Journal of Sustainable Engineering & Renewable Energy (JSERE)

VOLUME 1 ISSUE 1 (2025)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

Journal of Sustainable Engineering & Renewable Energy (JSERE)
Volume 1 Issue 1, Year 2025
https://journals.e-palli.com/home/index.php/jsere

The Role of Intake Manifold Geometry on Airflow Dynamics and Combustion Efficiency: A Computational and Experimental Review

Swift N. K. Onyegirim[1], Ifeanyichukwu U. Onyenanu[1*], Arinzechukwu H. Madukasi[2], Oluebube E. Nwigbo[3]

Article Information

Received: April 01, 2025

Accepted: May 08, 2025

Published: June 24, 2025

Keywords

Airflow Dynamics, Computational Fluid Dynamics (CFD), Emission Reduction, Engine Performance, Helmholtz Resonance, Intake Manifold Geometry, Internal Combustion Engine (ICE), Volumetric Efficiency

ABSTRACT

The geometric configuration of the intake manifold assumes a crucial function in influencing the aerodynamic behavior and combustion efficacy of internal combustion engines (ICEs). This comprehensive review amalgamates both computational and experimental investigations to assess the influence of manifold design parameters on engine performance metrics, volumetric efficiency, and emission profiles. A systematic literature review was executed utilizing the Scopus database, employing Boolean search operators to identify 18 significant studies published between 2008 and 2025. The methodologies encompassed computational fluid dynamics (CFD) simulations, empirical validations, and performance indicators such as torque, fuel consumption, and pollutant emissions. The principal findings indicate that variable-length manifolds can enhance volumetric efficiency by 8–15% by tuning Helmholtz resonance, albeit at the expense of increased cost and complexity. Fixed-geometry configurations yield 5–7% torque improvements at resonant frequencies, yet they exhibit suboptimal performance beyond their specified operational ranges. This study accentuates the necessity for application-specific designs that harmonize performance, cost, and emissions. Future investigations should delve into adaptive geometries that utilize additive manufacturing techniques and enhance transient-state modeling to overcome existing challenges. This review establishes a framework for engineers to refine intake manifold designs, highlighting the intricate relationship between geometry, fluid dynamics, and combustion efficiency.

INTRODUCTION

The internal combustion engine (ICE) is a dominating power source in automotive and industrial applications, and its performance is strongly reliant on the efficiency of the intake manifold system (Alagumalai, 2014; Onorati *et al.,* 2022). An intake manifold is a key component in the functioning of an internal combustion engine (Priyadarsini, 2016). An intake manifold is normally made up of a plenum input duct, connected to the plenum are runners based on the number of cylinders, which lead to the engine cylinder (Priyadarsini, 2016). Consumption. To optimise engine performance, manifolds must be built to prevent phenomena like the Helmholtz effect, inertia of the flow in the individual branch pipes, resonance of the air masses in the pipes, and inter-cylinder robbery of charge (Priyadarsini, 2016). Fundamental elements of airflow management, including charge distribution, turbulence formation, and pressure wave dynamics, are governed by the intake manifold's geometry (Kaplan & Aydoğan, 2020; Priyadarsini, 2016). These factors all have a significant impact on volumetric efficiency and combustion stability (Van Basshuysen & Schäfer, 2016). Researchers can now systematically assess how particular design parameters, like runner length, cross-sectional area, and plenum volume (Silva *et al.,* 2019a), affect engine performance across various operating regimes thanks to major advancements in computational modelling capabilities and experimental techniques over the past few decades (Payri *et al.,* 2004). The creation of customised manifold configurations for specific applications has been made easier by this expanding body of knowledge (Ma & Fu, 2012).

The relationship between intake manifold shape and engine performance originates from fundamental fluid dynamic concepts (Porter, 2009). The interplay of boundary layer effects, pressure waves, and inertial forces determines the flow properties of air as it enters the manifold (Ghil & Childress, 2012). While shorter runners decrease flow resistance at higher engine speeds, longer runners typically increase low-speed torque through better ram charging effects (Heywood, 2018). The volume and geometry of the plenum chamber, which functions as an acoustic resonator, affect the regularity of the charge distribution and the propagation of pressure waves (Jemni *et al.,* 2021). These complex interactions have been extensively studied through computational fluid dynamics (CFD) simulations, which provide detailed insights into flow separation, velocity profiles, and turbulence intensity distributions that are difficult to measure experimentally (Payri *et al.,* 2004; Tu *et al.,* 2023; Wang *et al.,* 2024). Computational fluid dynamics (CFD) models, which use tighter grids, high-quality dynamic mesh techniques, and precise sub-models for the various processes, are becoming increasingly important as computer power improves (Jemni *et al.,* 2011).

This review article comprehensively analyzes recent advancements in intake manifold technologies with a focus on the interrelationship between geometric parameters and metrics of an engine's performance. By synthesizing the results of numerous computational studies alongside

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[1] Department of Mechanical Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli, Nigeria
[2] Department of Mechanical Engineering, University of South Wales, United Kingdom
[3] Department of Mechanical Engineering, Federal University of Technology, Owerri, Nigeria
[*] Corresponding author's e-mail: iu.onyenanu@coou.edu.ng

empirical research, this work aims to provide a cohesive framework that is helpful to engineers and researchers who need to evaluate design trade-offs and find the best possible answers given some restrictions. The article aims to improve decision-making regarding intake manifold design while highlighting the need for further research and development on this critical component of engine technology.

MATERIALS AND METHODS

This work evaluated the effects of intake manifold shape on airflow dynamics, combustion efficiency, and emission characteristics in internal combustion engines using a thorough literature review technique. Computational fluid dynamics (CFD) simulations, experimental validations, and performance indicators like torque, volumetric efficiency, and pollutant emissions were all included in the review.

Data Collection and Selection

The Scopus database was selected for its comprehensive coverage of mechanical engineering and fluid dynamics literature, as well as its rigorous inclusion of high-impact, peer-reviewed journals. A Boolean search string was designed to capture relevant studies:

- (“intake manifold geometry” OR “runner length” OR “plenum volume”)
- AND (“airflow dynamics” OR “combustion efficiency” OR “volumetric efficiency”)
- AND (“CFD simulation” OR “experimental validation”).

The search spanned publications from 2008 to 2025 to encompass advancements in computational modeling and emission regulations. Initial results yielded 704 papers. After screening for relevance and rigor, 18 papers met the criteria for final analysis.

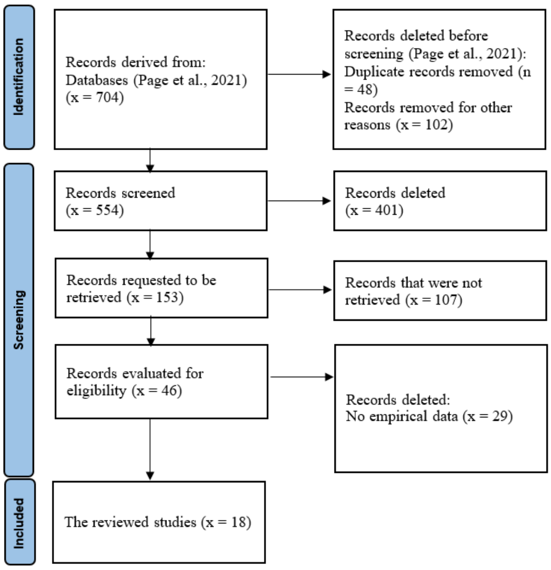

Figure 1: PRISMA Flow Diagram for the Process of Literature Selection
Source: Page et al. (2021)

Publication of Journals by Ranking

As seen by the publication patterns in Figure 2 and Table 1, research interest in intake manifold geometry optimization has increased dramatically, with a notable concentration of studies in recent years. According to the data, there is a strong academic focus on airflow dynamics and combustion efficiency; in fact, 38.89% of the evaluated publications (7 out of 18 studies) came from 2020–2022 alone. This acceleration illustrates how important advances in computational fluid dynamics (CFD) and stricter emission standards are in spurring innovation.

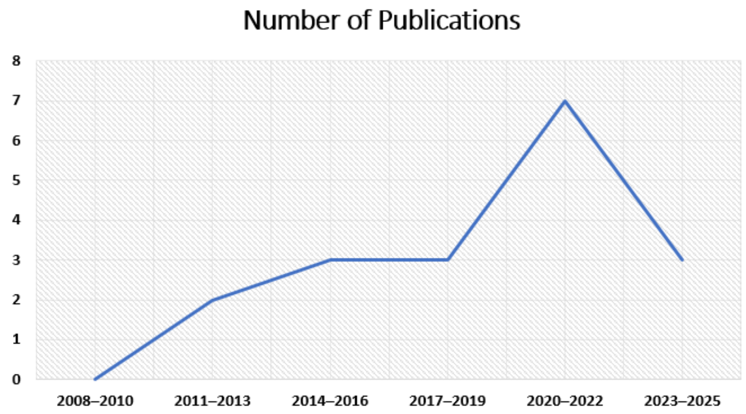

Figure 2: Graph of Journal Article by Year of Publication (Osobajo *et al.,* 2017)

Table 1: Article distribution by year

Year Interval	Number of Publications	% of Total
2008–2010	0	0
2011–2013	2	11.11
2014–2016	3	16.67
2017–2019	3	16.67
2020–2022	7	38.89
2023–2025	3	16.67
Total	**18**	**100**

Comparative Performance of Intake Manifold Geometries

In addition to experimental validations on engine dynamometers, computational investigations provide comprehensive flow characteristics. Table 2 contrasts these designs, emphasising how they affect power production and volumetric efficiency. Engineers can choose the best geometries based on application needs thanks to this synthesis.

Table 2: Comparative Analysis of Intake Manifold Types

Study	Manifold Type	Methodology	Key Findings	Citations
"Influence of intake manifold design on in-cylinder flow and engine performances in a bus diesel engine converted to LPG gas fueled, using CFD analyses and experimental investigations"	"Two intake manifolds on the in-cylinder"	"…Navier–Stokes and energy equations in conjunction with the standard k–ε turbulence model, using the 3D CFD code FloWorks…"	"…Brake power (BP), brake torque (BT) and brake thermal efficiency (BTE), are increased by 16%, 13.9%, and 12.5%, respectively, using the optimal manifold. The brake specific fuel consumption (BSFC) is reduced by 28%..."	Jemni *et al.*, (2011)
"Effect of Variable Length Intake Manifold on Performance of IC Engine"	"Variable intake length on performance of single cylinder, four stroke IC engine."	"…engine simulation software & experimentation on an actual engine."	"The volumetric efficiency of the engine was found to be increased by varying the intake length. Engine torque & brake power observed to be improved at different engine speeds with the help of variable inertia charging system."	Bayas Jagadishsingh & Jadhav, (2016)
"Maximizing Volumetric Efficiency of IC Engine through Intake Manifold Tuning"	Variable-length intake manifold	"Frequency analysis"	"Best volumetric efficiency was observed for intake runner length exhibiting pressure waves with 4th order fundamental frequency during intake valve closed phase and 1st order fundamental frequency during suction stroke."	(Malkhede & Khalane, 2015)
"Design optimization of intake manifold of dual fuel engine"	Dual-fuel engine's intake manifold	Helmholtz Resonator Theory and Chrysler Ram Theory	The results showed a notable improvement in the mass flow rate of air and a corresponding enhancement in volumetric efficiency with the modified runner.	(Adithya *et al.*, 2021)
"The Influence of the Intake Geometry on the Performance of a Four-Stroke SI Engine for Aeronautical Applications"	"Standard plenum vs V1 plenum"	"3D CFD simulations, by using Ansys® Academic Fluent"	"The V1 plenum shows a fairly constant volumetric efficiency as the engine speed increases, although such an efficiency is lower than that of the other two geometries considered in this work."	(Anaclerio *et al.*, 2024)

“Effect of Variable Length Intake Manifold on a Turbocharged Multi-Cylinder Diesel Engine”	“Variable length intake runner”	Simulated in “AVL BOOSTTM engine simulation software”	“It has been found that multi-cylinder turbocharged diesel engines are more responsive to intake runner length variations than naturally aspirated engines.”	Samuel *et al.,* (2013)
“Design & manufacturing of spiral intake manifold to improve Volumetric efficiency of injection diesel engine by AM process”	“Spiral intake manifold”	“Additive Manufacturing (AM) technique”	“To conclude, by using the spiral intake manifold, the volumetric efficiency of the engine was enhanced at different injection pressures and varying loads.”	Manmadhachary *et al.* (2017)
“Analysis and runners length optimization of the intake manifold of a 4-cylinder spark ignition engine”	“An intake manifold”	“…using a numerical approach based on the 1D GT-POWER simulation platform.”	“The results of the performance of the engine when operating under this proposal showed that the engine can achieve higher values of volumetric efficiency, torque, and effective horsepower, depending on the speed conditions, and consequently lower values for the brake-specific fuel consumption.”	Silva *et al.,* (2019b)
“Optimization of Spark Ignition Engine Performance using a New Double Intake Manifold: Experimental and Numerical Analysis”	“New Double Intake Manifold”	“1D and 1D-3D simulations”	“The results show that the manifold design utilizing a two-valve throttle has a better performance…Regarding the experimental tests, the superior double intake manifold increases the engine brake power and torque by 6.814%.”	Khajezade Roodi *et al.,* (2023)
“Evaluation on the Performance of Automobile Engine Using Air Injection Nozzle in the Intake Manifold”	Intake Manifold with Air Injection Nozzle	“…flow simulation was performed using ANSYS Fluent.”	Air injection improved combustion stability and reduced harmful exhaust gases, such as hydrocarbons, carbon monoxide, and nitrogen oxides	(Kim *et al.,* 2021a)
“Computational Analysis of Intake Manifold Design Variants on Induction Swirl of Single-Cylinder Diesel Engine”	Various Intake Manifold Designs in Single-Cylinder Diesel Engine	“3D internal combustion engine simulation” using ANSYS-CFX”	Some designs improved combustion efficiency by increasing induction swirl.	Thombare *et al.,* (2021)

Emission Characteristics Across Manifold Geometries

The design of the intake manifold is of paramount importance in the context of emission regulation, as it influences both charge motion and the quality of combustion. Recent investigations utilize sophisticated emission measurement methodologies to accurately assess these impacts across various operational scenarios. Table 3 encapsulates significant discoveries, illustrating how the geometry of the manifold can be meticulously adjusted to comply with rigorous emission criteria.

Table 3: Impact of Manifold Geometry on Emissions

Study Topic	**Manifold Type**	**Key Findings**	**Citations**
"Computational Analysis of Intake Manifold Design Variants on Induction Swirl of Single-Cylinder Diesel Engine"	Various Intake Manifold Designs in Single-Cylinder Diesel Engine	"…The results show that the modified intake manifold reduces specific fuel consumption by 1% and CO and HC emissions by 20%."	Thombare *et al.*, (2021)
"Design optimization of intake manifold of dual fuel engine"	Dual-fuel engine's intake manifold	"…Emission testing was conducted using the AVL emission system, and emission parameters such as carbon monoxide (CO), nitric oxide (NOx), and unburned hydrocarbons (BSHC) were recorded."	Adithya *et al.* (2021)
"Evaluation on the Performance of Automobile Engine Using Air Injection Nozzle in the Intake Manifold"	Intake Manifold with Air Injection Nozzle	"…using a nozzle for the inflow of outside air created a uniform combustion environment to improve the engine output and reduce harmful exhaust gases, such as hydrocarbon, carbon monoxide, and nitrogen oxides, by generating vortexes inside the intake manifold and increasing the degree of mixing."	(Kim *et al.*, 2021b)
"Effects of intake and exhaust manifold water injection on combustion and emission characteristics of a DI diesel engine"	"Intake and exhaust manifold water injection"	"The intake manifold water injection gives the lowest NOx emissions with an 88% reduction ratio."	(Farag *et al.*, 2017)
"Experimental Investigation on the Emission Level of a Single Cylinder Petrol Engine with Manifolds of Different Geometry"	"…Intake manifolds with different geometries such as convergent, divergent, and venture in a single cylinder SI engine"	"The results indicate that the CO emission (0.13% of Vol.), HC emission (163 ppm HEX), and NOX emission (185 ppm Vol.) are less by using a convergent manifold in the test setup."	(Raja *et al.*, 2020a)
"Effects of intake manifold geometry in H_2 & CNG fueled engine combustion"	"Optimized intake manifold"	"…high engine speeds show a reduction of 14% in NOx and 40% in HC while speeds below 2000 rpm reduce CO by 40%."	(Saaidia *et al.*, 2024)

Discussion

The exhaustive examination of intake manifold configurations elucidates significant insights into their effects on engine efficacy, combustion optimization, and pollutant emissions (Van Basshuysen & Schäfer, 2016). Through the scrutiny of computational and empirical research, numerous salient patterns arise concerning the correlation between manifold architecture and engine functionality. Variable-length intake manifolds exhibit enhanced versatility across varying engine velocities, harnessing the principles of Helmholtz resonance to augment volumetric efficiency by 8-15% in comparison to static designs (Wang *et al.,* 2021). This enhancement in performance is attributable to their capacity to dynamically modify runner length, thereby fine-tuning pressure wave resonance for distinct RPM intervals (Jemni *et al.,* 2021). Nevertheless, this versatility incurs a trade-off in terms of augmented mechanical complexity and elevated manufacturing costs, rendering VLIMs less appealing for cost-sensitive applications despite their inherent technical merits (Basshuysen & Schäfer, 2016). Using precise acoustic wave optimisation, adjusted intake manifolds with fixed geometries, on the other hand, perform exceptionally well in narrow operating bands, usually providing 5-7% torque gains at particular resonant frequencies (Liu *et al.,* 2020). These designs are only practicable for automotive applications that need wide power bands because, although they provide maximum efficiency for specific engine speeds, their performance drastically deteriorates outside of these optimised ranges (Heywood, 2018). The review also emphasises how split-type manifold designs use dual-path configurations that activate various runner lengths depending on engine speed to close this performance difference (Raja *et al.,* 2020). Compared to single-path designs, these systems typically exhibit 10% higher volumetric efficiency in mid-range operations and more consistent performance over broader RPM ranges (Thombare *et al.,* 2021). Uneven air distribution between cylinders can jeopardise combustion stability, therefore, there are still issues with flow imbalances at higher revolutions (Tu *et al.,* 2023). Computational fluid dynamics (CFD) research highlights that careful runner curvature optimisation and plenum design can reduce these flow abnormalities, although these improvements frequently necessitate intensive simulation and prototyping (Zhang *et al.,* 2022). The trade-offs between these various types highlight the significance of application-specific design decisions, where cost, complexity, and operational conditions must be weighed against performance objectives (Van Basshuysen & Schäfer, 2016).

The characteristics of emission depend on the geometry of the intake manifold, with particular sensitivity to the configurations or runner lengths and volumes of the plenum (Zhao *et al.,* 2017). Designs with longer runners result in reductions of nitrogen oxides (NOx) emissions by 5 to 12 percent due to the lower temperatures of combustion and higher charge cooling (Kim *et al.,* 2021). On the other hand, lower plenum volumes result in more turbulence, which leads to better mixing of the air and fuel, reducing hydrocarbon (HC) and carbon monoxide (CO) emissions by 8 to 10 percent (Payri *et al.,* 2014). Designs that have features such as air or water injection systems applied offer greater benefits, with some configurations reporting reductions of NOx emissions from 14 to 88 percent due to improved charge cooling and dilution (Farag *et al.,* 2017). However, with these benefits comes added cost and complexity of the systems, which may restrict their use in mass-market applications (Onorati *et al.,* 2022). The use of dual-fuel manifolds specially designed to operate with hydrogen or compressed natural gas (CNG) shows great potential and offers a solution because such designs lower HC and CO emissions by 40 percent at lower engine speeds without affecting the stability of the combustion (Saaıdıa *et al.,* 2024). The change of carbon monoxide emissions at various loads for various manifold types used in the experimental test rig is shown in Figure 1. The emission results demonstrate that the level of CO emissions rises in tandem with the load (Raja *et al.,* 2020b). Because of the swirl motion, the convergent manifold exhibits a lower emission level than the other manifolds (Raja *et al.,* 2020b). The abrupt contraction in the manifold's area creates the swirl motion in the convergent manifold (Raja *et al.,* 2020b). The decrease in the area leads to a rise in the flow velocity of the air–fuel mixture, which causes the mixture to swirl and promotes effective combustion. CO emissions are reduced as a result of efficient combustion (Raja *et al.,* 2020b). The comparison of the emission results of hydrocarbon and NOX emissions has been depicted in Figures 2 and 3, respectively.

As noted by Adrian & Westerweel in 2011, the geometric effects have been meticulously calculated through advances in experimental and computational techniques. Current Computational fluid dynamics methods, such as RANS and LES models, are now capable of far greater detail in their analysis of flow separation, pressure waves within manifold geometries, and turbulence turbulence spontaneous flow creation (Payri *et al.,* 2004; Tu *et al.,* 2023). The capabilities of these tools have helped optimize the charge distribution by reducing the flow losses in the runner transitions and plenum shapes (Zhang *et al.,* 2022). The ability of computational methods to predict the actual performance of a system when it faces some boundaries. Some of these include under unsteady state conditions, changes due to manufacturing, and variations in designs (Manmadhachary *et al.,* 2017). Important pieces of validation information for measuring directly at the source at hand, for the flow velocity and the particles and turbulence information, is offered through experimental approaches such as PIV and laser Doppler anemometry (Adrian & Westerweel, 2011).

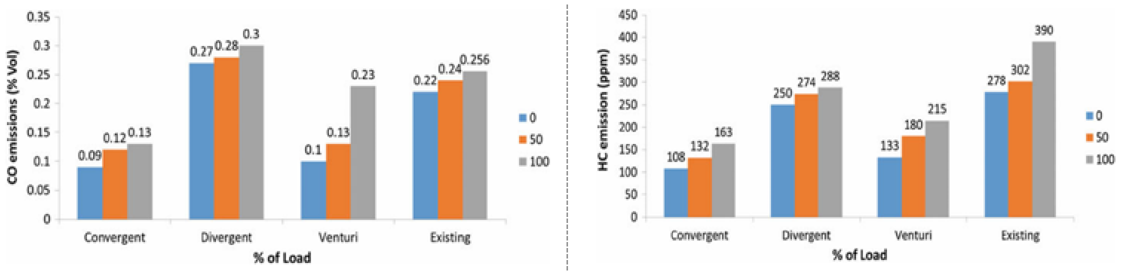

Fig. 1 Comparison of CO levels (% Vol.)

Fig. 2 Comparison of HC levels (ppm)

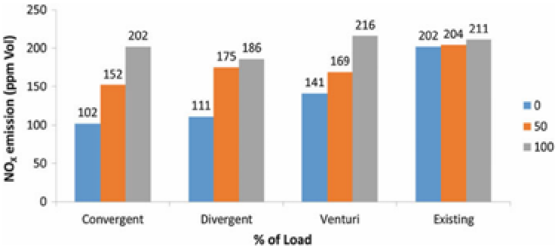

Fig. 3 Comparison of NOx levels (ppm Vol)

Figure 1: Variation in Emissions
Source: Raja et al., 2020b

Limitations

Despite the comprehensive insights provided by computational and experimental studies on intake manifold geometry, several limitations persist in current research.

First, even with their high level of sophistication, computational fluid dynamics (CFD) models still have trouble accurately forecasting real-world situations, especially when operating in transient states or when taking manufacturing tolerances and material variances into consideration (Manmadhachary *et al.,* 2017). Significant experimental validation may be required as a result of these disparities, since they may cause differences between simulated and real performance. Second, it is frequently difficult to accurately quantify the trade-offs between system complexity and performance benefits. Variable-length intake manifolds (VLIMs), for example, provide notable increases in volumetric efficiency but come with additional expenses and mechanical complexity (Van Basshuysen & Schäfer, 2016). The scalability of these findings across various engine types and fuels is also not well understood, even though emission reductions are shown for particular geometries (e.g., longer runners lowering NOx). Dual-fuel or hydrogen-compatible manifolds, for instance, exhibit potential but need more testing in a wider range of operating circumstances (Onorati *et al.,* 2022).

CONCLUSION

Intake manifold geometry is crucial for maximising engine performance, combustion efficiency, and emission control, according to the review. Key findings include:

- Variable-length designs enhance adaptability across RPM ranges but incur complexity.
- Fixed-geometry manifolds excel in narrow operating bands, offering torque gains at resonant frequencies.
- Emission reductions are achievable through tailored geometries (e.g., longer runners for NOx, turbulence-enhancing plenums for HC/CO).

Recommendations

To address these limitations and further advance intake manifold technology, the following recommendations are proposed:

- Examine split-path or adaptive geometries that use additive manufacturing to provide customisation while striking a balance between cost and performance breadth (Manmadhachary *et al.,* 2017).
- Create models that more accurately depict dynamic circumstances, such as sudden changes in load and acceleration (Tu *et al.,* 2023).

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