Exhaust system of commercial vehicle: a review

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\textbf{Abstract}. In Automobiles like Truck, Bus, Car, and other commercial vehicles, various exhaust emission norms like Euro IV and Euro VI are considered for a non-polluted environment. This paper focuses on increasing engine and vehicle performance of commercial vehicle by reducing back-pressure and noise due to after treatment systems, considering exhaust emission norms. Back-pressure in exhaust systems is calculated with advanced Computational Fluid Dynamics (CFD) technologies like ANSYS Fluent, GT Power. Backpressure in the exhaust pipe is reduced by varying length, diameter ,number of bends, exhaust mass flow rate and bending angle of exhaust pipe. Narrow band noise in vehicles is predicted by Large Eddy Simulation (LES). Selective Catalytic Reduction (SCR) converts harmful NOx to harmless N\textsubscript{2}. SCR non-linearities are calculated by CFD code CONVERGE and TRIZ method. SCR urea deposit is minimized by proper nozzle position of urea spray. Diesel and gasoline particulate filter is used to filter particulate matter in diesel and gasoline engine respectively. This research focuses on the optimization of commercial vehicle exhaust systems.

\textbf{Keywords}: Back-pressure, CFD, exhaust pipe, noise, SCR

1. Introduction
Automobile vehicles including commercial and non-commercial vehicles are increasing day by day. Increase in environment pollution is the effect of an increase in automobiles. Commercial vehicles like Trucks, Buses are a major source of pollution. Exhaust gases coming out from Trucks or Buses should have low NOx, Hydro Carbon (HC), CO, and particulate matter emission. Various exhaust emission norms are there, from which Euro VI emission norms will be mandatory in near future in India. According to Euro VI norms NOx emissions should be 0.46 g/KWhr for heavy commercial vehicles as per the World Harmonized Transient Cycle (WHTC). Concentration of NH\textsubscript{3} slip is restricted to 10 ppm during Euro VI emission norms. Exhaust emission norms of a heavy-duty diesel vehicle for NOx is described in figure 1. These norms are defined as per Automotive Research Association of India (ARAI). Treatment of exhaust gas is a better method as it does not need engine modification. After treatment devices such as Selective Catalytic Reduction (SCR), Diesel Oxidation Catalyst (DOC) ,and Diesel Particulate Filter (DPF) is used to stick to exhaust emission norms and hereby increases engine performance [17]. Enhancing engine performance is the ultimate goal of this paper.

Engine performance plays a crucial role in emission legislation, customer comfort, and cost point of view. Engine performance can be increased by decreasing backpressure in the exhaust pipe and other after treatment systems. The decrease in backpressure leads to less fuel consumption and high
shaft power which increases the efficiency of the engine. DPF, DOC and SCR should work smoothly to meet exhaust norms. Back-pressure in the exhaust pipe is caused due to roughness of the pipe, length and diameter of the pipe, bends in pipes, and exhaust mass flow rate. In the case of SCR, back-pressure is caused due to deposit of urea on exhaust pipe wall and SCR. In the case of DPF, back-pressure is due to the deposition of particulate matter on its wall.

The demand for human comfort is increasing in the modern world along with the demands of fuel efficiency. The air intake system and exhaust, tyres and engine produces unwanted noise, it should be reduced. Narrow-band noises are produced due to exhaust emissions. Various Computational Fluid Dynamics (CFD) simulations had been done to reduce this type of noise. Higher-order spectra techniques, Large-Eddy Simulations(LES), Reynolds- Averaged Navier-Stokes (RANS) equations, and Stochastic Noise Generation and Radiation (SNGR) method had been used in past for noise reduction. SCR, DOC and DPF should work efficiently in a diesel engine. For this purpose, optimization of the exhaust after-treatment system is required which involves a coating catalyst in SCR, valve angle of Exhaust Gas Recirculation (EGR), nozzle position of urea spray etc. In this paper, gasoline engine is also taken into consideration which has focused on Gasoline Particulate Filter (GPF). A complete review to enhance the performance of diesel and gasoline engines are presented in this work by considering the exhaust system following exhaust emission norms.

![Figure 1](image.png)

**Figure 1.** Exhaust emission norms as per ARAI, India

2. Related work

2.1. Effect of parameters on back-pressure

In this, a review paper on exhaust manifold was presented. The flow of exhaust gas depends upon runner length and bend angle in the pipe. The iteration method in ANSYS Fluent would denote the optimized bend angle with the least obstruction inflow. The iteration method was slight slow, so CFD analysis can be done with MATLAB software [1]. Regeneration of DPF had been done in this project which was based on the exhaust back-pressure threshold value. Burner type DPF with real-time data of engine speed, fuel consumption, load and DPF exhaust back-pressure was considered. MATLAB had been used to plot fuel consumption depending on real-time data and mapping of DPF regeneration depending on the exhaust back-pressure threshold value [2]. Finite Element Method (FEM) was used
in this simulation for calculating back-pressure in exhaust muffler. Muffler’s purpose is to minimize the sound generated by the exhaust gas circulation and thereby decreasing the velocity of gas flow. The virtual simulation had been done with help of CFD analysis using AcuSolve CFD. Better potential for attenuating noise leads to higher back-pressure, which results in loss of engine power and rise in the consumption of fuel [3].

CFD simulation on ANSYS fluent software had been performed for the exhaust silencer of a Car with 2 cylinder engine to get optimum sound quality and back-pressure. The sound quality of the given silencer was not acceptable though back-pressure was within the threshold limit. Existing model is as shown in figure 2. Different silencer cases had been taken into consideration as shown in table 1 to get the optimized case.

**Table 1. Different silencer concepts**

| Silencer concepts | Modification                                      |
|-------------------|--------------------------------------------------|
| Baseline          | Existing model                                   |
| Concept 1         | Variation in gas flow and 25% decrease in pipe diameters |
| Concept 2         | Concept 1 with existing model diameters           |
| Concept 3         | Concept 2 with gas bleeding provided to reduce back pressure |

![Figure 2. Existing model [4]](image)

By the combination of simulation and experimentation, an optimum design of silencer was obtained. Perforations were made for silencer bleeding to decrease back-pressure. Optimized concept 3 had fulfilled the desired back pressure and noise. Results obtained during simulation is as shown in figure 3 and 4 [4].

![Figure 3. Back pressure comparison [4]](image)
Figure 4. Overall exhaust tail pipe noises [4]

An important optimization approach to optimize the exhaust system is explained in this paper. The parameter of muffler design such as pipe diameter, distance of baffles, total number of perforation was optimized thereby reducing weight of the exhaust system by eliminating one silencer and retaining the same vibration, noise and back-pressure output as that of two silencer baseline exhaust system. This optimization technique reduced the weight of the new exhaust system by 25% as compared with given system [5]. The 1D simulation tool GT-power was used in this simulation to simulate flow and to predict the back-pressure of a cold-end exhaust system. Discretization in the direction of x, y, and z of the muffler, resonator shell, and pipes helped to get the optimized scenario [6].

This paper focused on the transfer of heat inside an insulated exhaust pipe. The heat transfer was carried out using a mathematical model. Insulation in exhaust pipe was highly efficient but costly [7]. Internal flow in the nozzle affects fuel injection and spray in a fuel injector. Model during simulation was based on 8-hole injector. At steady injector pressure, the internal cavitation process of the nozzle was divided into three phases i.e. no cavitation time, time of production of local cavitation and period of super cavitation. The decrease in back-pressure over the no cavitation duration increases the injection mass flow whereas coefficient of discharge remains constant. During the developmental period of local cavitation, a decrease in back-pressure contributes to cavitation and thus increases continuously the injection mass flow whereas coefficient of discharge remains constant. During super cavitation, when the inner flow of the nozzle become chocked, a reduction in the back-pressure did not really impact the injection mass flow and remains unchanged whereas coefficient of discharge decreases [8]. Paper from the author highlights the impact of intake and exhaust pipe on the efficiency of the rotary engine. A model of a 1D three cylinder reciprocating engine had been adopted to simulate the operation of a three-chamber rotary engine. The short inlet pipe and long outlet exhaust pipe up to a certain limit had better engine performance. Under a specific rotational speed, length, shape, and diameter of inlet and exhaust pipe, there was an enhancement of 20 % more work output [9].

Control of intake air and exhaust back-pressure in commercial vehicle helps in increasing efficiency of engine. Dynamic conditions are also important along with steady state conditions for exhaust emissions. Resonance compensation method was helpful in exhaust back-pressure management. Advanced controller with adjustment for resonance was more effective than standard Proportional Integral (PI) controller [10]. [11] investigated on the bend angle prediction and regulation of soft pneumatic actuators with built in flex sensors. In this case, a data-driven approach was employed. The bending response was captured using a high-speed camera and the difference in bend
angle was measured with the assistance of the image processing software. Regression analysis and neural networks had been used to model the calculated bend angle output.

2.2. Effect of noise
The pressure waves within exhaust system of automotive vehicles comprise of the frequency components and high-order harmonic components. It leads to non-linearity in the exhaust pipe. The error between the simulated and actual experimental value is due to this non-linearity. 1,500 cc 4-cylinder and 4-stroke engine was used in this simulation. In this paper, bispectrum analysis had been used for finding non-linearity in the exhaust pipe [12]. In this, the author focused on the exhaust pipe and muffler. Sound pressure rises across a wide spectrum of frequencies in broad band noise whereas in narrow band noise it increases at some certain frequencies. Narrow band noise thus produces a whistling sound which decreases human comfort as shown in figure 5. Figure 5 just convey information about nature of broad band and narrow band noise.

Figure 5 just convey information about nature of broad band and narrow band noise. Large-Eddy Simulation (LES) was done to forecast the level of narrow band noise from pressure fluctuations. LES is a turbulence model which is used in highly unsteady state such as vortex shedding. LES can model flows that are more detailed than RANS. Comparison of LES and RANS had been done in figure 6 with the help of vorticity contour. Narrow band noise in the exhaust pipe was produced at peak frequency of 4545 Hz for CFD simulation and at 4512 Hz during measurement as shown in figure 7 [13].

In this paper, an analysis of the relationship between the satisfaction of interior noise and several structural parameters of the exhaust system was carried out. Through Deep Belief Network (DBN) algorithm, the structure- Sound Quality Evaluation (SQE) exhaust system model was developed. The ratings of the satisfaction of inner noise of samples were obtained on the basis of evaluation model [14]. To minimize vehicle vibration, harshness and noise, an optimized hanger position in the exhaust system was needed. Hanger positions were chosen where the Average Driving Degree of Freedom Displacement (ADDOFD) was lower. ADDOFD was measured using general modal analysis. Dynamic and static analysis would pick the number of positions of the hangers [15]. In this, the author focused on noise generation during exhaust pipe bend. A 90° bend pipe carrying flow less than 0.3 Mach level was the experiment area here. A hybrid simulation of RANS equations and Stochastic Noise Generation and Radiation (SNGR) was used in the bend of the exhaust pipe to measure the generation of flow noise [16].

![Flow induced noise](image)

*Figure 5. Flow induced noise*
2.3. Selective catalytic reduction
Exhaust emission norms should be followed by automotive industries. Selective Catalytic Reduction (SCR) is generally used to reduce NOx from the system. New SCR technology that is pre-oxidation with urea SCR was considered in this experiment. Direct injection diesel engine with one cylinder had been used here. This SCR technology reduces NOx by 23.22%, HC by 10%, CO by 40%, and increase CO2 emission by 8.3 % as compared with engine without SCR setup. An overview of DOC, DPF and SCR of a diesel engine is shown in figure 8 [17]. In this, the author prefered a coating type catalyst for SCR. The minimum length from the nozzle to the SCR must be 6 times the diameter of the exhaust pipe. In this case, the optimum nozzle position was found at the bend of pipe [18]. SCR advancement is required to meet the exhaust emission norms. According to Euro IV and Euro VI norms, 3.5 g/KWhr and 0.46 g/KWhr NOx respectively is the maximum limit according to WHTC. A chemical reaction inside SCR is non-linear and complex hence challenging in nature. Computationally-intensive high-performance algorithms should be used in this type of non-linear systems [19].This paper had focused on finding kinetic parameters of after treatment systems. Algorithms were used in this case which eventually decreased time and cost. Three
optimization algorithms Genetic Algorithm (GA), Particle Swarm Optimization with niching (nPSO) algorithm and hybrid of both algorithms were used here. Among these, nPSO and hybrid algorithm had better results. Hybrid algorithm was best among all three algorithms for calculation of kinetic parameters in after treatment systems [20].

Optimization of SCR performance was selected for the given work. Using the TRIZ method i.e. Taguchi method, optimization of design components of SCR was done thereby preventing the wall wetting and decreasing the NOx emissions [21]. The efficiency of the Palm Kernel Shell activated carbon (PKS)-supported Mn and Ce catalyst in the removal of NOx from the diesel engine exhaust gas was evaluated here. It helped in passive NOx removal from exhaust gas hence no use of urea injection system in SCR thereby decreases cost. The given experiment decreased NOx by 74 % at low temperature of 140°C [22]. In this passenger car, SCR had been taken into consideration. Various feedback control systems had been used for control of urea in the SCR system. Improvement in the urea injector sub model helped in accurate Ad-blue to NH3 conversion rates [23].

Temperature-based model was used in this work to improve the calibration of SCR. The Normalized Stoichiometric Ratio (NSR) model had been computed in CAMEO software that used 2nd order polynomial approximation. The temperature of the inlet SCR was also used for adjustment of the urea dosage for the NSR model. Minimum NH3 slip and N2O are desirable for any diesel engine along with less NOx emission [24]. In this, the author focused on urea injection faults in the SCR system. There may be two types of faults i.e. pump pressure control fault and dosing control fault during urea injection. FFT algorithms were used here for the detection of a fault in urea injection. Alternatively, a time-domain-based algorithm was studied during vehicle transient operations to detect urea injection faults [25]. The area of interest in this work was the impact of valve angle of Exhaust Gas Recirculation (EGR) on exhaust gas flow through EGR. Results from the experiment indicate that, by increase in valve angle, the exhaust gas discharge rate through EGR increases with increase in throat velocity, thus reducing throat pressure. Using CFD study, an optimal valve seat angle can be chosen based on the flow rate requirement [26].

In this, the author concentrated on improving design of a medium-duty truck’s urea –SCR combination. In the given model, the S-bent tubing, the dual mixer, the co axially centred injector and the unique design of the SCR input cone were the modifications for proper urea mixing [27]. This paper focused on finding urea deposits on the inner wall of the exhaust pipe. 4.76 litres diesel engine was area of simulation here. By the use of multidimensional CFD code CONVERGE which includes all models related to urea –SCR mixing, Deposit Formation Possibility (DFP) was analyzed [28]. CFD spray modeling was considered in this paper. This paper focused on the parameter that decreases NOx emissions through the exhaust pipe. Parameters that influence a decrease in NOx are exhaust gas temperature, NO2/NOx ratio, O2 content. There was also several other influential factors such as NH3 adsorption process, form of catalyst, etc. but CFD research needs more development [29].

Figure 8. Overview of DOC, DPF and SCR of a diesel engine

2.4. Gasoline direct injection engine

The focus of this work was on the oxidation behaviour of charged Gasoline Particulate Filter (GPF). Four gasoline blends were used here, namely E0, E30, iBu24, and iBu48, where E0 is 100% gasoline, E30 is 30% ethanol gasoline blend, iBu24 is 24% isobutanol gasoline blend, and iBu48 is 48% isobutanol gasoline blend. E30 produced particulate matter with a greater reactivity to oxidation than E0, whereas iBu24 and iBu48 had much lower reactivity to oxidation. The difference of chemical and physical properties with oxidation showed that gasoline direct injection particulate was distinct from
diesel particulate matter [30]. The setup of this work was a gasoline engine with one-cylinder fitted with a direct-injection system. Particulate matter’s principal source varies with the timing of fuel injection. The film of fuel generated on piston in early injection was the key origin of particulate matter formation. Particulate matter was produced in high equivalence zone during late injection. As the exhaust charge rises, particulate matter drop [31].

In this work, fuel doping and oil injection two processes were compared for ash deposit. From this, oil injection was the best process that accurately reproduced the ash produced by vehicle back-pressure. A dense and homogeneous layer of ash with low density was formed with fuel doping. In oil injection, the oil droplets should not be atomized too far, as it contributes to further ash deposition on the walls, with increase in back pressure [32]. This paper showed that the solid particles and Black carbon particle emission from gasoline direct engines can be reduced with help of a gasoline particulate filter. A wall-flow gasoline particulate filter can be 90 % efficient in a short time interval without a change in fuel consumption [33]. In this work, the coated gasoline particulate filters (cGPFs) model had been presented. The results of experimental pressure drop showed that higher cell density and increased wall thickness lead to a rise in back pressure resulting in engine performance declining [34]. In this work, it was stated that turbulence inside a gasoline particulate filter can change the flow field and drop in pressure. Prediction of drop in pressure by models of RANS flow was more similar to the laminar flow model. For the turbulence model, porous wall conditions are of significant use [35].

3. Conclusion

CFD simulation has made things simpler with less computational time and low cost. Back-pressure in exhaust systems is calculated with advanced CFD technologies like ANSYS Fluent and GT Power. Backpressure in the exhaust pipe is reduced by varying length, diameter, number of bends, exhaust mass flow rate and bending angle of exhaust pipe. Enhanced controller with resonance compensation is helpful in exhaust back-pressure control. Kinetic parameters in after treatment system is calculated by hybrid of GA and nPSO algorithm.

The insulated exhaust pipe has better performance than the usual one. Vibration, noise and harshness in the vehicle is reduced by using optimized hanger locations with low ADDOFD. Deep belief network algorithm gives relation between interior noise satisfaction and parameters of the exhaust in a commercial vehicle. Large-Eddy Simulation (LES) is helpful in predicting narrow band noise. Selective Catalytic Reduction (SCR) converts harmful NOx to harmless N2. NOx removal is extremely important as per exhaust emission norms. SCR performance depends on various parameters like the location of the urea nozzle from SCR, catalyst, coating, handling capacity, proper fuel injection, fuel combustion, load, deposit formation possibility, NH3 slip, and NOx conversion efficiency. Non-linearities in SCR is predicted by computationally-intensive high-performance algorithms, multidimensional CFD code CONVERGE and TRIZ method. Palm Kernel Shell activated carbon (PKS)-supported Mn catalyst is helpful in passive NOx removal from exhaust gas at lower temperature. Gasoline Particulate Filter (GPF) is beneficial to be used in the gasoline engine to filter out particulate matter.

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