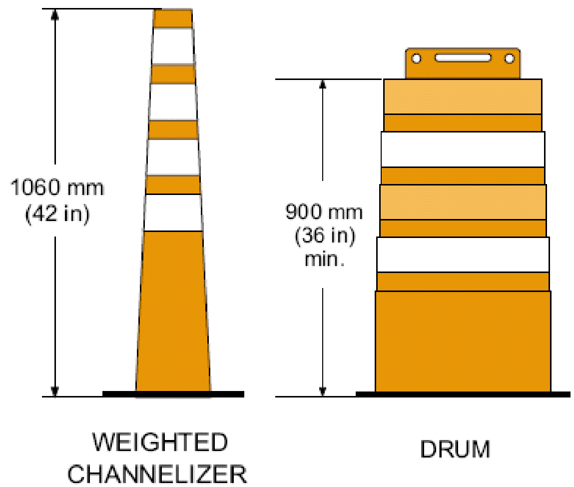
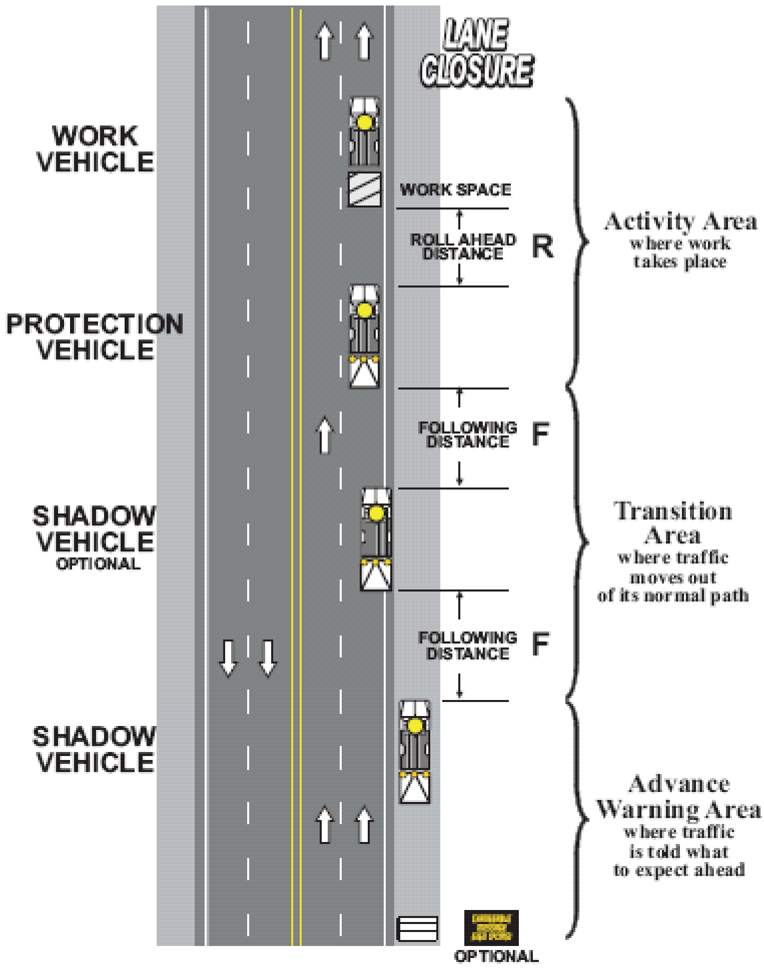


Figure 36 Work zone traffic control devices

In this case the size and weight of the equipment is not an issue but still a transportation cart need to be provided if the boundaries of the work zone are not static during a day's operation. One idea offered during a demonstration of the prototype directed audio warning device was the use of a robotic drum capable of moving autonomously keeping a constant distance from the actual flagger or the boundaries of the work zone.

Alternatively, for the case of a very large work zone where shadow vehicles are to be utilized instead of on foot flaggers (Figure 37) the device can be mounted on the arrow board of the shadow vehicle. In this implementation case the use of radar is necessary since there is no person looking backwards for approaching traffic.



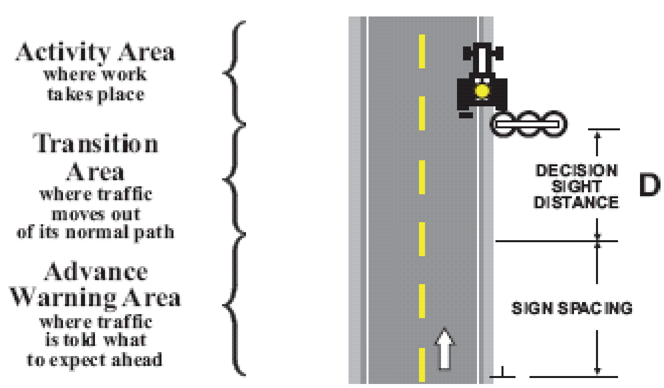


Figure 37 Elements of a mobile work zone

10. Conclusions

It is clear that the sound from a normal loudspeaker spreads in every direction. A single normal loudspeaker cannot generate directional sound. Directional sound can be generated from reflector-based loudspeakers. Nevertheless, its price, size and performance features are not balanced and have significant trade-offs. Thus a reflector-based loudspeaker is not appropriate for long distance auditory warnings.

An ultrasound based parametric array is capable of generating highly directional sound. However, it is not easy to use in a highway environment, due to the need for a vacuum pump. Also, it requires special expensive devices such as a very high gain power amplifier that works for specific high ultrasound frequencies and a modulator. Parametric Array with inexpensive components may be suitable for only short distance auditory warnings, but not for a highway application.

An array of multiple ordinary loudspeakers arranged in an appropriate pattern was found to be the most suitable for long distance auditory warnings, if one considers the performance, size, installation, and price. The loudspeaker is portable, very easy to install and maintain. It also does not need expensive components such as a computer, an expensive controller or a modulator. It needs only an audio power amplifier and a signal generator which are inexpensive. Moreover, its performance is good enough for long distance auditory warnings. With devices as described in this report, the system can generate a sound pressure difference between the first and second lanes of more than 6 dB up to 40 meters outside a car and more than 6 dB up to 30 meters inside a car when a test frequency of 3 kHz is used.

11. Completion of Project Tasks

The following tasks were listed as the major activities to be carried out in this one-year project.

1) Develop and evaluate a radar-based threat assessment system that can predict potential work zone intrusion.
2) Develop and evaluate an audio warning system that can provide audio warnings specifically to the intruding vehicle without affecting other nearby vehicles on the highway.
3) Evaluate and compare the effectiveness of several different audio signals in alerting both the driver and the work zone flag operator.
4) Test the developed systems in realistic work zone intrusion scenarios.
5) Prepare a comprehensive project report documenting system developed and results on evaluation of system.

All of the above tasks have been completed. An Eaton EVT 300 radar system was adequate for the specific work zone intrusion scenario chosen for study in the project. In this scenario, the distance and relative velocity of the vehicle needs to be measured in order to predict intrusion. Both can be measured at distances up to 150 feet by the EVT 300 radar. Newer versions of the radar also provide greater range of distances.

The majority of the project focused on development and evaluation of a directed audio warning system, since this was found to be the key bottleneck for the proposed work zone intrusion warning system. Two types of technologies – ultrasound based parameter array and time delay control based ordinary speaker array- were taken up for development and experimental evaluation of a long distance directed audio warning system. The project concluded that while an ultrasound based system has the potential to provide excellent directed audio beams, this could not be done for long distances at affordable cost. A time delay controlled system with ordinary flat panel speakers, on the other hand, could provide adequate directed sound performance while also meeting cost, size and portability constraints. Experimental results showed that differences of 6 dB or higher could be achieved at distances up to 40 meters for adjacent lanes on a highway using the controlled time delay technology. Further, an audio signal consisting of discrete consecutive single frequency tones for short durations of 0.5 seconds each would be suitable for the proposed application. The specific frequencies to be used are suggested as 2, 3 and 4 kHz, or other frequencies in the 2 – 4 kHz band.

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