Final Report

ACTIVE NOISE CONTROL FOR AUTOMOBILES

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TABLE OF CONTENTS

ABSTRACT

The goal of active noise control (ANC) is to reduce unwanted sound by producing an "anti-noise" signal that cancels the undesired sound wave. ANC has application to a wide variety of problems in manufacturing, industrial operations, and consumer products, such as noise-cancelling headphones, active sound design in car interiors, and noise reduction in ventilation conduits and ventilated enclosures.

The emphasis of this paper is on the practical aspects of ANC systems in terms of adaptive signal processing and digital signal processing (DSP) implementation for real-world applications. In this paper, the basic adaptive algorithm for ANC is developed and analyzed based on single-channel broad-band feedforward control. This algorithm is then modified for narrow-band feedforward and adaptive feedback control. "In turn, these single-channel ANC algorithms are expanded to multiple-channel cases. Various online secondary-path modeling techniques and special adaptive algorithms, such as lattice, frequency-domain, sub band, and recursive-least-squares." [9]

This paper put focus on ANC in interior of vehicle. The main problem for most of the cars in recent years is engine noises that are so load for most of the vehicles. To reduce automobile noise, engineers use the principle of Destructive Interference to physically cancel noise. The device consists of a microphone, to sense the incoming sound waves, a processor, to analyze the sound wave and to generate an opposing wave form, and a speaker, to physically deliver a new sound wave to destructively interfere with the primary, ambient, noise. Audio sound active control is a signal-processing methodology that reduces the effective sound amplitude to improve signal-to-noise ratio (SNR) so that unwanted noise is less perceptible. "The ANC methodology is also called audio noise reduction (ANR). ANC or ANR is based on coherent acoustics that accurately replicate the original sound field in all its forms. It uses microphones and speakers inside vehicle, along with digital signal processing (DSP), to cancel the noise. The sound can be described as a pressure wave consisting of an amplitude and phase." [7] As a result, the system will reduce the ambient sound, improving the focus on ride for driver and passengers.

1 INTRODUCTION

1.1Background

Today's drivers are on the road more often and for longer periods of time than ever before. Due to spending an extended amount of time in a vehicle drivers and passengers can get uncomfortable quickly. Many aspects of the driving experience have improved over the years. One of the most recent improvements was implementing sound cancelation for a quieter and more peaceful ride.

As the number of drivers on the road increase, more noises will be generated. Soon, this will become a large problem in urban areas. Today's automotive companies attempt to reduce the noise of the automobile by using science and engineering. Since engines arrived on the scene, they started working on design techniques for handling low frequency noise. Power-saving techniques have contributed to produce more environmentally friendly vehicles, but the noise persists in the interior of the car's cabin. Engineers reduced the number of cylinders thus making more efficient and more environmentally friendly engines. As a result, engine noise was lowered which increased the likelihood of hearing other exterior sounds. This furthered the problem of excess noise pollution leaking into the vehicle which led to an unpleasant ride for passengers.

Drivers' comfort is not the only reason driving the need for noise cancellation. Repetitive ambient noise is known to cause drowsiness which can end in a fatal automobile accident. According to the National Center for Statistics, up to 2.5% of all fatal crashes are a direct result of operating a vehicle while feeling drowsy [10]. Furthermore, a new study indicated that infrared and low frequency sounds elevate stress levels in drivers and passengers and increase driver fatigue [2]. With this in mind it is clear that noise canceling can also prove to be a safety measure in preventing accidents.

Many modern vehicles, especially luxury vehicles, strive to make the cabin of the vehicle as quiet as possible. Traditionally, this was achieved by using sound deadening, double pained windows, and extra soft shocks to reduce outside noise. This approach led to an undesired increase in vehicle weight. Scientists realized that there was a solution to both problems. The answer relies on using active noise control.

1.2 Purpose of the Project

This project will focus on active noise control (ANC) for automobiles. The objective is to reduce the amount of ambient noise in the cabin of an automobile by 5dB to 10dB. As stated previously, passive noise canceling has been implemented in the past, but it comes at a cost to the environment. Also, passive noise canceling does not cancel low frequency sound as well as ANC can. This is because ANC uses the principle of destructive interference to physically cancel noise. The system consists of microphones, to sense the incoming sound waves, a digital signal processor, to analyze the sound wave, an algorithm to generate an anti-noise wave form, and speakers, to physically deliver a new sound wave to destructively interfere with the primary ambient noise. As a result, the system will reduce the ambient sound, improving the ride of the driver and passengers.

1.3 Previous Work Done by Others

This project has been worked on last semester by another senior design team. Dr. Liu has given the team access to their documentation as a reference.

1.3.1 Existing Products

A prototype was not developed from the previous senior design team due to the restrictions put into place during the pandemic. However, there are several commercial products that relate to this project. Nearly every large automotive company has their own active noise cancelation hardware design. Additionally, companies that have automotive sound systems have their own ANC software that has been adapted from headphones or other speaks to be compatible with a vehicle. No aftermarket systems are for sale on a retail level.

1.3.2 Patent Search Results

Many patents exist pertaining to active noise control within an automobile, numerous additional patents exist relating to active noise cancellation in other applications such as headphones.

One patent uses active noise reduction in addition to artificial engine noise to achieve a quiet interior while driving at a steady speed, but it also amplifies engine noise when the vehicle is accelerating. “When the vehicle is in a steady state driving condition, the sound modification controller activates the ANR controller and deactivates the ESE controller. In contrast, when the vehicle is in a non-steady state driving condition, the sound modification controller activates the ESE controller and deactivates the ANR controller” [3]. ANR stands for active noise reduction and ESE stands for engine sound enhancement. This patent differs from this project as it will not vary sound output under acceleration. This project will only focus on noise cancelation, not amplifying engine noise.

Another patent uses a very wide range of parameters to account for when in the process of using active noise control. These are “dynamic control parameters selected from a group consisting of a current vehicle speed, tire pressure, vehicle on- or off-road status, dynamic driving modes, door/rooftop/trunk open/close states, windows/sunroof open/close states or an infotainment/entertainment operation/audio level” [5]. This patent differs from this project because it will be more of a basic approach to active noise cancelation. It will not account for driving modes, open windows, or vehicle speed. It will only actively cancel noise detected that has leaked into the vehicle.

Another patent is for providing adaptive noise cancellation depending on how many occupants and their location in the vehicle. “The system has at least one operating output. The system includes an occupant module and a vehicle system module. The occupant module receives at least one occupant signal indicative of occupants currently located within the vehicle and determines a current number of occupants in the vehicle based on the occupant signal. The vehicle system module receives as input the current number of occupants and where they are in the vehicle. The vehicle system module is configured to determine whether the current number of occupants located in the vehicle is less than a total number of occupants the vehicle is configured to seat” [12]. This patent differs from this project because it will not adjust the noise cancelation based on variable passenger location.

1.4 Brief Overview of the Report

Within this report, many aspects of designing an ANC system will be discussed. First, all the possible designs alternatives have been listed, ranging from what noise to be cancelled to how to implement the system. Then, the chosen design is noted with justification. Subsequently, all the applicable constraints and safety issues of the project are discussed. Additionally, the proposed budget and timeline are reviewed. Lastly, the team member's contributions are listed.

2 PROJECT DESIGN

2.0.1 Target Noise to be Cancelled:

A crucial variable in the design is what the targeted noise will be for the ANC system. The targeted noise will greatly influence the frequency and power level of the dominant sound wave to be canceled. Certain implications arise with each different sound. The microphones will have to accurately detect the frequency and power level. The ANC algorithm will have to be formatted in a way to accept the input frequency and power level. It will also have to be able to compute the anti-noise accurately. The algorithm must also output the desired anti-noise without any data loss. Lastly, the speakers must be able to output the desired frequency and be loud enough, with the help of an amplifier, to effectively cancel the dominant noise.

2.0.1.1 Engine Noise

Engine and exhaust noise can be one of the dominant noises to be cancelled. Exhaust noise either amplifies or quiets the combustion sound of the engine. Exhaust location can also affect how much noise leaks into the cabin. Engine noise primarily consists of the explosions within the cylinders of the engine. Other noises from the engine would include the interconnected pully system and possibly a supercharger or turbocharger. However, dominant noise is clearly from the combustion.

The frequency of engine noise is proportional to the engine's revolutions per minute or RPMs. "Calculating that dominant frequency at any given rpm is straightforward. First, convert engine rpm to Hertz, the frequency unit, with the following formula: 60 rpm = 1 revolution per second, or 1 Hz. Thus, a V-6 spinning at 1800 rpm can be said to be running at 30 Hz (1800/60 = 30)" [13]. In the example, 30 Hertz is not the audible sound emitted from the engine but rather the rotational speed of the engine's crankshaft. All vehicles the system could be implemented in have four-stroke engines, this means each cylinder fires once for two revolutions of the crankshaft. By multiplying the "30-Hz value by three (the number of ignition events per crankshaft revolution for a six-cylinder engine)" the result is a "90-Hz dominant frequency that defines the six-cylinder's sound at 1800 rpm" [13]. For a six-cylinder engine the 90 Hertz frequency is only dominant when the engine is running at 1800 RPM; when the engine is running faster, the frequency will increase. It is also important to note that other noise is created by the engine too. However, this non-dominant noise will not be as noticeable. To cancel the dominant frequency, the ANC algorithm will be set up to take a given input from the user or installer. Depending on the number of cylinders the engine has, the algorithm will adapt to cancel the target noise.

2.0.1.2 Road and Tire Noise

Road and tire noise can also be a focus of the ANC algorithm. Road terrain can vary greatly from smooth asphalt to grooved highways to gravel country roads. The terrain will cause a uniform hum which will be easy to be canceled since it is a constant noise. Constant noises are easier for adaptive filters within the ANC algorithm to pick up on.

Tires come in many different shapes and sizes. The tread pattern and groove design can greatly alter the frequencies produced by the tire. Tire frequencies can be divided into three main sections as seen in Figure 1. From 0 to 30 Hertz the tire transmits all forces directly to the vehicle. From 30 to 250 Hertz the tire can resonate for a long time after experiencing an impulse. From 250 to 1000 Hertz the tire experiences local vibrations but dampens them. Frequencies above 300 Hertz are also caused by wind interference.

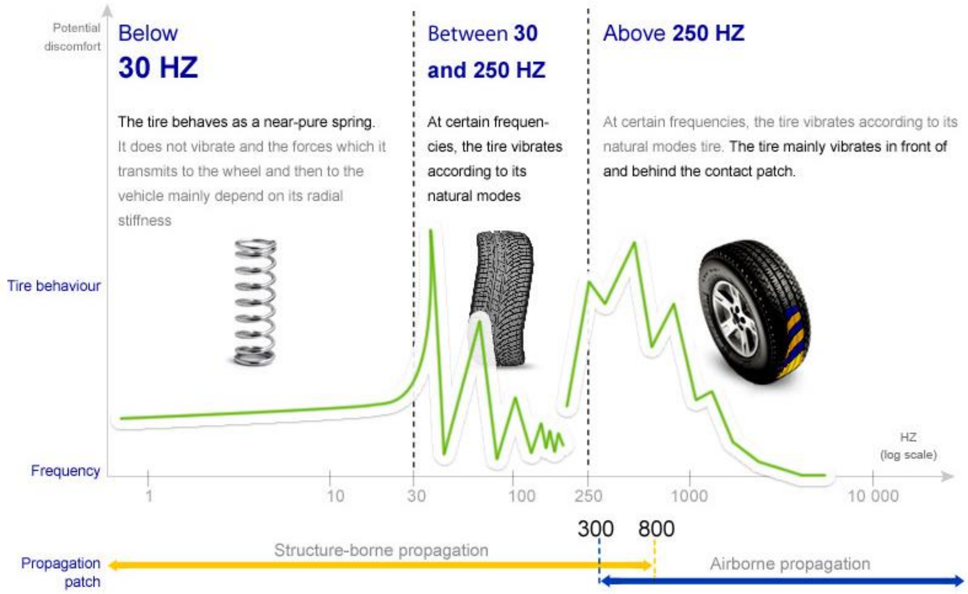

Figure 1: Tire Frequencies [11]

Much of the sound created by tires is rhythmic and at low frequency. This will make it relatively easy to cancel with the ANC algorithm. To ensure the best cancelation, microphones should be placed near the door panels or wheel wells of the vehicle.

2.0.1.3 Wind Noise

Wind noise is caused by the vehicle "pushing" the air molecules out of the way. Aerodynamics greatly affects the wind noise generated by the vehicle. Mirrors, antennas, tire tread, and gaps between panels of the vehicle all add to the wind noise. This noise is dependent on the fixed shape of the vehicle and its speed. "The frequency spectrum of steady wind noise is typically broadband and heavily biased toward the low frequencies (31.5 to 63 Hz). Gusting noise due to cross-wind, as an example, is impulsive and has content at higher frequencies (above 300 Hz or so)" [4]. Wind noise spans across nearly the entire audible frequency spectrum, but the dominant frequencies are very low. ANC typically is not very effective at canceling high frequency noise. However, since the noise is very repetitive the adaptive algorithm will be able to adjust and provide some silencing of the wind noise. Since the dominant frequencies are low the system should be able to filter out most of the noise. Perhaps the best way to filter wind noise would be through a combination of active and passive noise canceling.

2.0.1.4 HVAC Noise

Internal noise in the vehicle can also make the ride uncomfortable. Noise generated by the blower motor from the vehicles ventilation system can range from barely noticeable to so loud that the radio is barely audible. An experiment was conducted to determine the influence of HVAC noise on the overall ambient noise inside a vehicle. Five different settings of the vehicle's ventilation system were tested as seen in Figure 2, where Q_1 is the lowest setting and Q_4 is the highest setting.

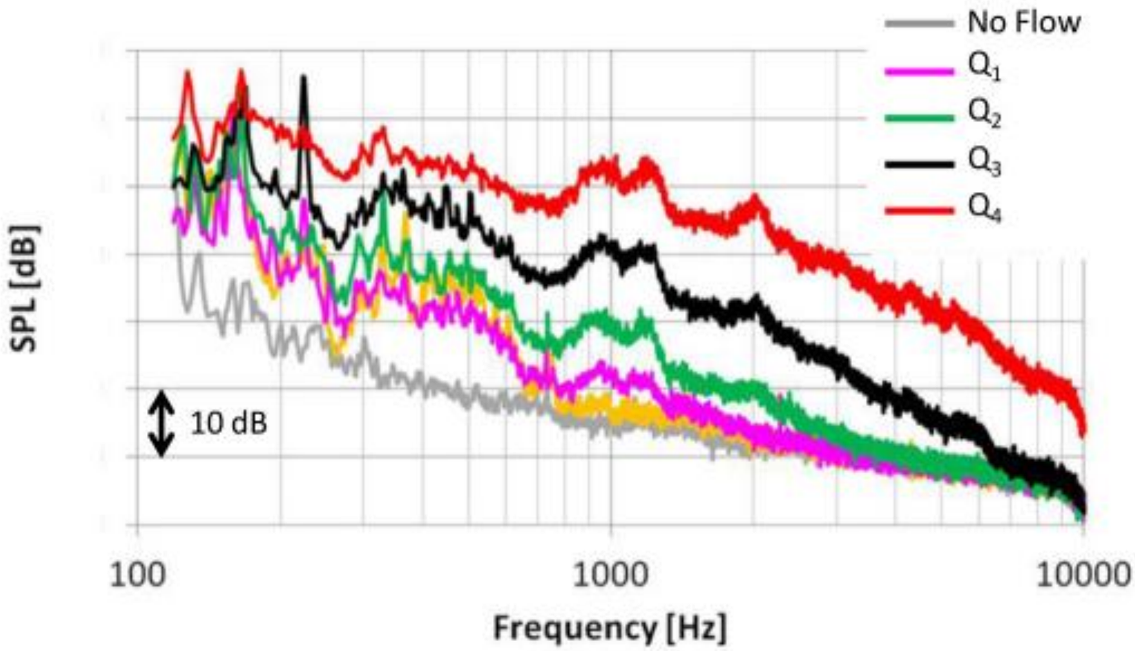

Figure 2: Vehicle HVAC sound comparison [1]

The most critical frequency range is between 100 and 3000 Hertz. The power spectrum level increases drastically in these areas. The ANC algorithm would be programed to target this frequency range. The adaptive filter will adjust to the specific repetitive noise produced by the vehicle's HVAC system. The most critical frequency range is between 100 and 3000 Hertz. The power spectrum level increases drastically in these areas. The ANC algorithm would be programed to target this frequency range. The adaptive filter will adjust to the specific repetitive noise produced by the vehicle's HVAC system.

2.0.1.5 Multi-source Noise

Realistically, more than one noise source will be targeted. Sound waves are additive and many of the above target noises share similar frequencies. This can result in destructive interference, which would be helpful to the ANC system; or this can result in constructive interference, which would increase the sound level of the respective frequency. The ANC system should be able to produce its desired output of a single target noise being cancelled even if multiple sources are present.

2.0.1.6 Error feedback via microphones

As the control source configuration generally affects the optimum error sensor placement, it is important that the error sensor configuration only be optimized after the desired control source configuration has been determined. Anything that the main microphones did not record or missed to capture; these error microphones will record. After recording the missed signals, microphones will send the data to computer and the computer program will generate another anti-noise signal that will help to reduce the error. The placements of the error microphones must be near the control or primary sources. Based on the system, using 1 or 2 error microphones will be helpful during the run.

2.0.1.7 Error feedback via accelerometers

Error feedback could also be input from vibrations detected in accelerometers. They provide purer frequencies with less interference of other noise. The accelerometers would be placed on the body of the vehicle to detect vibrations from the tires and suspension. They could also be placed on engine, transmission, or exhaust mounts to input specific frequencies from those components of the vehicle. Additionally, they could be placed on the windows in an inconspicuous location to detect wind noise. The number of accelerometers used would vary greatly based on how many error inputs the ANC algorithm is programmed for. According to figure 1, it turns out that an ANC system with an accelerometer is more effective than a system with microphone.

2.0.1.8 Speakers placement

Loudspeakers are an important element in active noise cancellation to duplicate the unwanted noise. In recent years, there have been a lot of implementations that can help achieve a better use of electronics for ANC systems. There are few general rules that apply to control sources placement. First, it is generally more difficult to obtain significant levels of global sound attenuation in free space that in an enclosed space. Global sound attenuation refers to a reduction in the total sound power radiated by the combined primary and control sources compared to that radiated by the primary source alone. This location can be determined theoretically or experimentally by trial and error. The optimal locations can be determined by a numerical procedure involving finite element analysis and genetic algorithm optimization. Furthermore, additional signal analysis methods such as direction-of-arrival (DOA) estimation may be applied on the basis noise pattern to identify principal noise sources, which helps in determining optimal loudspeaker placement. The system will use the integrated loudspeaker of the vehicle that already have the most optimum placements.

2.0.1.9 Microphone placement

The reference sensors measure the effectiveness of the controller. This provides a signal for the control algorithm to use in adjusting the controller output. It is important that the signal processing time of the controller must be less that the time for the acoustic signal to propagate from the reference sensor to the control source for broadband noise control. The performance of the ANC system will be determined by the location of the references sensors, which must be such that they can effectively sense all parts of both the primary and the control signal. The optimum references sensor locations are the locations of greatest difference in acoustic pressure levels between the primary and the controller sound, see Figure 3.

TABLE 1. Comparison of Selected Sources of Reference Signals: Acoustic and Vibrational

Source of Reference Signal	CPL (dB)
Accelerometer, side wall of engine compartment	20.5
Accelerometer, front radiator support of car	22.0
Microphone, above front seat	19.8
Directional microphone, between front seats	–5.4

Figure 3: Example of multichannel ANC system [6]

2.0.1.10 ANC target only Driver

A single channel ANC system requires a microphone as the reference source, a control source output speaker, a control source with the integrated FxLMS algorithm and an error microphones if desired. The microphone could be placed near the windshield mirror which is the center of the vehicle and could pick most of the noise perceive by the driver. The signal will be delivered to the control sources and use the FxLMS algorithm to create an anti-noise wave that will be deliver by the speaker that will be place on top of the cabin or using the integrated speaker of the speakers.

2.0.1.11 ANC target All Seats

A multichannel ANC system will be best suited to cancel the overall noise inside the vehicle. This system is more complex since it requires many speaker, microphones, accelerometer, and error sensor, see Figure 4. In this case the control algorithm becomes more complex, as it must consider the interactions between all sources and error sensors to provide the optimal cancelling signal to each control sources. This system can have accelerometers located on the body of the car to pick more noise, microphones above the seats of all passengers in the vehicle and speakers across the vehicle to deliver the anti-noise wave on the cabin vehicle to cancel most of the unwanted noise for all the passenger on the vehicle. Most of the existing multichannel system have proven to achieve attenuation level up to 8 dB below 40 Hz and around 4 dB within 80 to 200 Hz.

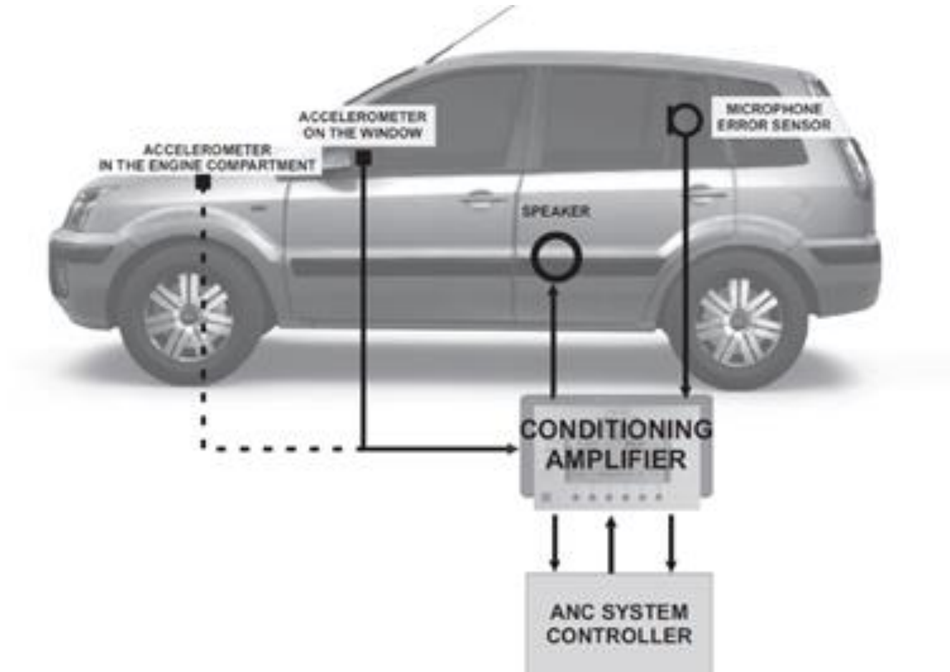

Figure 4: Example of multichannel ANC system [6]

2.1 Optimal Design

2.1.1 Objective

The goal of this project is to actively cancel noise from outside a vehicle to make the interior of the vehicle quieter. The system will specifically target low frequency noise to cancel since passive sound cancelation does not block low frequencies well. There are at least four possible noise sources that will be canceled by the algorithm: engine noise, tire noise, wind noise, and HVAC noise.

The result will consist of a working prototype implemented in a vehicle. Currently, the design plan requires an existing vehicle with a working sound system. The vehicle's existing sound system would provide the most uniform sound distribution throughout the vehicle. This would result in the best possible noise cancelation. It would also save on space and keep the total price of the product lower since less parts would be purchased. The speakers should be able to play music and other desired audio such as phone calls and provide active noise cancelation by producing anti-noise. This new noise will be phase shifted 180 degrees. Two reference microphones will be used to initially detect the ambient noise that is passing through the vehicle. There will be two error microphones, one placed near the driver's head and one placed by the passenger's head. They will be connected to the headrest or the headliner. These microphones will be used to make corrections to the speaker output to reduce the sound level even more. The signal from the microphones will go through a passive audio mixer, a preamplifier with a phantom power supply, an analog to digital converter (ADC), and finally a digital signal processor (DSP). The DSP will filter and alter the data with the ANC algorithm. It will create the necessary sequence of data to be output to the speakers for the active noise cancelation. The error microphones will also input data to the DSP, it will also be considering those inputs to further adjust the output sound. The anti-noise signal from the DSP will be converted back to an analog signal with a digital to analog converter (DAC) and amplified before going to the speakers. An example of the system can be seen below in Figure 5.

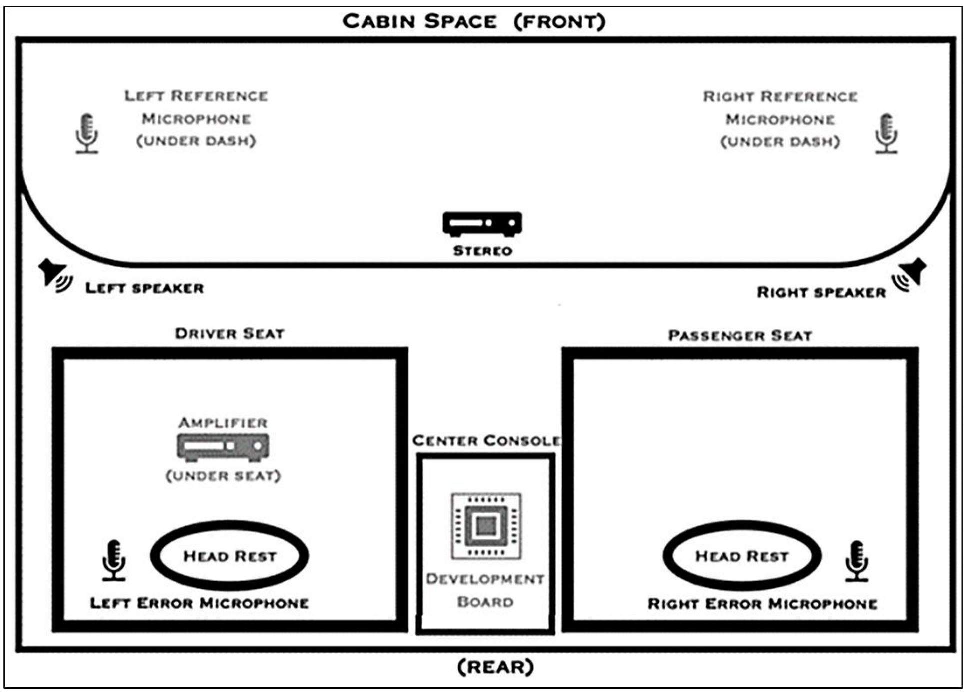

Figure 5: Control System of Automobile ANC System

The ANC algorithm will contain inputs from the source microphone. Then the data will be altered by the transfer function that will phase shift the input noise by 180 degrees. The system is defined as a closed-loop feedback system. It will consider the data being input from the error microphones and continually run that data through the transfer function to constantly reduce error in the output sound. This will allow for the ANC algorithm to reduce the ambient noise that is leaking into the vehicle from the four sources mentioned above. It will ultimately provide for a quieter and more comfortable ride.

2.1.2 Subunits

1.2.1 ANC Algorithm Target Noise:

The ANC algorithm will be configured to target a specific noise range. It will be limited by the code to only filter and create anti-noise for certain a frequency range. The targeted noise will greatly influence the frequency and power level of the dominant sound wave to be canceled. Certain implications arise with each different sound. The microphones will have to accurately detect the frequency and power level. The ANC algorithm will have to be formatted in a way to accept the input frequency and power level. It will also have to be able to compute the anti-noise accurately. The algorithm must also output the desired anti-noise without any data loss. Lastly, the speakers must be able to output the desired frequency and be loud enough, with the help of an amplifier, to effectively cancel the dominant noise. Four specific noise sources will be targeted in this design: engine noise, road noise, wind noise, and HVAC noise.

Low frequency noise is the most prevalent in vehicles since most have sound deadening within the vehicle. It is usually found in door panels, in the floor, or roof. Passive sound deadening is good at blocking medium and high frequency sounds. This leaves low frequency noise as the biggest factor in ambient noise. Additionally, as stated previously, repetitive ambient noise is a major cause of drowsiness. And infrared and low frequency sounds elevate stress levels in drivers and passengers and increase driver fatigue [2].

The dominant frequency range that the design will target will be from 40Hz to 1500Hz. The low end of the frequency range is dependent on how low of a frequency the speaker system can output. It is not crucially important that the speaker system can output ultra-low frequencies as these often are felt rather than heard. Nevertheless, the broader the range the more effective the design will be.

1.2.1.1 Engine Noise

Engine noise primarily consists of the explosions within the cylinders of the engine. Other noises from the engine would include the interconnected pully system and possibly a supercharger or turbocharger. However, dominant noise is clearly from the combustion. The exhaust system on the vehicle can either amplify or muffle the combustion sound of the engine.

Exhaust location can also affect how much noise leaks into the cabin. Depending on the setup microphone placement will vary.

The frequency of engine noise is proportional to the engine's revolutions per minute or RPMs. "Calculating that dominant frequency at any given rpm is straightforward. First, convert engine rpm to Hertz, the frequency unit, with the following formula: 60 rpm = 1 revolution per second, or 1 Hz. Thus, a V-6 spinning at 1800 rpm can be said to be running at 30 Hz (1800/60 = 30)" [13]. In the example, 30 Hertz is not the audible sound emitted from the engine but rather the rotational speed of the engine's crankshaft. All vehicles have four-stroke engines, this means each cylinder fires once for two revolutions of the crankshaft. By multiplying the "30-Hz value by three (the number of ignition events per crankshaft revolution for a six-cylinder engine)" the result is a "90-Hz dominant frequency that defines the six-cylinder's sound at 1800 rpm" [13]. For a six-cylinder engine the 90 Hertz frequency is only dominant when the engine is running at 1800 RPM; when the engine is running faster, the frequency will increase.

The design will not however be implementing a tachometer for data input into the ANC algorithm. Although this may increase the effectiveness of the initial anti-noise wave, it is very complex and outside of the scope of the current project. Based on the above example the following graph, Figure 6 can be created, calculating all dominant frequencies for each engine type.

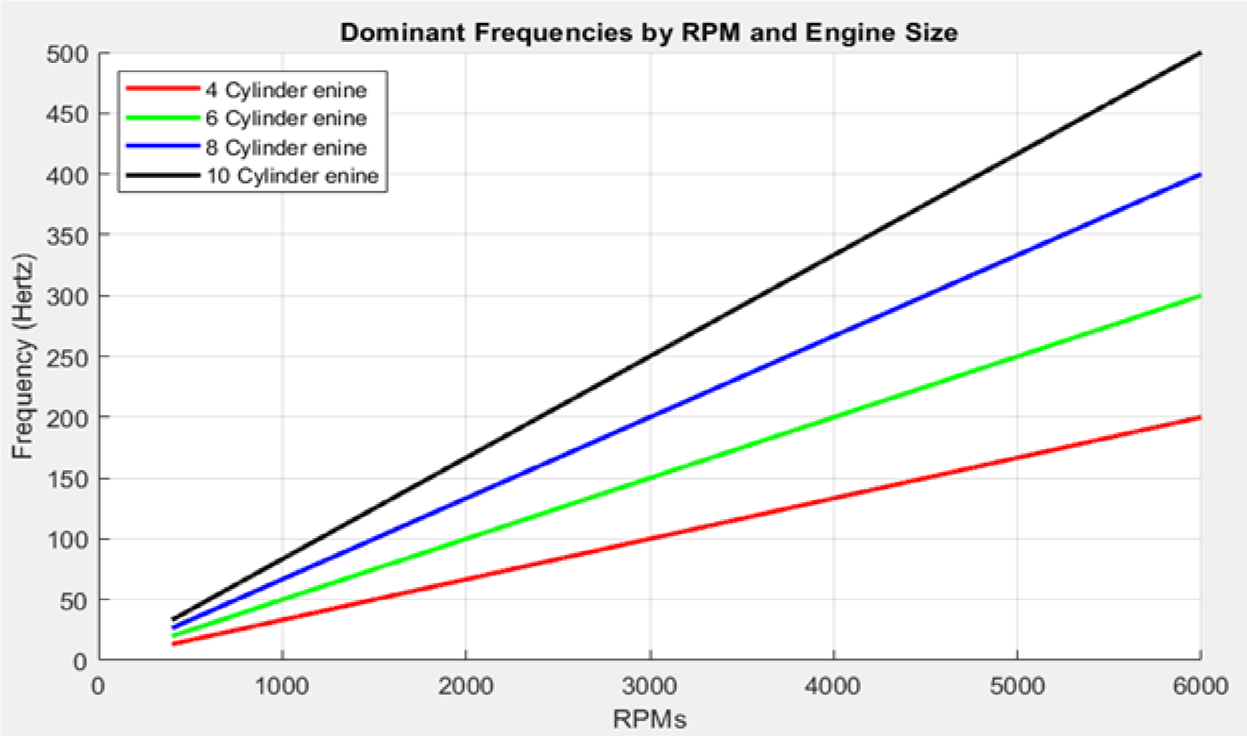

Figure 6: Graph of Dominant Engine Frequencies

The dominant frequency range is about 10 Hertz to 500 Hertz. For relaxed driving, the highest frequencies would likely be under 200 Hertz. This frequency is well within range of the specified design and will be effectively canceled by the system.

1.2.1.2 Road and Tire Noise

Road terrain can vary greatly from smooth asphalt to grooved highways to gravel country roads. The terrain will cause a uniform hum which will be easy to be canceled since it is a constant noise. Constant noises are easier for the system to identify and effectively cancel.

Tires come in many different shapes and sizes. The tread pattern and groove design can greatly alter the frequencies produced by the tire. Tire frequencies can be divided into three main sections as seen in Figure 7. The dominant frequency range is from about 30 Hertz to 100 Hertz and 200 Hertz to 1000 Hertz.

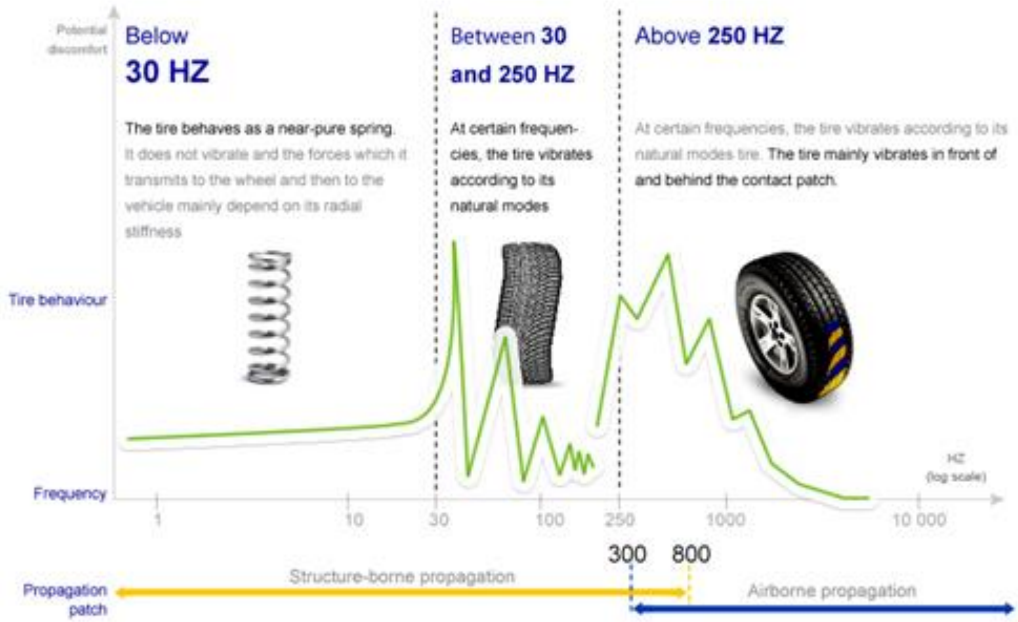

Figure 7: Tire Frequency [11]

Much of the sound created by tires is rhythmic and at low frequency. This will make it relatively easy to cancel with the ANC algorithm. The tire frequency is well within the range of the target values of the design. To ensure the best cancelation, microphones should be placed near the door panels or wheel wells of the vehicle.

1.2.1.3 Wind Noise

Wind noise is caused by the vehicle "pushing" the air molecules out of the way. Aerodynamics greatly affects the wind noise generated by the vehicle. Mirrors, antennas, tire tread, and gaps between panels of the vehicle all add to the wind noise. This noise is dependent on the fixed shape of the vehicle and its speed. "The frequency spectrum of steady wind noise is typically broadband and heavily biased toward the low frequencies (31.5 to 63 Hz). Gusting noise due to cross-wind, as an example, is impulsive and has content at higher frequencies (above 300 Hz or so)" [4]. Wind noise spans across nearly the entire audible frequency spectrum, but the dominant frequencies are very low. This is within the range of frequencies to cancel with the ANC algorithm.

1.2.1.4 HVAC Noise

Internal noise in the vehicle can also make the ride uncomfortable. Noise generated by the blower motor from the vehicle's ventilation system can range from barely noticeable to so loud that the radio is barely audible. An experiment was conducted to determine the influence of HVAC noise on the overall ambient noise inside a vehicle. Five different settings of the vehicle's ventilation system were tested as seen in Figure 8, where Q_1 is the lowest setting and Q_4 is the highest setting.

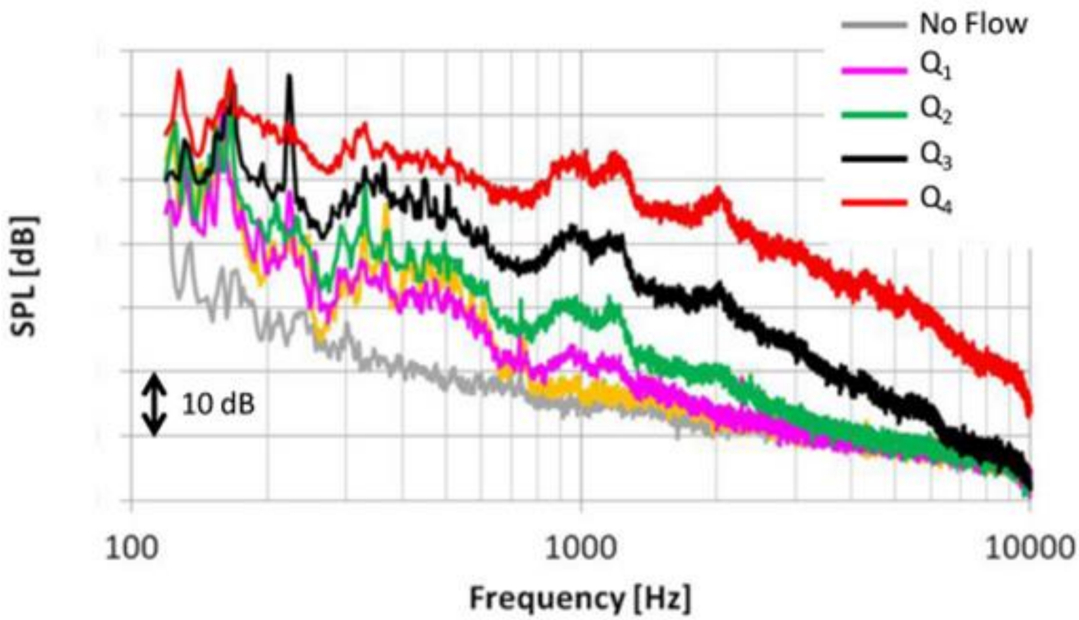

Figure 8: Vehicle HVAC sound comparison [1]

The most critical frequency range is between 100 and 3000 Hertz. The power spectrum level increases drastically in these areas. The ANC algorithm will be programed to target most of this frequency range. The adaptive filter will adjust to the specific repetitive noise produced by the vehicle's HVAC system. To obtain the quietest ride experience, having the blower on a low or medium setting would greatly reduce the noise to begin with. This would make it much easier for the algorithm to cancel the noise.

Sound waves are additive and many of the above target noises share similar frequencies. This can result in destructive interference, which would be helpful to the ANC system; or this can result in constructive interference, which would increase the sound level of the respective frequency. The ANC system will be able to produce its desired output of noise reduction by 5dB to 10dB even with multiple sources are present.

The dominant noise will vary due to the speed of the vehicle. At low speeds, the engine noise will produce the dominant frequencies. At moderate speeds, tire noise will produce the dominant frequencies. “Road noise generally starts to be noticeable at vehicle speeds above 30 mph, but its contribution to overall interior noise is maximum between 40 and 60 mph and then decreases at higher speeds, where aerodynamic noise becomes predominant” [4]. Lastly, at high speeds, wind noise will produce the dominant frequencies. “Wind noise is the predominant component of interior vehicle noise at speed above 100 kph” [4]. 100 kph is equivalent to 62 mph. All three sources vary depending on vehicle speed. The noise emitted from the vehicle’s HVAC system does not. It is solely dependent on how high of a setting the blower motor is on.

With the cancelation of all four noise sources the vehicle cabin will be much quieter. This is highly desired and the main goal of the design. Targeting specific noise sources would be difficult and require sound filtering to distinguish which frequencies are coming from a certain noise source. This could also leave certain low spectrum frequencies not canceled which is undesirable. The broad range of 46 Hertz to 1500 Hertz allows for all “uncomfortable” frequencies to be canceled.

1.2.2 Microphones

Microphones are the essential part of the noise cancellation system. The main purpose of the reference microphones is to pick the disturbance noise that is wanted to be canceled. The microphones need to be able to have a range of the desired frequencies that are the target of cancellation. If the microphone accuracy is not within a reasonable amount of error, it normally within a decibel of flat lining, the overall accuracy of the system will be affected by the degree of error the microphone shares. Basically, there are a few things that will affect the accuracy of the microphones. This will be calibration of microphone, type, size, and interface of the microphone.

Having well calibrated microphones is the main factor in reducing the error in sound sampling. Most companies of microphone manufacturing are testing every instrumental microphone that they are producing to make sure they are accurate enough by giving an individual calibration on record for that specific microphone. Depending on the accuracy of calibration, this can allow a relatively inexpensive microphone to be accurate for many applications. Some of these calibrations will be as accurate as +/- half of a decibel and some will still one be +/- 2 decibels of accuracy. Generally, the cost of the microphones is based on their sound capturing accuracy.

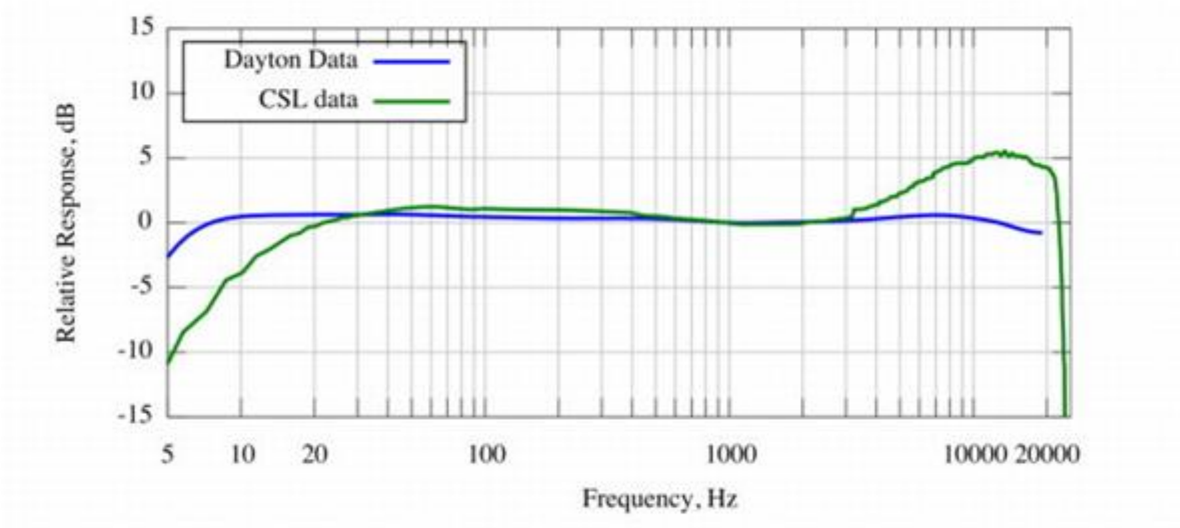

Figure 9: CSL Vs. Dayton microphone data

Audio interface the microphone uses is another factor that has smaller effect. Some of the microphones that are eligible for this project are analog while the others are digital. Digital microphones are simpler than analog microphones. They are powered and send signals through a USB into the computer. While analog microphone can add complexity to the signal. These will generally use a ¼' plug or an XLR cable, see Figure 6, and need an audio interface, see Figure 7, to power on and transfer signals. Also, to minimize the presence of unwanted extraneous noise in the reference and error, the microphones are often filtered with low band pass filters so only the noise to be controlled is present in both signals. The power section is not required for the analog microphones, but it will affect the signal strength and clarity of many models. This will require the system to have another component which will complicate the design and add another cost to an already expensive component.

Figure 10: XLR cable Figure 11: USB Audio Interface (Model: Focusrite Scarlett 2i2 ($169))

Form Factor is the last consideration for choosing a microphone. Many of the available microphones that fit the desired criteria are having large range from 6 to 8 inches long. To integrate this system into a vehicle, the microphone and bracket must be at their minimal size to install. A 3D printed can be helpful to optimize with respect to the size of the microphone to maintain the end location of the microphone. The only problem with these small form factor microphone that are both digital and accurate is the cost, some of these microphones are expensive in range of $1500-2000 each which compromise the entire budget. Without having leeway on the budget, some of the criteria will have to be sacrificed when choosing the optimal microphone.

Figure 12: Dayton EMM-6 Microphone ($70)

Figure 13: DPA Microphones 4006A Omnidirectional ($2,339)

Obviously, the system does not require calibrating the microphones while calibration already available for the selected microphone. The calibration of the microphone is important because it will reduce the error in sound sampling. This is due to the microphone having an abnormally flat response in the required 50-2000 Hz range for this design. Finding a microphone that eliminates the need for an audio interface, calibration, and staying at a relatively low cost and form factor will be ideal for the project.

1.2.2.1 Reference signal and placement

An ANC system based on digital filtering, in principle, modifies the reference signal only. It amplifies this signal within some frequencies and shifts in phase to resemble as best as possible the compensated signal. Therefore, the more the reference signal waveform is similar to the compensated signal, the better system. An ideal reference signal needs to resemble the compensated signal and only shifted by time and send it to the secondary source to the place where the place is being silenced. In ANC system microphones are used very often used between the primary source and the silenced place. The position of the microphone affects the effectiveness of the system. One way to determinate the reference signal position is using the coherence analysis. Coherence analysis is a natural technique that can help to select an optimal reference point. The common coherence function is a dimensionless multiplier, and a sum of partial coherences fulfils the dependence given Equation 1.

$$\sum_{i=1}^{N} \gamma_i^2(f) \leq 1, \quad \text{Eq. (1)}$$

Where N= number of propagation path, = square of partial coherence function in frequency domain, = frequency.

However, it is difficult to use coherence as an indicator off whether the reference point is good. Also, the closer the reference signal to the compensated signal, the more the effective the system. Thus, the lower the damping of the path, the more effective the system. Knowing this and with further research it has been determined that the best position could be on the side door of the cabin vehicle since it is close to the seat of the driver and passenger which are the desired quiet places for the cabin vehicle and near the controller which will be placed either under the driver passenger or in the glove box. Although the final position will be determined as the prototype is implemented and with further trial and error method.

1.2.2.3 Output sources and placement

With modern in-car entertainment system providing 4-6 built-in loudspeakers, the addition of an active noise cancellation system is considered to involve no greater cost. Having the right speaker is crucial to the operation of the system. Loudspeakers are an important element in active noise cancellation to duplicate the unwanted noise. In recent years, there have been a lot of implementation that can help achieve a better use of electronics for ANC systems. there are few general rules that apply to control sources placement. First it is generally more difficult to obtain significant levels of global sound attenuation in free space that in an enclosed space. Global sound attenuation refers to a reduction in the total sound power radiated by the combined primary and control sources compared to that radiated by the primary source alone. This location can be determined theoretically or experimentally by trial and error. The optimal locations can be determined by a numerical procedure involving finite element analysis and genetic algorithm optimization. So, to have an efficient system the control source must be coherent with the primary source output, the separation between the two sources must be small and the control sources must be of similar size to the primary source and capable of generating a similar volume at the frequencies to be controlled. One of the constraints in the placement of the speakers is that using the audio stereo of the vehicle the speakers cannot be moved to improve the system. Additionally, the existing audio needs to be able to reproduce the unwanted waveform.

1.2.2.1 Error signal and placement

The error sensor measures the effectiveness of the controller. Which provide a signal for the control algorithm to use in adjusting the controller output. It is important that the signal processing time of the controller must be less that the time for the acoustic signal to propagate from the reference sensor to the control source for broadband noise control. The performance of the ANC system will be determined by the location of the error sensors, which must be such that they can effectively sensing all acoustic modes excited in the vehicle cabin and the control signal. The optimum error sensor locations are the locations of greatest difference in acoustic pressure levels between the primary and the controller sound. Also, it is extremely important to minimize as far as possible, the number of error and control channels in an active noise control system so that the convergence speed and stability are maximized. The preferred location placement for the error sensor will be near the driver's head in the cabin of the vehicle since that will be the local cancellation zone for the design. Furthermore, to implement the noise cancellation in the whole vehicle there will have to be multiple errors sensors near all the passenger seats in the vehicle.

1.2.3 Implementation

The overall implementation is a consideration on the placement of the equipment inside the vehicle or a consideration of building a prototype enclosure. Many factors arise upon consideration of any implementation. The implementation choices will focus on how easily the ANC system can be integrated into a physical space, how well the overall effectiveness of the ANC system will be inside that physical space and deciding which implementation would allow for the most versatility and compatibility in contrast to other designs (is the design limited to any vehicle or types of vehicles).

There are three alternative implementations: prototype enclosure, a box placed inside the vehicle, or completely integrating the ANC hardware and software into an actual car. When considering box prototype, the box would simply house all the ANC hardware but the microphone, speaker, and, of course, cables. This design would allow the system to be compatible with most vehicles but the physical space the box occupies might be unappealing to the consumer. Additionally, this approach would require finding a power source, in the case that the power will be sourced independently. Also, there would be a great deal of wire management that would be ideal to “hide” from the consumer.

Examining the limitations choosing the box installed design has on the overall availability to integrate this model into multiple vehicles; Considering physical space, whether car or trucks, the most practical area to place the housing for the ANC system would be in the glove box. This would be the simplest way to send cables to the stereo and existing speakers. There is also a possibility of placing the box into the trunk, but this would require finding a way to run the cables from the trunk to the front of the car without the cables being seen. Though in the case of trucks, the placement is fairly limited to the glove box. From a software perspective there are not any limitations since all the software units would be provided and located in the container; this means it would be vehicle independent. From an electrical standpoint, arises many possible limitations. There would need to be additional information provided about the vehicle. The prototype is limited due to ensuring the ANC system could be compatible with a specific car model. This is a consideration of the voltage availability from the vehicle’s battery.

Another approach is building an ANC prototype that is completely integrated in the vehicle. There are many factors that come into play here. The ANC system would need to be compatible with the software provide by the vehicle and additionally, would require space behind the dash or in a different area to properly appeal or “hide” from the consumer. This design would limit the ANC system to one specific car.

This prototype enclosure design would consist of the team building an enclosure to “simulate” a cabin space. The only equipment that would be in the enclosure other than the ANC hardware would be a single seat to allow real-time demonstration of the system. There are essentially no limitations. The ANC system is completely left to optimize. This is essentially a complete prototype model; except modeling the enclosure to allow space for a single seat so that consumers may be provided a demonstration of the performance of the ANC design. This design keeps the ANC system generalized and could appeal to a wide variety of vehicles since the design would not be to a specific vehicle.

Upon consideration of the possible designs, building an enclosure prototype would allow the most flexibility in the system requirements, however, it might not fully appear to the consumer since the purpose is active noise control in automobiles. The ANC system must appeal to the automotive industry. Therefore, one on the integration models must be chosen. The box implementation is dominant over a complete integration because the ANC system can appeal to a larger variety of vehicles since the ANC system requirements has more freedom with respect to size and software compatibility. Appealing to a larger automotive community would be beneficial to the product and therefore the box implementation is the optimal design.

1.2.4 ANC Algorithm

The ANC algorithm will be a FXLMS algorithm. This is the simplest functional broadband algorithm. The FXLMS algorithm will receive the error and reference signal and adjust the coefficients of the filter to minimize the error and physically cancel the targeted noise. The FXLMS algorithm is built of the basic components required for an ANC system. That is, the noise source, reference microphone, error microphone, canceling loudspeaker, and ANC algorithm, as shown in the block diagram below,

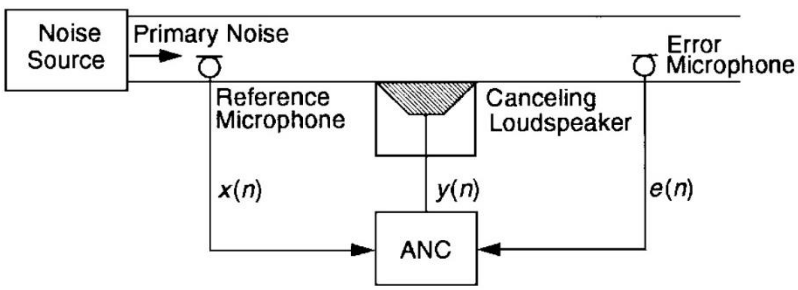

Figure 14. Basic Broadband ANC

Figure 14 must be transformed into a functional block diagram. This can be done by identifying the acoustic domain and electrical domain as shown below,

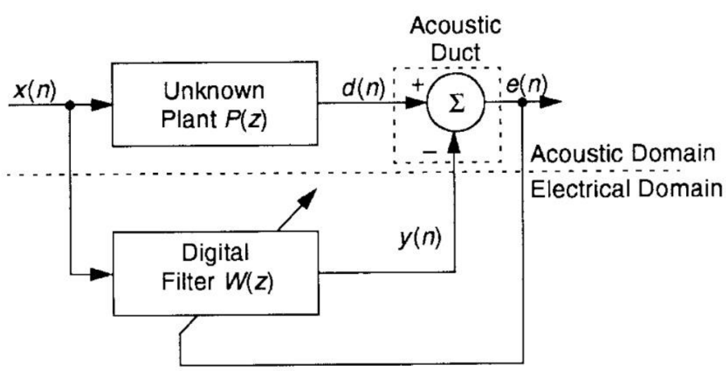

Figure 15. System Identification of ANC.

The block diagram Figure 15 identifies the logic of the ANC block in Figure 14. Figure 15 merely identifies the physical space as P(z) because the physical space that the primary noise propagates in acts as a filter and changes the characteristics of the noise, which is modeled by a block identified as P(z). The inclusion of P(z) in the block diagram does not mean it is a physical component. However, for optimal performance is it necessary to account for the effects the physical space, P(z), has on the system and therefore necessary.

The summation symbol simply represents the superposition effect of the noise. After all, the ANC system relies on the principle of destructive interference.

Lastly, Figure 14 includes a block W(z) labeled Digital Filter which contains the LMS algorithm and adaptive filter. The job of the Digital Filter is to use an algorithm that can adjust to the time-varying effects of the primary noise, as well as to adjust for the effects the Unknow Plant P(z) has on the primary noise. In essence, the Digital Filter adapts to minimize the error. The inclusion of the Digital Filter is necessary and will be expanded since, as represented currently, contains the adaptive filter and LMS algorithm. The expanded block diagram is shown below,

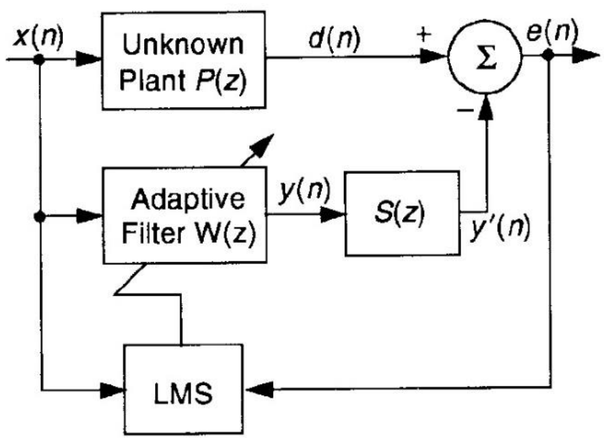

Figure 16. Expanded ANC System.

The LMS block show in Figure 16 is an expansion of the digital filter of Figure 15. The LMS block implements an adaptive least mean-square (LMS) filter; essentially, estimates the filter weight or coefficient needed to minimize the error e(n).

S(z) represents the many actions take place during the time that the signal y(n) takes to the time that the error signal is processed. The signal goes through a D/A converter, or digital-to-analog converter, a reconstruction filter, power amplifier, loudspeaker, acoustic path from loudspeaker to error microphone, preamplifier, antialiasing filter, and A/D converter, or analog-to-digital converter [7]. All these processes can be represented by its own respective block or transfer function, as shown with the introduction of S(z).

All the transfer functions here (represented as a block diagram) are necessary for the complete functionality. However, because of the presence of S(z), the error signal is no longer "aligned" in time with the reference signal. The most effective way to fix this is to place an identical filter in the reference signal path, as shown below in Figure 17. This is now called a filtered-X LMS algorithm or FXLMS algorithm.

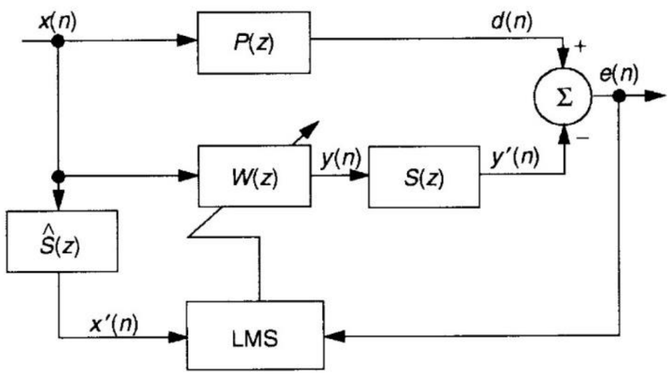

Figure 17. FXLMS ANC Block Diagram

This is the simplest functional ANC system because it only contains components necessary to work. The effectives come with adjusting the coefficients of the adaptive filter to accurately account for P(z). This analysis is to be determined by experimental methods. However, the ANC system will operate a FXLMS algorithm.

2.2 Prototype

2.2.1 Description and Operation

<u>Microphones:</u>

The prototype is comprised of five major physical components, microphones, an audio interface, a mini-PC, an amplifier, and an existing sound system within a vehicle. The microphones are studio grade condenser microphones from Dayton Audio, see Figure 18.

Figure 18: Dayton Audio Microphone

A condenser microphone requires phantom power, for more on phantom power see the description of the audio interface. The microphones have a flat frequency response curve, which means that the frequencies they detect is the same frequencies that will be transmitted to an audio interface, see Figure 19.

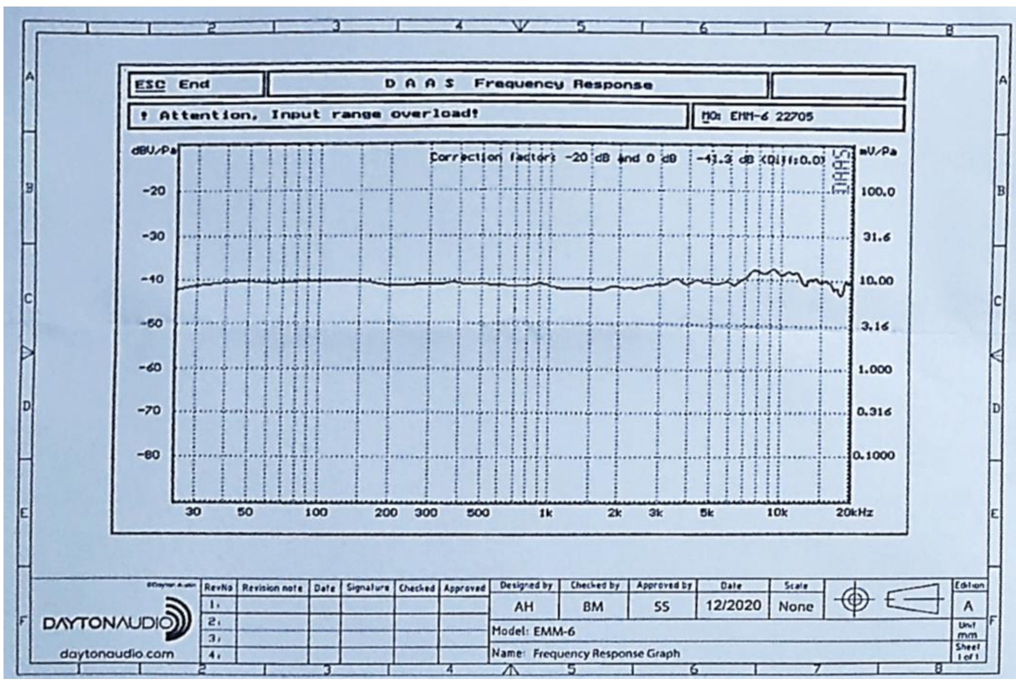

Figure 19: Dayton Audio Microphone Frequency Response Graph

Two reference microphones were used in the prototype to capture the ambient noise inside the vehicle. For more on the types of sound refer to the section in the report labeled “Target Noise to be Canceled” (2.0.1). The reference microphones were placed in their microphone stands and mounted under the vehicle’s dash in the footwell, see Figure 20.

Figure 20: Reference Microphone Placement

Audio Interface:

An XLR cable connects the microphone to the audio interface. The interface used was made by PreSonus, see Figure 21.

Figure 21: PreSonus Audio Interface

It has many functions designed for studio recording, however many of these were disregarded since a real time input and output was desired. There are many dials on the interface that do not affect the ANC system. The necessary functions of the interface include, providing phantom power to the microphones, mixing the two reference microphone signals, converting the analog microphone signal to a digital signal, and transferring that signal to the mini-PC.

Phantom power is required to power condenser microphones. They have active internal parts that require an electrical signal for the diaphragm to transmit the audio signal correctly. The phantom power button is located on the front of the audio interface, see Figure 22.

Figure 22: Phantom Power Button

The audio interface mixes the two audio signals coming from both microphones. This means that the system is not balanced with a right and left side perspective on the sound. Additionally, the interface has an analog-to-digital converter to convert the analog signal from the microphones to a digital signal that the mini-PC can recognize. Most importantly, the audio interface is used to transfer the audio signal from the microphones to the mini-PC for analyzation.

The placement of the audio interface was not that important as long as it was close enough for the cables to reach all the necessary parts. In the prototype, it was placed under the center console, see Figure 23. This kept it out of sight and out of the way for the driver and passengers.

Figure 23: Audio Interface Under Center Console

Mini-PC:

A mini-PC was used to run the ANC code. A LattePanda was used for this role, see Figure 24.

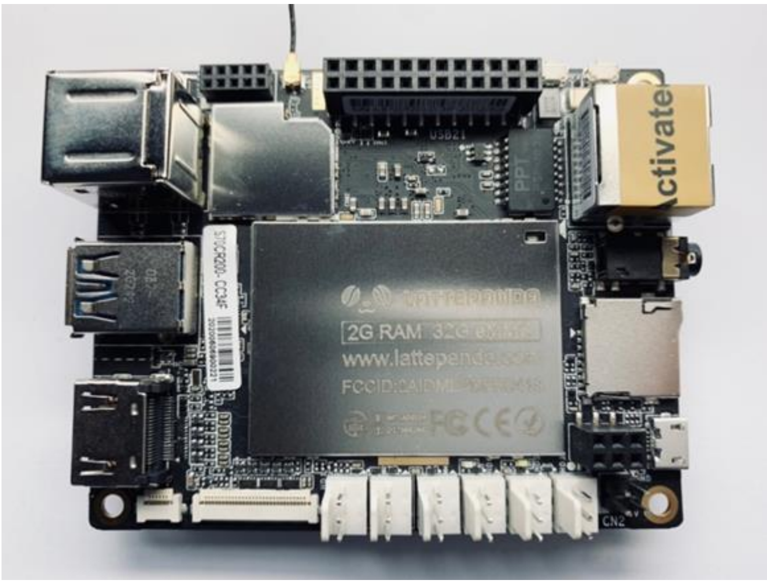

Figure 24: LattePanda

It has both a mini-PC with Windows 10 operating software and an Arduino board. Only the PC functionality was used during preliminary testing of the prototype. MATLAB and Visual Studio were run separately during prototype testing, for more on the testing see the Testing and Results section (2.2.3). The LattePanda has several USB ports on it; this is where the audio interface was connected to it. The LattePanda provided the power for the audio interface while being able to read the data being sent to it from the microphones.

Like all PCs, the LattePanda has a built in digital-to-analog converter that is connected to a 3.5mm TRS headphone jack, see Figure 25; this is where it sends data to the amplifier via a 3.5mm TRS to dual RCA cable.

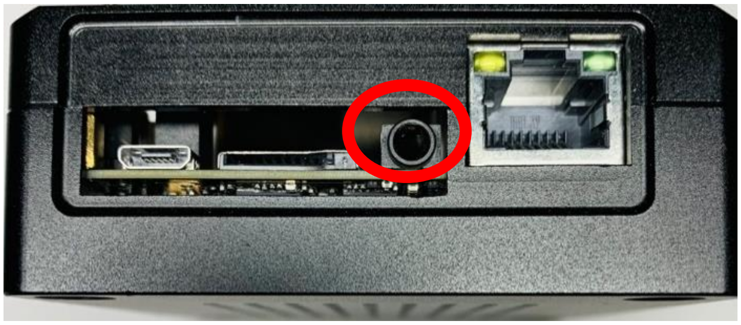

Figure 25: LattePanda Headphone Jack (In Case)

Amplifier:

An amplifier was used to amplify the anti-noise sound from the LattePanda. The amplifier used was made by JBL, see Figure 26.

Figure 26: JBL Amplifier

The amp has four channels that can be connected to four speakers; however, the prototype was tested with only the two front speakers hooked up to it. The amplifier has RCA ports on the front of it where the 3.5mm TRS to dual RCA cable could connect to it. The amplifier was positioned under the driver's seat to give quick access to it while keeping it out the way during operation of the vehicle, see Figure 27. All the power can speaker cables were run under the carpet.

Figure 27: JBL Amplifier Connected to LattePanda

Sound System:

The system was designed to operate with a vehicle's existing sound system. In the case of the prototype, the vehicle had JBL GTO speakers installed, see Figure 27.

Figure 27: JBL GTO Speakers

Speaker wires were run from the amp to the speakers. They were connected in parallel with the existing stereo. The design intent was to be able to have full use of the existing sound system and have the ANC system work at the same time, or separately if desired.

Code:

The coding of the digital signal processing was the most important part of the design. The coding was done in MATLAB and is highly reflective of the FxLMS algorithm mentioned previously. The coding description will contain details of each major section of the entire code. The code begins by importing the P(z) data or coefficients of the filter that accounts for the filtering effects of the cabin space. Because the experimental data collection of the filtering effects is quite rigorous this data was provided by our Faculty advisor. The code then defines an audio recording of 44,100 Hz at 16 clock cycles or bits. The section of code is the following Figure 28.

```
% Dynamic Range of Converter
n1 = importdata('SEC13R.mat'); %
%n2 = importdata('SEC18R.mat');
recObj = audiorecorder(44100, 16, 1);
disp('Start speaking.')
recordblocking(recObj, 10);
disp('End of Recording.');
play(recObj);
n2 = 1000.*getaudiodata(recObj);

load('TF.mat'); %
```

Figure 28: Section of code that initializes data collection.

Following the audio recording specification is other initialization requirements. Specifically, specifying the length of the data that will be sent into the adaptive filter. This is called buffering. The length of samples was chosen to be one hundred for convenience. The step size is very small and was chosen after multiple iterations that best optimize the system performance. The noise into the system is defined based off of the previous specifications and filtered based on the effects of the cabin space. The code described is Figure 29.

```
%% Online %% Code of specific noise (n1/n2)
T = length(n2);
L_w = 100; %u_w = 0.006;
U_w = 0.0000000122; % Step size
L_TEST = T; % Length of  entire n2 (n2 is input noise)
noise = n2';
noise = noise(1:L_TEST);
noisein = filter(shat,1,noise);

% Define the Vector
W = zeros(1,L_w); % Defining W,
e = zeros(1,L_TEST); % Preparing the error
In = zeros(1,L_w); % Setting the buffer to all zeros
d = filter(P_z,P_p,noise); % Original out put
```

Figure 29: Buffering and initial filtering.

Following, the adaptive filter matrix is defined. The length of the filter is identical to the length of the buffer, one hundred. Additionally, the error matrix is defined to be the length of the input noise. The original output is filtered to account for the effects of the cabin space P(z). The next section of code contains the iterative process of correcting the adaptive filter based on the data collected by the error microphone and data collected by the reference microphone. The adaptive filter is updated successively by each error calculation for the time varying sound.

```
%% Adaptive Filter
for n = 1:L_TEST
    In = [noisein(n),In(1:L_w-1)]; % Update the buffer
    y = In*W'; %
    e(n) = d(n) - y; % Error calculation. % d(n)
    W = W+U_w*In*e(n); % Update the W
end
```

Figure 30. Iterations of the Adaptive filter.

The code in Figure 30 sets coefficient values to the anti-noise signal y, the error e(n), and the adaptive filter W with each iteration of the code. The data values determined in each iteration help the adaptive filter adjust to the difference in the sound. This is why the buffer was set very small, so that progressive changes in sound won’t deviate too much from the previous set.

2.2.2 Testing and Results

The LattePanda was tested separately from the rest of the system due to time and distance restraints and COVID precautions. A laptop was substituted in place of the LattePanda. This would have no effect on the system since the LattePanda is a mini-PC and has all the functionality of a standard desktop or laptop.

The system was setup and tested in a 1997 Dodge Ram 1500. The testing was done while the truck was at idle to ensure consistent results on the decibel meter. In this way, the number of variables were decreased as the ambient noise the system was trying to cancel was predominantly from the truck's engine and exhaust. There was little to no sound deadening in the truck and it had a significant exhaust leak. The decibel meter gave a reading of about 57dBA, see Figure 28.

Figure 31: Decibel Meter Reading Only Ambient Noise

After during testing, the decibel meter read values as low as 55dBA, see Figure 29. Although a 2dBA decrease does not seem to be much, the decibel scale is logarithmic, so it is nearly a 50% reduction in sound. Additionally, the precision of the decibel meter is ±1.5dBA, so it is entirely possible that the reduction could be greater.

Figure 32: Decibel Meter Reading with ANC System Running

3 REALISTIC CONSTRAINTS

3.1 Engineering Standards

A. The completed system will follow all ISO manufacturing at all point throughout the design and testing of the system.
B. Chosen components are up to all necessary electrical standards.
C. All measurements on the device will follow ANSI standards and be in metric units.
D. The device will be properly tested and use the optimal materials for the application, per ASTM standards.
E. The product will follow all IEEE standards for electrical components, writing, and signal transmission.

3.2 Economic Constraints

A. This project has a strict budget of $1000. The total price all the parts and shipping cost must be less than the budget.
B. This project will keep the final product under $1000 that will make to more economically feasible for potential customers to purchase the product if it were ever to be offered for sale.
C. As a result of the budget, very high-end audio equipment cannot be purchased.

3.3 Environmental Constraints

A. All power wires and electronics will be UL listed to ensure the safety for the system and its operation.
B. The product should be able to withstand the voltage and current input and output without overheating, potentially causing off gassing of toxic chemicals.
C. The product should not catch fire as this would be extremely dangerous to potential users and their property.
D. This design should be well implemented specially the wire of power source that have direct connection to the vehicle's power engine. Not paying attention in this area can cause problem for the vehicle system itself.
E. The device must be able to withstand a temperature range of -45°C to 65°C, the typical interior temperature of a vehicle.

3.4 Sustainability Constraints

A. The finished product will be designed with the intent to use the vehicle's existing battery, relay, and fuse system as batteries and electronics are a limited resource.
B. The product will be configured to draw the least amount of power while consistently providing quality ANC for the vehicle. The vehicle's battery is charged by the alternator when the vehicle is running.

3.5 Manufacturability Constraints

A. The device will have to be mobile, functional, and easy to be assembled so anyone can use and learn its features.
B. The product will need to be able to fit into a vehicle whether it is in a small box or fully integrated behind the dashboard and using the vehicle's existing sound system to save space.

3.6 Ethical Considerations and Constraints

A. Final product and all parts of the system must be manufactured and produced in a workplace that follows the Fair Labor Standards Act (FLSA).

B. If a patent made the final product, it should not make any problem for other component that currently working on the system.
C. The product should follow every legal requirement in manufacturing, usage, marketing, and economic.
D. The product maker cannot be blamed if the use of the Active Noise Control (ANC) system causes the driver to not hear or recognize objects or person outside of the vehicle, which can result in injury or death.

3.7 Health and Safety Constraints

A. This product should not overlay the emergency sounds such as closing seat belt alarm, speed limit alert etc.
B. Electrical parts must be checked based of the standards to not be harmful for users such as making problem for engine, car electricity, electric shocks, and fire.
C. Parts of the system should not put the driver on limits of having less visual of road and making risk for driver safety.
D. Also, the system should not remove sounds that came from outside of the car that are required for the driver to know.

3.8 Social Constraints

A. The system should not cancel the music inside of the car, interrupt passengers' conversations and dialogues, and making problems for car assistance such as map speaker guide.
B. The product must be professional and well made to not bring any disturbance for passengers by making extra noises.
C. The design should not interrupt or cancel out any sound feature while they are active in smart and electrical vehicles such as Tesla that their focus of these cars is bringing maximum comfort for the occupants of the cars.

3.9 Political Constraints

A. This product must be sold through legal markets, so it properly taxed and agreed with the law of each county that this product is selling.
B. This product must follow the standards for the similar products on the market, so it reaches the maximum faith and trust for the customers to see this system as a legitimate product.
C. This product must only be sold in markets that they have no limitation for any individual race or believe.

4 SAFETY ISSUES

Aside from the design that must work without any problem is about safety of the final product. From an electrical engineering point of view, it is important that all electrical components properly insulated and installed. For both wiring and components must be implemented as its maximum standard, so the product prevents electric shock and in low possibility light up and start fire.

For the future, this product must have a complete instruction for users of this product in each selling package. This can help customers learn about the product's safety aside from the manual guide and installation. It is important for users to know that the electrical components must be properly isolated from the power source using a fuse block. This can prevent the problem of overload electrical power surge that can cause direct damage to components, electric shocks, and possibility of fire.

Aside from the component implements, it is also important that the product must be highly well programmed on the computer so the system work on its best shape without breaking or causing damage to driver's ears by sending harmful signals and making problem for hearing in long way run. Signals can make huge problem if the programming does not meet its standards. They can exit from their own noise cancellation axis and cancel other noises that require for drivers to know and prevent an upcoming disaster for the car itself and passengers.

By giving the program a proper frequency cancellation range, this risk of cancelling required noise will be lower and the result is the safety of occupants of the vehicle. The final product should not draw enough power from the vehicle battery to impede the function of other electrical systems within the vehicle.

From an electrical engineering point of view about safety, the product should not design with sharp edges or rough surfaces in locations that the user may injure themselves. All the components must be installed to prevent falling parts as the vehicle having its normal movements. As this product activate with the ideal safety, it can bring the complete silent and maximum focus for the driver and passengers as the vehicle cruising on roads without bringing any unwanted problems. These are all for the safety of passengers and driver of the vehicle, and the longevity of the system itself.

5 IMPACT OF ENGINEERING SOLUTIONS

Unwanted acoustic noise has become more and more of a problem as the number of cars on the road increases. Traditionally, the approach to control this noise was passive, it included barriers, enclosures, or essentially any material that could act as insulation; typically foam. Though these passive silencers were effective in a board frequency range, they are typically large, costly, and ineffective at low frequencies [7]. Additionally, passive silencers add weight to the car, which, negatively affects CO_2 performance. It has become clear, passive silencers are not the way of the future.

In comes Active Noise Control (ANC); ANC is a fairly new technology that is developing rapidly because it provides solutions that passive techniques could not. ANC comes with benefits of size, weight, volume, and cost. ANC involves an electromechanical system that cancels the unwanted noise based on the principle of superposition. Essentially, the unwanted noise or primary noise will be physically cancelled by a cancelling noise or secondary noise that is equal in amplitude and opposite in phase. The implication that ANC is active means that, opposed to passive techniques, the ANC system can adjust to a variety of noises. ANC effectively cancels low frequency noise, which tends to be the frequency that passes through the frame of the car into the space occupied by the passengers. Eliminating this low frequency noise should provide significant noise reduction. When trying to eliminate low frequency noise with passive techniques, the solution tends to be very bulky and expensive. ANC is the dominant noise cancelling solution.

The “best” or more acknowledgeable characteristic about ANC is that it can work effectively even for time-varying noise. The frequency, phase, amplitude, and sound velocity of the acoustic unwanted noise are always changing (time-varying). This requires that the ANC system be adaptive to deal with these variations, which is why ANC systems includes components such as an adaptive filter. This characteristic of ANC systems makes it a very beneficial and superior approach than that of passive techniques.

Aside from reducing cost, size, weight, volume, and indirectly increasing CO_2 performance in vehicles, it also provided solutions to the comfortability of the driver. The ANC system decrease the ambient noise in vehicles, which increases the appreciation of the drive to the consumer and makes the vehicle more appealing which gives the vehicle an edge over other vehicles that doesn’t have active noise cancellation technology.

6 LIFE-LONG LEARNING

The project provided an interesting and challenging experience to team 53. The specific project, ‘Active Noise Cancellation for Automobiles’ is an electrical engineering dominate project. The project involves advanced signal processing techniques, adjusting coefficient of adaptive filters, coding Least Mean Square (LMS) algorithms, and ensuring electrical and software compatibility on the entire ANC system.

Team 53 was initially composed of entirely mechanical engineers; However, this was very concerning to the team, so it was requested if the team could possibly have an additional electrical engineering on the team, a fourth member. Though the team received an electrical engineer, the rest of the members was faced with picking up fundamental electrical engineering principles very quickly in order to carry the weight of the project efficiently.

Typically, before being able to design and develop a system of any kind, there is a great amount of preliminary knowledge required. That is, to some degree, there is a certain skill set, and proficiency required within that skill set, before one can extend them to practical applications or beneficial use. It is necessary to understand the application and use of the tools before they become applicable. Though the team is composed of 75% percent mechanical engineers whose knowledge and studies have been primarily focused on mechanical engineering, the process and experience of completing the degree has allowed better development of mental agility, pattern recognition, and problem-solving skills. The team has developed life-long learning skills that grant the ability to learn anything and solve any problem.

The team has learned a plethora of fundamental electrical engineering knowledge within the first semester; Including, aside from what was mentioned above, what an adaptive filter is, how an adaptive filter works, what is a primary noise and what effects does it have on the system, what is a secondary noise and what effects does it have on the system, what physical principles are being used, how does the principle of destructive interference work and how that can be applied it to the system, what is a least mean square algorithm, how to effectively build the LMS algorithm to optimize the performance of the system, what noises should be canceled, how many speakers should be used, how many error sensors are need, should accelerometers or microphones be used, should the team try to completely integrate the system into the car or build a housing that contains all the hardware and place that box into the car, and where would the best placement be for that box.

So far this semester, this has been all the questions the team has had to provide solutions for. By the end of the semester, the team should increase/develop their signal processing skills, increase of C coding skills, and develop the techniques to analyze an ANC system.

7 BUDGET AND TIMELINE

7.1 Budget

Table 1: Team 53 Proposed Budget

Description of Item	Qty	Unit $	Total $
XLR cable	1	$15.99	$ 15.99
XLR cable	1	$19.99	$ 19.99
Dayton Audio EMM-6 Microphone	4	$68.25	$273.00
2 Way Audio Mixer or Switch	2	$29.99	$ 59.98
Female XLR cable to dual RCA	2	$12.99	$ 25.98
Analog to Digital converter	2	$15.99	$ 31.98
Male Coaxial to male 3.5mm jack	3	$6.99	$ 20.97
LattePanda V1.0 Edition	1	$129.00	$129.00
Case for LattePanda	1	$45.00	$ 45.00
USB to micro-USB power cord	1	$8.99	$ 8.99
12 volt car socket to 4 USB ports	1	$13.99	$ 13.99
Male USB to female 3.5mm jack	2	$10.99	$ 21.98
Digital to analog converter	1	$14.85	$ 14.85
JBL Amplifier	1	$128.00	$128.00
Boss audio systems amplifier wiring kit	1	$23.99	$ 23.99
Male XLR to Male 1/4 TRS jack	2	$8.99	$ 17.98
USB-A to USB-B	2	$4.82	$ 9.64
Male USB to female 3.5 jack	2	$7.99	$ 15.98
12v to USB power plug	1	$13.99	$ 13.99
USB to 5v circular power cord	1	$ 8.99	$ 8.99
RCA splitter	2	$8.99	$ 17.98
Presonus Audio Interface	1	$99.95	$ 99.95
3.5mm TRS to dual RCA	1	$5.93	$ 5.93
Total cost of all items	**Purchase total:**		**$1111.54**

Table 1 contains all the key components of the proposed design. All the prices were taken from the Amazon listing price. The microphones that will be used are high quality studio recording microphones. The system uses two error microphones and two reference microphones. The two signals from the reference microphones will be combined in an audio interface. The decision to combine the signals is mainly influenced by component cost. Additionally, processing two distinct signals would require that the algorithms run double, one for the left side and one for the right side, which would require more ram and processing speed and would hence make the components more costly. Combining the left and right reference and error signals (error and reference signals remain distinct) will decrease the cost significantly while reducing the overall effectiveness marginally.

Aside from the main components mentioned above, much of what is listed is connection cables and power cables. The XLR cables will be used to connect the microphones to the audio interface. The audio interface also provides phantom power to the microphones. A case and power cable were purchases to protect the DSP and provide power to the DSP, respectively. The 12-volt car socket will be the power adapter use to power the DSP. The amplifier wiring kit contains both the speaker cables and the power cables to provide signal to the speakers and power the amplifier, respectively. Lastly, Zip ties will be used to keep all the wiring neat and orderly. They will also be used to secure the microphones.

There is no readily available aftermarket ANC system that can be installed in a vehicle. With that said, all ANC systems would have to be custom built in the same manner that the proposed design will be. Starting from the ground up would require an enormous amount of engineering that the normal do-it-yourselfer would not know about. Most newer vehicles come with audio system that already has an ANC system from the audio company. However, buying a new vehicle solely for its ANC capabilities is illogical and sidesteps the point of this project.

7.2 Timeline

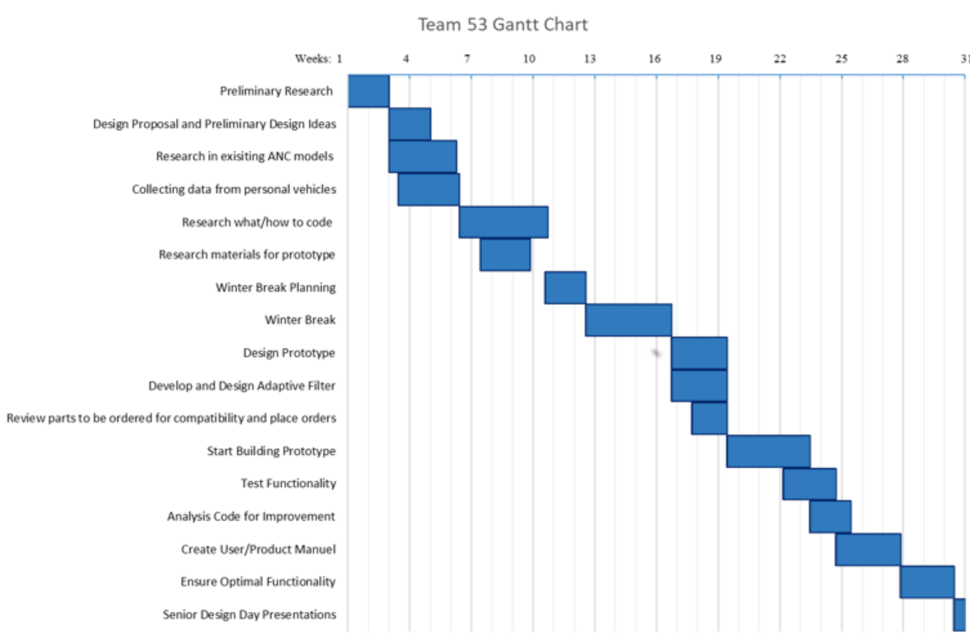

Figure 33: Team 53 Gantt Chart

Figure 18 is the Gantt chart produced for the project. The Gantt chart helps access how long a process should take, the order is which tasks should be completed, and the resources required. The process begins with determining the problem proposed and asking the client to identify key features or restraints for the design. After the problem has been identified, much research goes into understanding ANC systems. By week three the team is researching and gathering data required to determine which frequencies to cancellation and researching what to code and how to code it. Once the problem has been identified and the preliminary research gathered, the team evaluates alternative designs. The designs are evaluated by effectiveness of the system, simplicity of integration, and versatility. By week 8 the criteria to evaluate each method has been established, as well as an optimal design. By week 10, the team has a basic filtering code on MATLAB and more research is being done on the effects the cabin will have on the noise; specifically, how to properly model the filtering effects and account for it accurately in the design. By week 12 the plan is properly arranged to begin creating the prototype.

8 TEAM MEMBERS CONTROBUTIONS TO THE PROJECT

8.1 Team Member 1 – Ed Mims (MEE)

During the semester of Fall 2020, Ed researched specifications of the average vehicle electrical system to gain preliminary knowledge on what would be required of the proposed device. He also researched existing patents to gain insight on how successful companies designed their ANC systems. His main focus was on the audio aspect of the project. He analyzed audio recordings from his truck to determine the dominant frequency range and power spectrum level. He found and analyzed data from 1800+ vehicles to gain further understanding on how loud the average vehicle cabin is at varying speed. He has also researched permissible noise levels according to regulated standards and recommended noise reduction based on other ANC systems. Additionally, Ed has researched the frequencies of common noises heard in a vehicle while driving to better understand what frequency range the design should focus on for cancelation. Lastly, he has been reviewing the example FXLMS code from Dr. Liu to better understand how the ANC algorithm should function.

During the semester of Spring 2021, Ed conducted research to determine the necessary components for the prototype. He continued reviewing the provided MATLAB code and did additional investigating into C# code, primarily regarding the input and output of sound. Furthermore, Ed setup the prototype in his truck and conducted testing with it.

8.2 Team Member 2 - Fernando Olmedo (MEE)

During Fall 2020 semester, Fernando focused extensively on the functionality of an FXLMS ANC system algorithm. This includes how the system should be modeled, what data is being transferred, how the acoustic domain interacts with the electrical domain and vice versa, and the effects the primary and secondary path have on the system. Additionally, understanding what algorithms are embedded in the ANC system, why those algorithms are necessary for the complete functionality, and how to model them. Most of the semester was spend understanding the above-mentioned material and a smaller fraction was spend on considerations to the most optimal implementation method (complete integration, box in vehicle, modeled enclosure). Lastly, Fernando has researched how to determine errors in the ANC system, how to implement filtering on a digital signal processor, and overall performance analysis techniques.

During the Spring semester Fernando worked extensively with the Latte Panda. This includes some hardware setup but mainly software setup within the development board. Specifically, ensuring the correct library base for the Arduino was installed on the device and, furthermore, connecting the Arduino feature of the Latte Panda to Visual Studio. Fernando also performed extensive research on sound digitization that was essential in understand the how-to audio was being manipulated from within. Lastly, Fern wrote much of the code that allowed the prototype to operate successfully; mainly, reading in data from a microphone and sending that data through the adaptive filter. Fern performed numerous test runs of the prototype to successful reduced noise from input sound.

8.3 Team Member 3 – Mohammadreza Mir (ELE)

During Fall 2020 and Spring 2021 semesters, Mohammadreza researched about designs/prototypes of active noise cancellation and how the device analyzing the noise and sending anti-noise by ANC system. The result of the research was focusing on Codes in different languages such as Assembler in studio 7 and C in Dev-C++ compiler. The research and learning about coding were not enough for this design and it needed to use more professional compilers such as MATLAB and Simulink. It was needed to use previous years ideas and codes to boost this design much further. Thankfully, Dr. Liu introduced Mohammadreza to previous year team (Team 32) and Mr. Alvin (Team 32 member: Coding task) sent some important materials to Team 53 for better performance during full semester. Unfortunately, last semester Team 32 could not finish their project, but Team 53 did much better as expected. This design completed within Spring 2021 semester. On this paper, Mohammadreza mostly researched about choosing proper microphones for this design and studies about best possible locations for implementation of devices in vehicle without putting occupants (Driver and passengers) in danger and making problem for the vehicle systems.

8.4 Team Member 4 – Raul Hernandez (MEE)

During the first semester, Raul researched about the control system optimization, it consisted of four main topics the maximum levels of attenuations is possible in a ANC system depending on the placement of the reference microphones, the maximum performance of the ANC system can be determined by the location of the errors sensor, which must be able to sense all parts of both the primary and control signals, after the control source and the sensor error have been optimized, the maximum performance will be limited by the quality of the reference signal, and the final performance limiting factor will be the performance of the electronic control system. Also, did research in some existing ANC system such as the Harman RNC system, the ANC system of the Nissan Altima and the ford focus. Those systems have multi-channel ANC system that were able to reduce the Ambiental noise inside the vehicle cabin by 3 dB. Also, did research in the components of the system to and how to assemble the system as well as look at different ANC algorithm.

9 CONCLUSIONS

In conclusion, active noise control relies on the simple concept that combines two acoustic waves with equal magnitude, but opposite phase that makes silence at the conjunction point, this principle called ‘destructive interference’ will be used to develop an ANC system that will cancel most unwanted noises inside the cabin of the vehicle. Inside a vehicle’s cabin the most frequent noises are road noise, tire noise, engine noise, wind noise and the HVAC noise.

These noises have a frequency range from 30 Hz up to 3000 Hz. The goal of this ANC system will be to reduce the amount of ambient noise by 5 dB to 10 dB.

The proposed system will use a FxLMS algorithm which is the simplest functional broadband algorithm and use a digital filter that converges rapidly. As stated, this system consists of two reference microphones to detect unwanted noises that will be send to the LattePanda that contains FxLMS algorithm that will generate the anti-noise wave form, that will be outputted by the integrated speakers of the vehicle to destructively interfere with the primary source, and two error microphones that will adjust the ANC system output. The proposed system will be implemented in the inside of a car, at the best of the placement for the microphones and using the existing audio of the car that will constraint to find the best placement for the output source, and the error sensor will be placed at the headrest of the seats of the vehicle. The designed ANC was able to reduce the ambient noise by 3 dB.

The designed ANC system will be cancelling most of the unwanted noises while all the realistic constraint is taking place such as to not except out limit budget, following all the engineering standards and well as the environmental and health constraints to deliver a safe system to use in any car. Further improvements can be done to increase the noise reduction such as better implementation of the FXLMS algorithm and a faster DSP.

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12 APPENDIXES

12.1 Updated Specifications

12.1.1 OPERATIONAL SPECIFICATIONS

ANC requires at least three components:

- **Power source**. Active noise cancelling (ANC) always requires a power source to detect and analysis noise and then generate a negative wave.
- **Noise detection**. One or more microphones are used to sample the ambient sound.
- **Anti-noise sound wave generator**. Once the ambient noise is sampled, an active noise cancelling (ANC) system must generate an inverted (negative) sound wave (with similar amplitude) to cancel the low-frequency noise.

12.1.2 TECHINICAL SPECIFICATIONS

Physical:

Material: Plastic

Mechanical:

Size: Must fit in a vehicle

Maximum combined weight: 10 kilograms

Electrical:

Maximum Input Voltage: 14 Volts DC

Maximum Input Current: 1.5 Amps

Maximum Output Voltage: 5 Volts DC

Maximum Output Current: 0.75 Amps

Speaker Output Frequency: 45 Hertz to 20 Kilohertz

Speaker Sensitivity: 90 Decibels

DSP:

Minimum Sample Rate: 48 Kilohertz

Maximum Input Voltage: 5 Volts DC

Maximum Input Current: 500 Milliamps

Maximum Input Impedance: 7 Kilohms

Maximum Output Impedance: 600 Ohms

Environmental:

Temperature Range: -45°C to 65°C

Operating Environment: Inside vehicle