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Design and Implementation of Active Noise Cancellation for Car Cabin on Sulaimania Roads Using Arduino Embedded System

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ABSTRACT

Car drivers hear many kinds of noise inside their vehicles' cabins, and the most annoying ones are the noise generated by tires, engines, and outside winds. Noise affects the comfort of the passengers inside the cabin, and it’s sad to say that modern cars are noisier in many kinds of noise signals due to using a lot of plastic materials in new budget cars. For expensive and luxury cars, the problem is solved by using better sound insulation materials, but for the budget ones, the approach used here is effective. It is called Active Noise Cancellation and can be done using analog or digital electronics. An operational amplifier and filters are used for the analog one, and in the digital one, signal processor chips are used. In engineering, cost reduction is a significant goal, and it is here, by using low-cost signal processor chips to achieve this, and our nominee is the Arduino processor. It is a low-cost open-source processor used in many digital control fields but not for noise cancellation, which is the concern of this paper.

Considering the moderate signal processing capabilities of Arduino processors, a decision is required on what type of cabin noise signals our nominee can remove, and our selection is road noise. To a great extent, road noise relates to its quality, and the metric of concern is road roughness. In this work, three types of roughness are considered, low, medium, and high, the noise obtained from each type is analyzed, and countermeasures were applied to reduce them. Max cancellation obtained per three types, low, medium, and high roughness are 10 to 12 dB.

Keywords: Active Noise Cancellation, Analog based Signal Cancellation, Digital based Signal Cancellation, Arduino Processor, Car Cabin Noise, Roads Characteristics, and Profiles

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تصميم وتطبيق الالغاء الفعال للضوضاء بأستخدام المعالج المدمج اردينو لطرق محافظة السليمانية

افين رؤوف همزة
ماجستر في نظام اتصالات
طالب دكتورا في معالجة الإشارات
كلية الهندسة– جامعة السليمانية التقنية
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الخلاصة

مقصورة السيارة هى المكان التى يسمع فيها الركاب والسائق العديد من الاصوات وأكثرها إزعاجا هي الضوضاء الناتجة عن الإطارات, المحرك والرياح الخارجية. يؤثر ذلك على راحة الركاب داخل المقصورة ومن المحزن أن نقول إن السيارات الحديثة الزهيدة الثمن هي الاكثر ضوضاءً بسبب كثرة استخدام المواد البلاستيكية، حيثُ ان الباهظة الثمن والفاخرة تستخدم مواد عزل صوتية جيدة و يتم حل المشكلة عن طريق ذلك.

النهج المستخدم هنا يسمى بالفعال، او الالغاء النشط للضوضاء ويمكن القيام به إما باستخدام الإلكترونيات التناظرية أو الرقمية. التناظرية منها تستخدم المضخمات التشغيلية والمرشحات اما في الرقمية فيتم استخدام شرائح معالجات الإشارة الرقمية. تم في هذا البحث استخدام كلا الطريقتين حيثُ ان الهدف في النهاية هو تقليل الضوضاء بأقل تكلفة ممكنة وذلك بأستخدام المعالج الزهيد الثمن Arduino حيثُ يعد ذلك احد ابعاد البحوث والمشاريع الهندسية.

نظرآ لمحدودية امكانيات المعالج Arduino في مجال معالجة الأشارات كان علينا تحديد الرزم الترددية التي يستطيع فيها العمل بنجاح من اجل الغاء فعال للضوضاء، وكان علينا اختيار الطرق التي يتم فيها قياس ضوضاء مقصورة القيادة، وكان ذلك.

ان جودة الطرق في اي بلد تعتمد على الوضع الاقتصادي فيهِ، وبالتأكيد تمتلك الدول الأكثر ثراءً الطرق الأفضل والنامية الأسوء، ونحنا منها. نتائج البحث خاصة بطرق محافظة السليمانية في شمال العراق (إقليم كردستان)، حيثُ تم تحليل ثلاثة أنواع من خشونة الطرق تتدرج من منخفضة الى متوسطة ثم عالية، وتم تحليل الضوضاء لكل نوع وتطبيق الإجراءات المضادة لتقليلها. افضل قيم تم الحصول عليها في معالجة الضوضاء تتدرج من 10 الى 12 ديسيبل لطرق تتدرج من الأقل خشونة الى اقساها، و على التعاقب.

الكلمات الرئيسية: الالغاء النشط للضوضاء، الالغاء الفعال للضوضاء، ألغاء الاشارات بالطريقة التماثلية، ألغاء الاشارات بالطريقة الرقمية، المعالج أردوينو، ضوضاء المقصورة، خصائص وخشونة الطرق

1. INTRODUCTION

Many kinds of noise signals accompany modern life. Equipment, devices, and tools are cheaper in price and more affordable today, but in many cases, they generate more noise. Competition between companies forced using low-cost materials and embedding more electronics for cheaper end products. In the end, the customer is the victim. For example, electric fans manufactured in the fifties and sixties of the previous century were much quieter than the ones manufactured after that. Also (in general), cars manufactured during that period were much quieter, especially for the inside cabin noise. Why is that? This is all due to competition and the run for low-cost plastic materials to have a better end product price. Here we are trying to emphasize this issue and show how we can use electronic means to reduce environmental noise to have a better life. Noise is an unwanted wave, and several noise sources inside the automobile cabin range from road, engine, structure, wind, and inside materials vibration to outside traffic. Among all, road noise is the most common and predominant. The approach used is called Active Noise Cancellation (ANC).

Active Noise Cancellation or cabin noise cancellation uses a second signal to cancel the noise signal or unwanted signal to get a quiet surround. As shown in **Fig. 1**, the ANC produces the second wave with the same amplitude and out phase as the noise signal. The ANC adds the second signal with the unwanted signal and eliminates or reduces the noise signal **(Yee, et al., n.d.).**

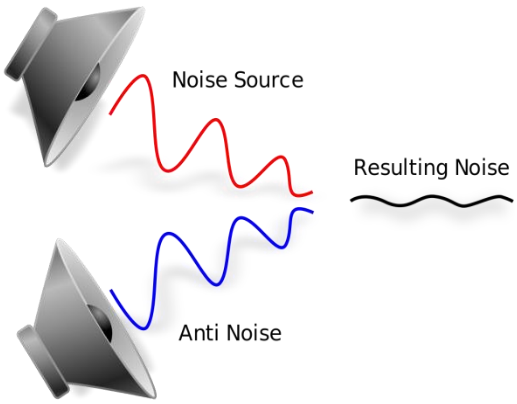


Figure 1. Active noise cancellation

Noise sources inside the vehicle can be categorized into interior and exterior. Interior noise that is heard inside the vehicle cabin comes from road tire noise, engine noise, exhaust noise, carpet noise, structure-borne noise, and wind noise **(Thilagam & Karthigaikumar, 2019) (AlDhahebi, et al., 2016)**. These are the most important noise(s) that needs to be canceled to drive cars more comfortably with a quiet cabin. Outside car cabin noise(s) are referred to as exterior noise(s), and they are usually called traffic noise **(Thilagam & Karthigaikumar, 2019).** Generally, two main techniques to overcome the aforementioned problem are Passive Noise Cancellation (PNC) and ANC. PNC depends on absorption, damping, and barriers **(Cheer, 2018)**, and it has better efficiency at higher frequencies. At low frequencies, they are less effective as the acoustic wavelength is bigger than the thickness of a typical acoustic absorber, and it is here where ANC can have an effective role. Hence, the main advantages of ANC are effectiveness at low frequencies and low cost **(Johansson, 1998)**. **Fig. 2** shows the Signal Cancellation Performance (SCP) of PNC and ANC versus frequencies **(Cheer, 2018)**.

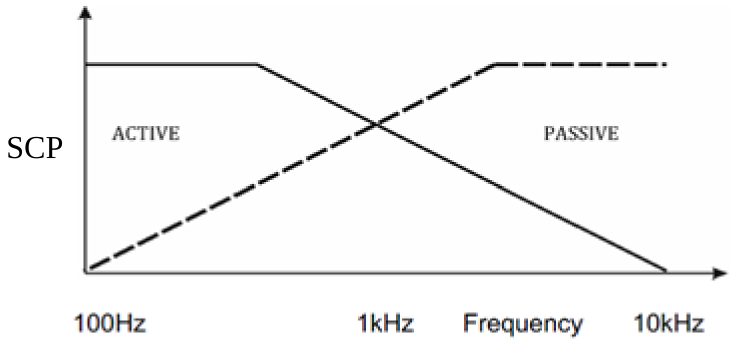


Figure 2. Performance analysis of ANC and PNC

Because of dealing with an industry-related issue in which researchers are working for companies, and their outcomes are directly fed to their sponsors, there is a lack of publicly published papers. The traces available are listed below:

Coanda first published ANC for low frequency in (1931 and 1934), but with an improper description of the physics. The beginning of ANC was started by Paul Lueg (1936, 1937), which published a patent that included the proper description and utilization of the sound cancellation inside a duct. The transducer (control source) was used to produce a secondary signal to cancel the input signal corrupted due to noise signal, thus reducing the original sound. Noise cancellations inside ducts, rooms, earmuffs, and headsets were studied by Olson in 1953 and 1956, but at that time the technology was at the state to make these systems commercially available. Commercially available systems appeared in the 1970s and 1980s due to progress in control theories and microelectronics **(Hansen, et al., 2012).**

In the 1990s era, some systems were developed successfully, such as earmuffs, active headsets, and cooling fan noise reducers. In cars, Nissan Bluebird was the first car equipped with an ANC system, and the purpose was to reduce engine noise. However, the system was not effective **(Hansen, et al., 2012)**. In 1997, Toyota installed a system to reduce interior noise according to the road profile and the vehicle velocity. The system was able to reduce 5-10 dB. In 2000, Honda Accord used a fixed feed-forward and fixed feedback controller to cancel the engine noise and road noise **(Thilagam & Karthigaikumar, 2019)**.

Currently, some companies manufacture products claiming that they have canceled annoying noises or are embedded with active noise cancellations. Although no feedback is available on how effective these systems are, they are addressed based on the company's advertisements.

Many professional headphones are labeled that it has noise cancellations. As it has been mentioned before, sound cancellation should work well for headphones because the surrounding environment is very small, as headphones are directly attached to the ear.
For headphones, and if someone visits any electronic trading platforms like Amazon or Ali-express and types "Noise Cancellation Headphones", a list of products will be shown. Here we list a sample manufactured by Sony cooperation. However, mentioning that product should not be taken as pros or cons for it, but Sony is selected as it is an old company in the field of electronic products manufacturing. We choose Ali-express, and the product name is "Used, Sony WH-XB900N Hi-Res Noise Canceling Wireless Headphone". The price is around 120 USD for the used one, and as the name refers to, it has noise cancellation.

In the case of open environments, a company manufactured a product named Muzo, and the advertisement for this product is Your Personal Zone Creator with Noise Blocking Tech **(Kickstarter, 2017)**. The cost is around 500 USD. We tried to check the product's availability on Amazon.com, but until the time of writing this article, it was not available. Although, the availability of the product on Amazon should not be taken as pros or cons, as we wittiness sometimes products on that link but they are not good (not only on Amazon but on all trading platforms).

This paper provides analysis and countermeasures applicable to road profiles available at Sulaimani, a city located in the north of Iraq (Kurdistan Region). The paper's organization is as follows: Section 2 is about road profiles. Section 3 is on recording devices and their locations inside the car. The sound pressure level is discussed in section 4. Section 5 is about used techniques in implementing ANC system by operational amplifier and Arduino. In Section 6, the program flow chart is explained. Section 7 discusses the obtained results. The conclusion is in Section 8.

2. ROAD PROFILE

For the last 30 years, reducing or canceling the noise inside the vehicle cabin has had a big role in designing and developing vehicles. One of the main concerns in the progress of vehicles is noise, vibration, and harshness (NVH) to have a quieter passenger ride. As the tires pass over roads, noise is generated and is well hearable with speeds above 60Km/h. Road noise frequency ranges from (20 - 500 Hz) and consists of vibration-induced noise and air pumping noise. By driving the tire on rough roads, air pumping noise is produced. Air pumping noise relies on parameters such as road size, tire cavities size, the pressure inside the tire, and load on the tire. However, the irregularity of the road, velocity of the vehicle, and non-uniformly tire treads pattern produce vibration-induced noise **(Jung , et al., 2019) (Sun, et al., 2015)**. According to the ISO 8606 standard, road profiles are classified into 6 classes. The threshold of various ISO Roads is defined by the roughness coefficient C_r. **Table 1** shows the road's upper and lower roughness coefficient Cr with each class **(Tud́on-Mart́ınez, et al., 2014)**.

Table 1. Road profiles categories

ANC systems design parameters are vehicle-based and need examination for various ones with different velocities and road profiles. In this work, three road profiles were considered: low roughness (Dukan road), medium roughness (Qaradagh road), and high roughness (Mergapan road), as shown in **Fig. 3**.

A. Low Roughness Road (Dukan Road)

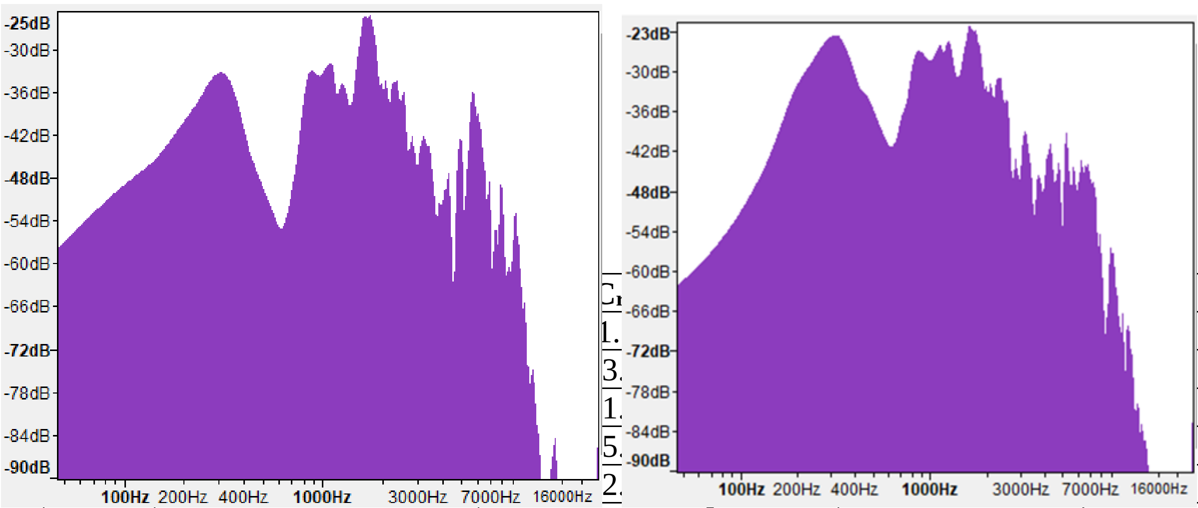
B. Medium Roughness Road (Qaradagh Road)

C. High Roughness Road (Mergapan Road)

Figure 3. Sulaimani road profile

3. RECORDING DEVICE

Two different mobiles (Huawei P20 Pro and Huawei P30 lite) were used inside the vehicle cabin to record the noise signals. To ensure having same readings, audio signals are recorded by both, and frequencies spectrum are plotted (for both Huawei P20 Pro and Huawei P30 lite), as shown in **Fig. 4**. According to the frequency spectrum, both devices have the same spectrum with slightly different amplitude, the purpose is to calibrate each device against the other.



F	Plowed field	8.2 x10^{-5}	3.3 x10^{-4}

Figure 4. Frequency spectrum analysis for **a.** Huawei p20 pro and **b.** Huawei p30 lite

Fig. 5 shows the three different locations of recording devices inside the car for measuring the cabin noise.

Figure 5. Three recording devices location inside the Toyota Yaris

4. SOUND LEVEL METER

The range of audible frequencies in human ears is between 20Hz to 20 kHz, and one of the main parameters used for measuring audio exposure to the human ear is sound pressure level (SPL). SPL is measured in dB and can be expressed as **(Vesilind, et al., 2013):**

$$SPL = 20 log \frac{P}{P_O} dB \qquad (1)$$

Where P_o= 20 µpa

For measuring SPL, a portable digital sound level meter Extech 8925, was used. The digital sound meter is fixed at the center of the testing box, about 5 cm above the ground. The digital sound meter has an accuracy of ±2dB and 0.1 dB resolution; also, it has manual and automatic ranges, as shown in **Fig. 6.**

Figure 6. Digital Sound Level Meter 8925

5. METHODOLOGY

In this study, two different methods are used to make noise cancellations. In the first method, an operational amplifier is used; in the second method, Arduino due is used. In the following paragraphs, each method's circuit diagram and hardware requirement are identified.

5.1 Cancellation using Operational Amplifier

This analog approach allows noise cancellation using an operational amplifier without any processing device. The circuit diagram is shown in **Fig. 7.** It consists of a microphone to capture the actual signal (recorded cabin noise saved as an audio file inside the computer), two operational amplifier LM358 circuits, and two speakers, one for the signal and the other for inverting it. The digital sound meter measures the SPL between the two speakers. In the beginning, the oscilloscope is used to test the signals. The operation amplifier LM358 is a dual operational amplifier with a low power drain, and it has some advantages over other operational amplifiers, as indicated in **Table 2 (Protosupplies, 2021).**

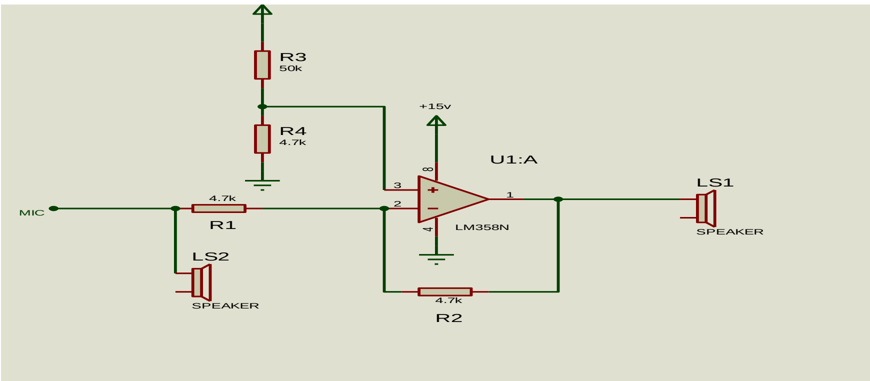


Figure 7. Noise cancellation using operational amplifier

Table 2. Features of Lm358

Features	Operating Range
Supply voltage	3-32 V
Maximum source current	30mA
Open Loop DC Voltage gain	100 dB
Max Bandwidth	700KHz – 1MHz

5.2 Cancellation by Arduino

This is the digital approach where noise cancellation is implemented through the Arduino due board. The due is a programmable board based on the Atmel SAM3X8E ARM Cortex-M3 CPU. It can be easily connected to the computer by using a power or micro-USB cable. The Arduino IDE supports a slightly modified language of C. it consists of 12 analog input, 2 digital to analog conversion (DAC0 and DAC1), 84MHz clock, 54 digital input and output, 4 hardware serial ports (UARTs), a power jack, an SPI header, a JTAG header, a reset button and an erase button. The resolution of the analog output DAC is 8 bits **(Store.arduino, n.d.)** The features of the Arduino due are explained in **Table 3.**

Table 3. Specification of Arduino Due

Parameters	Features
Microcontroller	AT91SAM3X8E
Clock Speed	84 MHz
SRAM	96 KB
Flash Memory	512 KB
Digital I/O Pins	54
Analog Output Pins	2
Analog Input Pins	12
Operating Voltage	3.3V
Input Voltage (limits)	6-16V
Input Voltage (recommended)	7-12V
DC Current for 5V Pin	800 mA
DC Current for 3.3V Pin	800 mA
DC Output Current	130 mA

The implementation of a noise cancellation system consists of software and hardware parts. Code is written for reading recorded noise signal, and an out of phase (by 180^o) signal is generated, and both are fed to DAC0 and DAC1 pins on the Arduino due. The DAC0 and DAC1 are connected to speaker 1 and speaker 2, respectively, as shown in **Fig. 8**. The sound level meter is used to measure the noise level between the two speakers at different distances for different vehicle speeds.

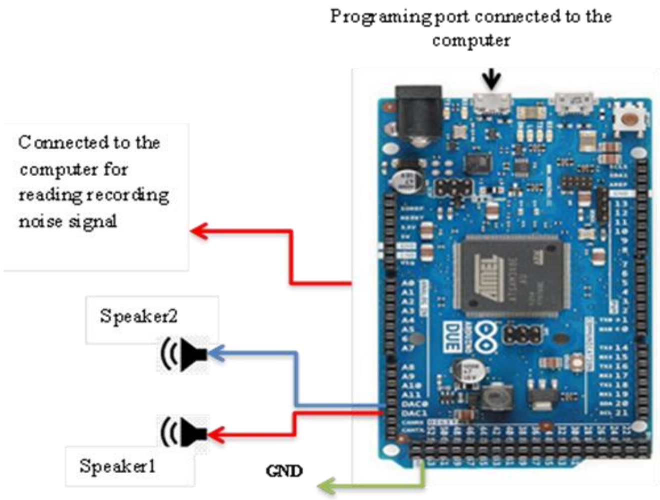


Figure 8. Noise cancellation using Arduino due

6. NOISE CANCELLATION PROGRAM FLOWCHART

Digital noise cancellation needs a program to accomplish it. This is not the case with analog cancellation which is carried by hardware as a whole. **Fig. 9** shows the flowchart of the program that carries the cancellation process.

The program starts with initializing input and output ports. It then reads the analog signal at the input port, scale, and invert it before getting sent to the output port.

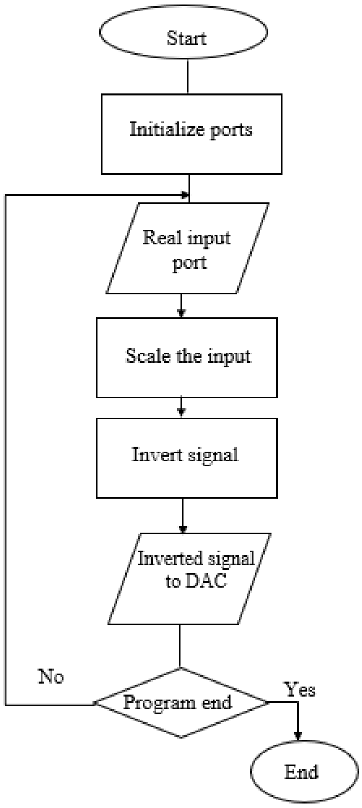


Figure9 . Cancellation program flowchart

7. RESULTS AND DISCUSSION

This study used a Toyota Yaris 2013 with 4 cylinders and a 1.5cc engine for experimental tests. The car is a budget one, and for most driving conditions, the cabin is noisy. Attempts were made to drive the car on different local road profiles that range from low roughness roads to high ones. In fact, the classification is for three types; low roughness, medium, and high. Three recording devices are placed in three locations; driver, passenger, and rear of the cabin. The recording process per location was for 5 minutes.

The recorded cabin noise is played back and fed to the signal processor board, and the processed output is obtained from DAC0 and DAC1 are fed to the two speakers. The cabin noise is recorded for different speed velocities 50 Km/h, 70 Km/h, and 90Km/h. **Fig. 10** shows the specified distance (d) and angles between speaker 1 and speaker 2. In all cases, θ1 will be equal to θ2 in value; hence θ is used instead of both in all tables.

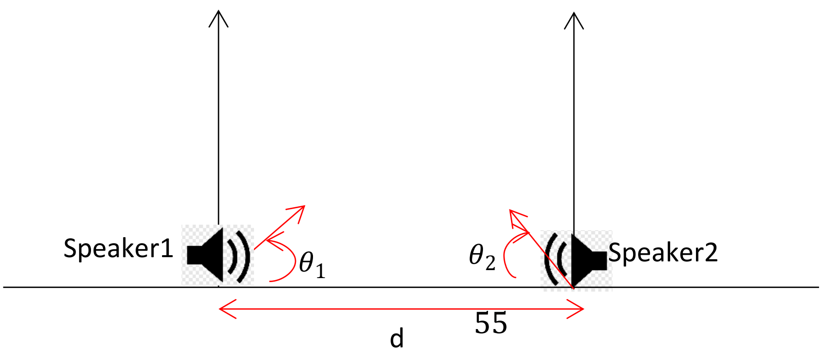


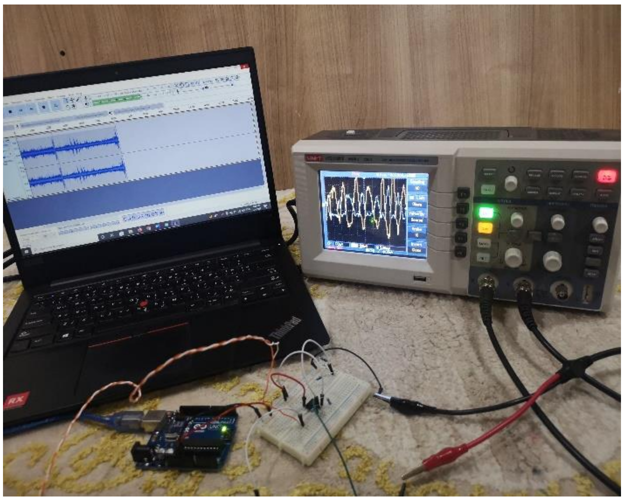
Figure 10. The distance (d) and angles (θ1 and θ2) between speaker1 and speaker2

As it was mentioned before, two techniques are used for noise reduction (countermeasures), analog and digital. The analog is through operational amplifiers (OP-Amps), and the digital is through Arduino processors.
Measured values and readings are available in Appendices A and B. It was found (in the noise recording process) that noise signal values on the driver side are close to the rear and larger than that at the passenger side by approximately 2 dB.

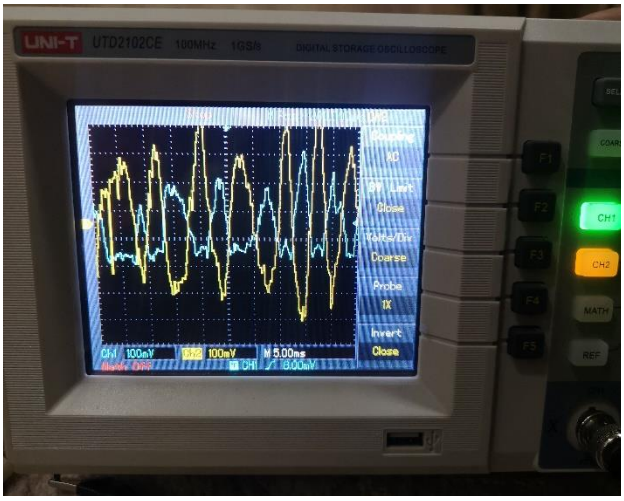
For analog countermeasures, the maximum and average noise signal levels for the low roughness (Dukan road) are 81 dB and 79 dB, respectively. The maximum and average noise signal levels for medium (Qaradagh) and high (Mergapan) roughness roads are 83 dB and 79 dB, respectively. Using the Arduino, maximum and average noise signal values for Dukan, Qaradagh, and Mergapan roads are 81: 79; 81: 79; and 82: 78 dBs, respectively.
Throughout the signal recording process, additional unwanted noise signals were encountered due to outside traffic. That was the case with Dukan road due to heavy traffic on that path. It was less severe with Mergapan as its medium traffic road. Qaradagh road has light traffic, which means that the least amount of external noise on that path was encountered.

7.1 Analog Technique:

Fig. 11.a shows the experimental setup for operational amplifier-based cancellation. The yellow signal shows the noise signal, and the blue is the anti-noise signal (noise signal inverted with the same amplitude and shifted by 180o degree) as shown in **Fig.11.b.**



a. Setup



b. Noise signal with anti-noise signal

Figure11 . Experimental set-up for operational amplifier-based cancellation

The obtained results show that cabin noise signals are obviously affected by phase angles and distances between speakers. 10 to 12 dB maximum noise reduction achieved by the OP-Amp was at a distance of 5 cm with the various phase angles of 0^o, 22.5^o, 67.5^o, and 90^o.

Fig. 12, Fig.13, and **Fig.14** show noise cancellation for 45Km/h, 70Km/h, and 90Km/h of various road profiles with 0°, 45°, and 90° phases angles at the driver side of the car. When the distance is increased, noise cancellation is less effective, the best noise cancellation is achieved at 70Km/h for low roughness for all phase angles.

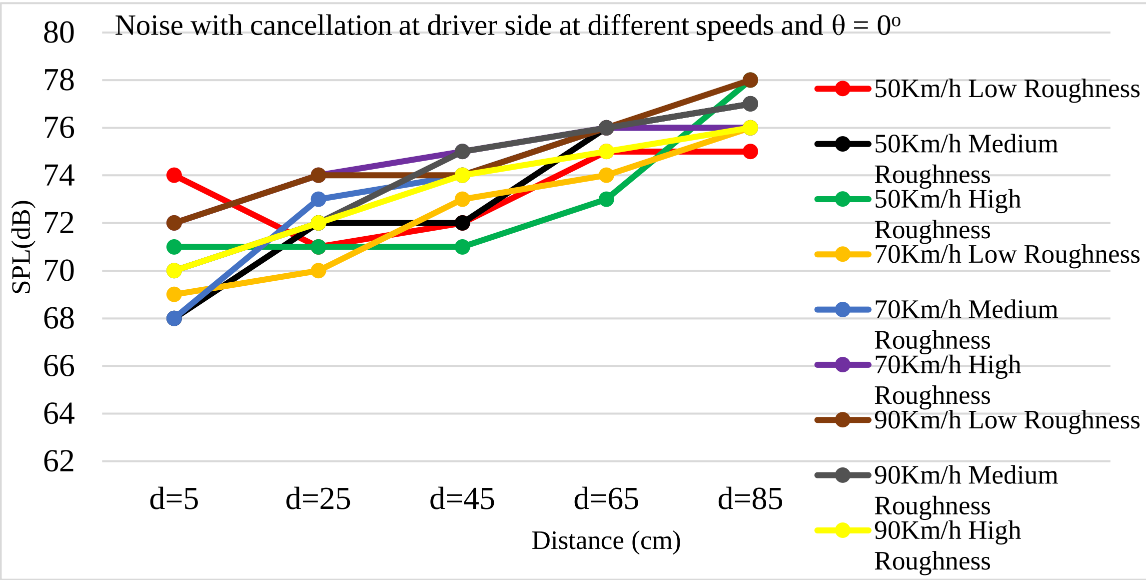


Figure 12. Noise cancellation at driver side using analog technique with θ=0°

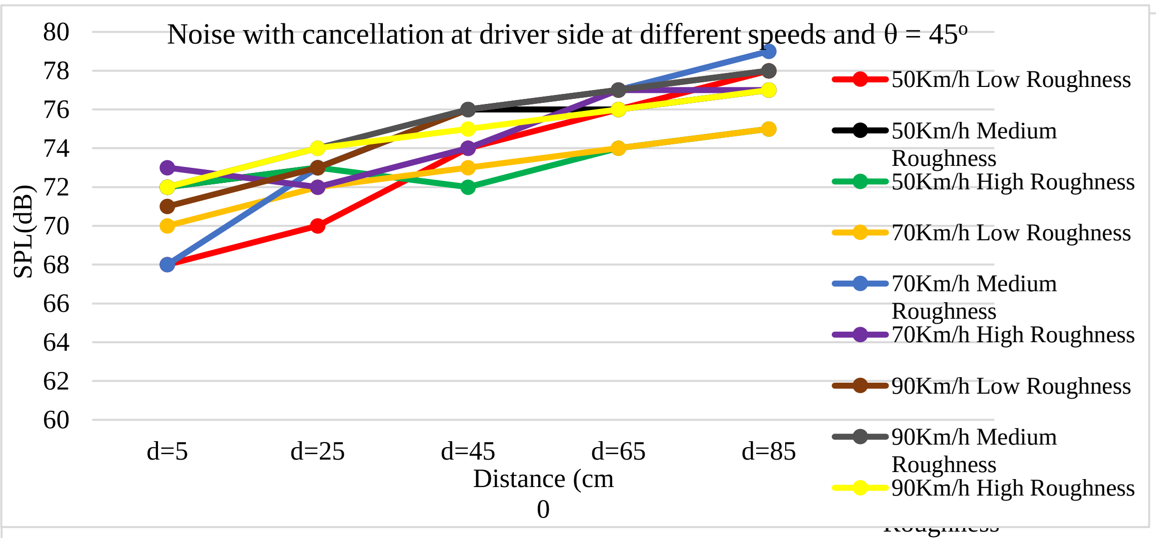


Figure 13. Noise cancellation at driver side using analog technique with θ=45°

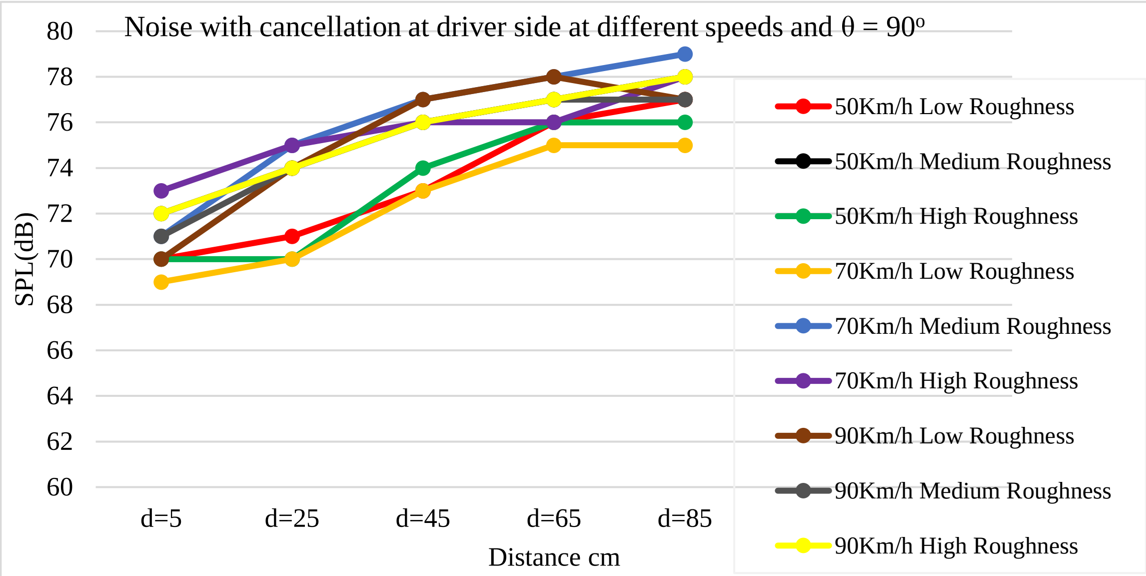


Figure 14. Noise cancellation at driver side using analog technique with θ=90º

Fig. 15 and **Fig.16** show noise cancellation for 50Km/h, 70Km/h, and 90Km/h for various road profiles with θ=0º, θ=45º, and θ=90º at the passenger side of the car. The best noise cancellation is achieved at 50Km/h for high road roughness with θ=0ºand θ=45º.

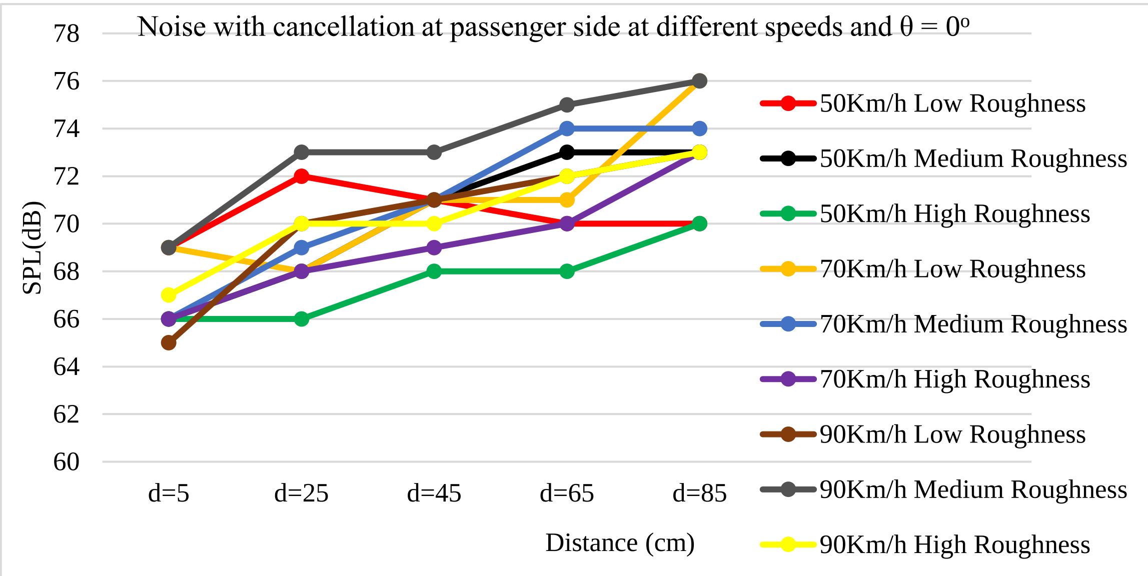


Figure 12. Noise cancellation at passenger side using analog technique with θ=0º

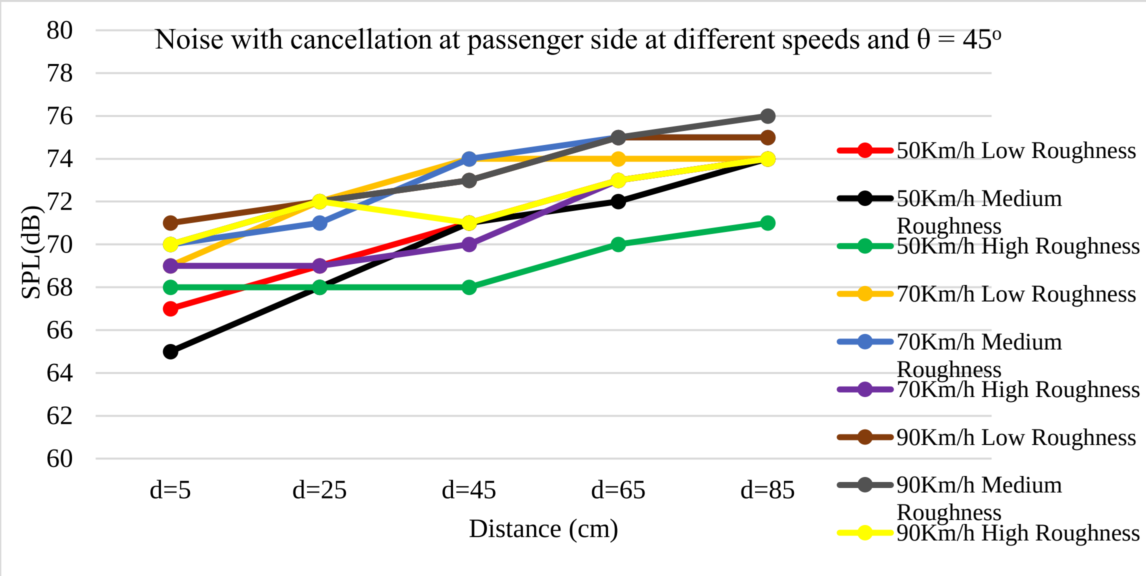


Figure 13. Noise cancellation at passenger side using analog technique with θ=45°

For noises at the passenger side, **Fig.17** shows noise cancellation at 50Km/h, 70Km/h, and 90Km/h speeds for various road profiles with θ=90°. Best noise cancellation was achieved at 50Km/h for low roughness roads.

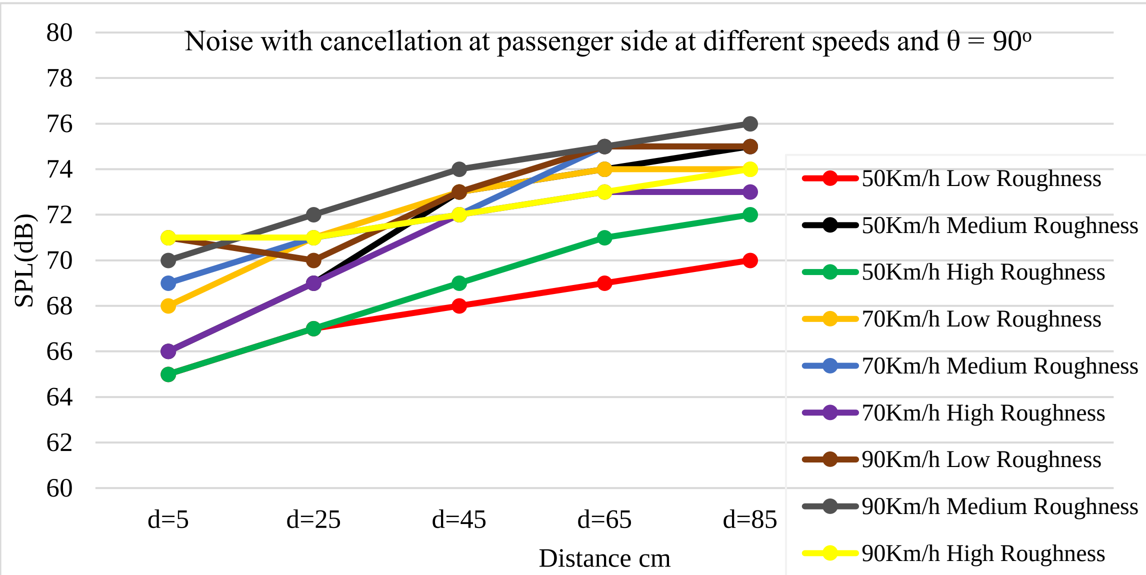


Figure 14. Noise cancellation at passenger using analog technique with θ=90°

Fig. 18, Fig.19, and **Fig.20** show noise cancellation for 50Km/h, 70Km/h, and 90Km/h for various road profiles with θ=0°, θ=45°, and θ=90° phase angles. Best cancellation is achieved at 50Km/h for medium roughness roads with 0° phase angle. For high roughness roads, the angles are 45° and 90°.

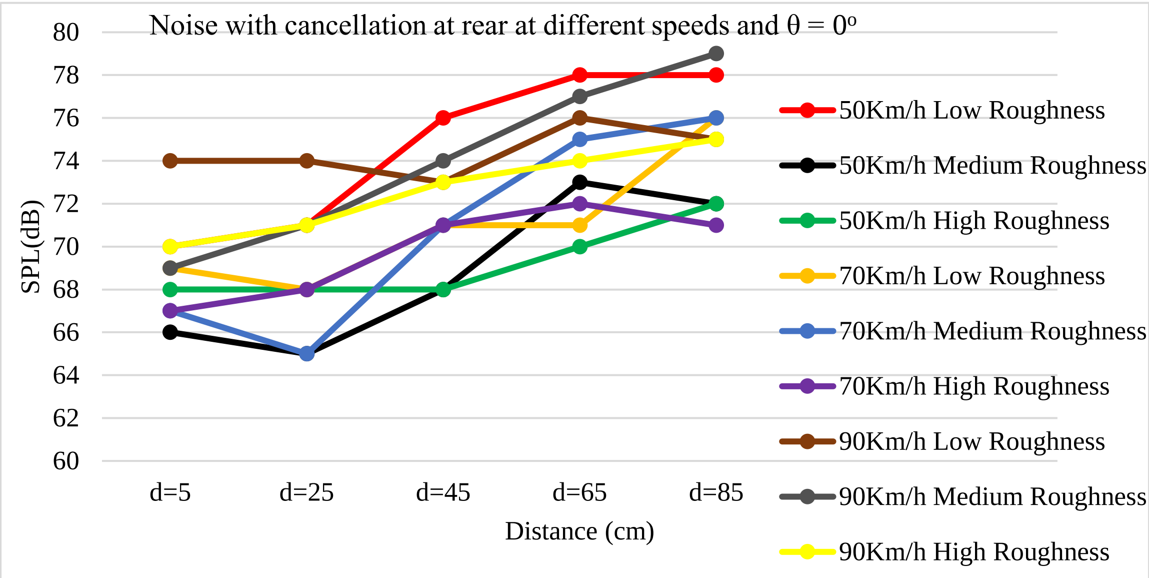


Figure 15. Noise cancellation at rear using analog technique with θ=0º

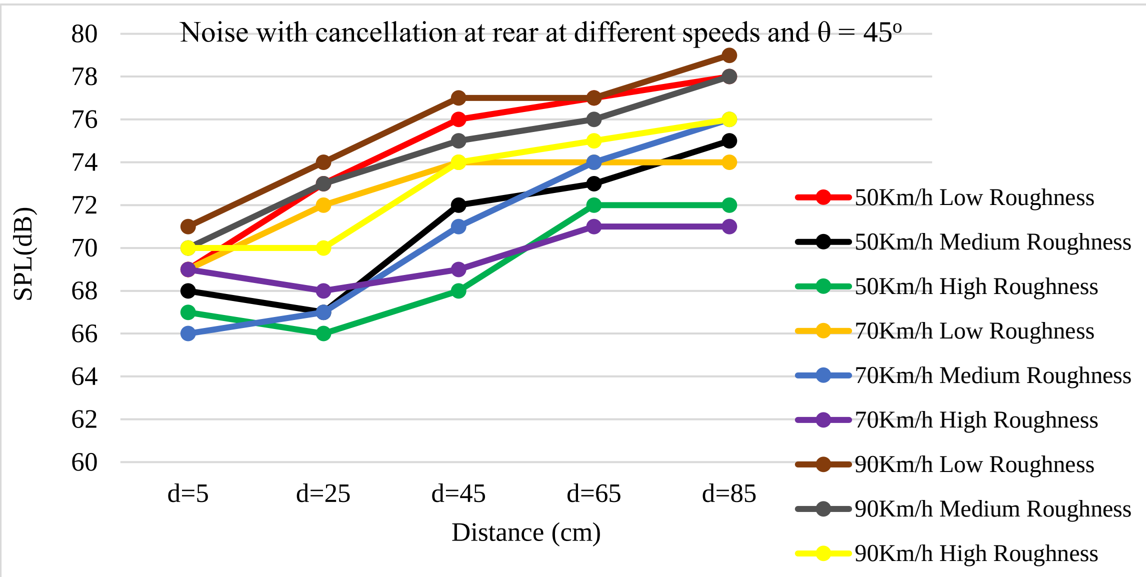


Figure 16. Noise cancellation at rear using analog technique with θ=45º

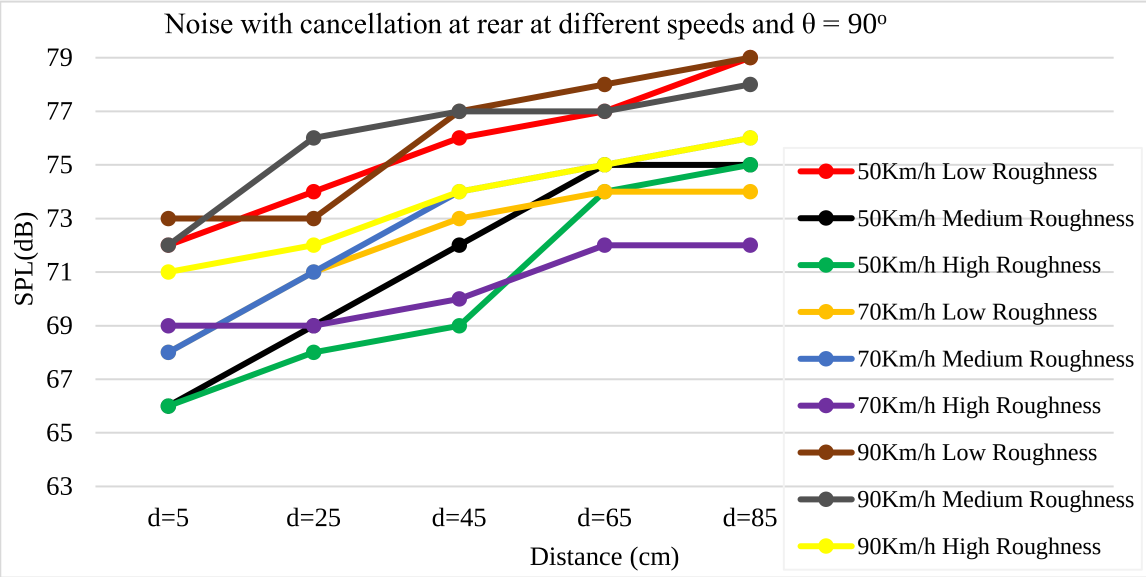
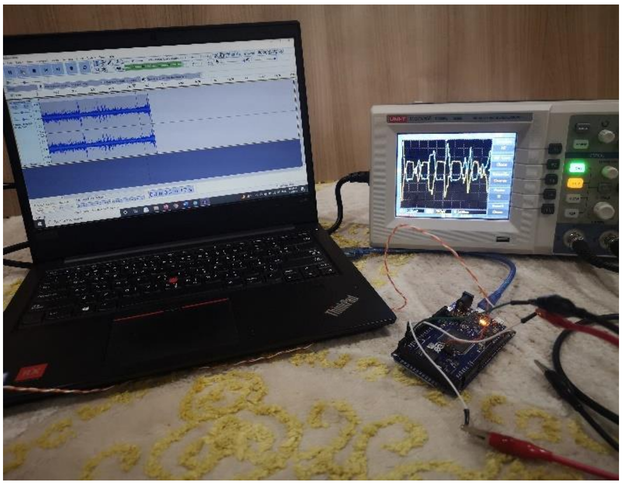
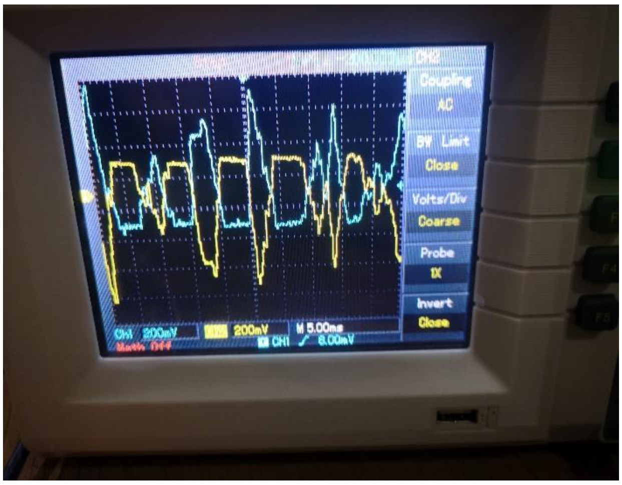


Figure 17. Noise cancellation at rear using analog technique with θ=90º

7.2 Noise Cancellation using Digital Technique:

The experimental setup for the digital approach is shown in **Fig. 21.a.** The unwanted signal is represented by the yellow signal and the anti-noise signal is the blue one, as shown in **Fig.21. b.**





a. Setup b. Noise signal with anti-noise signal

Figure18 . Experimental setup for Arduino based cancellation

In the digital approach, maximum noise cancellation values are between 10 to 12 dB at a distance of d=25 cm with 0° phase angle.

Fig. 22 and **Fig. 23** show noise cancellation for 50Km/h, 70Km/h, and 90Km/h for various road profiles with 0°, 45°, and 90° phase angles at the driver side. From the figures, the best noise cancellation values are achieved at 50Km/h for medium roughness roads at phase angles of 0° and 45°.

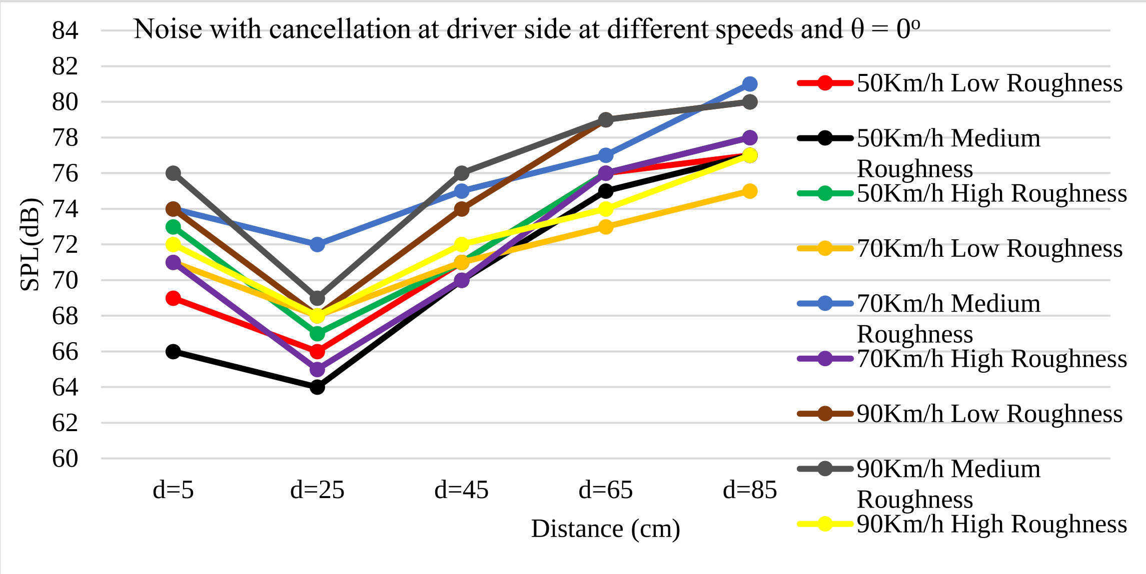


Figure 19. Noise cancellation at driver side using digital technique with θ=0°

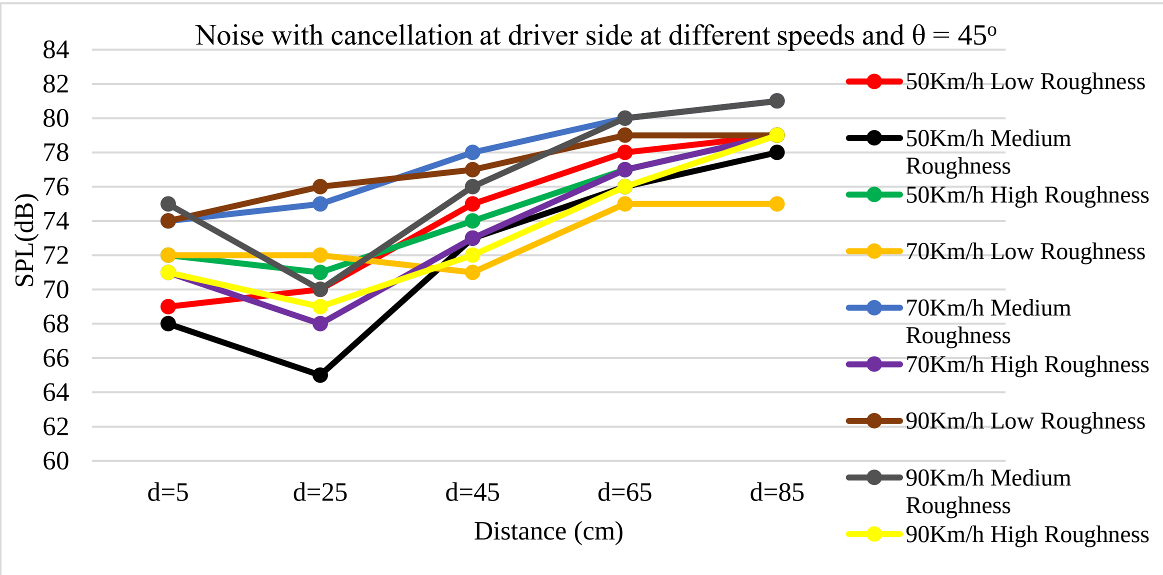


Figure 20. Noise cancellation at driver side using digital technique with θ=45°

Fig. 24 shows that best noise cancellation is achieved at 70Km/h for low roughness roads at 90°.

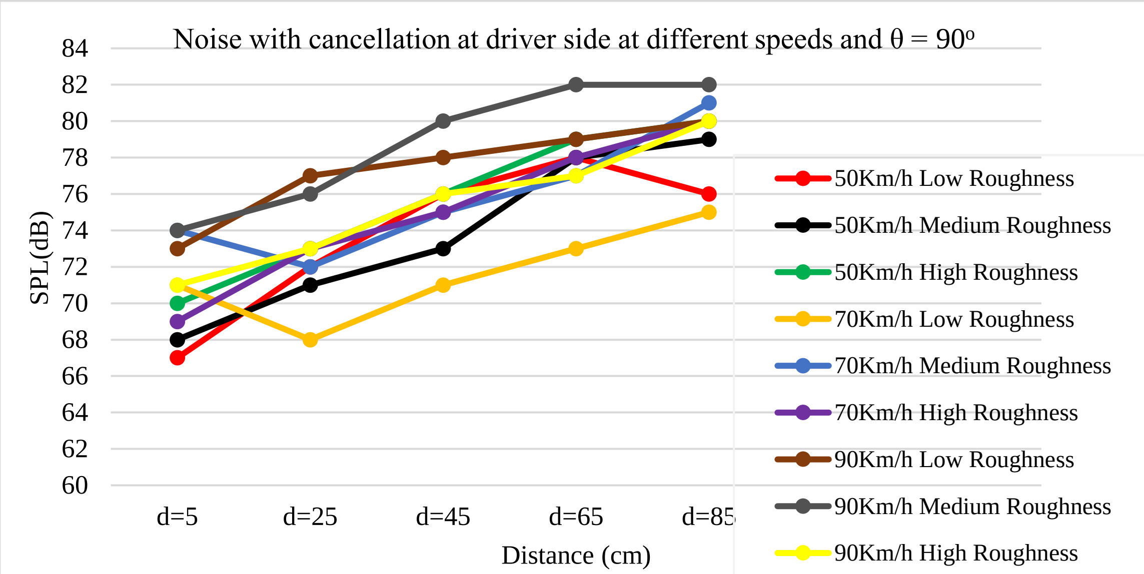


Figure 21. Noise cancellation at driver side using digital technique with θ=90º

Fig. 25 and Fig. 26 show noise cancellation for 50Km/h, 70Km/h, and 90Km/h of various road profiles with θ=0º, θ=45º, and θ=90º at the passenger side of the car. Best noise cancellation is achieved at 50Km/h for low roughness roads at angles of 0º and 45º.

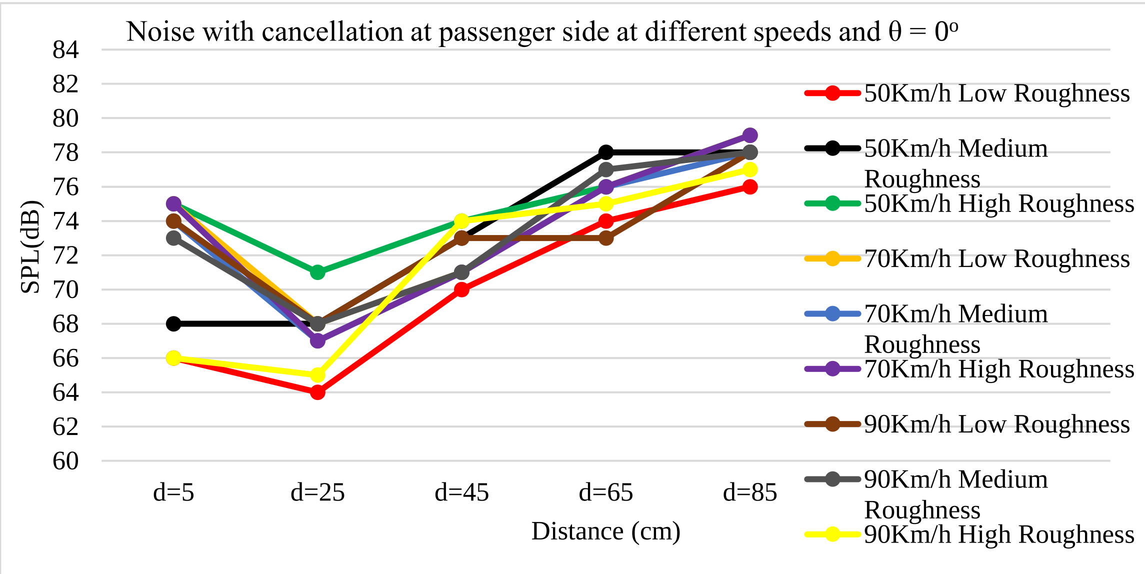


Figure 22. Noise cancellation at passenger side using digital technique with θ=0º

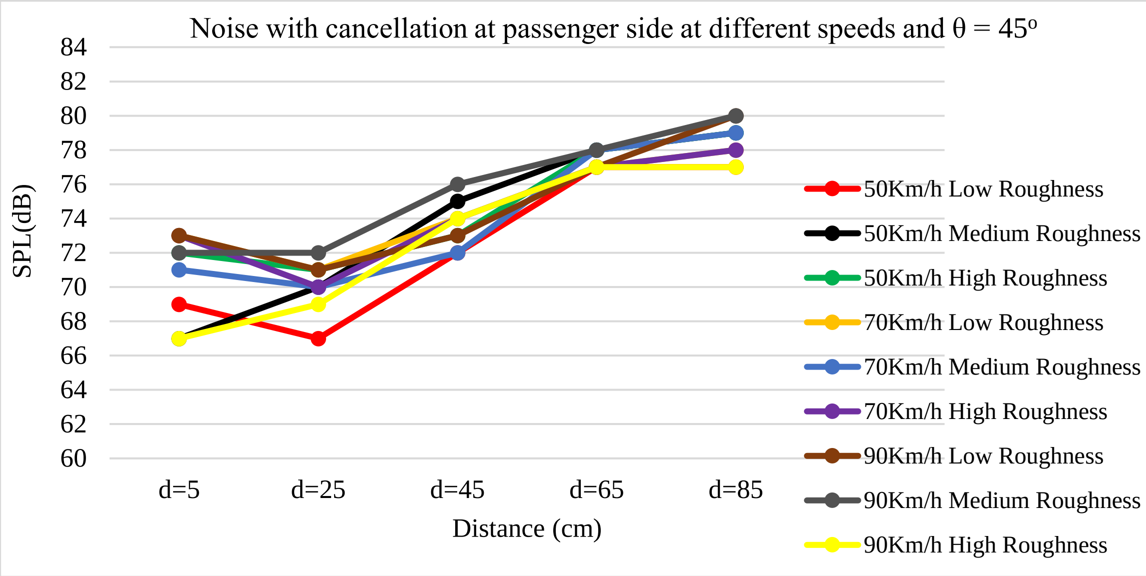


Figure 23. Noise cancellation at passenger side using digital technique with θ=45°

From **Fig. 27**, the best cancellation is achieved at 70Km/h for medium roughness for θ=90°.

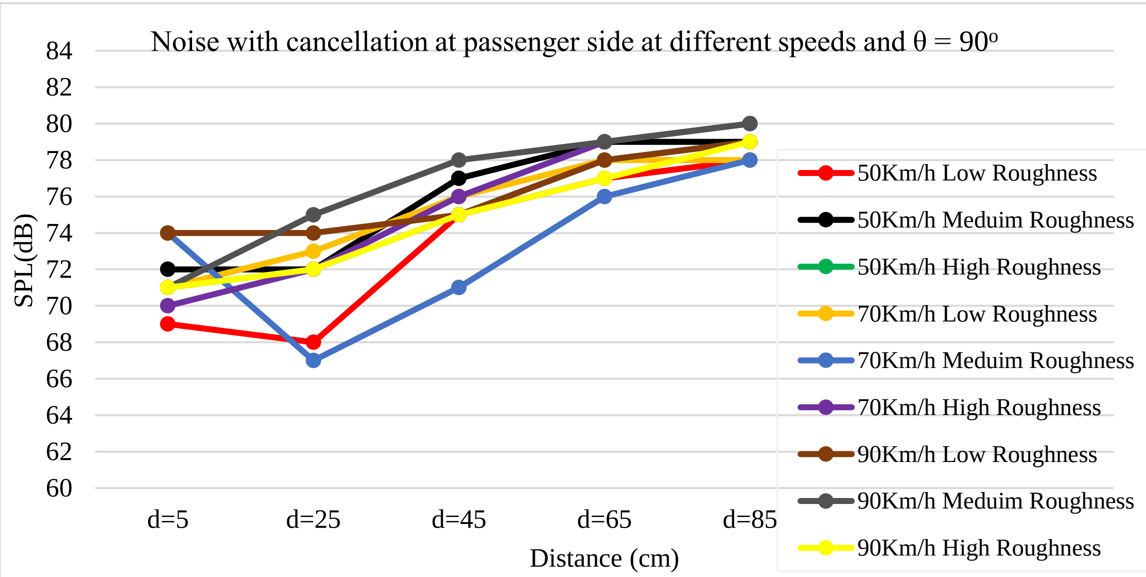


Figure 24. Noise cancellation at passenger side using digital technique with θ=90°

Fig. 28, Fig. 29, and **Fig. 30** show noise cancellation for 50Km/h, 70Km/h, and 90Km/h speeds for various road profiles with θ=0°, θ=45°, and θ=90° taken at the rear of the car. From the figures, the best cancellation is achieved at 50Km/h for high roughness for all phase angles.

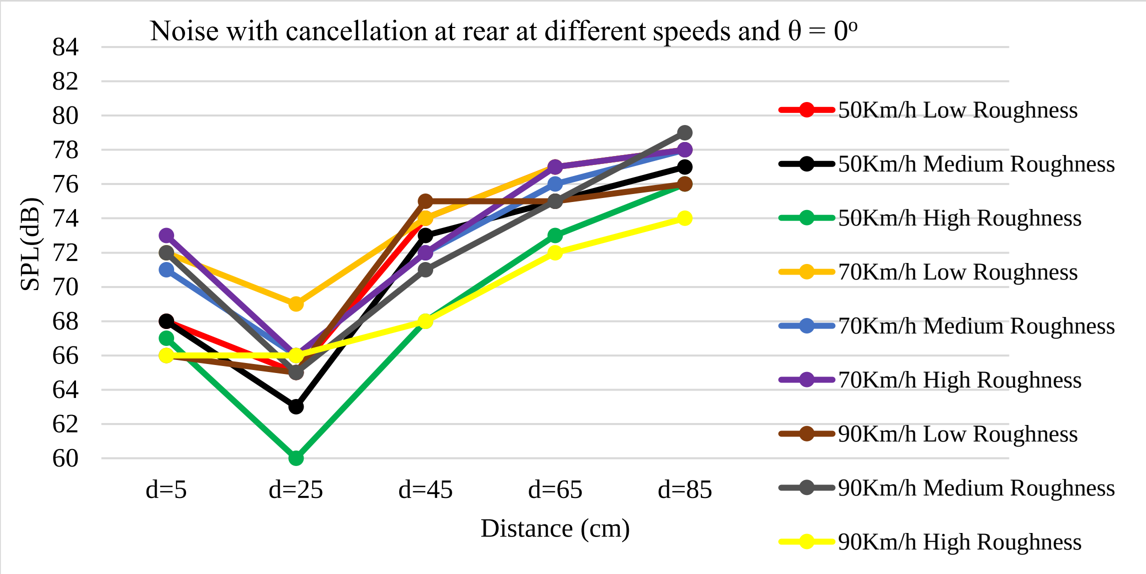


Figure 25. Noise cancellation at rear using digital technique with θ=0º

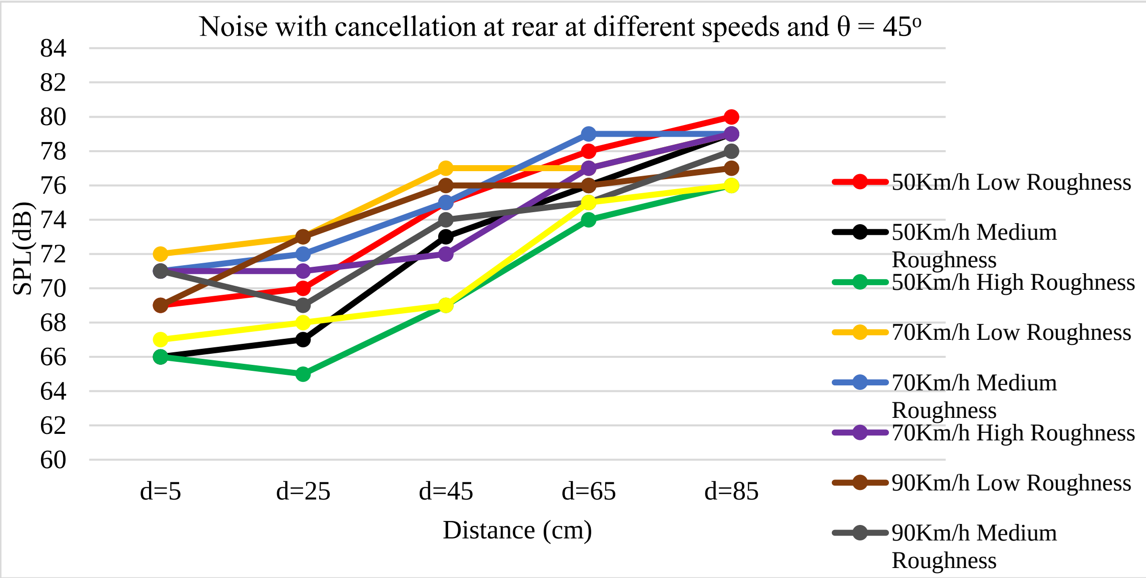


Figure 26. Noise cancellation at rear using digital technique with θ=45º

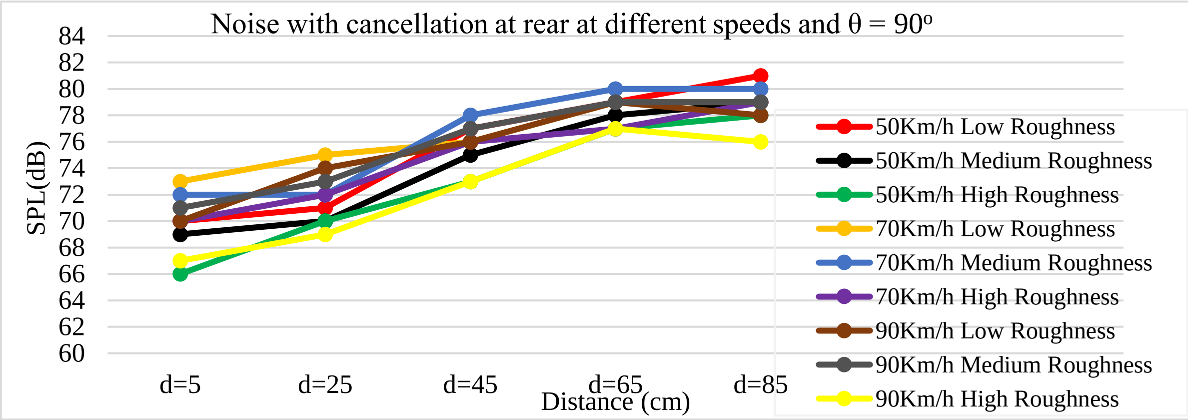


Figure 27. Noise cancellation at rear using digital technique with θ=90^o

Fig. 31 shows a comparison of curve-wise best between analog and digital techniques for the vehicle's driver side. The Arduino processor provides more cancellation compared to the analog one at 00 and 45o degrees angles.

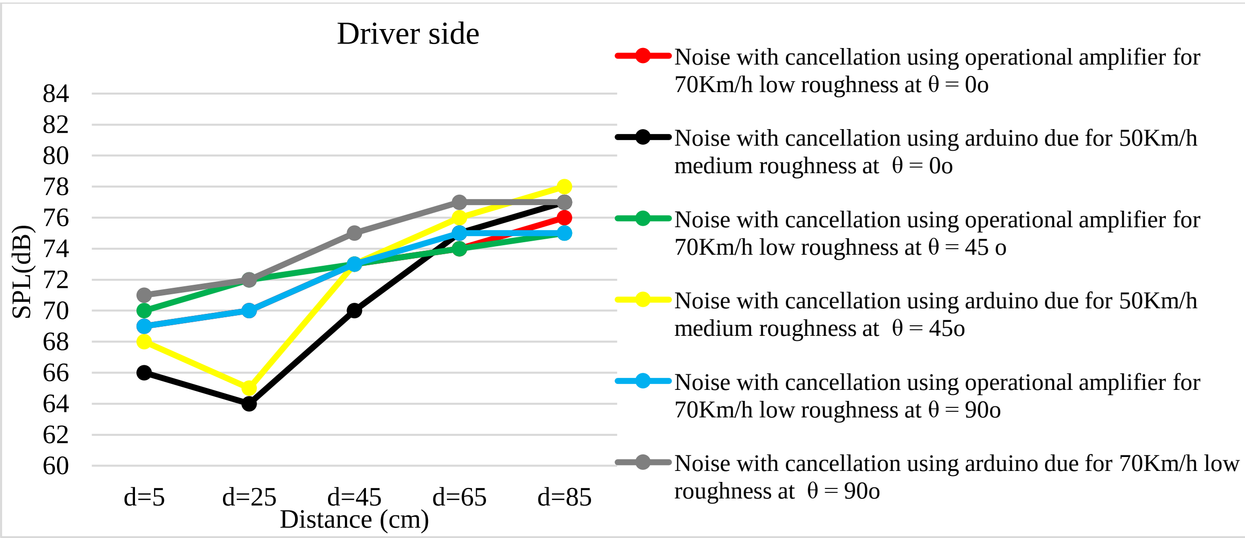


Figure 28. Comparison between analog and digital techniques at the driver side

Fig. 32 shows the curve-wise best comparison between analog and digital techniques for the vehicle's passenger side. The operational amplifier provides more cancellation compared to the Arduino processor for 0^0, 45^o, and 90^o phase angles for all distances except 25cm, at which the Arduino is more effective.

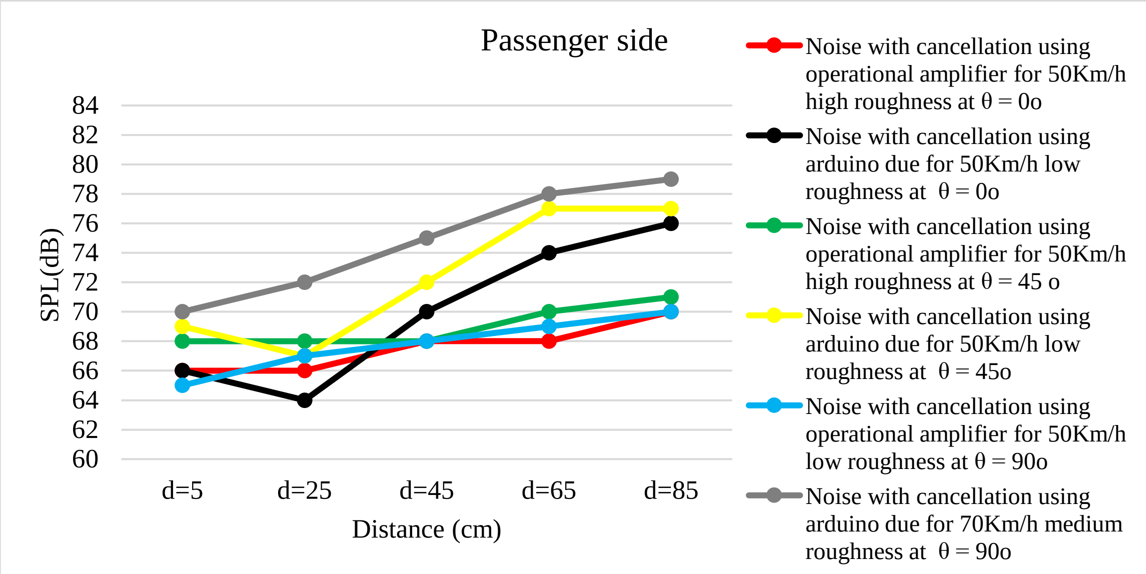


Figure 29. Comparison between analog and digital techniques at passenger side

Fig. 33 shows the curve-wise comparison between analog and digital cancellation techniques at the vehicle's rear. The digital approach provides more cancellation at distances of 5, 25, and 45 centimeters compared to the analog approach; however, at other distances, the OP-Amp is more effective.

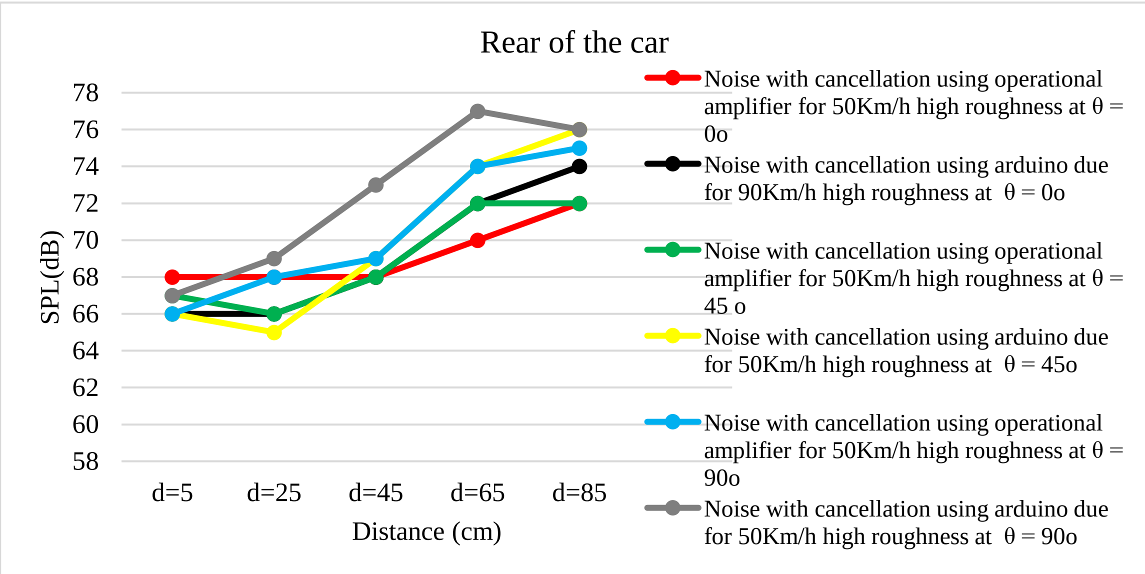


Figure 30. Comparison between analog and digital techniques at rear

Considering a real scenario where cancellation speakers are installed in vehicles. It will be hard to put speakers far from each other by 5 centimeters, but 45 cm seems logical, and that distance is our nominee. Cancellation at that distance (d=45) is around 7dB with zero phase angles between the speakers.

Results show that cancellations decrease in values with an increase in the car's velocity. Hence, the greatest noise cancellation is obtained at a velocity of 50Km/h for various road roughness. In addition to that, the digital approach offers more cancellation at 0^o and 45^o phase angles with small distances between the speakers; however, the analog approach is more effective at larger distances with 90^o phase angle.

8. CONCLUSIONS

The obtained results show the effectiveness of the noise reduction approach in reducing inside cabin noise. It was effective for all road profiles at different vehicle speeds. At this stage, the cancellation process was carried out inside a special box designed for that purpose, but the actual on-vehicle cancellation may differ from this.

Using both analog and digital techniques, good noise reduction values were obtained, which were 7 dB for a separation distance of 45 cm and larger than 10 dB for 5 cm distance (with 0^o phase angle).

The 7 dB value is more realistic as it will be hard to have a 5 cm distance between speakers in real scenarios. In addition, the digital approach was more effective than the analog one and more stable with phase angle variations.

Further works are required to separate noise frequencies to different bands and to work on band frequencies cancellation band by band. In addition, obtained results should get compared with vehicle measurements to find where deviations will occur.

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