Energy Efficient Design and Modification of an Automotive Exhaust Muffler for Optimum Noise, Transmission loss, Insertion loss and Back pressure: A Review

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Abstract: This review paper showcases the various kinds of practical muffler designs available and attempted by several researchers and pioneers in muffler designing. The various design methodologies, design principles and lead factors that they have considered while designing is explained in this paper. The objective behind this study is to have a satisfactory knowledge about the various elements that comes into being when muffler designing is put forth to practice. The transmission loss and backpressure of the exhaust muffler, has been the key factor of consideration in most of the works done by the researchers as these have a direct impact on the engine performance, exhaust noise attenuation and finally fuel efficiency of the engine.

1. Introduction
In an internal combustion engine, the exhaust gases that emanates out of the exhaust port, produces sound waves of high intensity in a way that it creates noise of undesired amounts [1]. The burning of the fuel air mixture in the cylinders can be almost compared to a timely explosion within the cylinder. These acoustic waves have to be properly attenuated to recommended levels as per the jurisdictions of the respective country’s government under which this engine is licensed to run. Though the exhaust manifold, headers, catalytic convertors, turbo chargers or the long angled or twisted exhaust pipes that runs from the front to the rear of the vehicle provides remarkable attenuation, it won’t suffice the requirement of recommended muffling. So comes in the importance of our component in discussion, the exhaust muffler which does the rest of the work.

The exhaust muffler is basically a device that contains multiple expansion chambers, diffluent holes, perforated pipes, extended tub resonators, baffles or reflecting plates, sound absorbing materials etc. [2] all housed and dimensioned optimally to attenuate the noise within the benchmarked frequency range in consideration. The flow within the muffler or the interior design,
determines the pressure drop, velocity, noise reduction, transmission loss, insertion loss, etc. within the muffler. The muffler would use a combination of the principles of resonance, reflection, absorption, expansion etc. to meet its intended purpose [3].

2. Classification of Mufflers
Previously in the earlier ages, all we had is a narrow classification of muffler, reflective or absorptive type. But now with the advancements in design and researches done on optimal attenuation of noise, several other types are also introduced and used widely depending on the application. They are:

- Baffle Type
- Resonance Type
- Wave cancellation
- Absorptive Type
- Reactive Type
- Combination Type

2.1. Baffle Type
These types of muffler are generally cylindrical in shape, on the inside of which several baffles would be spot welded as per flow requirement. As the exhaust gases reaches the inlet of the muffler, it gets deflected to the sides one by one slightly. The intension behind this design is to avoid any wave from directly exiting the muffler without attenuation. But these has the drawbacks of low efficiency and engine power loss.

2.2. Resonance Type
Also known by the name Helmholtz resonator muffler, these contain a number of tapping with resonators attached. These resonators are connected in series to the flow line of exhaust gases. Main noticeable advantage in this kind is that there is least resistance to the straight flow of gas, so attenuation is not obtained at the expense of engine power.

2.3. Wave Cancellation Type
Also known as chambered mufflers, in these mufflers the incident sound waves after entering the muffler, happens to reflect back by a metallic wall in a way that it inverts the sound wave. These inverted waves are focused back to the incoming waves, wherein crests of the reflected wave intersects with the troughs of the incident wave, ultimately cancelling out each other. These attenuate the high frequency noise, so these mufflers produce a less annoying low frequency noise. Recent advancements in these type of mufflers uses a wave generator that sends a wave 180 degree in phase to the incident wave. These will not alter the straight flow of waves within the muffler and is the most efficient type in attenuating the noise. But its practicality is questioned owing to its high-power requirement for such a wave.

2.4. Absorptive Type
As the name suggests, these mufflers contain blankets of absorptive materials like fibre glass or glass wool, mineral wool etc. wound around the porous pipes or the inner casing of the muffler. These materials absorb sounds of different frequency. They are very efficient in sound attenuation
if wise judgment of the porosity or density of these are made and installed within the muffler. These proves its real efficiency in open flow or straight through mufflers where there is no much noise cancellation techniques utilized.

2.5. Reactive Mufflers
Reactive muffler contains many complex lumped elements for the wave to travel through. At the intersections, through a change in impedance the amount of wave energy transmitted is reduced. More of back pressure is created in these kind of muffler which affects engine performance drastically. But one sole advantage is that it is best in attenuation of noise.

2.6. Combination Mufflers
As it is named, these mufflers use a combination of various design aspects used in the above said types of mufflers. The benefit of such an approach is that the limitations of any type of muffler can be overcome by implementing a different type of design in conjunction with it. These are commonly used in all vehicles as it is effective over a good frequency range and noise spectrum [4].

3. Performance of Mufflers
When describing the performance of mufflers, the 3 main parameters that comes into being are Noise Reduction, Transmission Loss and Insertion Loss.

3.1. Noise Reduction (NR)
Variation between the pressure levels of sound of the source and receiver side is called noise reduction. Basically defined as the amount of reduction in the power of sound along the muffler from the inlet to the outlet. Equation (1) shows how it is calculated numerically.

\[ NR = L_{P1} - L_{P2} \]  
\[ (1) \]
Where, \( L_{P1} \) = Pressure level of sound at inlet, \( L_{P2} \) = Pressure level of sound the exit. Measurement of NR is easy, but there is a typical variation of pressure at the source side, owing to standing waves.

3.2. Transmission Loss (TL)
The variation of the power level of incident wave at the muffler inlet from the transmitted wave at the outlet is called the transmission loss. It can be analyzed numerically with the equation (2) [5].

\[ TL = 10\log \left( \frac{P_{w1}}{P_{w2}} \right) \]  
\[ (2) \]
Where, \( P_{w1} \) is the incident wave power and \( P_{w2} \) is the transmitted wave power. The above expression shows the difficulty of analytical measurement of TL because the decomposing of the sound field into transmitted and incident wave becomes difficult for complex systems.

3.3. Insertion Loss (IL)
It is defined as the variation in pressure level of sound wave at the receiver, with and without the sound attenuating devices or barriers. In a car muffler, this can be understood by considering a straight pipe internal configuration muffler and an expansion chamber muffler. The expansion chamber is better at attenuating the noise so it has a higher insertion loss compared to a straight through muffler and is better desired.

\[ IL = L_{P, \text{without}} - L_{P, \text{with}} \]  
\[ (3) \]
Where, $L_{p,\text{without}}$ and $L_{p,\text{with}}$ are the levels of pressure at the side of receiver of muffler end, without and with the barrier or attenuating structure in consideration whose insertion loss has to be found out.

4. Design Methodology
An exhaust muffler that is designed should satisfy the underlying five basic criteria to be accepted to be used widely in the market.

- Acoustics
- Aerodynamics
- Geometry
- Mechanical/ Material
- Economy

Acoustics: It specifies the noise attenuation required at minimum, as a frequency function. For this a thorough study on the conditions of operation has to be done, because large velocities of alternating or any steady-flow waves can alter its acoustics.

Aerodynamics: At a particular mass flow or temperature, the maximum allowable pressure drop comes under this criterion. So accordingly weighted multi-objective problems has to be formulated to incorporate the required transmission loss of the muffler.

Geometry: In the geometrical criteria, the allowable volume of muffler is concerned, its shape as well in a way that it is easily accommodated and accessible. The muffler volume need not be in excess of what is required and this can be calculated by some basic calculation involving combustion chamber geometry.

Mechanical/ Material: This criterion determines the type of material to be used, the thickness of body, depending upon the purpose of vehicle, the terrain characteristics it is supposed to traverse, the environment it is subjected to etc. Normally nowadays stainless steel is recommended owing to its durability and strength to absorb impacts or greater temperature, even though it is slightly heavier than conventional sheet metal.

Economy: The economic criteria plays a direct impact upon all these criterions. You can’t have a titanium body muffler, owing to its high durability, as it is one of the most expensive metal. In the marketplace first factor that matters is cheap production rates. So the material that is cheaply available if it performs its basic purpose neatly then it is better selected. The complexity in design which determines the type of process required to make such a design, all matters under this criterion.

In earlier decades no much importance was given to the design aspects of the component muffler. It was just designed on trial basis where in if it serves the purpose of noise attenuation then design was finalized. It did not look into any of the above criterions but may be geometry and economy.

4.1. Benchmarking and target setting
In benchmarking, the transmission loss and pressure drop targets are set by comparing the engine under examination, with the engines of same power from the market competitors. For this we take data of engine input parameters.
4.2. Calculation of target frequencies

The frequencies of sound waves that are to be attenuated, for transmission loss are calculated making use of engine maximum rpm.

Theoretical Formulation:

\[
CFR = \frac{\text{Engine rpm}}{60} \quad \text{(2-stroke engines)} \tag{4}
\]

\[
CFR = \frac{\text{Engine rpm}}{120} \quad \text{(4-stroke engines)} \tag{5}
\]

\[
EFR = n \times CFR \tag{6}
\]

Where, \(CFR\) = Cylinder Firing Ratio, \(EFR\) = Engine Firing Ratio, \(n\) = No. of cylinders, \(rpm\) = Revolutions per minute

4.3. Muffler Volume Calculation

The following equation is used to calculate the muffler volume as per theory of acoustics and expertise.

\[
V_M = V_F \times \left(\frac{\pi}{4}(d^2 \times l)\right) \times \left(\frac{\text{No. of cylinders}}{2}\right) \tag{7}
\]

4.4. Internal Configuration and Concept Design

Now that the volume of muffler required is obtained, the designer has to carefully arrive at the internal configuration and exterior design for component packaging of muffler in the vehicle. Several internal design concepts are worked on and formulated with multi-objective problems to arrive at the effective design with maximum transmission loss at least pressure drop. Several other parameters like diameter of holes to be drilled or punched on the internal tubes or pipes, its porosity and open area ratio etc. are calculated using eq.’s (8), (9) and (10).

\[
\text{Diameter of holes, } d_1 = \left(\frac{129}{\sqrt{N}}\right) \tag{8}
\]

\[
\text{Porosity, } \sigma = \left(\frac{\pi/4 \times d_1^2}{C^2}\right) \tag{9}
\]

If the porosity is decreased, the more will be the transmission loss and hence more the backpressure generated which affects the engine performance.

Open area ratio = \(\frac{\text{Perforated area}}{\text{Area of plain pipe}}\) \tag{10}

If the transmission loss and hence the acoustic attenuation properties has to be increased, then the open area ratio has to be minimum.

4.5. Virtual Simulation

From the above arrived formulations and designs, the best designs are put into software analysis using CAE simulation softwares like MATLAB, ANSYS etc. The pressure drop across the muffler can be predicted at steady wave conditions using CFD analysis. It is detrimental for the efficiency of the engine and very important before manufacturing of prototype. In the calculation of transmission loss beyond 3000Hz, the theory of plain wave will not suffice as the wave is 3D than 2D in lower frequencies. Hence the computations become more complex and barely approximate to practical results. Anyway after the virtual simulation the best two or three designs are selected for next step.

4.6. Prototype Manufacturing

While manufacturing the prototypes, a few mandatory precautions are to be followed,
• Inter chamber leakage of gases should be nil.
• Complete welding is preferred in place of stitch welding.
• Perforated and extruded tubes are to be used rather than tubes made of perforated and welded sheet rolls.
• Cold drawn electric resistance welded (CEW) or normal ERW are to be used in common.
• Flanged tubes are better preferred over flared tubes in leakage point of view, to be used as connections of muffler at the end. But this may also add to the weight and cost of the muffler.
• Jackets that are full-welded or crimped can be used.

Considering all the above precautions, a prototype is manufactured optimally that no more tooling is to be invested.

4.7. Experimental Testing and Finalization
The prototypes that are manufactured in the previous step are put to testing and verification by two-source method and transmission losses are found and verified with the simulated results. After arriving at a satisfactory requirement of transmission loss of the engine by the muffler the value is now input for the several iterations to get the least backpressure. There will be two or more iterations till we arrive at an optimum balance between the noise requirement and reduction in backpressure. Finally, the concept with best particulars are accepted and put for actual manufacturing or implementation.

5. Research Reviews
In 2005, M. Rahman et al. designed and constructed a muffler for reducing noise level. The muffler was designed for a stationary petrol engine and various noise performance characteristics were experimentally analyzed and compared with that of the conventional muffler. The low frequency noise waves are emanated off by the side branch resonator. In order to use the muffler with different engines there is tunable resonator accommodated within the muffler. Both the high and low frequency noises can be attenuated by the proposed muffler. The resonator has a working bandwidth of 110Hz, so if the residual frequency exceeds the range of this bandwidth, the resonator becomes largely ineffective [7].

M.C. Chiu and Y.C. Chang in their paper on muffler designing, published in 2011, explains their researches on side inlet or outlet type mufflers that has perforated tubes which are open ended. The designing is done using simulated annealing. In conjunction with a simulated algorithm, a 4-pole matrix system is derived in order to calculate the acoustic performance. They concluded that mufflers with perforated tubes that intrude from expansion chamber to chamber is superior in performance of attenuation to a non-perforated tube. They showed that perforated or non-perforated open ended tube incorporated multi-expansion chamber mufflers together with surface algorithm optimizer can be efficiently incorporated or optimized into the given limited space using a 4-pole transfer matrix, plane wave theory and a technique of decoupling that is generalized. They found that a three chambered non perforated intruding pipe muffler and a two chambered perforated tube muffler possesses the same noise reduction capacity, showing us that perforated tubing’s has more to do with noise attenuation [8].
In 2010, Shital Shah et al. explained in their paper about the proper and systematic steps involved in designing, developing and prototyping of exhaust muffler and its validation which will give advantages over the conventional method which will shorten the cycle time for product development and its validation [6].

Jin Woo Lee and Gang-Won Jang in their paper published in 2012, focuses upon designing topology for improving noise attenuation of muffler and betterment of characteristics of flow, without creating much resistance to flow for improving transmission loss. So they have formulated a problem of multi-objective for optimization of topology, with an intention of maximizing the transmission loss and minimizing the backpressure. The sum of the weighted TR and weighted backpressure or pressure drop is the functional objective in the formulation. Finally, in conclusion they could arrive at an optimal topology based design where they have carefully increased the weightage of minimizing the pressure drop without giving of the transmission loss. The advantage is that this could be applied to non-concentric muffler internal orientations too. It was found way better than the initial muffler design that was based on a single objective of increasing the transmission loss for obtaining maximum noise attenuation [9].

In 2013 Tachung Yang and Sheng-Shian Tsai came with the idea of designing an optimal muffler with Taguchi method. Their experiments were done for a Roots blower of 40HP. They used blankets of fiber glass with different densities inside the chamber to reduce the high frequency noises and plates or sheets with micro perforations and chambers with multiple resonance with the intention of minimizing the noise by low to medium range of frequencies. They could get a good noise reduction of 33dBA. The design they concluded. ANOVA analysis was done on the acoustic simulation results in finding performance and the sensible factors in designing. The best combination of these sensible factors was obtained by the S/N ratio and curves of S/N obtained by Taguchi method. In conclusion this work is more of an approximation to optimal designing and only a single frequency is considered. Considerations for a wide frequency range has to be done further. Improvements can be obtained by using multi objective optimizations and surface methodology responses for better design factor values and design optimization [10].

In 2014, Rahul D. Nazirkar et al. designed and optimized an exhaust muffler which has a working frequency different from the natural frequency so as to avoid resonance and hence reduce the noise. The solid modeling of exhaust muffler is created by CATIA-V5 and modal analysis is carried out by ANSYS to study the vibration and natural frequency of muffler. They conclude that Double expansion chamber gives better results as compared to single expansion chamber and that transmission loss of the muffler can be increased by adding protrusion pipe at inlet and outlet [11].

In 2014, Atul A. Patil et al. designed and constructed an exhaust system to improve the brake thermal efficiency while considering to limit the back pressure. Using CFD analysis 2 exhaust diffuser systems with different angles were simulated and backpressure variations were analyzed by inputting the boundary conditions that are corresponding to it and the system fluid properties. They concluded that there will be a reduction of the recirculation zones, with the increase in pressure of flow when inlet cone angle is increased [12].

In 2014 Xueguang Liua et.al finalized their researches in designing a muffler that is semi-active and based on H-Q (Herschel–Quincke) tube. It contains in addition, microphone to determine the incident wave potential, valves and a stepper motor which are controlled by a control system. Refer fig.1. The muffler was designed to control in the frequency range of 35-100Hz, focusing more on the lower frequency range. The controlled range of frequency could be varied by the valves and the stepper motor compensates the resonance conditions in these frequency range
automatically by the working of the control system which adjusts the length of the pipeline to meet optimal purpose. Insertion loss and transmission loss experiments were carried out and it shows that the semi-active muffler has a substantial noise reduction capacity of 35 dB transmission loss and 11 dB insertion loss in the range of 35 to 100Hz. Owing to the structural size of the muffler it is most suited to be equipped with large vehicles [13].

In 2014 there were considerable efforts done by Yue Chen and Lin Lv, in whose paper mentions about an integrated SCR-Muffler combination. They used two-load method and AVL/Boost engine model to calculate source impedance for initial inputs. 3D finite element method was used to form the transfer matrix. CFD simulations used proved that integrated SCR-Muffler increased homogeneity of NH3 and improved NOx reduction efficiency due to silencing parts used in muffler. The combination performs better in comparison to stock SCR or muffler in terms of insertion loss, pressure loss and NOx reduction efficiency [14].

In 2014, Kee Seung Oh and Jin Woo Lee deduced a two stage design process for the optimal design of a suction type of muffler used in a reciprocating compressor, being topology of acoustics and optimization of shape, aimed at maximizing the value of transmission loss at a proposed frequency. In their approach, they considered topologies through creative optimization and ratios of partition volume such the uniform partitions are obtained before subjecting them for problems concerning optimization of shape. In conclusion, through calculated and experimental verification, they validated their method of designing a suction muffler [15].

In 2014 Zhihao Zhou et.al designed and simulated an exhaust muffler for implementing in a diesel engine. This paper deals with the use of a swift method to analyze the acoustical performance of a muffler which is designed based on basic muffler theory. They designed two mufflers and the one with maximum transmission loss over a wide frequency range was chosen based on software analysis. The work that they presented is not at all focusing backpressure that the design could generate due to its wide transmission loss [16].

![Figure. 1 Model of the semi-active muffler. 1-6: Electric Valve; 7: Telescopic tube; 8: Linear rail; 9: Inner tube; 10: Stepper motor; 11: Controller; 12: Import; 13: Export; 14: Flange. [16]
In 2014 X.U. Xiao-mei et.al in their work on designing a muffler optimally, used the theory of orthogonal test. Using orthogonal theory, mufflers with complicated structures can be designed and analyzed. In their work they took the position of second baffle plate, rate of perforation of outlet pipe, diameter of connecting pipe and rate of other perforations as the levelling factors. The evaluation index was of a range of 510Hz to 640Hz. GT-Power was the software that they used for analysis of the index under the different factors. They made a design based on the orthogonal analysis table and found that the new muffler is performing better in the optimized band in terms of attenuation performance. In conclusion they have to concentrate on the several affects that a muffler focused on transmission loss alone could generate and come with a novel design that works efficiently [17].

In 2014, Jin Woo Lee put forth and validated experimentally the concept of a muffler design based on topology optimization. He incorporated the principles of making the partition volume as small as possible and locating them scientifically as in a muffler that gives optimum performance. The transmission loss was made high enough to reduce the noise during flow through the ducts. Simulations were carried out numerically and the formulated muffler design problem was solved for different targeted frequencies and different possible muffler configurations. The new formulation demands a lower volume of partition than the previous formulation which is much preferred. Among the numerical issues of applying this to 3-D design problems in acoustics, the difficulties in selecting the volume of partitions before optimization was overrun and proved experimentally [18].

In 2015 Seungjae Oh et.al came with the phenomenon of Acoustically Supercharged Energy Efficiency (ASEE), which is focused to improve the energy efficiency rather than volumetric efficiency because the energy shortage issue in compressors or IC engine. To provide as a design guide for suction muffler an Energy Efficiency Design Map (EEDM) was developed by creating the same acoustic effect as in the acoustic part of the IC engine [19].

In 2016 Vaibhav D. Prajapati presented a paper on automobile exhaust muffler, which is designed to attenuate maximum amount of noise and to make a pressure drop that takes place with minimum back pressure. The analysis was done using Ansys. The muffler was designed to improve the existing muffler of Maruti-Suzuki Wagon R car. Several models were designed and he found a few models which actually outperformed the stock muffler in aspects of pressure drop, but he could not account for the increase in backpressure. He concluded that increase in pressure loss will increase the backpressure which is not a desirable property of an automobile exhaust muffler [20].

There were research and studies by Vidya Sagar and M.L. Munjal on the design and analysis of three pass double reversal kind of muffler and they produced a paper in 2016, which emphasizes on the fact that introducing tubular bridges in the end chambers can help minimizing of free shear layer in the muffler, providing good acoustic transmission loss and further reduce backpressure. 1-D integrated transfer matrix and 3-D FEM were used to validate the results [21].

Chulho Yang et.al. in their paper published in 2010, explains the usefulness of applying theory of shell vibration at the initial stages of muffler designing, to avoid the time and economy consumption for later corrections to muffler, after it is actually made. The NVH behavior of mufflers that includes implosion, annoying buzzing tones, noises that are radiated out, rattling of component etc. can be predicted analytically by applying the theory of shell vibration in conjunction with FEA analysis and modal tests. On the basis of these theories they made an analytical model to test the natural frequency and mode shapes. They could predict the natural
frequencies of muffler shells with circular and elliptical cross-sections and also of shells with two constant radii with their mode shapes. Refer fig. 2. They concluded that using the theory of shell vibration, the various variables or parameters that come into investigation in designing of a muffler can be inputted variably to know the NVH characteristics of the muffler at the early stages of design. Thereby best combination of parameters can be used to derive the optimum results. This approach is also used to determine the shift of frequencies with change in muffler shell temperature. When the initial calculation of natural frequency is done and compared with FEA, different modification options like changing of spacing of baffles, material, shell thickness etc. and their characteristic effects can be understood in the stages of problem solving itself [22].

![A typical muffler](image)

**Figure 2.** A typical muffler [22]

In 2014, Shubham Pal et.al designed a muffler that has the provision to change the resonator length within it with the help of cylinder piston arrangement. The rest of the construction is as simple as any other muffler. Tested on a 3-cylinder engine setup, they calculated the noise level at various resonator positions or lengths of muffler in a broader context. They concluded that if we reduce the resonator size the insertion loss would be more and hence the noise reduction. Since the resonator is housed directly after the inlet pipe the higher frequency waves are minimized early and the lower frequencies by the oncoming internal configurations. The disadvantage is that the cost of this muffler is more as it has to accommodate the piston cylinder arrangement for variable resonator. This paper does not look for pressure drop, but in all it concludes that a resonator of smaller length is better in acoustic attenuation and economical [23]

6. Conclusion

This review paper explains the research works done by several authors. The designs they have found the most suited for the particular engine or device they have worked on and the methods they used to arrive at that conclusion is understood. Several principles and theories or methodologies to be used while designing an exhaust muffler is well explained in all the research works, which gives a greater understanding of designing a muffler as a science rather than as an art as in present scenario.

The above research concludes that there is a wide scope or an unexplored area of open flow or straight through mufflers which are much efficient in terms of minimized pressure drop, improved fuel efficiency and increased power at the throttle. But because the transmission loss which is essential for noise attenuation is minimum in these mufflers than a combination of
reactive/absorptive type of muffler, these are never legalized under any governments’ jurisdiction and is limited to illegal street racing cars or non-mass-produced vehicles of sport, adventure or military purposes or customized cars of car fanatics. But with advancements in science and invention of new technologies these can be made possible by incorporating the right mechanism for its effective noise attenuation and proving its worth of being a least pressure drop generator type which would finally help the engine deliver a better efficiency in terms of power and fuel efficiency. This review paper thence opens a scope for me to do research on open-flow mufflers and how they can be made legal by bringing them within the permissible limits of noise pollution.

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