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CFD Studies of Flow Dynamics in Exhaust Manifolds Configuration

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ABSTRACT

Efficient internal combustion engines require optimized exhaust flow to minimize backpressure and emissions. Complex pulse interference in the manifold can affect engine performance and catalyst light-off time. In this context, two common four-cylinder manifold configurations – the 4-1 and 4-2-1 types – were compared via computational fluid dynamics. The study uses steady-state ANSYS Fluent simulations on a simplified geometry to examine velocity and pressure profiles in each design. Results show that the 4-1 layout generates higher peak gas velocity but at the expense of a greater overall pressure drop, indicating stronger flow pulses from converging runners. In contrast, the 4-2-1 configuration smooths pressure gradients and yields more uniform flow along the runner network. These findings align with analyses highlighting the 4-2-1 manifold's ability to mitigate flow interference and enhance exhaust scavenging. The more uniform flow in the 4-2-1 case implies faster catalyst warm-up and the potential to advance ignition timing, which can improve engine performance and reduce emissions. By contrast, the 4-1 design may support high-power operation but incurs higher backpressure. Overall, this comparative CFD study clarifies how manifold choice influences flow characteristics and engine efficiency. These insights, though based on idealized steady simulations, may guide manifold selection in high-efficiency engines and downsizing strategies.

Keywords: CFD, Exhaust Manifold, Flow Characteristics.

1. INTRODUCTION

Internal combustion engines (ICEs) continue to serve as one of the primary propulsion systems in modern transportation [1-2]. In an ICE, the chemical energy of the fuel is converted into mechanical power through combustion in the engine cylinder. When the air–fuel mixture is ignited, it produces high-temperature and high-pressure gases that drive the piston downward, turning the crankshaft and generating useful mechanical output. At the same time, these combustion processes produce exhaust gases that must be removed efficiently to maintain stable and continuous engine operation.

The exhaust manifold is the first component that directs exhaust gases from multiple cylinders into the downstream exhaust system. Although relatively simple in appearance, it performs a critical role in governing engine breathing behaviour, scavenging efficiency, fuel consumption and emissions [3-6]. An effective manifold design allows exhaust gases to flow smoothly out of the cylinders, thereby reducing backpressure. In contrast, poor manifold geometry can cause flow separation and turbulence, increasing pressure losses and restricting exhaust discharge [7–9].

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When backpressure becomes too high, exhaust gases remain trapped in the combustion chamber, leading to reduced volumetric efficiency, power loss and unstable combustion behaviour [10-11].

In addition to performance considerations, exhaust manifold design is closely tied to environmental and regulatory requirements. Inefficient exhaust flow can increase pollutant formation and tailpipe emissions. With increasingly strict global emission standards, manufacturers are required to develop exhaust systems that not only support catalytic treatment and noise reduction but also promote efficient gas discharge [12-13]. As a result, optimization of exhaust manifold geometry has become an important focus in engine design.

In recent years, Computational Fluid Dynamics (CFD) has emerged as a powerful tool for investigating exhaust system behaviour. Unlike conventional prototype-based testing, CFD allows engineers to simulate and visualize internal flow characteristics, including velocity distribution, pressure gradients and turbulence structures, before physical components are produced [14-18]. Among the many manifold configurations, the 4-1 and 4-2-1 designs are among the most widely used in automotive engines. The 4-1 manifold merges all four runners directly into a single outlet, while the 4-2-1 design combines cylinders in two stages. These structural differences influence gas motion, scavenging and backpressure across different operating speeds [19-22].

Although both designs are commonly used in industry, there remains a need for a systematic CFD-based comparison under consistent modelling assumptions. Improving our understanding of the relationship between manifold geometry and exhaust flow behaviour can support more informed engineering decision-making. Therefore, this study investigates the flow characteristics of 4-1 and 4-2-1 exhaust manifolds using CFD simulation, with emphasis on exhaust gas velocity and pressure distribution. The results aim to provide insights into the performance implications of each design and contribute toward the optimization of future exhaust systems.

1.1 Problem Statement

Although the exhaust manifold plays a critical role in controlling exhaust gas flow behaviour in internal combustion engines, its geometric influence on flow distribution, backpressure and scavenging efficiency continues to present significant design challenges. The internal flow within the manifold is inherently complex due to pulsating exhaust gas behaviour and merging flow interactions at the collectors. Poor manifold design can result in pressure losses, turbulence development, and non-uniform velocity profiles, ultimately reducing volumetric efficiency and engine performance.

One key concern in exhaust manifold design is excessive backpressure. When backpressure exceeds the recommended threshold, exhaust gases are unable to exit the cylinder efficiently, leading to incomplete scavenging, increased residual gas content, and reduced power output. Previous studies have shown that manifold geometry strongly affects backpressure formation; however, the correlation between runner configuration and pressure gradients remains insufficiently quantified for common manifold layouts such as 4-1 and 4-2-1 system [23].

Another major issue is the non-uniform distribution of exhaust gas flow at the manifold junctions. Flow separation and turbulence may occur due to sharp merging angles or poor runner alignment. This condition creates uneven velocity fields and localized pressure zones, which not only affect engine breathing but may also influence downstream catalytic converter efficiency and thermal loading [24]. Despite the importance of these effects, detailed comparative flow characterization across alternative manifold geometries remains limited.

Although Computational Fluid Dynamics (CFD) has become an essential tool in analyzing manifold performance, many previous works have focused on single design configurations or thermal effects, rather than performing systematic comparisons under consistent modelling conditions. This limits the ability to generalize findings for design optimization.

Therefore, there is a clear need for a controlled CFD-based comparative study to evaluate the flow characteristics of different manifold configurations, particularly the 4-1 and 4-2-1 designs. Understanding how geometry affects velocity distribution, pressure variation and turbulence intensity will provide valuable insights for improving manifold design and enhancing engine performance.

1.2 Research Objectives

The purpose of this study is to examine how different exhaust manifold geometries influence exhaust gas flow behavior in an internal combustion engine. In particular, the work focuses on comparing two commonly used manifold configurations: the 4-1 and 4-2-1 designs. Both manifolds were first developed using CAD software before being analyzed through Computational Fluid Dynamics (CFD) simulation.

The study aims to observe how the velocity distribution and pressure variation develop within each manifold, especially at the runner junctions and the collector region, where flow interaction is most significant. By comparing the flow behavior between the two designs, this research seeks to better understand how manifold geometry contributes to backpressure formation, flow uniformity and potential scavenging performance. Ultimately, the objective of this study is to provide useful insights that may support more informed exhaust manifold design and optimization in future engine applications.

1.3 Scope of the Study

This study focuses specifically on analyzing the internal flow characteristics of exhaust gases within two different exhaust manifold configurations, namely the 4-1 and 4-2-1 designs, using Computational Fluid Dynamics (CFD). The investigation is limited to steady-state flow simulations, with the main performance indicators being exhaust gas velocity distributions and pressure variations along the manifold runners and the collector region. Thermal effects, combustion chemistry, acoustic behavior and structural stresses are not included in the analysis, as this work intends to isolate and understand the aerodynamic influence of manifold geometry alone.

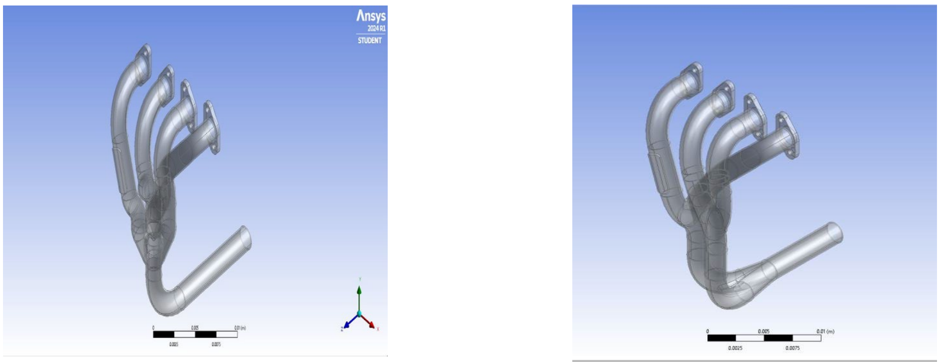
The models used in this study are based on a representative four-cylinder spark-ignition engine, with manifold geometries developed in CAD software and imported into ANSYS Fluent for simulation. Although experimental validation is beyond the scope of the present work, CFD is widely recognized as a reliable tool for understanding flow behavior in exhaust systems and provides meaningful insight into the effect of manifold design on backpressure and scavenging characteristics [25-26]. The findings from this study are therefore expected to serve as a useful reference for future manifold optimization studies rather than as absolute performance predictions for a specific engine.

2. MATERIAL AND METHODS

This study used a numerical simulation approach to analyze the internal flow behaviour in two exhaust manifold configurations: the 4-1 and 4-2-1 designs. Both manifolds were first developed in SolidWorks, based on the geometry of a Honda EK9-type four-cylinder petrol engine manifold. To satisfy the computational limits of the ANSYS Student Version, the original manifold dimensions were scaled by a factor of 1:20, while maintaining the internal diameter ratio to preserve realistic flow behaviour. The original inner runner diameter of approximately 36.07 mm was therefore reduced to about 1.8 mm, ensuring that only geometry influenced the resulting flow characteristics.

Geometric scaling was implemented due to computational limitations in the ANSYS Student Version. Although strict Reynolds number similarity cannot be perfectly preserved under geometric scaling, the internal diameter ratios and flow path geometry were maintained to preserve the relative flow behaviour. Since both manifold configurations were simulated under identical boundary conditions, the scaling does not affect the comparative analysis of velocity and pressure distribution between the two designs.

Once the geometries were completed, the models were exported into ANSYS Workbench for CFD simulation. Within DesignModeler, the manifold domains were separated into fluid and solid bodies to better represent physical boundaries and enable appropriate mesh refinement in critical regions, particularly in the flow passages, as shown in Figure 1. The meshing process also plays a central role in solution accuracy, as shown in Figure 2. In the study, unstructured tetrahedral elements were used due to the complex curved geometry of the manifold runners. Refinement was applied near the walls and at merging junctions, and inflation layers were generated to adequately capture the steep velocity gradients in the near-wall boundary layer region.



(a) (b)

Figure 1: The Exhaust Manifold design using DesignModeler (a) 4-1 Exhaust Manifold and (b) 4-2-1 Exhaust Manifold.

Mesh quality parameters, including orthogonal quality, skewness, and aspect ratio, were monitored to minimize numerical instability and ensure simulation robustness. The final mesh consisted of elements distributed more densely around high-gradient regions to improve local flow resolution, in accordance with recommended CFD practice for internal duct flows. This ensures that the governing conservation equations are satisfactorily resolved over the computational domain.

A formal grid independence (mesh convergence) study was not conducted due to computational constraints associated with the ANSYS Student Version. However, mesh refinement was applied near the runner junctions and collector regions where strong velocity gradients occur. This approach ensures that the primary flow features are adequately captured for comparative analysis.


(a) (b)

Figure 2: The Exhaust Manifold Meshing Image (a) 4-1 Exhaust Manifold and (b) 4-2-1 Exhaust Manifold.

The mesh quality generated for both exhaust manifold configurations was evaluated based on the total number of nodes and elements produced during discretization in ANSYS Meshing. For the 4-1 exhaust manifold, the final mesh consisted of 140,990 nodes and 614,126 elements, while the 4-2-1 manifold produced 128,157 nodes and 565,746 elements, as shown in Table 1. These values indicate that both models were discretized using a sufficiently fine unstructured tetrahedral mesh, with additional refinement applied around the wall boundaries and merging junctions to accurately capture local velocity gradients and turbulence effects.

Table 1: Mesh statistics for 4–1 and 4–2–1 exhaust manifold.

Manifold Configuration	Total Nodes	Total Elements
4-1 Exhaust Manifold	140,990	614,126
4-2-1 Exhaust Manifold	128,157	565,746

2.1 Governing Flow Model

The CFD analysis was based on the solution of the steady-state, incompressible Navier–Stokes equations, which govern conservation of mass and momentum in fluid flow:

Continuity equation,
$$\nabla \cdot \mathrm{u} = 0 \tag{1}$$

Momentum equation,
$$\rho(\mathrm{u} \cdot \nabla)\mathrm{u} = -\nabla p + \mu \nabla^2 \mathrm{u} \tag{2}$$

where u represents the velocity vector (m/s), ρ is the gas density (kg/m^3), p is the static pressure (Pa), and μ is the dynamic viscosity (Pa·s).

Because exhaust gas motion inside the manifold is turbulent due to runner curvature and collector merging, a turbulence model was applied. The k-ε model, widely used in internal flow simulations for engineering applications, was selected due to its balance between accuracy and computational efficiency, enabling realistic predictions of turbulence-induced velocity fluctuations and pressure losses in the manifold passages.

The incompressible flow assumption was adopted as a simplified approach to isolate the influence of manifold geometry on flow behaviour. Although the predicted peak velocity is relatively high, the present study focuses on the comparative flow characteristics between two manifold configurations rather than exact thermodynamic exhaust conditions. Therefore, the simplification allows clearer interpretation of velocity and pressure distributions while maintaining computational efficiency.

2.2 Boundary Conditions and Simulation Setup

In this study, the working fluid in the exhaust manifold was defined as an exhaust-equivalent gas, modeled in ANSYS Fluent as an ideal gas mixture. Temperature effects and thermal energy transport were not explicitly included in the present simulation. The ideal gas model was therefore used as a simplified approximation to represent exhaust gas behaviour, allowing the study to focus primarily on the aerodynamic flow characteristics within the manifold. The solid manifold body was assigned aluminium as the material, consistent with common exhaust manifold manufacturing practice. This material definition allowed realistic wall–fluid interaction behaviour to be captured during the simulation. Thermal effects and temperature variations were not explicitly modelled in this study. The ideal gas representation was used as a simplified approximation of exhaust gas behaviour to focus on aerodynamic flow characteristics inside the manifold.

At the inlet boundaries, a uniform velocity condition of 70 m/s was imposed for all four-cylinder runners. The selected inlet velocity represents a simplified and representative exhaust gas velocity commonly adopted in CFD studies of internal duct flows in automotive exhaust systems. The same inlet velocity was applied to both manifold configurations to ensure consistent boundary conditions for comparative evaluation. The velocity specification was set to Magnitude Normal to Boundary under the absolute reference frame, ensuring that the incoming exhaust flow entered the manifold perpendicularly to the inlet plane. The inlet turbulence intensity was specified at 5%, with a turbulent viscosity ratio of 10, representing typical internal-flow turbulence levels for automotive gas flow. The selected inlet velocity represents a simplified and representative exhaust gas flow condition commonly used in CFD studies of internal duct flows. The same inlet velocity was applied to both manifold configurations to ensure a consistent basis for comparative analysis.

A pressure outlet boundary condition was applied at the manifold exit, enabling exhaust gases to discharge freely to the downstream system while allowing the solver to dynamically adjust the outlet flow field. All solid walls were modelled as no-slip boundaries, meaning that the fluid velocity at the wall surface was assumed to be zero, consistent with viscous flow theory. These boundary conditions were applied consistently across both manifold configurations to ensure a fair comparison of flow characteristics. Table 2 shows the Summary of Boundary Conditions and Simulation Parameters.

Table 2: Summary of Boundary Conditions and Simulation Parameters.

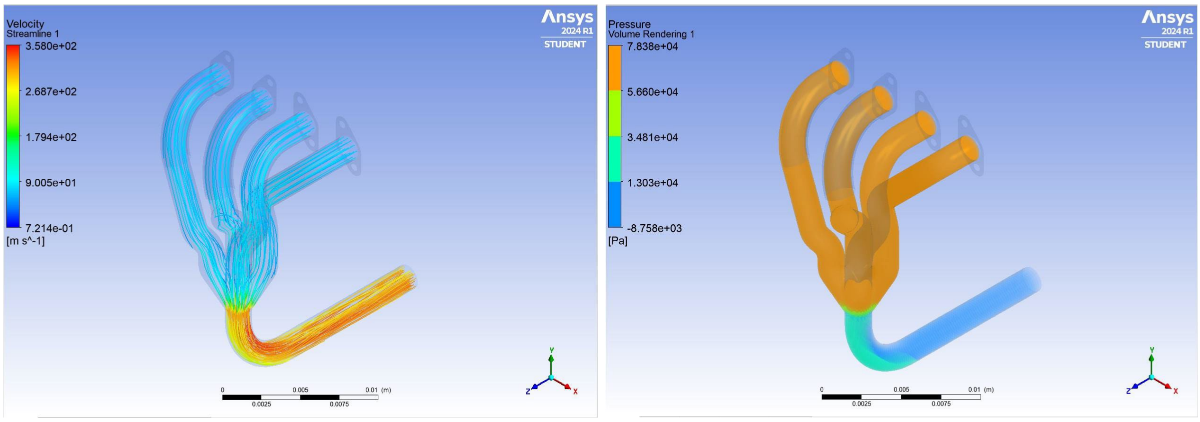
Parameter	Setting	Description
Fluid Material	Exhaust-equivalent gas (ideal gas)	Working fluid inside the manifold
Solid Material	Aluminium	Manifold wall material
Inlet Type	Velocity inlet	Applied to four cylinder runners
Inlet Velocity	70 m/s	Uniform velocity, normal to the boundary
Reference Frame	Absolute	Global flow reference
Turbulence Specification	Intensity & viscosity ratio	Turbulence model input
Turbulent Intensity	5%	Represents moderate flow turbulence
Turbulent Viscosity Ratio	10	Ratio of turbulent to molecular viscosity
Outlet Type	Pressure outlet	Flow discharge boundary
Wall Condition	No-slip	Zero velocity at the wall surface

3. RESULTS AND DISCUSSION

This section presents the findings from the CFD simulations conducted for the 4-1 and 4-2-1 exhaust manifold configurations. As outlined earlier, the purpose of the simulation is not to replicate real-engine exhaust behaviour, but rather to analyze the internal gas-flow characteristics within the manifolds themselves. The results therefore focus on velocity distribution and pressure variation, which serve as key indicators of flow performance and potential backpressure effects.

3.1 Flow Characteristics in the 4-1 Exhaust Manifold

The velocity and pressure fields for the 4-1 exhaust manifold are shown in Figure 3. The results indicate that exhaust gas velocity increases progressively as the individual runners merge toward the collector. The highest velocity recorded in the convergent region is approximately 268.7 m/s, before rising further to 358.0 m/s at the outlet. This trend reflects the reduction in effective flow area, which accelerates the gas stream as it approaches the exit.



(a) (b)

Figure 3: The 4 -1 Exhaust Manifold Flow Characteristic (a) Velocity Simulation and (b) Pressure Simulation.

Correspondingly, the pressure field exhibits an inverse relationship with velocity. The peak pressure of approximately 56,600 Pa occurs near the merging zone, where flow interaction and compression effects are greatest. From this point onward, the pressure decreases gradually toward the outlet, consistent with the observed acceleration of the gas flow.

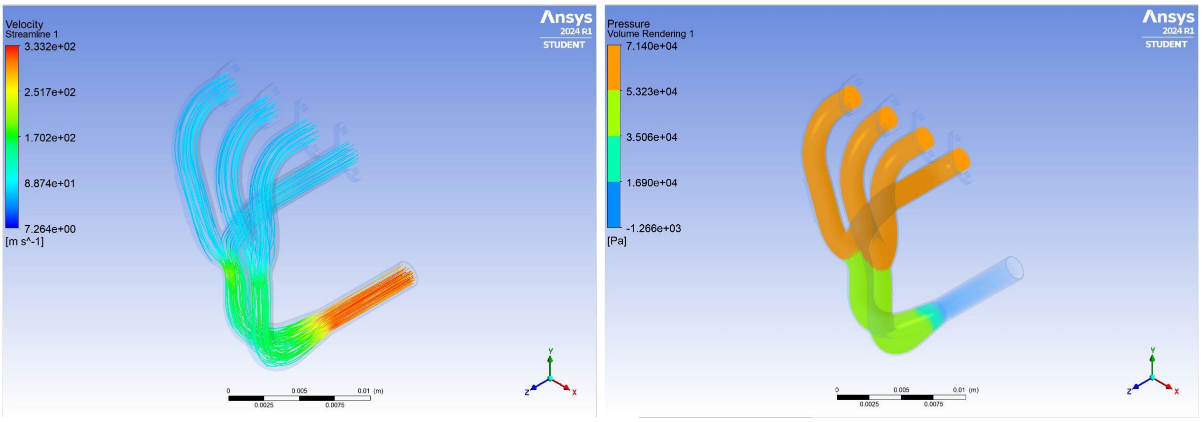
The combined velocity–pressure behaviour demonstrates that the 4-1 manifold produces a strong acceleration effect, and a significant pressure drop along the flow path. This implies a reduction in backpressure at the cylinder outlets, promoting more effective exhaust evacuation and enhancing cylinder scavenging. This suggests a relative reduction in flow resistance along the manifold, which may correspond to lower backpressure when comparing the two configurations, rather than an absolute prediction of engine backpressure under real operating conditions.

The relatively concentrated high-velocity core at the outlet also suggests that the 4-1 configuration is well-suited to high-speed engine operation, where strong gas momentum is beneficial for clearing combustion products. Overall, the results show that the 4-1 manifold supports highly energetic gas discharge, with limited recirculation or stagnation zones within the runners.

It should be noted that the reduction in backpressure discussed here represents a relative comparison between the two manifold configurations rather than an absolute prediction of engine backpressure in real operating conditions.

3.2 Flow Characteristics in the 4-2-1 Exhaust Manifold

The flow characteristics of the 4-2-1 manifold are presented in Figure 4. Like the 4-1 configuration, the exhaust gas accelerates as it progresses toward the outlet. However, the acceleration occurs more gradually due to the two-stage merging layout, where the runners first combine in pairs before entering the main collector. The maximum flow velocity reaches approximately 251.7 m/s at the initial convergent section, increasing to 333.2 m/s at the outlet, which is slightly lower than the peak values observed in the 4-1 manifold.



(a) (b)

Figure 4: The 4 – 2 -1 Exhaust Manifold Flow Characteristic (a) Velocity Simulation and (b) Pressure Simulation.

The pressure field follows the same general trend: pressure decreases along the manifold length as velocity increases. The maximum pressure recorded is approximately 35,060 Pa, which is significantly lower than in the 4-1 configuration. This indicates that the 4-2-1 manifold induces less intense compression and flow interaction at the merging zones, resulting in smoother and more evenly distributed pressure gradients.

When the velocity and pressure results are considered together, it becomes clear that the 4-2-1 manifold produces a more gradual energy transition within the exhaust flow. While the resulting exit velocity remains sufficiently high to ensure efficient evacuation, the absence of sharp pressure peaks suggests reduced turbulence intensity and potentially lower structural loading. This more uniform flow behaviour is often associated with broader operating-range performance characteristics and improved drivability, rather than peak high-speed performance.

4. CONCLUSION

This study investigated the internal flow behaviour of two different exhaust manifold configurations, namely the 4-1 and 4-2-1 designs, using Computational Fluid Dynamics (CFD). The analysis focused on the distribution of exhaust gas velocity and static pressure within the manifolds in order to understand how geometry influences exhaust evacuation characteristics.

For the 4-1 manifold, the results showed a strong acceleration of exhaust flow as the runners converged into a single outlet. The maximum velocity reached approximately 358 m/s, accompanied by a significant pressure drop from the merging region toward the outlet. This behaviour indicates efficient exhaust gas discharge and a notable reduction in backpressure, which would generally support better scavenging performance at higher engine speeds [27].

In comparison, the 4-2-1 manifold produced slightly lower peak velocities, with an outlet velocity of approximately 333 m/s, and lower maximum pressure levels within the convergent regions.

The two-stage merging layout resulted in smoother flow transition and more uniform pressure distribution throughout the manifold. While the gas acceleration was less aggressive than in the 4-1 design, the flow remained sufficiently energetic to promote effective exhaust evacuation.

In summary, the CFD results confirm that exhaust manifold geometry significantly influences the velocity distribution, pressure variation, and, therefore, potential backpressure characteristics. Although both manifolds can support efficient exhaust discharge, their flow behaviour differs in ways that align with their intended performance objectives. The outcome of this study highlights the importance of selecting manifold geometry based to engine operating requirements rather than treating the exhaust system solely as a structural component.

Overall, the results indicate that the 4–1 manifold configuration promotes stronger exhaust gas acceleration and may therefore support high-speed engine operation where rapid exhaust evacuation is beneficial. In contrast, the 4–2–1 manifold produces smoother pressure gradients and more uniform flow distribution, which is commonly associated with improved performance across a broader engine operating range. These findings highlight the importance of selecting exhaust manifold geometry based to specific engine performance objectives rather than treating the exhaust system solely as a structural component.

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