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# A Comprehensive Review on Understanding Car Air Filters: Structure and Mechanism of Operation

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**Abstract:**
Modern lifestyles necessitate adaptation to contemporary technologies, as approximately 80% of our time is spent indoors or in vehicles. This raises significant concerns about indoor air quality, including issues like particles, dust, volatile organic compounds (VOCs), harmful gases, unpleasant odors, and biological contaminants such as airborne viruses and bacteria. Car air filters play a crucial role in trapping dirt particles that can negatively impact engine performance and longevity. They also purify the air inside the cabin, significantly enhancing passenger health. In developed countries, around 80% of cars utilize nanotechnology-based filters that effectively eliminate odors and trap fine particles. This study aims to examine the impact of air pressure on engine performance using both clean and dirty air filters. Research indicates that dirty air filters lead to increased fuel consumption and greenhouse gas emissions while diminishing engine performance. Specifically, fuel consumption rises and exhaust gas temperatures increase with dirty filters. In modern cars equipped with electronic pressure transducers, notable pressure differences between clean and dirty filters are observed. For carburetor engines, dirty filters markedly reduce acceleration performance. Consequently, maintaining clean air filters is vital for optimal engine performance, fuel efficiency, and reduced emissions, while nanotechnology filters enhance filtration and improve overall vehicle performance.

**Keyword**: Element filters, Dust, Chemical pollutants, Filter covers, Impregnations.

## 1. Introduction:

Contemporary ways of life force people to prepare according to modern technology[1]. About 80% of people spend their time daily in closed environments as residents, in offices and vehicles Therefore, the bacteria in the indoor air affect human health, which is why the risk of airborne fungi increases[2]. At the same time, exposure to indoor air bacteria or vehicles is attracting much attention and can be related to the characteristics of buildings and vehicles. So, we want to know how car air filters act against bacteria when car air filters get dirty[3]. The air filter traps dirt particles that can damage cylinders, walls, pistons, and piston rings. The engine needs internal combustion and clean air to run smoothly. The entire service

life of the air filter acts as a barrier between the ambient air it enters with, particulate matter and the sensitive interior of the engine[4]. Many factors affect the air filter. Performance, such as pressure drop, efficiency, and dust retention capacity. Many external factors such as driving style, engine type, if equipped, also affect the air filter. Car air filters also purify the air inside the car and allow passengers to breathe healthy and clean air[5]. Different markets and engines may extend the life of air filters in certain vehicles with certain engines or allow smaller filter sizes for the same service. Today, car owners use filters based on nanotechnology to improve cabin air quality. Such filters contain carbon layers that eliminate odors[6]. These filters enable "mechanical filtration", in which filter fiber material with specific pore sizes traps particles larger than the pore size. Almost 80% of cars used in advanced countries, such as America, China, Japan, etc., have an internal filter based on nanotechnology[7]. One of the main topics of nanotechnology is the creation of materials with new properties. These materials will have a very high added value and higher activity in all industries, and the automobile industry is no exception to this rule[8]. The car of the future will come with affordable advancements based on miniaturization, lighter and stronger materials, and new energy and smart car systems. Automotive companies use nanotechnology and nanomaterials to improve the performance of their cars and meet the needs of customers and existing standards. The use of nanomaterials leads to the improvement of the structural, electrical, thermal, magnetic and catalytic capabilities of technologies developed for the automotive industry. In addition to providing high performance, these materials are highly compatible with the environment and can replace toxic or expensive materials. Nanomaterials can be used in a wide range of applications. These applications include polishing, glass processing, variable colors, nano-filled polymers and resins, nanostructured ceramics and coatings, electric vehicle batteries, and sensors and advanced electronic components[8]. These applications can provide improved performance or additional functions such as wear and erosion resistance, light weight, reduced friction, increased strength, UV resistance, corrosion control, or enhanced aesthetics[9].

The air pressure entering the car engine is one of the important factors that affect its performance. The use of car air filters can directly or indirectly affect the air pressure entering the engine the purpose of this study is to investigate the effects of air pressure entering the engine using car air filters on two types of engines that use clean and polluted air filters and the way of fuel consumption and the effects of pressure on car air filters[10].

## 2. Principles:

Different types of car air filters, such as cabin, engine, and oil filters, are crucial for passenger health, engine performance, and oil efficiency[11]. As illustrated in (Figure 1b), each filter serves a specific purpose in maintaining the vehicle's overall functionality. The cabin filter ensures clean air for passengers, while the engine filter protects the engine from harmful particles. Oil filters help maintain oil quality by removing contaminants. The effectiveness of these filters depends on high-quality components. Regular maintenance and timely replacement are essential for optimal performance of each filter type[12]. A typical car air filter consists of the following parts:

**2.1. Filter elements**: are essential components in various systems, designed to remove contaminants from air or liquid while allowing continuous flow. These elements are commonly manufactured using materials such as pleated paper, foam, or cotton gauze, each suited to specific filtration needs[13]. Pleated paper serves as a semi-permeable barrier, effectively separating fine particles from air or liquid. The pleated design increases the surface area available for trapping contaminants, enabling efficient filtration

while maintaining a compact form. Foam filter media, with their porous structure, are flexible and reusable, making them ideal for applications that require durable and adaptable filtration solutions. These filters capture particles while allowing smooth airflow or liquid flow through the material see (figure 1a). Cotton gauze, recognized for its absorbency and loosely woven texture, efficiently traps dust and dirt without significantly obstructing airflow, making it particularly useful in applications where airflow performance is critical[14]. The primary purpose of a filter element is to trap dust, dirt, and other particles while ensuring uninterrupted airflow or liquid flow. They play a vital role in automotive air filters, HVAC systems, and industrial gas purification, where maintaining clean and efficient systems is essential for optimal performance and safety[15].

To enhance their effectiveness, filters are often pleated or layered. Pleating significantly increases the surface area within a limited space, enabling the filter to capture more contaminants without reducing flow. Layering, on the other hand, helps capture particles of varying sizes at different depths, improving overall filtration efficiency[16].

**2.2. The frame or housing:** of a car air filter is a crucial component designed to support and secure the filter element in place see (figure 1a). Its role is integral to ensuring the efficient filtration of air entering the engine, which is vital for the engine's performance, longevity, and fuel efficiency[2]. Air filter frames or housings are constructed using materials such as plastic, rubber, or metal, each chosen for its unique benefits of durability, flexibility, and performance. Plastic; lightweight and corrosion-resistant, plastic is a commonly used material for air filter housings. Its cost-effectiveness and design versatility make it a preferred choice for many standard applications. In other hand rubber is also often utilized for seals or soft frames due to its flexibility and ability to create a tight fit between the filter and housing. Its elasticity helps absorb vibrations and ensures an airtight seal, preventing unfiltered air from bypassing the filter. The same as rubber metal also use for more robust or high-performance applications, metal frames provide superior strength and heat resistance. This makes them suitable for heavy-duty environments or vehicles that require enhanced durability under extreme conditions[17].

**2.3. Rubber Seals or Gaskets:** Rubber seals or gaskets are important components in ensuring the air filter functions effectively by providing a secure and airtight connection within the filter housing. These seals are designed to prevent air leaks by creating a snug fit between the filter and the housing see (figure 1a). This ensures that all the air entering the intake system is properly filtered, without bypassing the filter element[17]. Without these seals, unfiltered air containing harmful particles like dust or debris could enter the engine, leading to potential damage and reduced performance. The gaskets are strategically placed along the edges of the filter frame. This placement allows the gasket to compress slightly when installed, forming an effective barrier against leaks while maintaining structural stability[14].

**2.4. Support Mesh or Grid:** The support mesh or grid is an essential reinforcement feature in many air filters. Its typically made from metal or plastic, depending on the application and desired durability. Metal meshes are more rigid and heat-resistant, while plastic grids are lightweight and corrosion-resistant. The main purpose of this component provides structural support to the filter element, ensuring it remains intact under high airflow or pressure changes. It prevents the filter from deforming, which could compromise filtration efficiency or airflow consistency, particularly in high-performance engines[18].

**2.5. Filter External Housing:** The filter housing is the external casing that encases the entire air filter assembly see (figure 1a). Typically made of plastic or metal. Plastic housings are lightweight and resistant to corrosion, while metal housings provide superior durability and resistance to extreme temperatures, making them ideal for heavy-duty or performance vehicles. the housing secures the air filter within the

intake system and protects it from external contaminants such as dirt, moisture, and debris. It also ensures proper alignment with the intake ducting, facilitating smooth and efficient airflow while preventing damage to the filter from environmental exposure[19].

And also some high performance air filters may include additional protective layers (optional) to enhance their efficiency[20]. Protective layers often consist of oil coatings or fine synthetic materials designed to trap finer particles that might bypass standard filter elements. by working together, these components ensure that the air entering the engine is clean, promoting optimal performance, fuel efficiency, and longevity[21].

**Figure 1: (a) illustrate the different parts of car air filters. (b) exhibit the different type of car air filters that is utilized for car cabin, engine and oil filtration.**


## 3. The basic pollutants that stain car air filters are:

**3.1. Dust**: small particles that come up from around the car and enter the ventilation system and engine, these particles can quickly reduce the efficiency of the engine and damage the internal parts of the engine[22].

**3.2. Chemical pollutants:** including gases like nitrogen oxides (NOx), carbon dioxide (CO2), carbon monoxide (CO), and hydrocarbons, are produced from fuel combustion in an engine[23]. Based on the chemical relationships of these pollutants, van der Waals forces are generated between the air filter paper and its impregnation, leading to the creation of intermolecular forces as well[22].

**3.3. A collection of organic matter and bacteria:** leaves, branches, organic matter and bacteria and microbes that rise from the environment around the car and enter the engine system, these pollutants can destroy the performance of the car's air filter. and damage the engine[11].

**3.4. Urban pollutants:** includes pollutants such as suspended particles PM2.5 and PM10, pollutants in urban smoke and other chemical compounds that are released into the air from various sources such as traffic, industries, etc. Considering these pollutants, car air filters are designed to effectively purify these pollutants and provide clean air to the car engine[18].

## 4. Type of car air filters:

The car air filter is used to remove suspended particles, dust and other pollutants from the air, these filters

has different types according to their chemical structure and mechanism of filtering, that separates these pollutants from the air, here are some types of car air:

**4.1. Combined filters**, these types of filters are made of a combination of synthetic fibers and chemical substances such as activated carbon or antibacterial substances. Synthetic fibers attract suspended particles and chemicals, including activated carbon, in addition to removing particles, also absorb odors and harmful gases[19].

**4.2. HEPA filters** stand for "High Efficiency Particulate Air" and are effective at removing very small particles such as viruses, bacteria, and allergenic particles. These filters are made of a fiber matrix with a specific diameter smaller than 0.3 micrometers, which absorb particles.

**4.3. Electrostatic filters**, these filters are made of electrostatic fibers that act as a magnet for charged particles. The charged particles that are placed on the fibers are absorbed and separated from the air flow[24], [25].

**4.4. Biological filters**, these filters are made of materials such as cotton, sesame, or cellulose materials that act as a habitat for bacteria and fungi, these microorganisms analyze and absorb contaminated materials[11]. The performance of car air filters by using chemical relationships, and chemical interactions, including absorption, surface reactions, and ion exchange, van der Waals forces help maintain air quality and remove harmful and allergenic particles[27].

## 5. Chemical structure of car air filters:

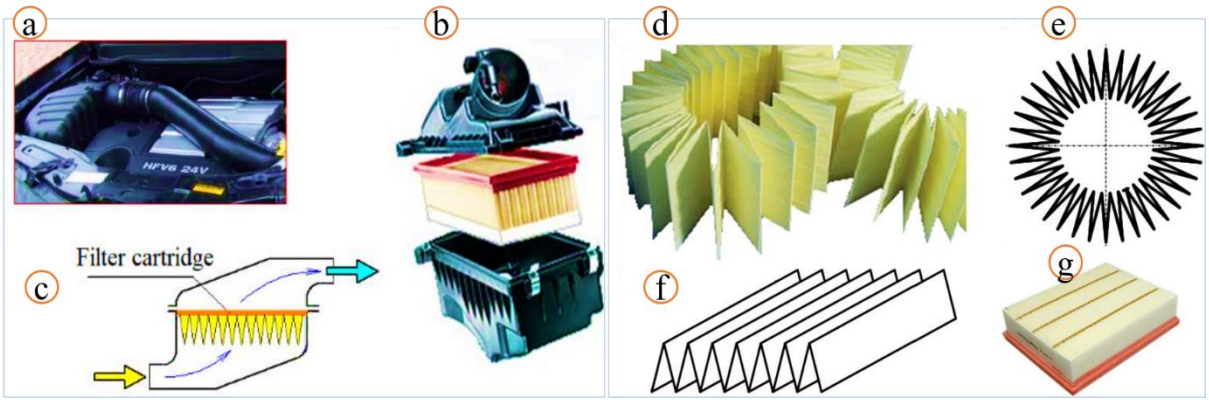
### 5.1. Filter Media Materials:

The materials used in car air filters vary depending on their type and intended function, ensuring optimal filtration and durability across different applications.

#### 5.1.1. Paper (Cellulose):

Car air filters frequently utilize paper made from cellulose as their primary filtering medium. This material is highly effective at capturing various airborne particles, including dust, pollen, and debris, the functioning procedure and various forms of paper filters illustrate in (figure 2). The cellulose fibers form a dense network that traps larger particles while allowing cleaner air to flow through[27]. Over time, the filter can become clogged with accumulated contaminants, which may reduce airflow and engine performance, underscoring the need for regular maintenance and replacement. Cellulose filters are widely used due to their affordability and capability to provide adequate filtration for most driving conditions. This material, derived from plant-based cellulose fibers, is often reinforced with resin coatings to enhance strength and improve filtration efficiency. The resin helps the paper maintain its structure under airflow pressure while effectively trapping fine particles like dust and dirt, making it an eco-friendly choice[29], [30].

**Figure2: car air filter; (a) illustrate the location of car air filter in engein compartment, (b) filter component and its installation, (c) functioning of filters, (d) Pleating the paper, (e) Forming it into a multi-arm star shape, (f) Shaping it into a panel, (g) Assembling a panel filter cartridge[5].**




### 5.1.2. Foam:

Polyurethane foam filters are designed with variable pore sizes, enabling them to capture particles of different dimensions effectively see (figure 3 b,c). This adaptability makes them suitable for a wide range of filtration applications, from coarse to fine filtration. A major advantage of foam filters is their ability to be washed and reused multiple times. This feature reduces waste and helps lower replacement costs over time, making them a cost-effective choice for long-term use[24]. Some foam filters are enhanced with an oil coating, which improves their filtration performance. The sticky surface created by the oil traps smaller debris, making these filters especially efficient in dusty environments where fine particles are abundant. Known for their durability, polyurethane foam filters resist degradation even in challenging conditions. Their resilience ensures consistent performance over extended periods, making them a reliable option for diverse filtration needs[27], [30].

### 5.1.3. Cotton Gauze:

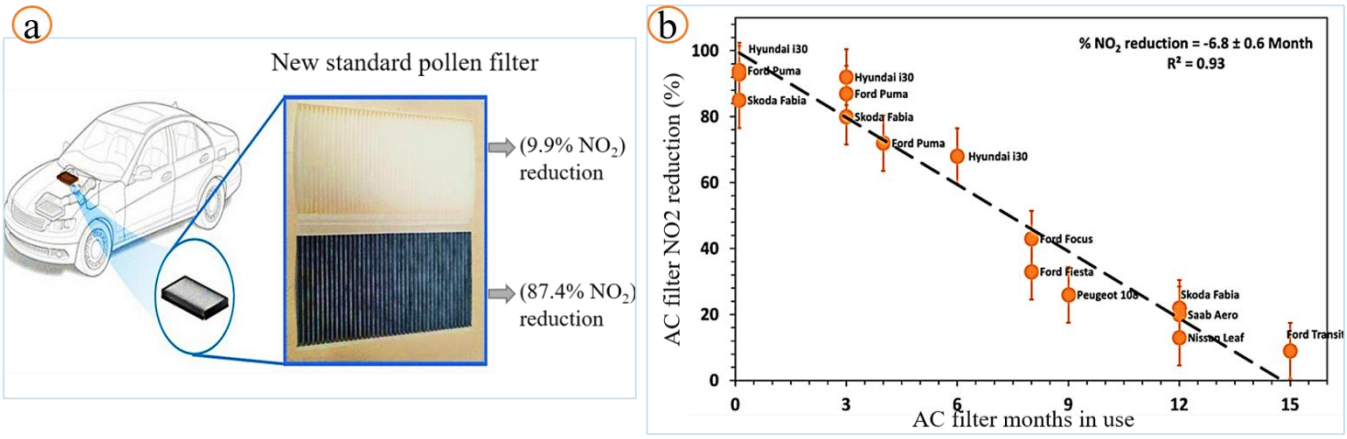
Cotton gauze is a widely used material in high-performance air filters, especially in automotive applications. These filters are designed to offer superior filtration while maintaining optimal airflow, making them ideal for vehicles requiring enhanced engine performance see (figure 3a) a. Cotton gauze filters are constructed with multiple layers of cotton fabric. This layered design improves the filter's ability to trap contaminants while ensuring that airflow remains unobstructed. Additionally, the cotton is treated with a special oil that significantly enhances its ability to capture microscopic particles. The oil creates a tacky surface that effectively traps dirt and debris without restricting airflow. One of the primary benefits of cotton gauze filters is their ability to support high volumes of airflow. This is essential for high-performance vehicles, as it helps increase horsepower and torque[29]. The combination of multiple fabric layers and the oil coating enables these filters to capture fine particles, ensuring clean air for the engine and reducing the risk of dirt entering the intake system. Cotton gauze filters are particularly well-suited for high-performance and racing vehicles, where both optimal airflow and reliable engine protection are vital. These filters are designed to endure harsh conditions, providing efficient filtration even under demanding circumstances[31].

**Figure3: (a) cotton filter media, (b,c) foam filter media for car cabin and engine filters respectively.**


### 5.1.4. Activated Carbon:

Certain filters, particularly cabin air filters, incorporate an activated carbon layer that is highly porous and chemically treated. This design enhances the filter's ability to absorb gases, odors, and volatile organic compounds (VOCs), which are common indoor air pollutants[32]. The activated carbon layer features a unique porous structure that provides a large surface area for adsorption[33], allowing it to capture a wide range of gaseous pollutants effectively see (figure 4b) [32]. The carbon is often chemically treated to enhance its ability to attract and hold onto specific contaminants, making it particularly effective against VOCs and odors. By absorbing harmful gases like $NO_2$, as shown in (figure 4a) and unpleasant odors, activated carbon layers significantly improve the air quality inside vehicles, creating a healthier environment for passengers. These filters are particularly effective at removing odors from sources such as smoke, food, and pet dander, contributing to a more pleasant driving experience[35]. Additionally, the use of activated carbon in cabin air filters helps protect passengers from exposure to harmful pollutants that can enter the vehicle from outside sources, such as exhaust fumes and industrial emissions[36].

**Figure 4: (a); Activated carbon filter used for $NO_2$ adsorption, (b) Relationship between mean $NO_2$ reductions with windows closed and mechanical ventilation settings, along with months of using the activated carbon filter. Bars represent the standard error of the mean reduction for each vehicle [32].**




### 5.1.5. Impregnated Chemicals:

**Zeolites**: Natural or synthetic zeolites can be added to the car air filter media to enhance the removal of certain gaseous pollutants[34]. Zeolites are aluminosilicate minerals that have a porous structure, allowing them to trap cations and small molecules[35].

**Metal Oxides**: Materials like titanium dioxide (TiO2) can be used for photocatalytic processes, helping to break down organic pollutants when exposed to light[36].

### 5.2. Frame and Support Materials:

Frames for air filters are typically constructed from durable polymers such as polypropylene or thermoplastic elastomers (TPE)[24]. These materials are chosen for their excellent properties, including flexibility, strength, and resistance to environmental factors. The flexibility of these polymers allows the frame to maintain a secure seal within the filter housing, which is crucial for preventing air leaks. This ensures that only filtered air enters the engine or cabin, optimizing performance and efficiency[38]. In addition to the frame, many air filters incorporate a supporting metal mesh, often made from stainless steel or aluminum. This metal mesh provides structural integrity to the filter, ensuring that it retains its shape even when subjected to high airflow and pressure fluctuations [30]. The use of stainless steel or aluminum is advantageous because these materials resist rust and deformation, which helps maintain the longevity and reliability of the filter throughout its service life. in high-performance or off-road vehicles, some air filters are treated with an oil coating made from hydrocarbon-based oils. This coating forms a sticky layer on the surface of the filter media, which significantly enhances its ability to capture smaller particles[26]. By creating a tacky surface, the oil helps trap dirt, dust, and other contaminants that might otherwise bypass the filtration system. This feature is particularly important in environments with high levels of airborne debris, where maintaining optimal engine performance is critical [29].

## 6. Filtration Mechanisms:

The filtration mechanism in car air filters involves a multi-faceted approach that includes particle filtration, chemical and biological filtration, and moisture control by different interaction bonds see (figure 5a). Together, these processes ensure that vehicles operate efficiently while providing a clean and healthy environment for occupants. Regular maintenance and replacement of air filters are vital to sustaining these benefits and optimizing vehicle performance[42].

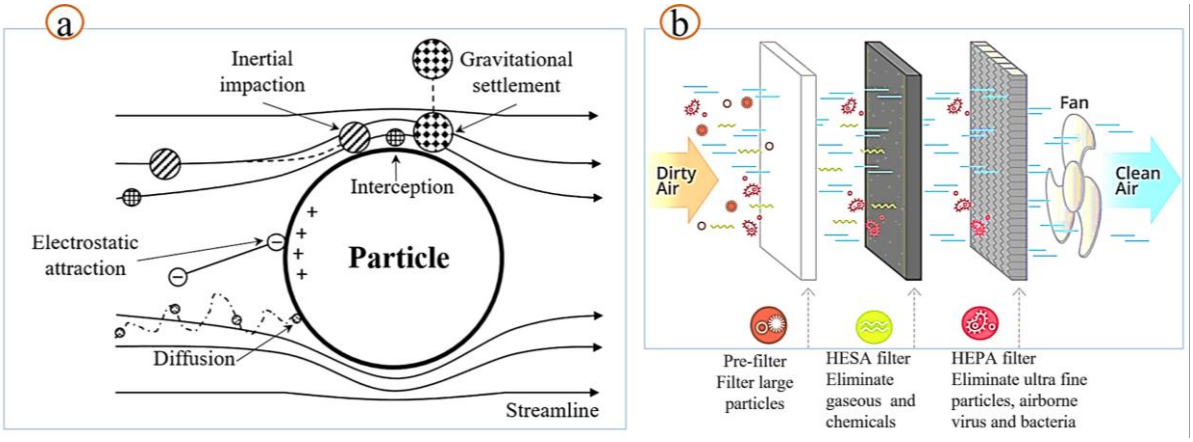
### 6.1. Particle Filtration:

Air filters are typically constructed from fibrous materials, such as cellulose, synthetic fibers, or a combination of both. These fibers form a network that effectively traps particulate matter, including dust, pollen, and soot see (figure 5b)[41] . As air flows through the filter, larger particles tend to collide with the fibers due to inertia, which leads to their capture. Medium-sized particles follow the airflow but get caught in the fibers as they come close to them. Additionally, smaller particles, particularly nanoparticles, exhibit Brownian motion, which increases their chances of coming into contact with the filter fibers [42].

### 6.2. Chemical Filtration:

Some air filters are designed with advanced features, including impregnation with activated carbon or other chemical substances, to effectively adsorb gaseous pollutants such as volatile organic compounds (VOCs), nitrogen oxides (NOx), and sulfur dioxide (SO2)[45]. Activated carbon is particularly effective in this role due to its large surface area, which provides ample opportunity for gas molecules to adhere to its surface. This high surface area allows activated carbon to trap a significant amount of these harmful gases, significantly improving air quality. In addition to activated carbon, some advanced air filters incorporate catalytic materials[46]. These materials facilitate chemical reactions that convert harmful gases into less harmful substances. For example, in the presence of a catalyst, nitrogen oxides can be transformed into nitrogen and oxygen, while sulfur dioxide can be converted into sulfate compounds. This catalytic reduction process enhances the filter's ability to mitigate air pollution, making it a crucial component in both automotive and industrial applications where emissions control is vital[47].

**Figure5: (a) illustrate different filtration mechanisms of particles by filter media, (b) show steps of filtration of particles according to their types and sizes.**




### 6.3. Moisture Control:

Incorporating moisture-absorbing materials into air filter designs is essential for preventing water from entering the engine, which can adversely affect performance and durability[48]. These materials, often hygroscopic, help capture moisture from the intake air, reducing the risk of inefficient combustion and potential corrosion of internal engine components. Some filters also feature drainage systems to channel excess water away, ensuring only dry air reaches the engine. Advanced designs may combine moisture-absorbing and hydrophobic layers for enhanced protection[47]. By effectively managing moisture, these filters contribute to improved engine efficiency, longevity, and overall vehicle reliability. This focus on moisture control reflects ongoing advancements in air filtration technology, addressing challenges posed by varying environmental conditions. Ultimately, such innovations are key to maintaining optimal engine performance in diverse driving scenarios [47].

## 7. Conclusion:

Various types of car air filters employ different filtering media and supporting components to effectively purify the air entering the engine and cabin of cars. These filters utilize a combination of mechanical and chemical mechanisms to capture harmful particles and gases. The choice of materials and their chemical structures is vital for ensuring the filter's efficiency and longevity. Understanding these aspects is key to selecting the right filter for specific vehicle requirements, which can lead to improved engine performance and reduced emissions. Regular maintenance and timely replacement of air filters are essential to maintain optimal vehicle operation. By ensuring clean air intake, drivers can enhance fuel efficiency and protect engine components from wear. Ultimately, investing in the right air filter contributes significantly to the overall health of the vehicle.

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