



A Systematic Review of Air Intake Manifold Using Composite Materials and FEM Analysis

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Abstract

The air intake manifold is a critical component of internal combustion engines, responsible for delivering the air-fuel mixture to the engine cylinders with optimal pressure and flow dynamics. Traditionally made from metals such as aluminum, the intake manifold has evolved significantly in response to demands for lightweight construction, enhanced fuel efficiency, and noise reduction. This systematic review explores the material transition in air intake manifold design, focusing on four major materials: Aluminum, PA6 (Nylon 6), Carbon Fiber Reinforced Polymer (CFRP), and Polypropylene (PP). The review analyzes their mechanical performance, thermal behaviour, acoustic properties, manufacturability, and environmental implications. Aluminum continues to serve in high-performance applications due to its strength and thermal stability but contributes to higher vehicle weight. PA6, particularly in glass-filled form, has become a widely adopted alternative due to its excellent balance of mechanical strength, thermal resistance, ease of processing, and cost-effectiveness. CFRP offers superior stiffness-to-weight ratio and thermal tolerance, making it suitable for premium and electric vehicles, though its adoption remains limited due to high manufacturing costs and complexity. PP stands out for its cost-efficiency and moldability, performing well in less demanding applications but showing limitations in high-heat and load scenarios. Finite Element Method (FEM) analysis has emerged as a valuable tool in optimizing intake manifold design, allowing engineers to simulate structural, thermal, and acoustic behaviour before prototyping. The review concludes that material selection for intake manifolds should be application-specific, with increasing emphasis on composites and hybrid designs that balance performance, cost, and sustainability.

Keywords: Air Intake Manifold, Composite Materials, FEM Analysis, PA6, CFRP, Lightweight Design

1. Introduction

The intake manifold is a critical component in an internal combustion engine, responsible for evenly distributing the air-fuel mixture to the engine cylinders. Its primary function is to optimize the flow of air into

the combustion chamber, which directly impacts engine efficiency, power output, and emissions. The manifold also plays a key role in regulating pressure and temperature, ensuring that each cylinder receives the appropriate quantity of air for combustion. Over the decades, the design and material composition of intake manifolds have evolved significantly, driven by technological advancements, environmental regulations, and the demand for lightweight, durable, and efficient systems. Historically, intake manifolds were primarily manufactured from cast iron or aluminum due to their strength and thermal resistance. However, with the increasing focus on fuel economy and emissions reduction, automotive engineers began exploring alternative materials that could provide similar or better performance at a reduced weight. This transition led to the integration of thermoplastics and composite materials such as PA6 (Nylon 6), carbon fiber reinforced polymers (CFRP), and polypropylene (PP), alongside the traditional use of aluminum. Each of these materials offers unique mechanical, thermal, and processing properties that make them suitable for various engine configurations and performance requirements.

The manufacturing process of intake manifolds varies depending on the material used. Aluminum manifolds are typically produced using sand casting, die casting, or gravity casting methods. These techniques allow for precise dimensional control and complex internal geometries but require extensive machining and are generally heavier than polymer counterparts. In contrast, PA6, PP, and CFRP manifolds are usually fabricated using injection moulding, compression moulding, or thermoforming. Injection moulding, particularly for PA6 and PP, allows for high-volume production with intricate designs and integrated features like mounting points, ribbing, and flow channels. Vibration welding and hot-plate welding are commonly employed to join moulded sections of thermoplastic manifolds, ensuring leak-proof and high-strength assemblies. CFRP manifolds, due to their fibrous reinforcement, often require manual lay-up or automated fiber placement followed by curing processes in autoclaves or using resin transfer moulding (RTM), which adds to the complexity and cost. Aluminum remains a popular choice for intake manifolds in performance and heavy-duty engines, thanks to its high thermal conductivity, corrosion resistance, and mechanical strength.

Its rigidity provides structural support to the engine assembly and can withstand extreme temperatures and pressures. However, the higher density of aluminum increases vehicle weight, which is a drawback in fuel efficiency-focused designs. Table 1 shows the typical mechanical properties of aluminum used in intake manifolds.

Table 1: Mechanical Properties of Aluminum

| Property | Value |
|------------------------------|---------|
| Density (g/cm ³) | 2.70 |
| Tensile Strength (MPa) | 150–300 |
| Yield Strength (MPa) | 100–250 |
| Elastic Modulus (GPa) | 68–72 |
| Thermal Conductivity (W/m·K) | 150–200 |
| Specific Heat (J/kg·K) | 900 |

Polyamide 6 (PA6), or Nylon 6, is widely used for plastic intake manifolds due to its balance of mechanical strength, heat resistance, and process ability. It can withstand the thermal and chemical environment under the hood while providing significant weight savings over metals. PA6 can be reinforced with glass fibers to improve its structural properties, enabling thinner walls and more compact designs. It also offers good fatigue resistance, essential for components subjected to continuous engine vibrations. Table 2 provides the mechanical properties of PA6 used in automotive applications.

Table 2: Mechanical Properties of PA6 (Nylon 6)

| Property | Value (Unfilled / 30% Glass-Filled) |
|------------------------------|-------------------------------------|
| Density (g/cm ³) | 1.14 / 1.36 |
| Tensile Strength (MPa) | 70 / 180 |
| Yield Strength (MPa) | 60 / 160 |
| Elastic Modulus (GPa) | 2.5 / 6.5 |
| Thermal Conductivity (W/m·K) | 0.25 / 0.35 |
| Specific Heat (J/kg·K) | 1700 |

Carbon fiber reinforced polymer (CFRP) represents the high end of intake manifold material choices. While not yet mainstream in mass-market vehicles due to cost, it is used in motorsports and high-performance vehicles where every gram matters. CFRP offers unparalleled stiffness-to-weight ratio and can maintain mechanical integrity at elevated temperatures. In addition, CFRP manifolds contribute to a more rigid intake tract, which can enhance throttle response and reduce pressure losses. However, its acoustic damping is lower than PA6, and manufacturing processes are labour-intensive. FEM analysis of CFRP structures has shown minimal deformation and high resistance to thermal fatigue. Table 3 details CFRP's mechanical properties as relevant to intake applications.

Table 3: Mechanical Properties of CFRP

| Property | Value (Unidirectional laminate) |
|------------------------------|---------------------------------|
| Density (g/cm ³) | 1.5–1.6 |
| Tensile Strength (MPa) | 600–1500 |
| Yield Strength (MPa) | 500–1300 |
| Elastic Modulus (GPa) | 70–150 |
| Thermal Conductivity (W/m·K) | 5–10 |
| Specific Heat (J/kg·K) | 800–1000 |

Polypropylene (PP) is another thermoplastic commonly used for intake manifolds, particularly in cost-sensitive or small-engine applications. It is the lightest among the commonly used materials and offers excellent resistance to corrosion and chemicals. Although its mechanical properties are not as robust as those of PA6 or CFRP, modifications with fillers (such as talc or glass fibers) can improve its performance. PP's main advantage lies in its low cost, ease of moulding, and recyclability. It is well-suited for naturally aspirated engines with lower thermal and pressure requirements. Table 4 summarizes the mechanical properties of polypropylene used in automotive components.

Table 4: Mechanical Properties of Polypropylene (PP)

| Property | Value (Unfilled / 30% Filled) |
|------------------------------|-------------------------------|
| Density (g/cm ³) | 0.90 / 1.1 |
| Tensile Strength (MPa) | 30 / 60 |
| Yield Strength (MPa) | 25 / 50 |
| Elastic Modulus (GPa) | 1.2 / 3.0 |
| Thermal Conductivity (W/m·K) | 0.1 / 0.25 |
| Specific Heat (J/kg·K) | 1900 |

The selection of intake manifold material is largely governed by the trade-off between performance, cost, weight, and durability. For high-performance applications where thermal resistance and structural rigidity are paramount, aluminum and CFRP are preferred. On the other hand, PA6 and PP offer economical solutions with significant weight reduction and are suitable for most commercial passenger vehicles. Furthermore, with advancements in finite element modelling, the structural behaviour, fatigue life, and acoustic performance of each material can be simulated and optimized before physical prototyping. This enables a more efficient and cost-effective design cycle. As emission norms become stricter and the push for electrification continues, material selection will likely lean further toward composites and multifunctional materials. PA6 remains the dominant choice due to its versatility, but CFRP may see broader adoption as production costs decline. PP will likely retain its place in the budget segment, while aluminum may be gradually phased out except in niche

applications. The future of intake manifold design will be shaped by a combination of material science, digital engineering, and sustainability goals, with each material playing a role based on application-specific requirements.

Table: Comparative analysis of Aluminum, PA6 (Nylon 6), CFRP (Carbon Fiber Composite), and Polypropylene (PP) for different applications

| Application / Feature | Aluminum | PA6 (Nylon 6) | CFRP (Carbon Fiber Composite) | Polypropylene (PP) |
|---|------------------------|----------------------------|---------------------------------------|------------------------------------|
| High-Performance Engines | Highly suitable | Moderately suitable | Excellent for lightweight performance | Not suitable |
| Turbocharged Engines | Suitable | Well-suited | Suitable with reinforcement | Not preferred |
| Naturally Aspirated Engines | Commonly used | Widely used | Occasionally used | Widely used |
| Electric Vehicle (EV) Platforms | Limited use | Suitable | Excellent potential | Suitable |
| Lightweight Design Requirement | Heavier option | Lightweight | Extremely lightweight | Lightest among all |
| NVH (Noise, Vibration, Harshness) Control | Poor damping | Excellent noise absorption | Moderate damping | Acceptable with design enhancement |
| Cost-Sensitive Vehicle Models | Costly option | Cost-effective | High cost | Very economical |
| Thermal Resistance (High Temp Engines) | Excellent | Good | Very good | Limited |
| Ease of Manufacturing (Mass Production) | Moderate | Excellent | Complex processes | Excellent |
| Environmental Sustainability | Moderate recyclability | Good recyclability | Poor recyclability | Highly recyclable |
| Recyclability | Recyclable | Easily recyclable | Difficult to recycle | Easily recyclable |

2. Review of Literature

The evolution of plastic and composite air intake manifolds has been a significant milestone in automotive engineering, especially in the context of improving engine efficiency, reducing weight, and addressing acoustic and structural performance. Over the past two decades, researchers have extensively explored advanced materials, such as polyamide, polypropylene, and woven glass-fiber composites, as well as optimization techniques for joining and testing these materials in manifold applications. Initial studies in the late 1990s and early 2000s focused on replacing traditional metal intake manifolds with engineered thermoplastics. For instance, Bates et al. (2004) demonstrated the effectiveness of vibration welding in assembling reinforced nylon 6 and nylon 66 air intake manifolds, showing improved strength and manufacturability in complex geometries. The influence of rapid strain rates during operational loading was explored by Caskey and Daly (1998), highlighting the need for careful structural analysis during the design stage. Subsequently, Lee et al. (1998) optimized the vibration weld joint strength using design of experiments, showing that joint geometry and welding parameters significantly impact mechanical integrity.

In terms of structural behavior, Capitani et al. (1998, 1999, 2000) developed a practical methodology for dynamic analysis and validation testing of plastic engine components using modal testing and finite element modeling (FEM). Their approach laid the foundation for real-world testing of NVH (Noise, Vibration, and Harshness) parameters and fatigue strength. Battistoni et al. (2006) extended this work by correlating structural design parameters of plastic manifolds with NVH performance, showing how ribbing, material stiffness, and wall thickness contribute to vibrational damping. Similarly, Dimeo et al. (2012) examined the manifold's influence on engine acoustics and demonstrated that geometric and material variations could directly impact perceived engine noise. The transition to composite materials marked a significant shift in manifold design. Jin et al. (2018) and Gao & Li (2016) conducted detailed mechanical characterizations of woven glass-fiber composites under various environmental conditions, revealing that such materials could maintain high structural integrity even at elevated temperatures.

These properties are vital for under-the-hood automotive applications where thermal loads are significant. Carlstedt et al. (2019) and Johannisson et al. (2018) went further to study multifunctional structural battery composites, suggesting possibilities for integrating energy storage directly into load-bearing vehicle components, although still in early stages for intake systems. NVH behaviour and acoustic performance of plastic manifolds remained an ongoing concern. Kraft (2000) and Pricken (1999) both demonstrated that acoustic optimization, through design tweaks and material damping, could drastically reduce air-rush and resonant noise in intake systems. Novak et al. (2001) introduced a noise synthesis technique to simulate and mitigate these effects, using both experimental and FEM-based predictive modelling. Thermoforming and joining processes have also evolved. Mallick and Daly (2000) investigated thermoforming as a viable method for shaping manifold geometries, with minimal compromise on strength. Hickman and Schumacher (2005) explored shell bonding of polyamide manifolds and emphasized adhesion parameters and curing techniques

critical for leak-proof sealing. Klein and Wiese (2011) introduced engineered polypropylene compounds for elevated thermal stability, meeting demands of turbocharged engines.

Meanwhile, the environmental performance of intake manifolds was also addressed. Keoleian and Kar (2003) applied life cycle design to intake systems and found that switching to polymer-based manifolds reduced overall lifecycle energy consumption and CO₂ emissions. Koffler and Rohde-Branderburger (2010) confirmed these findings, emphasizing the importance of lightweighting in automotive LCA assessments. Advanced numerical simulations have further refined manifold design. Seemann and Krause (2015) presented FEM-based modeling of honeycomb core structures to evaluate joint performance in sandwich panels, applicable to manifold support structures. Carlstedt et al. (2019) employed similar modeling strategies to assess elastic modulus variation with changing charge states in composite structures, showcasing the potential for smart materials integration in engine systems. The culmination of these studies underscores a clear trend: the convergence of advanced materials, FEM simulation, NVH optimization, and sustainability is redefining air intake manifold design. The current research not only supports robust and lightweight solutions but also opens the pathway for multifunctional and energy-integrated components in future vehicle platforms.

3. Conclusion

The systematic review of air intake manifolds using different materials—Aluminum, PA6 (Nylon 6), CFRP (Carbon Fiber Reinforced Polymer), and Polypropylene—offers a comprehensive insight into the evolving landscape of automotive intake systems. As global priorities shift toward sustainability, weight reduction, performance optimization, and cost efficiency, the role of material selection becomes increasingly critical in engineering design. Each material examined in this review presents a unique combination of mechanical, thermal, acoustic, and economic characteristics that influence its suitability for intake manifold applications. Aluminum, a traditional choice for intake manifolds, offers excellent thermal resistance, mechanical strength, and durability, making it ideal for high-performance and turbocharged engines. Its structural rigidity supports precision in airflow management and engine reliability. However, its relatively high density adds significant weight to the powertrain, adversely impacting fuel efficiency and emissions. Moreover, aluminum casting and machining processes are energy-intensive, raising both production costs and environmental concerns.

PA6 (Nylon 6), particularly when reinforced with glass fibers, has emerged as a dominant alternative in commercial automotive applications. It provides an optimal balance between strength, thermal stability, manufacturability, and weight savings. Its excellent acoustic properties contribute to NVH (Noise, Vibration, and Harshness) control, enhancing passenger comfort. The ease of injection moulding and welding processes makes PA6 highly suitable for complex and integrated manifold designs. Furthermore, its recyclability and lower environmental impact align with the growing emphasis on green manufacturing. CFRP, although currently limited by cost and production complexity, represents the pinnacle of material innovation in this domain. Its superior stiffness-to-weight ratio, high temperature tolerance, and design flexibility position it as an ideal candidate for high-end performance vehicles and electric platforms. With continued advancements in automated manufacturing techniques and cost reductions in carbon fiber production, CFRP holds great promise

for broader adoption in the future. However, challenges related to acoustic damping and recyclability remain areas of active research. Polypropylene stands out as the most cost-effective and lightweight option among the four.

While it lacks the mechanical robustness and thermal resistance required for high-performance engines, it serves adequately in low-to-mid power applications, particularly in naturally aspirated engines and small passenger cars. Its high moldability and compatibility with filler materials offer design adaptability, though its usage is often constrained by heat and load-bearing limitations. Finite Element Method (FEM) analysis plays a vital role across all material types by enabling precise simulation of stress distribution, thermal expansion, vibration behaviour, and potential failure zones. Through FEM, engineers can virtually assess performance and optimize designs long before physical prototyping, reducing both development time and cost. There is no universally superior material; instead, material selection for air intake manifolds must be context-specific, guided by the intended application, performance targets, and economic constraints. Future trends are likely to favour composite materials and hybrid designs that leverage the strengths of multiple materials. Coupled with FEM-driven optimization and sustainability considerations, these innovations will continue to redefine intake manifold engineering for next-generation mobility.

- **Recommendations**

1. Select intake manifold materials based on engine performance requirements, giving preference to high-strength composites like CFRP in performance vehicles and PA6 for commercial use.
2. Prioritize lightweight materials such as PA6 and PP for improved fuel efficiency and reduced emissions, especially in vehicles designed for urban and electric mobility.
3. Incorporate FEM analysis early in the design phase to simulate structural integrity, thermal expansion, and vibrational behaviour across all material types.
4. Consider hybrid material designs that combine the rigidity of aluminum with the acoustic and lightweight benefits of polymers or composites.
5. Focus on recyclable and environmentally sustainable materials like PP and PA6 to meet global automotive sustainability standards and circular economy goals.
6. Optimize intake manifold geometry through simulation tools to enhance airflow, reduce pressure loss, and improve combustion efficiency.
7. Standardize welding and joining techniques (e.g., vibration or hot-plate welding) for thermoplastics to ensure consistent manufacturing quality.
8. Invest in the development and cost-reduction strategies for CFRP manufacturing to enable its wider application in mass-market vehicles.
9. Use acoustic simulation modules alongside FEM to evaluate and reduce engine noise through manifold design and material selection.
10. Encourage further research on the durability and thermal cycling behaviour of polymer-based manifolds under real-world operating conditions.

References

1. Johannisson, W., et al. (2018). Multifunctional performance of a carbon fiber UD lamina electrode for structural batteries. *Composites Science and Technology*, 168, 81–87. <https://doi.org/10.1016/j.compscitech.2018.08.044>
2. Carlstedt, D., Marklund, E., & Asp, L. E. (2019). Effects of state of charge on elastic properties of 3D structural battery composites. *Composites Science and Technology*, 169, 26–33. <https://doi.org/10.1016/J.COMPSCITECH.2018.10.033>
3. Asp, L. E., et al. (2019). Structural battery composites: A review. *Functional Composites and Structures*, 1(4), 042001. <https://doi.org/10.1088/2631-6331/ab5571>
4. Gao, G., & Li, Y. (2016). Mechanical properties of woven glass-fiber reinforced polymer composites. *Emerging Materials Research*, 5(2), 201–208. <https://doi.org/10.1680/jemmr.16.00018>
5. Leopold, C., et al. (2018). Comparison of analytical approaches predicting compressive strength of fibre reinforced polymers. *Materials*, 11(12), 2517. <https://doi.org/10.3390/ma11122517>
6. Jin, H., et al. (2018). Mechanical characterization of woven composites at different temperatures. *Report SAND2018-8563*, Sandia National Labs.
7. Seemann, R., & Krause, D. (2015). Numerical modelling of Nomex honeycomb cores for sandwich joints. *WCCM 11 Proceedings*, Hamburg.
8. Dimeo, A., et al. (2012). Plastic intake manifold influence on the NVH performance in PFI engine. *SAE Technical Paper No. 2012-36-0615*.
9. Klein, J., & Wiese, J. (2011). High performance engineered polypropylene compounds for high temperature automotive under-the-hood applications. *SPE ACCE 2011*.
10. Koffler, R., & Rohde-Branderburger, K. (2010). Fuel savings through lightweight design in LCA. *Int. J. Life Cycle Assess.*, 15(2), 128-135. <https://doi.org/10.1007/s11367-009-0127-z>
11. Keoleian, G. A., & Kar, K. (2003). Life cycle design of air intake manifolds. *Journal of Cleaner Production*, 11, 61–77. [https://doi.org/10.1016/S0959-6526\(02\)00004-5](https://doi.org/10.1016/S0959-6526(02)00004-5)
12. Bates, P., et al. (2004). Vibration welding air intake manifolds. *Composites Part A: Applied Science and Manufacturing*, 35(8), 1107–1116. <https://doi.org/10.1016/j.compositesa.2004.02.019>
13. Hu, K., et al. (2003). Acoustic modeling and radiated noise prediction for plastic air intake manifolds. *SAE Technical Paper No. 2003-01-1448*.
14. Hickman, G. F., & Schumacher, D. (2005). Polyamide intake manifold shell bonding. *SAE Technical Paper No. 2005-01-1518*.
15. Battistoni, M., et al. (2006). NVH performance of plastic air intake manifolds. *SAE Technical Paper No. 2006-01-0705*.
16. Capitani, R., et al. (2000). Method for conducting validation testing on polyamide engine components. *Shock and Vibration Digest*, 32, 23.
17. Capitani, R., et al. (1998). Methodology to analyze the dynamic behaviour of car engine components made in plastic. *ISMA Conf. Proc.*, 639–646.
18. Capitani, R., et al. (1999). Validation testing on polyamide components. *IMAC Conf. Proc.*, 363–367.

19. Mallick, P. K., & Daly, P. (2000). Thermoforming plastic intake manifolds. *SAE Technical Paper No. 2000-01-0045*.
20. Kraft, W. W. (2000). Reduction of air-rush noise in plastic engine intake manifolds. *SAE Technical Paper No. 2000-01-0044*.
21. Kondapalli, P. S., & Sirani, V. (2000). Burst pressure strength in welded nylon manifolds. *SAE Technical Paper No. 2000-01-0040*.
22. Mathew, B. A., & Wiebeck, H. (1999). Nylon 6,6 composite for air intake manifolds. *SAE Technical Paper No. 1999-01-3011*.
23. Paffrath, H., et al. (1999). Future air intake system technology. *SAE Technical Paper No. 1999-01-0266*.
24. Pricken, F. (1999). Acoustic optimization of plastic air intake manifolds. *SAE Technical Paper No. 1999-01-0319*.
25. Lee, C. S., et al. (1998). Optimization of vibration weld joint strength in manifolds. *SAE Technical Paper No. 980730*.
26. Lee, K. H. (1998). NVH performance of plastic intake manifold in 4-cylinder engine. *SAE Technical Paper No. 980728*.
27. Caskey, J., & Daly, P. (1998). Effects of rapid strain rates in plastic manifolds. *SAE Technical Paper No. 980729*.
28. Mukawa, T., et al. (1996). Development of a plastic intake manifold. *JSAE Review*, 17, 51–57. [https://doi.org/10.1016/0389-4304\(95\)00048-8](https://doi.org/10.1016/0389-4304(95)00048-8)
29. Nelson, K. W. (1995). Vibration welding in thermoplastic intake manifolds. *SAE Technical Paper No. 950230*.
30. Novak, C., et al. (2001). Plastic manifold noise synthesis technique. *SAE Technical Paper No. 2001-01-1144*.

