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# Analysis of the changes impact in the construction of the vehicle exhaust silencer on the noise emission level

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**Abstract.** Each element of the exhaust system has a different function. The element that has the greatest impact on reducing the noise associated with exhaust gas discharge is the final silencer. The design of the final silencerr has a significant impact on vehicle noise. The paper presents the study of the impact of modifications of the final silencer with a construction other than the factory one on the noise emission level of the vehicle. The tests were carried out in accordance with the Polish standard PN-92/S-04051 regarding the permissible level of external noise of vehicles.

## 1 Introduction

The exhaust system of an internal combustion engine consists of a set of elements connected by exhaust pipes. The first element of the system, located directly behind the engine is the exhaust manifold, connected by pipes to the catalyst. In diesel engines, there is also a particulate filter in the system. The exhaust system is also equipped with silencers -there are two important ones: a middle silencer and rear final silencer. In addition, there are probes and sensors in the exhaust system to read information about exhaust gases. Systems such as supercharging or exhaust gas recirculation may be connected to the exhaust system.

The exhaust manifold is an element attached to the engine block, which receives the exhaust gases and leads them to a common outlet, which then connects to the catalytic converter, or to the turbocharger of the supercharger. In some designs, the exhaust manifold can be combined with an EGR exhaust gas recirculation valve. During operation, the exhaust manifold is subjected to high temperature changes resulting from the flow of engine exhaust. The thermal load of the collector requires the use of cast iron or high-quality steel for its construction, and in modern solutions it is also made of durable plastics [1,2,3,15]. Lambda sensors and exhaust gas temperature sensors are usually installed in the exhaust manifold.

The catalyst is part of the exhaust system, whose task is to minimize the emission of harmful substances. Catalytic reactions take place in it, reducing harmful compounds in exhaust gases. The most important function in the catalyst is performed by the cartridge, which includes precious metals in which catalytic reactions take place, responsible for the reduction of harmful substances from exhaust gases. The precious metals that occur in catalysts are most often platinum, rhodium and palladium [1,2,3,15]. These elements are rarely found in nature, which directly translates into a high market price of catalysts. The

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catalyst insert is usually cylindrical in shape, consisting of a very large number of narrow channels through which exhaust gases flow. In the tubules there are catalytic reactions and reduction of harmful compounds to neutral ones. For chemical reactions to occur, a high operating temperature of the catalyst is required. It is assumed that the minimum cartridge temperature at which the catalyst begins to neutralize harmful substances is 300 degrees Celsius, and the optimal operating temperature is 400-800 degrees Celsius [4,5,6,7].

Another element of the exhaust system of motor vehicles is the diesel particulate filter, most often referred to by abbreviations: DPF (diesel particulate filter), FAP (filtre a particules), GPF (gasoline particulate filter).

The task of the diesel particulate filter is to reduce particulate matter understood mainly as unburned carbon in the form of soot. The particulate filter is similar in its construction to a catalyst. The main difference is a ceramic filter with very densely arranged channels located inside the diesel particulate filter. During filtration, engine exhaust gases penetrate through the filter channels, leaving soot particles on the walls. The walls of the tubules are made of silicon carbide coated with aluminium oxide and cerium oxide. Soot particles trapped on the walls of the filter channels over time limit the flow of exhaust gases, because of this, there is a process of burning out solid particles, as a result of which soot particles turn into ash and carbon dioxide. Filter cleaning is carried out actively or passively. After reaching the right temperature by the filter – about 500 ° C, soot particles are spontaneously burned out, but this is usually a small amount, which is why the engine controller starts active filter burning every certain number of kilometres. It consists in injecting fuel into the filter using an injector mounted in front of the filter or injecting fuel into the combustion chamber just after the work cycle (in the exhaust stroke), when the exhaust valves are open. Thanks to such injection, the fuel will not burn in the combustion chamber of the engine, but only in the particulate filter, causing the burning of part of the soot deposited in the filter channels [3,4,5,6,7,16].

In the exhaust systems of modern cars, many types of probes and sensors are installed to monitor the composition, temperature and pressure of exhaust gases. The most commonly used probe in exhaust systems is the zirconium lambda sensor. It is a probe that reacts to the presence of oxygen in the exhaust gases. Zirconium probes generate a signal in the form of a voltage that arises between the outer and inner surface of a one-sided closed sleeve, which is an essential element of the lambda sensor. The sleeve is washed externally by the flowing exhaust gases, and from the inside it is in contact with atmospheric air. Based on the information recorded by lambda sensors, the engine control unit managing the operation of injectors can adjust the amount of fuel supplied on an ongoing basis so that the composition of the air-fuel mixture is as close as possible to the desired one. In the case when the fuel-air mixture is lean, there is a lot of oxygen in the exhaust gas, the voltage on the probe in this case is usually 100-200 mV. When the mixture is rich, the amount of oxygen decreases and the voltage supplied by the probe increases to 800-900 mV [3,4,5,6,7,16].

Silencers in the exhaust system are used to reduce the noise level caused by the flue gas pressure wave traveling through the exhaust system. Today, several types of silencers are used in motor vehicles [3,4,5,6,7,16]:

- *Absorption silencer* – consists of a perforated pipe with a large number of holes, which is surrounded by damping cotton wool. The exhaust gases flow through the perforated pipe, and through the holes made in it they come into contact with the damping cotton wool. Damping cotton wool is not elastic and has a significant surface area, dampens the movements of particles. Heat is generated. Vibration damping is due to mechanical friction. Mineral cotton wool, steel and glass wool is used to fill the absorption silencers.
- *Reflective silencer* – a reflexive silencer consists of several chambers and tubes of variable cross-section, arranged in series or parallel to the direction of exhaust gas flow. The principle of operation of the reflective muffler is based on repeated

reflection of a sound wave moving with the exhaust gases. The wave reflection occurs as a result of a change in the cross-section of the flue gas pipes or when the muffler element stands in the path of the exhaust gas. Repeatedly reflected exhaust gases lose their energy, and reflected sound waves fall into resonance. The loss of energy with each reflection causes the wave to be dampened. [11, 12].

- *Interference silencer*– when two or more types of vibrations meet, they overlap, i.e. interference occurs. These vibrations can be amplified or extinguished. An interference attenuator works on the principle of extinguishing sound waves of the same frequency if they overlap and are shifted in phase by half. This phenomenon can be achieved by bifurcating the main wire into two or three of different lengths, and then connecting them.
- *Combined silencer* – different damping methods are used simultaneously in a combined silencer.

## 2 Exhaust system damage study

Exhaust system elements damage depend mainly on the way that the car is used. Exhaust systems in cars used generally in the city wear out faster than those in vehicles used mainly on the road. This is due to very frequent temperature fluctuations. Cars used in cities often drive on very short distances, which causes underheating of the exhaust system, resulting in the accumulation of excess condensate and corrosion of the exhaust system. The basic factors affecting the degradation of exhaust systems include [3,11,12,17]:

- corrosion - progressive corrosion weakens the structure of the material until a cavity is formed. The resulting loss causes a leak, which results in a loud, characteristic sound during engine operation. The elements most susceptible to corrosion are places where there are welds and housings of silencers. The repair consists in cutting out corroded elements and welding new ones;
- damage to the system fasteners - the most common fault in the muzzle system suspension is mechanical damage to rubber hangers, usually caused by the exhaust system hitting obstacles on the road. Steel clamps and brackets corrode over time and need to be replaced with new ones. Rubber hangers also degrade over time. The rubber from which they are made burns and cracks with age. A cracked hanger causes knocks on the exhaust system;
- damage to the catalyst and DPF filters - in catalysts used in gasoline engines, the cartridge is most often damaged by too high operating temperature, caused by clogging its channels. The catalytic converter can become clogged by poor exhaust gas composition, especially driving on too rich a mixture or excessive consumption of engine oil by the power unit. Clogging of the cartridge leads to an increase in the operating temperature of the catalyst, which leads to its melting over time. In diesel engines, the DPF filter is very often clogged. Symptoms accompanying the clogging of the filter are: excessive smoke from the exhaust system, reduced engine power, increased fuel consumption, the controller falling into emergency mode, appearing lights from the DPF filter or glow plugs. The main reason for this phenomenon is the use of diesel engines mainly in the urban cycle. Using a diesel car for short distances causes that the DPF does not reach the right operating temperature, which makes it unable to burn the soot in the filter cartridge. Another reason for the DPF filter to clog is damage to the diesel injectors. An inadequate, too high dose of fuel causes its incomplete combustion, which clogs the filter;

- heat shields damage.

One of the ways to assess the technical condition of the exhaust system is organoleptic control, which consists in visual inspection of the exhaust system. During the inspection, noticeable system leaks, incompleteness of components and mechanical damage affecting the free flow of exhaust gases are unacceptable [13,17]. During organoleptic control, leaks in the system can be observed with the naked eye, or revealed after starting the engine. Leaks in the exhaust system emit a characteristic, easily locating sound caused by the uncontrolled release of the exhaust stream.

Another way to assess the technical condition of the exhaust system is to analyse the composition of the exhaust gases. This method allows you to diagnose the efficiency of the catalyst by analysing the exhaust gases. In this way, the quantities of individual exhaust gas components in the exhaust gases expelled can be precisely determined. The measurement consists in quantifying the contribution of flue gas components in the exhaust gas mixture by methods based on the physical or chemical properties of the individual components included in the gas mixtures. [6,7,8,14,17].

Some failures in the exhaust system cannot be checked organoleptically or by analysing the composition of the exhaust gases. Such damage may be, for example, a burned-out interior of the muffler, blocking the free flow of exhaust gases. In the event of such damage, it will be helpful to measure the pressure in the exhaust system. To do this, drill a hole in the outlet pipe and screw the tip of the pressure gauge into it. Then, when the engine is running under load, the maximum readings of the meter should be read, if the pressure exceeds 0.3 Bar, the exhaust system is not fully unobstructed [6,7,8,13,17].

## 3 Research problem

For the purposes of this work, bench tests were carried out on a real BMW model 325i vehicle, equipped with an in-line engine type: M54B25 with a maximum power of 141 [kW].

The rear end silencer of the test vehicle is characterised by a complex design. It is a reflective silencer, consisting of four resonance chambers and a set of parallel pipes, arranged in the direction of exhaust flow. Two of the three partitions separating the individual chambers are perforated. This is to disperse the sound wave moving with the exhaust gases. The loss of some energy when overcoming obstacles causes the wave to damp.

The pipes used in this silencer have variable cross-sections and construction, and in addition, some of the flue gas pipes are perforated. The wave reflection occurs when there is an element in the path of the exhaust gases and when the cross-section of the exhaust pipe changes. The sound wave is reflected in each of the places of change of the pipe cross-section, and the waves created as a result of reflection in each of the places travel repeatedly between two adjacent places of cross-section change. This reflection and scattering of waves causes the phenomenon of resonance, when the frequency of vibrations coincides with the frequency of natural vibrations of exhaust gases in the chamber in which they move [3,10].

The construction of the silencer is shown in Figure 1.

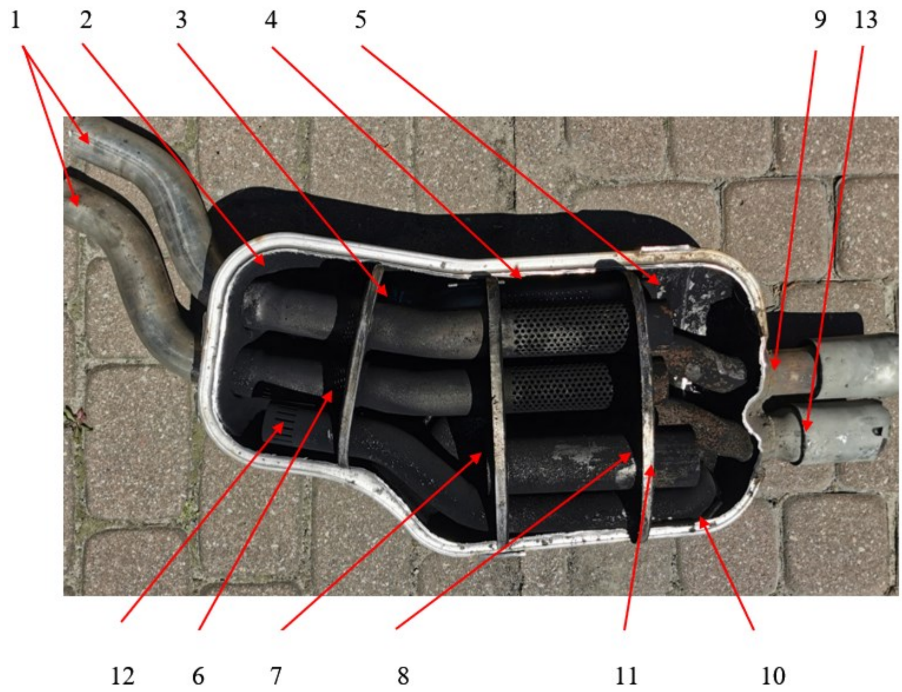


**Fig. 1.** Design of the test silencer. Silencer elements: 1 – exhaust gas supply pipes, 2 – first resonance chamber, 3 – second resonance chamber, 4 – third resonance chamber, 5 – fourth resonance chamber, 6 – internal perforated partition, 7 – internal perforated partition, 8 – full internal partition, 9 – first exhaust gas outlet pipe, 10 – housing, 11 – through pipe, 12 – exhaust pipe from chamber 2, 13 – second exhaust pipe

### 3.1. Examples of rear silencer construction change

The purpose of the construction changes to the final silencer is to analyse the impact of structural modifications to the final silencer of a non-factory design on the level of noise emitted by the test vehicle. For this purpose, the following other variants of the silencer have been proposed, which will be discussed below.

**Variant first.**

In this solution, it was proposed to change the construction of the silencer, from reflective to combined. The first stage of the modification was to cut out perforated cover 6 and shorten pipe 12 to allow holes to be drilled in the flue gas supply pipes. Then holes were drilled in the pipes in question in order to convert part of the tested silencer into a classic absorption silencer. After drilling holes, perforated pipes were wrapped with steel wool. The exhaust gases flowing through the perforated pipe, through the holes made in it, are in contact with the space filled with steel wool. Steel wadding during contact with exhaust gases dampens their vibrations due to mechanical friction. The finished silencer was mounted using clamps to the exhaust pipes of the exhaust system, and then its noise was examined using a sound level meter.

The construction of the silencer is shown in Figure 2.

**Fig. 2.** The construction of the silencer in the first variant.

**Variant second.**

In this solution, it was proposed to change the construction of the silencer from a combined silencer to an absorption silencer, consisting of perforated pipes and filling. The entire cartridge of the first version of the silencer was cut out. Inside the silencer, only the ends of the inlet and outlet pipes were left to fit the perforated pipes with them. The perforated pipes were then welded to the muffler inlet and outlet pipes. The next stage of modification activities was the wrapping of pipes perforated with steel wool. The construction of the silencer is shown in Figure 3.

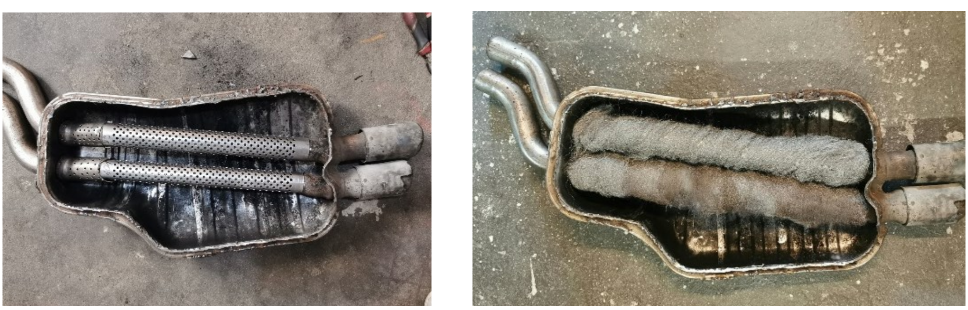

**Fig. 3.** The construction of the silencer in the second variant.

**Variant third.**

In this solution, a change was proposed, which included the insertion of an additional filling in the form of fiberglass wool into a previously made absorption silencer. For this, the muffler housing was cut open again, and an additional filling was inserted inside it. This silencer was made to investigate the effect of the use of additional filling on the noise level of a vehicle with an absorption silencer. For the modification, 400g dedicated to silencers of fiberglass wool, characterized by resistance to high temperature, was used.

The construction of the silencer is shown in Figure 4.

**Fig. 4.** The construction of the silencer in the third variant.

**Variant fourth.**

In this solution, a change was proposed, which consisted in making a through silencer. The silencer housing was cut open and the entire damping cartridge was stripped of it. After removing the cartridge, the housing was welded. The implementation and examination of the through silencer was aimed at creating a reference point in relation to previous versions with a damping insert. The construction of the silencer is shown in Figure 5.

**Fig. 5.** The design of the silencer in the fourth variant.

## 3.2. Measurement methodology

Each of the silencers made was examined with a sound level meter to examine the impact of the modifications on the noise of the vehicle. The first measurements were made on the original silencer, treated as a reference silencer. The measurements were made in accordance with the Polish standard PN-92/S-04051 [9], concerning the permissible level of external noise of vehicles. Noise level measurements should be made using a sound level meter according to PN-79/T-06460 [10] of class 0 or 1 on the correction curve A and for the time constant of the meter F (fast-fast). If the meter readings before and after measurement differ by more than 1 dB, the measurements shall be repeated. The engine speed and the vehicle speed during the tests shall be measured to an accuracy of 3 %.

The measurements were made using the UNI-T UT352 sound level meter. The height of the microphone above the surface of the test area shall be equal to the height of the tailpipe tip of the vehicle. The microphone should be directed towards the exhaust tip and 0,5 m away from it, with a tolerance of 0,01 m. The axis of maximum sensitivity of the microphone shall be parallel to the surface of the measuring area and shall form an angle of 45° with a tolerance of 10°, with a vertical plane passing through the axis of the direction of the exhaust outlet. In addition, the microphone shall be positioned as far as possible from the contour of the vehicle.

At least three consecutive measurements shall be made, each time bringing the engine to the measured speed. Only measured values obtained from three consecutive measurements not differing by more than 2 dB shall be taken into account. Otherwise, the measurements should be carried out until three values are obtained, meeting the above condition [9,10]. The diagram of the arrangement of measuring points is shown in Figure 6.

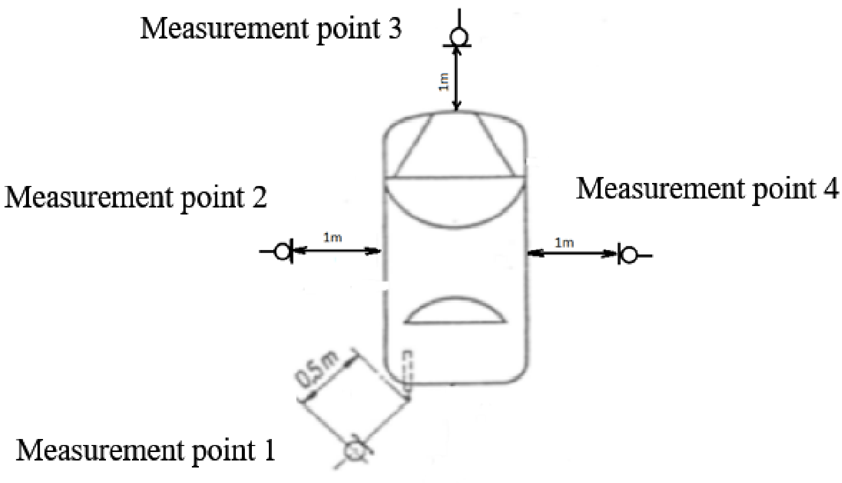


**Fig. 6.** Microphone setting for individual measurements [9,10]

For each type of silencer, measurements were made at four assumed measuring points, at idle speed of the internal combustion engine equal to 700 rpm and at a constant speed corresponding to 3/4 of the maximum engine power. At maximum power speeds of 6000 rpm, the value of the revolutions at which the measurements were made was 4500 rpm.

### 3.3. Measurement data results and analysis

In accordance with the adopted design changes of automotive silencers and in relation to test procedures in accordance with the relevant standards, bench tests were carried out. Due to the large amount of research data, only selected results of the obtained research will be presented for the purposes of this work.

Figure 7 presents the results of noise measurements at the assumed rotational speed of 700 rpm, for each of the silencers, at measuring point No. 1 - after the end silencer, in accordance with the requirements of PN-92/S-04051.

Figure 8 presents the results of noise measurements at the assumed speed of 4500 rpm, for each of the silencers, at measuring point No. 1 - after the end silencer, in accordance with the requirements of PN-92/S-04051.

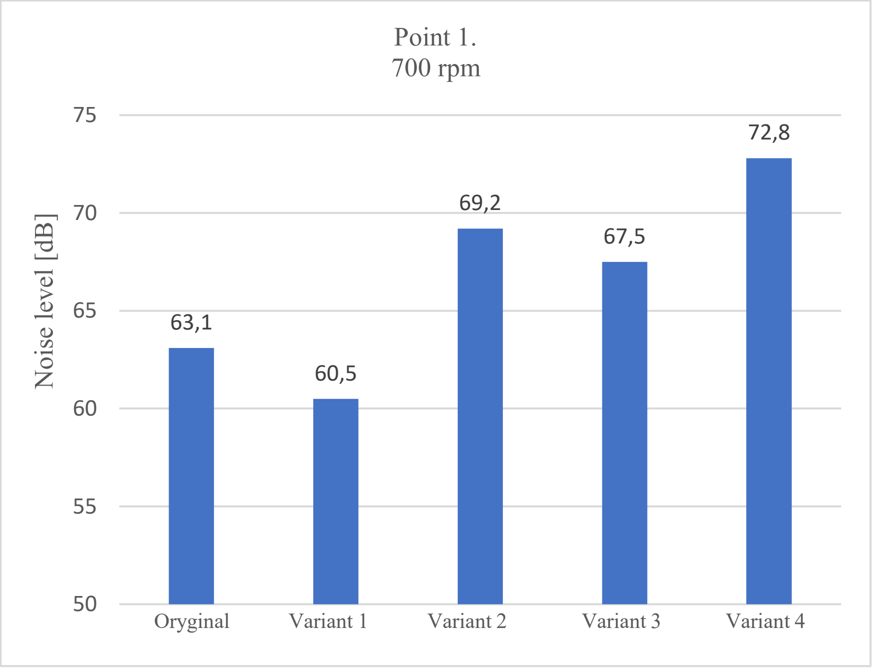


**Fig. 7.** Noise measurement results for 700 rpm rotational speed

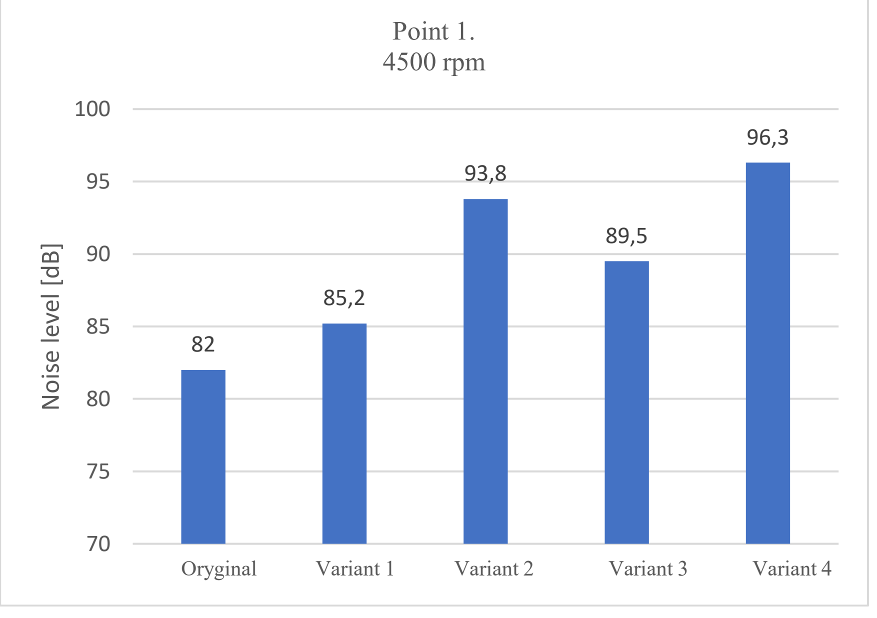


**Fig. 8.** Noise measurement results for 4500 rpm rotational speed

Figure 9 shows the results of noise measurements at the assumed speed of 700 rpm for each of the silencers at the other measuring points.

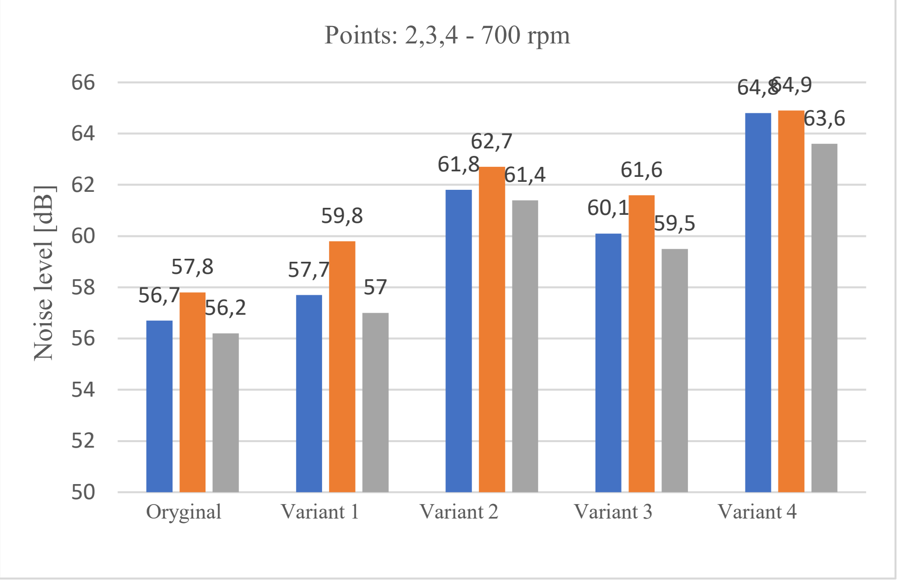


**Fig. 9.** Comparison of results for 700 rpm at measuring points 2, 3, 4

Figure 10 shows the results of noise measurements at the assumed speed of 4500 rpm, for each of the silencers, other measuring points.

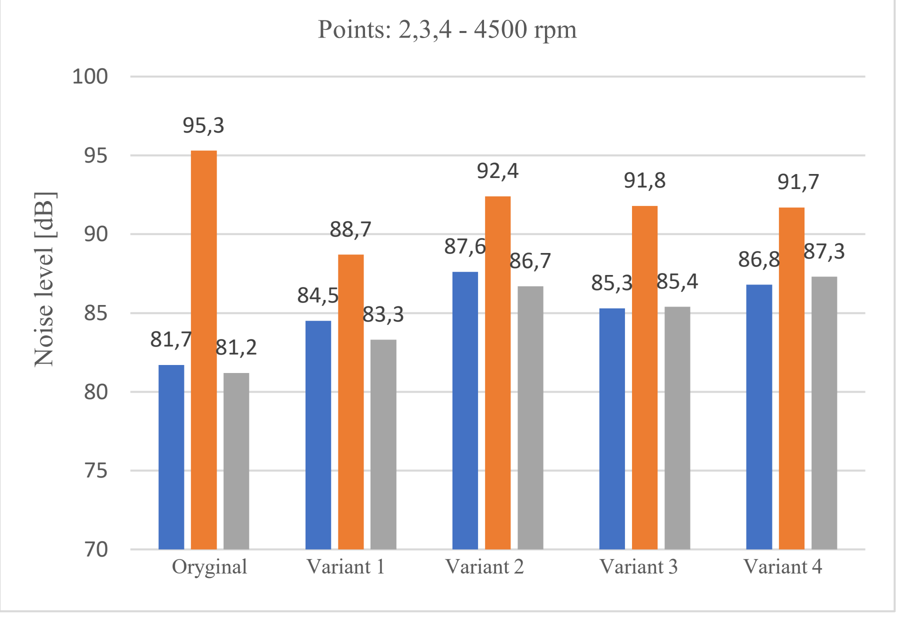


**Fig. 10.** Comparison of results for 4500 rpm at measuring points 2, 3, 4

# 4 Conclusion

The aim of the research was to analyze the impact of structural changes in the final tailpipe silencer on vehicle noise. The measurements show that the structural changes made to the final silencer under test have a significant impact on the final noise of the vehicle.

Comparing the noise level results after the installation of the first version of the revised silencer, you can see clear differences from the results of the reference silencer. When testing at engine idle, a decrease in noise level of less than 3 decibels is noticed. The situation is the opposite, when tested at high speed. In this case, the noise level on the redesigned silencer increased by more than 3 decibels. This indicates that the use of perforated pipes and steel wool in the appropriate fragment of the reflective muffler can further reduce the noise of the vehicle. On the other hand, the increased noise of the vehicle at high speed means that the application of this modification is only helpful under certain vehicle operating conditions.

In the case of the second version of the silencer, i.e. the absorption silencer with steel wool filling, an intense increase in the noise level is noticed, compared to the reference silencer. In the idle test, the noise level increased by more than 6 decibels, while in the high-speed test, by less than 12 decibels. This is a high increase in noise levels, indicating that the use of a cartridge consisting of two perforated tubes wrapped in steel wool does not produce the desired results in combination with the rest of the exhaust system on this vehicle.

The situation is different when using the second version of the absorption silencer, i.e. its typical form, having an additional fiberglass filling. Comparing the measurement results in relation to the reference silencer, a high increase in the noise level is noticed, but it is clearly lower compared to the first version of the absorption silencer. When tested at idle, the noise level is less than 2 decibels lower than the first version of this silencer, while when tested at high speeds, the difference is over 4 decibels. This proves the legitimacy of using an additional filling in the form of glass fiber in the tested silencer.

Measurements of the vehicle's noise level showed the highest values after using a hollow through silencer. The lack of a contribution does not allow to significantly reduce the noise level.

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