Smart Cities: Reducing Noise Pollution with an Adaptive Barrier

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***Abstract*—Urban environments are notorious for producing high levels of noise pollution due to the constant influx of traffic, construction activities, and bustling city life. To confront the long-term impacts of noise pollution on health, this paper explores the development of a wall employing reflection and absorption properties emphasized by the structure and material to attenuate sound. Through changing the curvature of the wall panels, the absorption and reflection properties of the various panel shapes were discovered. Of the tested curvatures, data was compiled and analyzed to determine the optimal curve. The wall consists of numerous panels on axles that rotate in response to sound pressure levels indicated by sensors located across the wall. Beyond a certain threshold, the individual panels will close, but below this threshold these panels remain open, letting in light. This aforementioned technology will be incorporated to improve the mental and physical well being of urban inhabitants.**

I. Introduction

Rapid population growth is directly connected to the expansion of cities. Recent estimates predict that the percentage of people inhabiting urban areas will rise from 57% to 70% by 2050 [1]. The relationship between urbanization and the environment, alongside current and future needs, is incorporated into a smart city. Thus, developing cities require sustainable design to accommodate growing populations [2]. One major issue of population growth and its consequences, such as increased transportation use and product consumption, is excessive noise. The short and long-term consequences of such exposure have been shown to cause noise-induced hearing loss, poor cognitive performance, reduced sleep, disturbed stress response, mood changes, and high blood pressure [3]–[5].

Noise pollution is characterized by excessive sound levels within an environment that disturbs surrounding organisms, including humans and wildlife. Loud and harmful noises are constantly present within urban centers, with a singular siren being over 20 decibels louder than what is considered safe for hearing loss prevention [4]. Some of the world's most populous cities, such as Cairo, Delhi, and Mexico City, contain noise levels at 85 dB and more. However, even noise at 70 dB has the capacity to harm the human body [6]. Road traffic, including cars, trucks, and buses, make up a large percentage of the noise produced within cities and also contributes to significant levels of annoyance for urban dwellers [7]. Increased noise from road traffic also has inversely affected mental health, cardiovascular activity, and sleep quality of nearby residents [8], [9], which also correlates to increased risk for type-two diabetes [10]. Limiting the transportation noises within cities is necessary in order to prevent residents from the short and long-term impacts of exposure. Implementing noise walls within urban centers would allow for the ambient noise to be dampened, protecting pedestrians and urban residents from the impacts of noise exposure. The absence of sound-dampening technology leads to enduring and widespread physiological and physical effects of noise pollution. This wall design aims to enhance the understanding of how porous wall structures can limit noise penetration and incorporates convex geometries to combat noise pollution based on the intensity and source of noise. Due to noise levels constantly adapting within an urban center, this prototype seeks to modify the wall to best dampen sounds above a certain threshold while maintaining a visually appealing environment at safe noise pressure levels. Implementing adaptive and noise-dampening walls would help to prevent future exacerbation of noise-related hearing loss.

II. Background

A. Smart Cities

Smart cities employ technologically advanced frameworks to construct sustainable solutions that tackle a wide range of issues in urban environments. This approach to infrastructure development incorporates innovation and environmental consciousness to solve modern problems.

The origin of smart cities traces back to the late 1990s, emerging as a response to past economic, social, and environmental challenges that afflicted urban centers [11]. Los Angeles pioneered this transformative movement and constructed the path for future global enterprises such as Singapore, London, and New York to follow suit [12].

Central to the structure of smart cities are technologies such as artificial intelligence (AI), blockchain, and sensors [13]. With these key features, smart cities can enter a new era of optimization and data-driven decision-making to enhance the quality of life for a diverse population.

B. Wave Propagation

Wave propagation is a fundamental process that facilitates the transfer of energy between various points in a medium. Through this mechanism, individual particles within the medium experience oscillations, generating vibrations that propagate sound energy. These vibrations initiate a sequence of compressions where particles become densely packed in specific regions. Simultaneously, rarefactions occur and are characterized by low particle density within the medium. This dynamic interplay between compressions and rarefactions defines the nature of a longitudinal wave, as seen in Figure 1.

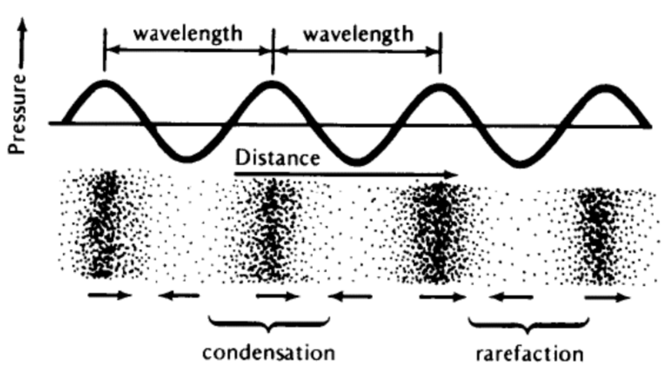

Fig. 1. Representation of the series of compressions and rarefactions that make up a sound wave [14].

Unlike transverse waves, where particles move perpendicular to the direction of wave propagation, longitudinal waves exhibit motion parallel to the wave's propagation. It is these unique properties of longitudinal waves, such as sound waves, that distinguish them from other well-known waves such as light [15].

C. Geometric Spreading

Sound waves propagate in all three dimensions, causing energy to disperse in multiple directions. Consequently, in unrestricted conditions, sound spreads out uniformly through a sphere, which is commonly referred to as spherical spreading. The source of sound serves as the center point of the sphere, and if the radius is doubled, the surface area expands fourfold. As a result, in this situation, the sound pressure, quantified in decibels (dB), diminishes by 6 dB, thus demonstrating the logarithmic relationship between sound pressure and distance.

Sound pressure denotes the fluctuation in pressure resulting from the various compression and rarefaction in the medium. While this property is typically measured in Pascals (Pa), it is more conventionally expressed on a logarithmic scale as decibels. This conversion can be understood through the following equation, wherein P represents the sound pressure measured in Pascals, and P_0 denotes the reference sound pressure.

$$SPL(dB) = 20 \cdot log_{10}(\frac{P}{P_0})$$

As unrestricted conditions are not present in urban areas, the sound originating from traffic forms a cylindrical shape as the energy spreads, as shown in Figure 2. This behavior characterizes a line source and diverges from the spherical distribution observed with a point source. Within these intricate scenarios, the sound intensity diminishes by 50% as the distance from the source doubles. This effect is a direct consequence of the expanded surface area over which the auditory waves disseminate.

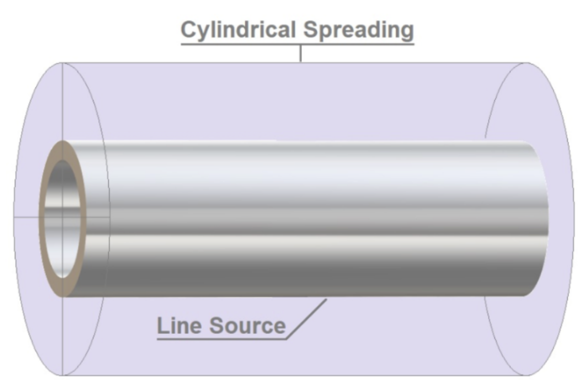

Fig. 2. Graphic of the sound properties of a line source [16].

D. Reflection

When sound is emitted from a line source, acoustic principles state that for every doubling of distance from the source, there is an expected 3 dB of sound reduction [16]. In the context of typical urban road noise acting as a line source, this principle applies as sound waves propagate in all directions from the traffic flow.

Considering the standard distance of 15 meters between a noise barrier and the source [17], an attenuation of approximately 6 dB is predicted as the sound energy dissipates over the increased distance. This distance-based attenuation forms the foundational step in reducing the impact of noise on an urban center.

By combining the effects of distance-based attenuation, sound dispersion, and reflection, the expected sound pressure level at a noise barrier can be determined. Since there is an average sound pressure level of 70 dBA within the urban center [18], and considering the standard 6 dB loss from the geometric spreading of a line source, it is calculated that there will be a sound pressure level of approximately 58.2 dBA at the noise barrier location. The unit dBA denotes the weighed scale for decibels that takes into consideration the biased human perception of noise levels.

E. Diffraction

Sound waves possess the unique capability of navigating around small obstacles and passing through narrow openings. This phenomenon, known as diffraction, allows sound to be audible even when the source is obstructed from the listener's direct view. Diffraction can occur in two distinct ways: through an aperture or across an edge.

The ease of diffraction is contingent on the frequency of sound waves. Lower frequencies, characterized by longer wavelengths, undergo diffraction more readily than higher frequencies, as they can circumvent obstacles with more ease. This occurs because sound waves with longer wavelengths interact less with the size of the obstruction compared to higher frequencies.

When sound waves encounter a small opening, they can continue to propagate through the disturbance. True diffraction takes place when the disturbance in the obstacle is either smaller or the same size as the wavelength of the sound. In this scenario, the wave retains its original properties on the other side of the obstacle, initiating a spherical wave pattern centered around the opening. The speed, frequency, and wavelength of the diffracted sound remains identical to the incident wave, but the amplitude, or volume, is reduced.

When coming in contact with the edge of an object, sound waves can move around the obstacle as long as the dimensions are smaller than or equal to the wavelength [20]. Because of this, even when the source of a sound can not be seen, the sound is still audible. Diffraction is even more pronounced with larger wavelengths, meaning it is easier to hear low frequencies around an obstacle such as a sound dampening barrier [21].

F. Absorption

Sound absorption is a process that occurs when a surface assimilates the sound energy transmitted through waves, preventing the reflection of noise back into the environment. This process leads to the conversion of sound energy into heat or its transmission through the material. By facilitating absorption, sound waves are prevented from echoing and reverberating off surfaces, which could otherwise generate undesirable background noise.

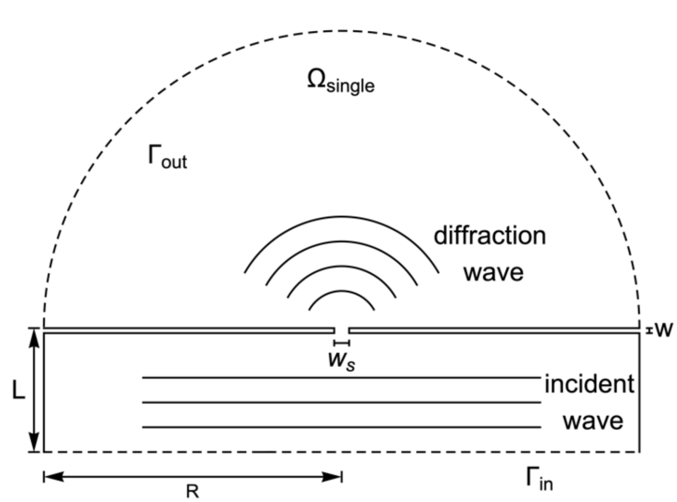

Fig. 3. Single slit sound diffraction [19].

Porous materials exhibit exceptional sound absorption capabilities, primarily due to the friction between air molecules and the walls of their pores, converting the sound energy into heat. A sound absorption coefficient (α) is used to quantitatively assess a material's ability to dissipate sound energy upon contact. This coefficient represents the ratio of energy absorbed by the material (E_a) to the total incident energy (E_i), which previously reached the material.

$$\alpha = 1 - \frac{E_r + E_1}{E_i} = \frac{E_a}{E_i}$$

A higher sound absorption coefficient signifies an increased sound-absorbing capacity, which is influenced by thickness, density, and porosity.

When producing a practical noise barrier, the use of absorbent materials is critical in ensuring that sound energy from roadways is not reflected into the environment, thus preventing the creation of excessive ambient noise. Due to their fibrous and porous structure, sufficiently porous materials such as cloths, foam, and felts stand out as the most efficient in mitigating sound echoing.

G. Sound Transmission

Sound transmission refers to the propagation of sound waves through a medium. Depending on the density of the medium, the sound propagation characteristics change. Sound travels faster through water than through air due to the higher density of water. Sound transmission depends on the compression and rarefaction of the particles within these materials when energy is transferred to them. Denser materials contain particles within closer proximity to each other, thus energy is more easily transmitted between particles [22]. However, materials with more chemically complex structures contain larger molecules that are more difficult to move and require more energy.

Depending on the physical and chemical characteristics of a material, the amount of sound transmission can be determined and tested. Ultimately, sound transmission references the net sound pressure level that travels through a medium.

III. Experimental Design

A. Creating the Wall

By employing a material that is highly absorbent and shaped into convex geometry, both absorption and reflection are maximized to dampen and disperse sound. Pairing absorption characteristics with the optimal convexity, which was determined through experimentation, facilitates an affordable and effective solution for noise reduction. Additionally, sound sensors located outside and on top of the wall send real time data to the motors which rotate the individual panels, opening and closing gaps between them. Thus, when implemented to scale, the wall reduces the unhealthy levels of noise pollution coming from busy streets that pedestrians are exposed to.

B. Ethylene Propylene Diene Monomer (EPDM)

Ethylene propylene diene monomer (EPDM) rubber is a synthetic material that has multifaceted applications in engineering, industry, and construction. EPDM was chosen as the primary sound insulator for this research project due to its distinctive properties and characteristics.

EPDM possesses one of the most important factors in building an outdoor noise barrier: durability. This material exhibits superior resistance to ultraviolet (UV) radiation, precipitation, and weather-related effects. It also demonstrates exceptional thermal stability - the performance and function of the noise barrier will be negligibly affected by even extreme differences in temperature [23]. Since the moving panels are steel frames covered by EPDM, they retain their flexibility and elasticity. This frame provides minimal contact to the material whilst maintaining the desired convex shape and at a precise curvature. Its structural integrity is demonstrated in industrial and domestic buildings.

The current noise barrier prototype features curved panels that fit tightly together. Because of its flexibility and compressibility, EPDM can easily be customized for specific shapes and create a sound tight wall. Other commonly used materials for sound attenuation such as concrete, wood, and fiberglass, do not have these properties. EPDM has a porous structure, allowing it to dissipate sound energy by converting it to heat through friction as sound waves pass through the material [24].

Although EPDM's sound absorption qualities are not recorded to be as effective as materials specifically designed for soundproofing, the benefits of EPDM make it easier to implement [25]. Likewise, the effectiveness of EPDM for soundproofing was proven during testing. Overall, the low manufacturing cost, durability, and wide range of sound absorbing frequencies makes EPDM the ideal candidate for a roadside-pedestrian noise barrier.

C. Properties of Convexity

Convex shapes are known to reflect and disperse sound, however, different geometric shapes interact with sound differently. Three different arcs defined by quadratic equations will be tested to determine which shape is most effective at reducing sound. The small curve is modeled in 3D space and described by the following expression

$$-0.14x^2 + 3.5$$

as shown in Figure 4. The medium curve, as shown in Figure 5, is modeled by

$$-0.2076x^2 + 3.75$$

The large curve, as shown in Figure 6, is modeled by

$$-0.3951x^2 + 4.5$$

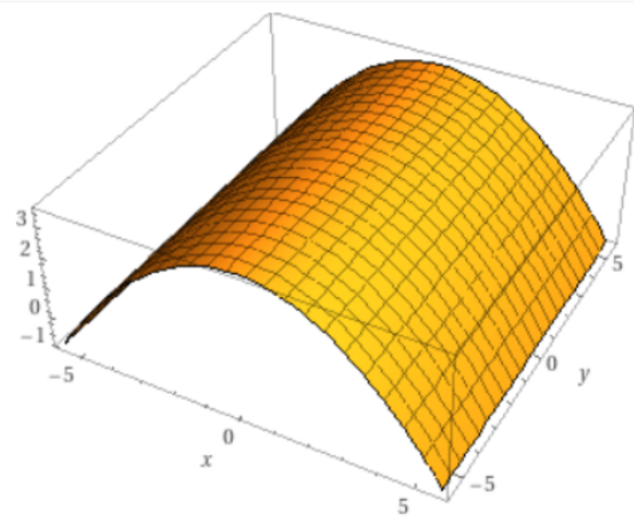

Fig. 4. Small Curve.

D. Properties of Concavity

The three different orientations used for the surface were concave, flat, and convex. All shapes interact with the sound waves differently and therefore generate different effects when the noise is reflected back into the environment. It has been shown that at a specific frequency, concave shapes can significantly increase ambient noise within the environment, as shown in Figure 7 [26]. Δ L represents the sound pressure, or amplification of the noise, in the focus point relative to the direct sound at 1 m from the source. As the focus on the curve for a concave shape is in the same direction as the source of the noise, reflection off of concave shapes amplifies the sound rather than efficiently dispersing it in the environment. The amplification of the sound is positive proportional to the frequency of the source and is more dramatic for increased concavity.

Using a concave shape would be counterproductive as it amplifies sound in an environment. The curvature would cause

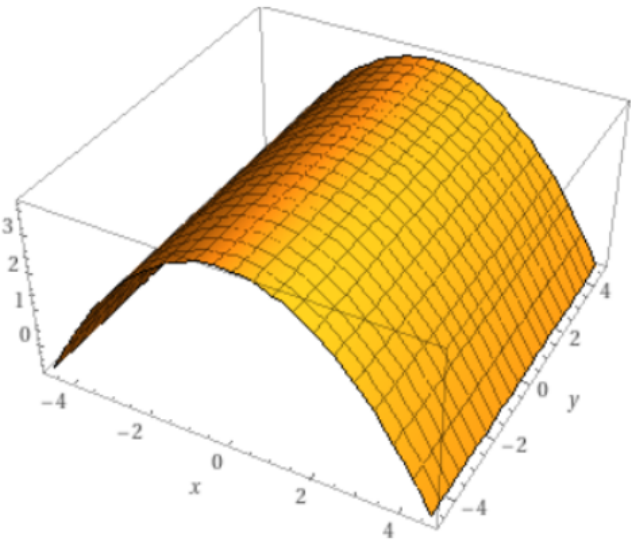

Fig. 5. Medium Curve

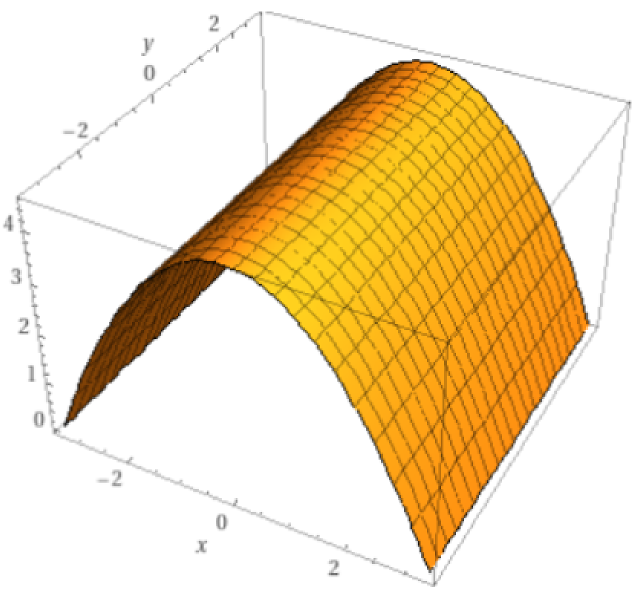

Fig. 6. Large Curve

sound waves to reflect the sound towards a concentrated point. These reverberations would create distracting and harmful ambient noise (Figure 8). Conversely, sound attenuation can be amplified with a convex structure. As the EPDM targets sounds between 500-1000 Hz, this may not be able to completely mitigate the sound produced by highways which averages 80 dB. Since 80 dB represents the amplitude of the sound wave, and 500-1000 Hz measures the frequency, any decibel value can be associated with the described frequency. Alongside the experiment that was conducted, additional research has proven that convexity can mitigate sound, as shown in Figure 8 [27]. A negative Δ L represents sound attenuation while a positive value shows sound was amplified upon hitting

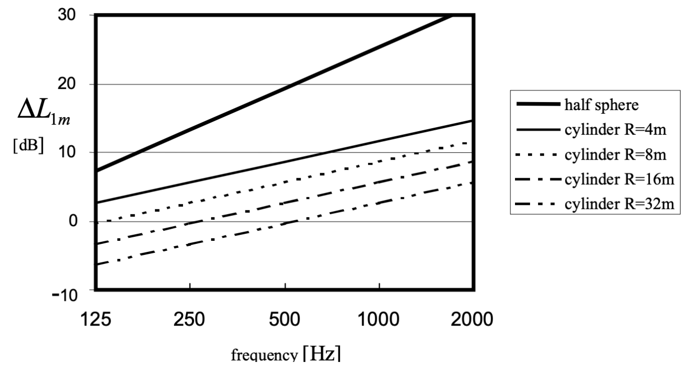

Fig. 7. Amplification of sound due to increased concavity [26].

the surface. When the material was convex, it continually decreased the sound, dispersing the sound more efficiently as the curvature increased, having a considerable downward trend. For the majority of the curvatures tested, the concave shapes continually amplified sound. Even when the change in sound levels was negative for the concave shape, the level to which the sound was attenuated was still significantly less than the convex shape. In order to prevent sound amplification, the wall prototype experimented on utilizes only convex shape to reflect sound.

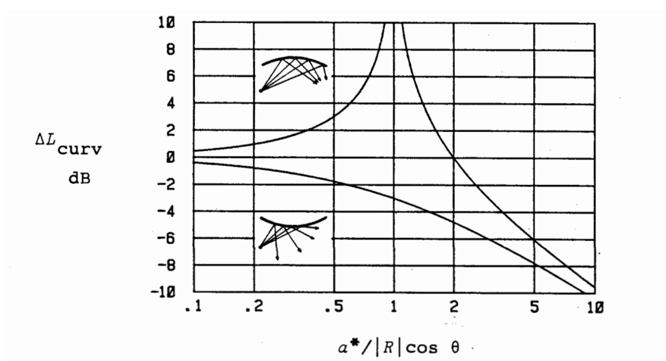

Fig. 8. Attenuation due to curvature [28]

E. Coding and Sound Sensing

To introduce an intelligent component of the wall, noise sensors will be administered to gather and analyze noise levels throughout the day. These sensors play a critical role in amplifying the barrier's efficiency by providing essential data on its real-world-performance. Designed to detect specific sound frequencies, the sensors control the wall's movement with noise levels surpassing a threshold determining whether the wall remains stationary or its panels move. To facilitate this functionality, the sensors are be linked to multiple motors.

During periods of an elevated frequency of greater than or equal to eighty decibels, the wall remains motionless, while during quieter intervals of less than eighty decibels with intervals with reduced traffic or activity, the panels spin on the y-axis to allow natural light for pedestrians. To ensure the accuracy of noise detection, each panel would be equipped with two noise sensors - one at the bottom and the other in the middle, effectively accounting for the noise coming from both short and tall vehicles. Given that urban street noise predominantly remains close to the ground, these sensor placements would be most optimal [29].

After initial testing post-implementation, the sensors would be adjusted to adapt to the average sound location, creating a balance between height and efficiency. This would also account for the sound waves' interaction with the wall surface, and thereby improve the accuracy and responsiveness of the barrier.

F. Prototyping

To assess the functionality of the rotating panels and incorporate a noise threshold, a prototype was developed using Arduino and 3D Printing. The 3D model that was created using Computer-Aided Design comprises of five convex panels and a rectangular frame. Each panel was printed with a vertical axis joined to the vertex of the curve, and the frame was 3D printed as separate components. Additionally, the EPDM foam was pasted on the surface of the panels to create a more accurate model.

The axles on the panels were fabricated with inset cylinders to accommodate the size of the motor shafts. During the assembly phase, the motors and panels were joined using glue, thus creating a continuous axle that could display the rotating feature of the theoretical wall.

Additionally, a noise threshold was integrated into the system. The schematic was designed with software, as shown in Figure 9, and then implemented. Using an Arduino micro controller, breadboard and sound sensor, the system could sense and process external noise levels as input signals. This dynamic feature allows the prototype to respond to sound pressure levels located above a certain value, resulting in a 90 degree rotation of the panels.

This prototype demonstrates a miniature version of the desired wall. In conjunction with the Arduino sound sensors, this system displays an accurate model of the electrical and physical mechanisms to be implemented.

Included is the code for the Arduino powering the motors.

```
int motorPin = 3;
int sensorPin = 7;
boolean wallClosed = true;

void setup()
{
  pinMode(motorPin, OUTPUT);
  pinMode(sensorPin, INPUT);
  Serial.begin(9600);
}


void loop()
{
  int sensorData = digitalRead(sensorPin);
  Serial.println(sensorData);
  if(sensorData == 1 && wallClosed){
    Serial.println("opening");
    digitalWrite(motorPin, HIGH);
    delay(200);
    digitalWrite(motorPin,LOW);
    wallClosed = false;
  }
  else if(sensorData==1 && !wallClosed) {
    Serial.println("closing");
    digitalWrite(motorPin, HIGH);
    delay(600);
    digitalWrite(motorPin,LOW);
    wallClosed = true;
  }
}
```

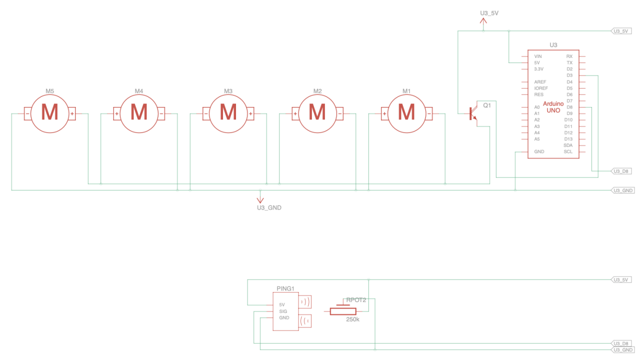

Fig. 9. Circuit diagram of the Arduino.

G. Data Collection: Preparation

The primary goal of the experiment was to determine the most effective convex shape for an ethylene propylene diene monomer (EPDM) panel by testing its audio transmission. The EPDM sample, which was 12 inches in length, 8 inches in height, and 3/8 inch in thickness, was attached to a frame located 1.5 inches away from the audio source (Figure 10). Behind the EPDM wall was an internal receiver located 4 inches away, which was used to collect the amount of sound transmitted in decibels. Located behind the source, and 9.75 inches away from the vertex of the EPDM wall, was an external receiver, used to measure the amount of sound reflected in decibels. By directing the sound source at the EPDM panel, the external receiver is able to measure the sound reflected back by the barrier. The source sound was calibrated at 80 decibels before each test, which is the CDC threshold for harmful noise [30]. The first orientation tested was flat, with the farthest edges of the EPDM being 12 inches apart.

Fig. 10. Experimental set up with EPDM secured by clips onto a frame.

H. Data Collection: Experimentation

The source produced a sinusoidal sound wave at a constant frequency for intervals of ten seconds at a time. Each orientation of the material was tested at intervals of 200 Hz, starting at 500 Hz and reaching 1300 Hz [32]. Most noise emitted by traffic falls in the frequency range of 900 Hz to 1100 Hz. However, trucks create low frequency sound waves between 500 Hz and 900 Hz. Similarly, sirens emit high noise frequencies up to 1300 Hz. These high pitched sounds can cause even more damage than the more common lower frequency sounds [31]. Thus, data from sound waves ranging from 500Hz to 1300 Hz will be analyzed. Both the internal and external receiver began recording the frequency and decibel level of the noise at the same time. The mobile application on the receivers collected sound data (in dB and Hz) at a rate of 10 measurements per second. After ten seconds of recording elapsed, the recordings were paused and the roughly 100 data points were exported. This process was repeated five times for each orientation to obtain data within a range of frequencies. After these five tests were executed on the flat, the EPDM was manipulated so that the frame created a 25° angle, forming a sharp curve in the material. The five frequencies process was repeated for this orientation as well as for 35° and 45°. The data collected from the receivers was the average frequency of the sound played and the decibel level measured every ten milliseconds. As a control, the sound receivers collected data from the sound source without the wall to account for the actual noise reduction of the wall. In total, 25 trials were conducted with varying frequencies and wall orientations, resulting in 5,000 data points to analyze. The results are reflected in the next section.

IV. Results

A. Reflected Noise

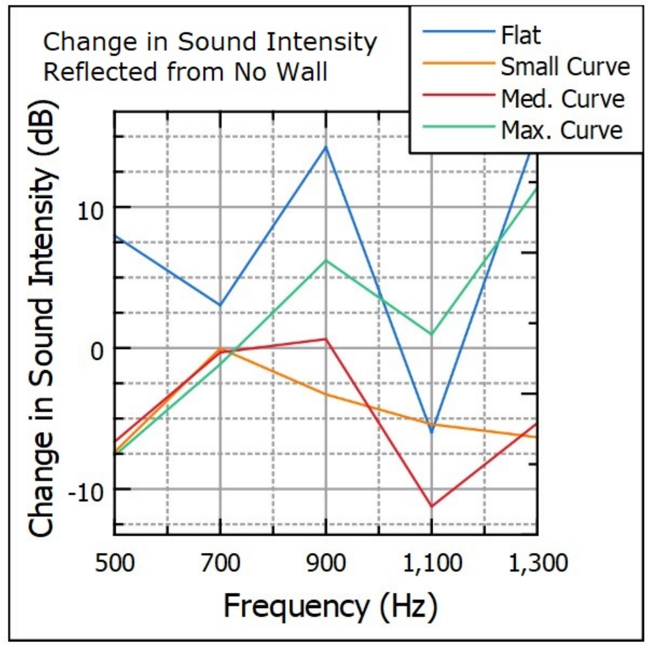

Fig. 11. Change in Sound Intensity Level (dB) of various EPDM orientations from Sound Intensity Level tested without the wall

TABLE I
Sound Intensity (dB) Reflected

Reflect	500 Hz	700 Hz	900 Hz	1100 Hz	1300 Hz
Flat	78.7	66.79	67.51	62.1	71.95
Small Curve	63.35	63.73	49.97	62.69	50.25
Med. Curve	64.08	63.45	53.89	56.86	51.25
Max. Curve	63.10	62.61	59.47	69.06	67.95

To summarize the experimental procedure explained above, the EPDM rubber was arranged into four orientations: a flat surface, a minimally curved surface (45°), a medium curved surface (35°), and a heavily curved surface (25°). The sound waves that penetrated through and reflected from the EPDM were measured across five different intervals, from 500 Hz to 1300 Hz in 200 Hz increments. As the data from the average decibel values across all frequencies show, the noise reduction by the small and medium curve orientation were most similar, to each other while that of the flat and most curved orientation were most similar.

The flat surface provided more ambient noise than if there was no wall present for all of the frequency levels other than 1100 Hz (Figure 11). The largest curve gave a similar result, creating a louder environment than if there was no barrier in place. This effect was more noticeable for higher frequencies, increasing the sound level by over 10 dB when the sound played was at 1300 Hz. Both of these orientations were counterproductive to the goal of attenuating sound. The small and medium curve continually reduced the noise level reflected back into the environment. The effect was most drastic and significant at frequencies higher than 1000 Hz.

The experiment showed the benefits of using a convex surface for increased noise attenuation (Figure 12). The flat wall reflected the most sound energy for each frequency, showing a significant difference between a flat and curved orientation. Only at 1100 Hz was the maximum curve less efficient at attenuating sound than the flat surface. These results aligned with research previously done which showed that reflections from flat surfaces are highly specular and disperse the noise poorly [33]. The data collected showed significant difference in the attenuation between varying levels of curvature in the convex surfaces. For lower frequencies (less than 1 kHz), the sound waves reflected off each of the curvatures were relatively at the same level, with only a 0.8 dB level difference between the three orientations at 500 Hz. A similar result occurred at 700 Hz, with all of the curved surfaces having a reflection result within 1.1 dB of each other. As the frequencies increased, the disparity between the different curvatures became more pronounced. At 900 Hz, the noise level in the environment was proportional to the curvature of the wall. The largest curve created the greatest environmental noise out of all the convex orientation and the smallest curve diffused the sound energy most efficiently. At 1100 Hz, the maximum curve showed to be ineffective at dispersing the sound energy, creating a louder environment than the flat wall did. For this frequency, the medium curve was the most effective at efficiently reflecting the sound, reducing the noise by 6 dB more than the small curve (Table I). At 1300 Hz, the disparity between the small and medium compared to the maximum curve is prominent, with a difference of over 15 decibels between the maximum and medium curve. Such a result would more than double the noise heard by a listener in the environment. The difference between the small and medium curve at 1300 Hz is 1 decibel, representing a difference that would have little effect on what a listener would hear. While the small and medium curve orientation generally decreased as the frequency increased, the flat and maximum curve orientation generally increased as the frequency increased.

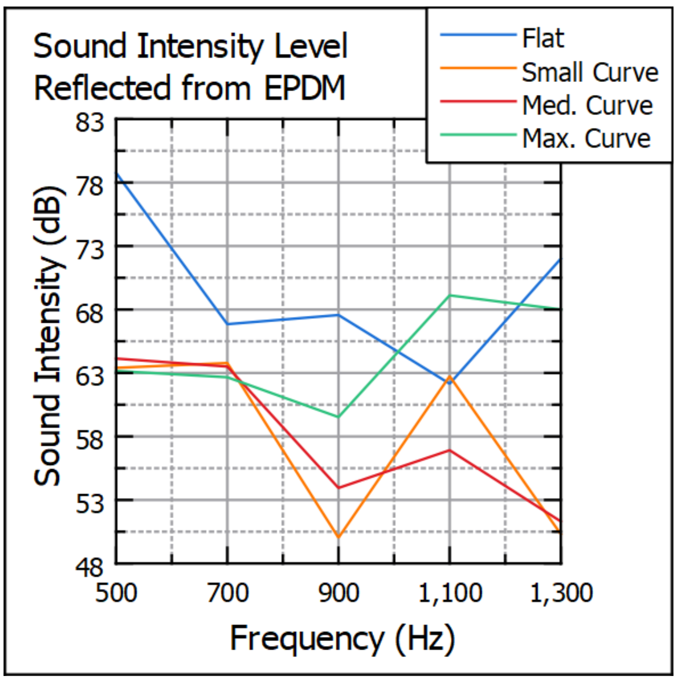

Fig. 12. Sound Intensity Level measured by the receiver behind the sound source

Comparing the average decibel level across all frequencies, the small and medium curve reduced the reflected noise most efficiently, with a 16.4% and 16.6% reduction, respectively. For the most common frequencies on a highway, around 1000 Hz, the small curve reduced the reflected noise by 25% and the medium curve by 20%. If used in the noise barrier, either of these orientations would provide a drastic reduction in noise reflected back to the road.

As typical noise barriers are flat surfaces, there is a significant level of noise reflected back to commuters who drive on roads with these barriers. It has been shown that individuals who commute with significant levels of noise surrounding them have increased risk of hearing loss, stress, and heart disease [34]. Creating a barrier with a small curvature would allow for the noise reflected back to drivers to be greatly reduced and prevent the adverse effects of prolonged noise exposure. Both the small and medium curve demonstrated relatively the same effects for medium to low frequencies, however as the frequency increased, both orientations demonstrated a decrease in the ambient noise levels. Either one of the orientations, if implemented in an urban setting, would reduce the noise pollution experienced by individuals in the roadways.

B. *Absorbed Noise*

The data shown in Figure compares the sound levels across different frequencies using a flat wall against that of no wall. A lower decibel level is indicative that the material was able to prevent the transmission of sound energy, creating a quieter environment on the other side of the obstacle. This result shows how effective the material itself is at absorption sound in the environment. The data demonstrates that at lower frequencies (500-700 Hz), EPDM made little difference in the noise level present. While the noise level was slightly lower with the flat wall, a difference of less than 3 dB is statistically insignificant as a 3 dB decrease is the threshold for the change that a human ear can perceive. Once the frequency reached 900 Hz the difference between the absence or presence of the

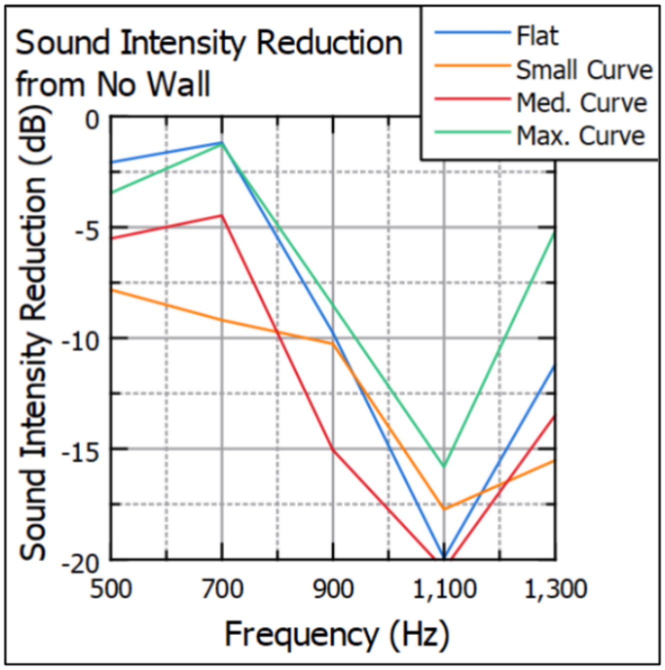

Fig. 13. Reduction of Sound Intensity from absorption through EPDM compared to when no wall was present

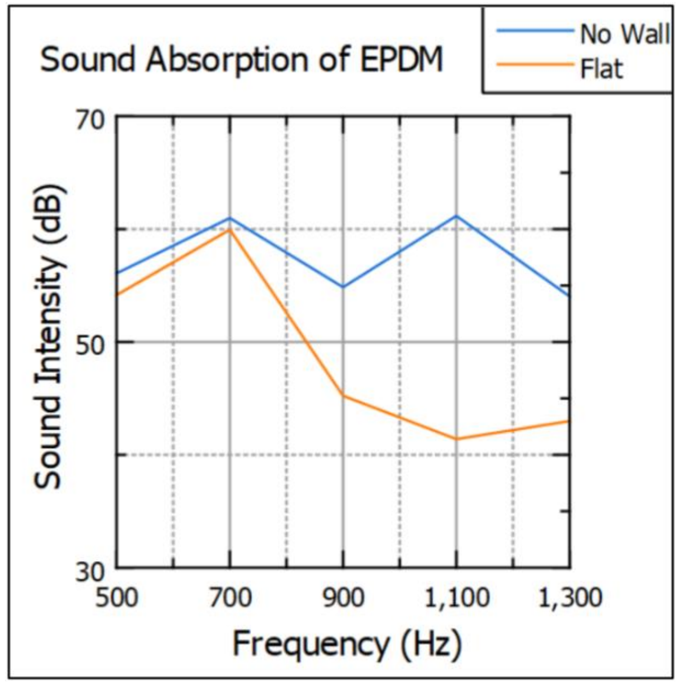

Fig. 14. Graph of Sound Intensity vs. Frequency: Sound Absorption of EPDM

material became almost 10 db. At 1100 Hz this difference increased to 20 decibels and was 12 dB at 1300 Hz. To the human ear, a sound that is 10 dB greater is twice as loud, meaning that the EPDM is significantly effective at absorption sound energy at frequencies around in the range of 900-1300 Hz, a range accurate to what is normally present in areas of dense traffic. The material alone is significantly beneficial in reducing the noise that is transmitted through a noise barrier.

To optimize the efficiency of the noise barrier, the absorption of sound energy was tested at different curvatures. There was not a drastic difference between the absorption of different orientations, however the small and medium curvatures were the most effective at sound reduction. At 500 Hz, the flat wall and maximum curvature transmitted the most sound, while the small curve transmitted the least. At 700 Hz, the flat surface and narrowest curve demonstrated similar absorption, reducing sound pressure level to nearly 60 dB. The small curve displayed significant absorption levels compared to the medium curve, with a 5 decibel difference in the sound energy transmitted through the material. At 900 Hz the level of absorption increases dramatically, with the various curvatures exhibiting significant sound reduction. Although the smallest curve attenuated the most sound at 1300 Hz, the medium curve transmitted only 2 dB more sound at 1300 Hz, and the least sound at both 900 Hz and 1100 Hz. Analyzing the trends of Figure 15, the medium curve absorbed the most sound compared to the other curvatures. This was most apparent at the frequency range 900-1300 Hz, where a barrier composed of panels with a curvature similar to the medium curve would allow for optimized noise absorption. Pedestrians walking behind the barrier would experience a noticeable reduction in noise level, due to the material and orientation optimizing noise absorption.

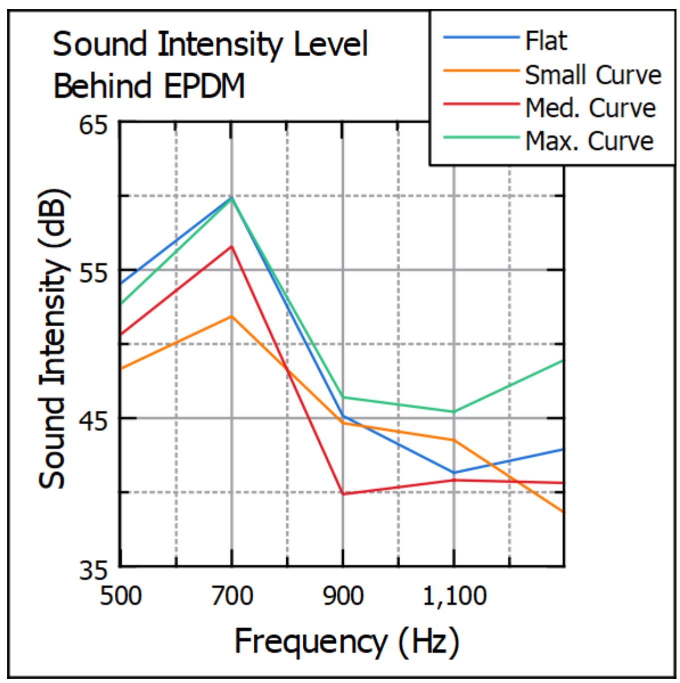

Fig. 15. Noise Level in decibels measured on other side of EPDM, comparing various curvatures

C. Implementation of Barrier

The solution proposed combines reflection and absorption to maximize sound attenuation. There are a combination of individual panels, each containing a curved piece of EPDM. The experiment showed the smallest and medium curve provided roughly the same result in terms of reduction upon reflection, however the medium curve best optimized the absorption of the EPDM. Because of these results, the curvature of the EPDM in the solution will match the middle curvature tested in the experiment. The dimensions of the panel are specified in order to generate the 35 degree angle created by the frame. Using this curvature allows the wall to optimize the noise attenuation for both pedestrians and those on the roadway as the middle curve had the most favorable results for both reflection and absorption. The panels used within the experiment had a width of 1 foot, however, when scaled, this could be increased up to 30 inches while also keeping the same curvature as the one tested.

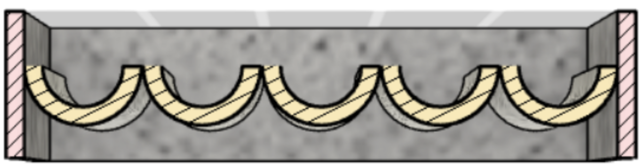

Fig. 16. Top cross section view of Computer Aided Design model of the noise barrier with optimized curvature

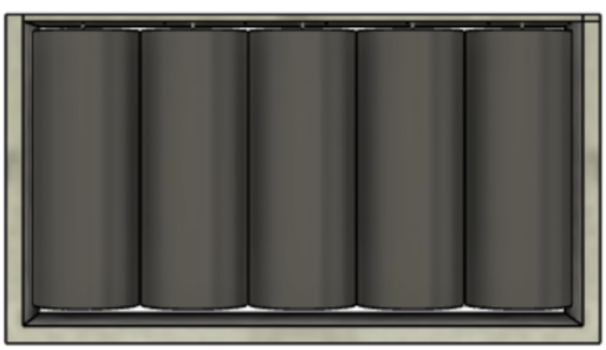

Fig. 17. Front view of computer Aided Design model of the noise barrier with curved panels

The entire soundproofing portion of the wall would be eight feet high, as a barrier must block the line of sight in order to be sufficiently effective [35]. Blocking the line of sight can produce a 5 decibel reduction of noise just through limiting the spreading of sound waves above the barrier [36]. Sound on roadways mostly comes from the interactions between the tires and road as well as from engines, meaning the source will be coming from a low height [37]. Having a wall less than eight feet would be ineffective at blocking these sources low to the ground as many pedestrians could still maintain an unobstructed line of sight. Minuscule benefits are seen once more height is added to the wall, therefore increasing the height of the wall would not provide a substantial decrease in noise level

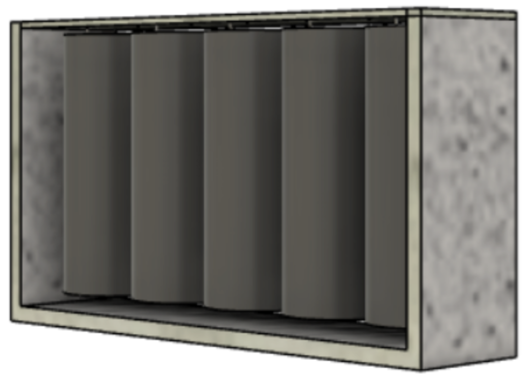

Fig. 18. Computer Aided Design model of the noise barrier

D. Noise Barriers in a Smart City Environment

The proposed solution will include a rotating aspect where motors within the wall will respond to the noise level of the environment and respond once the sound reaches a certain threshold. The threshold will be 80 decibels so as to prevent the adverse impacts of prolonged noise exposure of this level. When noise is above this threshold, the curved panels will be rotated so the edges touch and create a solid barrier. There will be a continuous pattern throughout the wall and will be completely opaque. When sound is below the threshold, the motors will respond by turning each panel so that there is space between each panel, providing a clear line of sight between the pedestrians and roadway. Each panel rotates on a vertical axis and synchronously turns 90 degrees.

Fig. 19. Computer Aided Design model of noise barrier with rotated panels

The rotation of wall panels can offer significant advantages in terms of safety, aesthetics, and health factors. When the wall is completely closed, it functions as a soundproof barrier, effectively obstructing sound transmission between the street and the sidewalk. The soundproofing also decreases the ambient noise level within the lanes of traffic themselves. This will support the physical and mental health of both the pedestrians and individuals in the vehicles. The relationship between sound and rotating is directly proportional, implying that as activity levels increase, so does the corresponding sound level. Pedestrians will be able to recognize the intensity of traffic by the position of the noise barrier, as a closed barrier corresponds to high density of traffic. Notably, pedestrian-vehicle contact has been associated with numerous injuries and fatalities, as reported by reputable sources like the Insurance Institute for Highway Safety [38]. According to previous research, creating a physical barrier separating pedestrians and the roadway can reduce the amount of pedestrian-vehicle collisions [39]. The combination of a physical barrier and a visual reminder of traffic conditions will contribute to a safer city environment due to the protection of pedestrians.

The adaptive design of the rotating wall panels offers multifaceted advantages, tailoring itself to different environmental conditions and human requirements. During periods of minimal sound and when there is no need for a sound barrier, the panels rotate open, facilitating the passage of natural light and affording pedestrians an unobstructed view of their surroundings. The introduction of natural light through the open panels contributes significantly to various health benefits. Sunlight exposure plays a pivotal role in synthesizing vitamin D, a vital nutrient essential for overall well-being [40]. Furthermore, access to natural light has been empirically associated with improved mental health outcomes, as substantiated by research published in the esteemed journal MDPI [41].

This dynamic adaptability proves particularly beneficial when vehicles come to a stop at red lights, leading to reduced noise emissions. Consequently, the panels open during these quieter intervals, providing pedestrians with a safer crossing opportunity without compromising their visual awareness or introducing visual impediments. Additionally, the adaptive wall design effectively curtails noise pollution during quieter periods when the panels are open, fostering a more tranquil and serene urban environment. This strategic approach to mitigating noise impacts further contributes to the overall enhancement of human health and well-being.

V. CONCLUSIONS

A. Significance of Findings

Through extensive testing, the relationship between the shape of wall panels and their ability to reduce noise was analyzed. As urbanization and population growth occur, it is imperative that noise pollution is addressed. Specifically, road traffic noise and its health concerns were focused on in this project. This challenge can be overcome by utilizing the absorptive and reflective properties of EPDM and its configuration to minimize the magnitude of the sound waves heard by pedestrians. Using this material to construct wall panels that can be placed alongside city streets creates a safer and more comfortable outdoor environment. EPDM was chosen because of its porous and absorbent structure as well as its durability, flexibility, and cheap cost which allows for it to be easily implemented. The data collected showed that the curvature of the small and medium curve were optimal for mitigating sound. For pedestrians, the sound they hear appears to be five times quieter than without the wall.

B. Applications

Noise reduction barriers placed along busy streets can gather data about noise pollution in specific areas within cities, making it easier for policy makers to determine where to incorporate additional walls. They can also be constructed at intersections, near railroad tracks, and in front of parks to maximize their impact. This allows for a healthier walking and living environment in front of busy streets, minimizing the number of pedestrians who avoid loud areas.

C. Future Developments

More experimentation will be conducted to determine scalability and convexity. Using a larger sheet of EPDM, similar angles and shapes can be constructed to test the performance of the material in a realistic setting. This procedure would utilize the same parameters but scaled to a larger size to demonstrate the application on a larger convex surface. Additionally, the experiment can be improved by testing more panels and varying sound sources. For instance, once one large panel is tested, additional panels could be attached adjacently to test interference between the panels. Then, a sound source moving at a constant speed across all panels could be used to demonstrate the varying sound transmission and reflection as the sound travels through multiple points of the panels.

Throughout the conducted experiment, the angle was increased at 10 degree increments. Which generated a range of angles that provide the maximum sound attenuation. However, to optimize the exact convexity of the panel, the individual angles should be tested between this range at 1 degree increments. The culmination of these tests will optimize the sound panels and demonstrate their feasibility and effectiveness in an urban environment. Advertisements and art can also be displayed on the wall, which can help recuperate costs after production. On the backside of the panels facing pedestrians, visual advertisements can be installed without interfering with the sound attenuation ability of the wall. Additionally, to increase sustainability, solar panels can be installed on top of the frame to create a self-sufficient system. Minimal electricity is needed to power the sensors and motors on the wall. Thus, the remaining energy can be returned to the energy grid and used to fund other endeavors including, expanding the wall. Furthermore, efficient ways of converting sound energy into electrical energy are being developed that can be implemented within the wall.

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