Analyzing Optimization Solutions for Internal Combustion Engines in Automobiles

Jielin Li

Huafu International Department, Guangzhou, 510630, China

Abstract. Throughout the last decade, electric cars have become a popular alternative to traditional fossil fuel vehicles. The rapid development of electric vehicle technology is due in part to the fact that internal combustion engines (ICE) that burn fossil fuels are inefficient, noisy, and pollute the environment. However, because ICEs are still more prevalent than electric vehicles on the road, there is a need to understand, improve, and optimize their performance. In this work, we review the limitations of ICEs to provide solutions for improving their performance. First, we establish basic ICE components and their limitations. Then, we collect and analyze data and conclusions from relevant literature to identify potential solutions for improving ICEs. Using the information from these studies, we present a statistical analysis that compares variables and parameters on ICE performance. Through our analysis, we determined three technical solutions for optimizing ICEs: turbocharging intake to increase engine efficiency, applying composites to the vehicle for soundproofing, and using biodiesel to reduce emissions. By applying statistical analyses of novel technologies to ICE fundamentals, we hope that this review provides impactful insights into improving ICE performance, which can positively affect daily life in environments with fossil fuel-burning automobiles.

Keywords: Internal Combustion Engine (ICE); Turbocharging; Soundproofing Materials; Active Structural Acoustic Control (ASAC).

1. Introduction

Internal combustion engines (ICEs) are less powerful and more polluting when compared to electric engines. ICEs typically have less torque than electric motors, which means that they are less efficient at accelerating vehicles. Additionally, electric engines can provide quicker acceleration while minimizing noise. Moreover, ICEs have a more negative impact on the environment due to emitting particulate matter such as carbon monoxide. Despite the obvious advantages of electric vehicles, ICEs are more common today for everyday and commercial uses. The abundance of ICEs can be attributed to economic factors such as cost, prevalence of replacement parts, and a well-established industrial base. Therefore, there is a need to develop practical technical solutions that address ICE limitations. In this work, we identify and suggest improvements for ICEs that increase power and reduce noise and pollutants. First, we establish the fundamental components and principles of ICEs. Then, we review technologies that can improve ICEs and analyze their relevant parameters. Finally, we recommend and discuss solutions for improving ICEs.

2. Working Principle and Key Components

Combustion is the reaction of fuel and air to release energy and is the main working principle of ICEs. Simply put, fuel burns inside the engine, and the expanding gases move a piston to do work [1,2]. The piston then turns the crankshaft, and power is translated through gears that drive the axles and wheels.

Figure 1 [3,4] shows the cross-section of an ICE. The cylinder, piston, and crankshaft form the core of the ICE. Cylinders typically occupy the upper part of an ICE. Inside each cylinder, a piston moves up and down in a repeating cycle, which enables motion. Pistons also play a crucial role. As they move up, the air-fuel mixture is compressed, and when the mixture ignites due to compression, the pressure from the explosion forces the piston to move down. The crankshaft then converts the pistons' cycle of motion into the wheels' rotation.

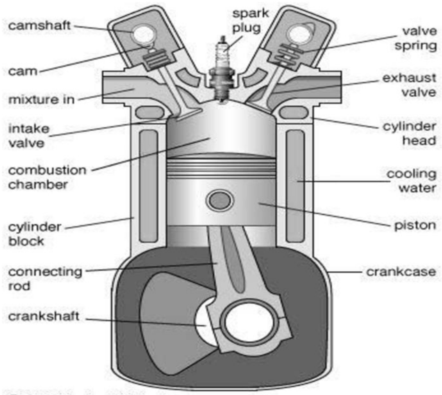

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Figure 1. Cross section showing one cylinder of a four-stroke internal-combustion engine. Adapted from Heinloo, M. [3,4].

Valves and a fuel system control the air-fuel mixture. Two valves control airflow. The intake valve lets the air-fuel mixture in during the intake stroke, and the exhaust valve releases waste gases during the exhaust stroke, which continues the engine's cycle. The fuel system has three main parts: the fuel tank, fuel pump, and injectors. The tank stores fuel, the pump sends it to the injectors, and the injectors spray it into the combustion chamber in a controlled amount so that the air-to-fuel ratio can be maintained within an appropriate range.

In addition to the primary components that enable combustion, lubrication and cooling systems are crucial for an engine's performance. The lubrication system reduces friction using oil, while the cooling system prevents overheating with coolant. The lubrication system includes an oil pan, an oil filter, and an oil pump. This reduces wear on moving parts, which extends engine life. The cooling system consists of a water pump, a thermostat, and a radiator. Together, they maintain a safe engine temperature [5,6,7,8]. Without these systems, the engine would fail due to unsustainable temperatures.

2.1 Factors that Affect Performance

2.1.1 Environmental conditions

At very high temperatures, engine performance declines. Generally, it remains stable up to 30–35° [9]. Above this range, efficiency and output decrease. High humidity exacerbates this effect, causing performance loss at lower temperatures. Engine efficiency is also diminished by reduced air pressure at high altitudes.

2.1.2 The power factor

An alternating current generator produces both active and reactive power (the former is used to perform work, and the latter oscillates between the generator and the inductive loads), which are quantified by the power factor (P.F.). The p.f. is the ratio of active power to apparent power. A p.f. of 1.0 (purely resistive load) describes maximum efficiency and is often used to define ideal parameters in data sets. However, some data sets list performance at p.f. = 0.8, which is a common generator design standard. In reality, the p.f. Typically, it ranges between 0.90 and 0.95. If a generator's efficiency is rated at p.f. = 1.0, its physical efficiency will be lower; if p.f. = 0.8, its physical efficiency will be higher. This discrepancy makes direct comparison between machines rated at different power factors inconsistent.

2.2 Emission optimization

Generator data sets usually reflect machinery designed for maximum efficiency, which often results in higher NOx emissions. Most gas engines can be optimized to meet lower emission levels, often down to "½ TA-Luft" standard or even 200 mg/m^3 at 5% O2 (75 mg/m^3N at 15% O2). Achieving these lower levels usually reduces efficiency by about 1% to 1.5%. Alternatively, higher-efficiency engines with selective catalytic reduction (SCR) systems can be used, or a combination of both approaches. The best engines balance the higher generation cost from engine optimization with the investment and operational costs of an SCR system.

2.3 Tolerance

The ISO 3046 standard is for ‘Reciprocating internal combustion engines – performance,’ which allows up to a 5% higher fuel consumption than the declared value unless stated otherwise. This means that an engine's actual fuel consumption could be up to 5% higher, and it would still technically meet the specified value. Similarly, efficiency values stated with "ISO tolerance" could be up to 5% lower than claimed. For instance, if a generator set claims 48.0% efficiency "with ISO tolerance," the actual efficiency could be as low as 45.7%.

2.4 Energy Losses and Efficiency

An ICE generates power by burning a fuel-air mixture in its cylinders, but not all the energy from the reaction is directly used for driving the axles. Most of it turns into heat, noise, and other forms of energy that don’t contribute to useful work. ICEs are relatively inefficient compared to other energy conversion systems, due to a large portion of the generated energy being wasted.

Figure 2 [10,11,12,13] summarizes the energy flow and losses in an ICE. The overall efficiency of an ICE is determined by the combination of these losses and can be calculated as: Efficiency = 1 - Thermal Losses - Pumping Losses - Time Losses.

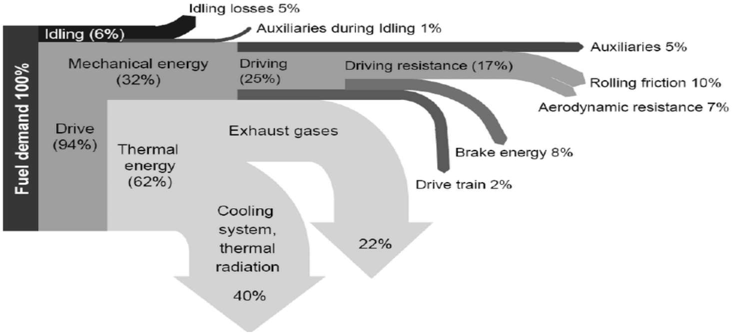

Figure 2. Representative Energy Flow in an Engine. Adapted from Hay, Bruno. [10-13].

While technology and engine design have improved ICE efficiency, the shift towards more efficient and eco-friendly energy sources is pushing the automotive industry toward hybrid, electric, and hydrogen fuel cell vehicles [14,15].

3. Technology Review

3.1 Increasing Airflow in ICEs

Enhancing airflow in ICEs plays a significant role in increasing engine power, efficiency, and overall performance. Li et al. [16,17] emphasized that when the diesel flow rate is 7.3 mL/min, an air flow rate of 2.4 m/s results in a shorter preheating time for the engine. Also, a 10 m/s air flow velocity can raise the temperature more slowly and has a higher combustion efficiency when the fuel flow rate increases [18].

Intake Manifold Optimization: Davis et al. [19,20] proposed a method to optimize the intake manifold. They used a 1.8 L turbocharged engine and experimentally compared the original intake manifold against the optimized one. The average power of the optimized intake manifold increased by 1.5 hp/psi when the RPM was beyond 5000, and the fuel consumption was reduced by about 4% [21].

Electric Turbocharging and Supercharging: As mentioned by Lee et al. [22,23], forced induction systems like turbochargers and superchargers increase the density of air entering the engine, improving the combustion process and power output. However, there are still some challenges related to heat generation and response times at low speeds [24].

3.2 Using Boxer Engines to Reduce Shaking Noise

Boxer engines, which include horizontally opposed cylinders, have the ability to reduce shaking when operating. The unique design of the boxer engine enables it to balance forces while running, which reduces engine noise that would typically be generated by the vehicle frame's vibration. In addition to vibration reduction, the boxer engine also offers a lower center of gravity, improving vehicle stability and handling, which is particularly useful in sports and racing cars.

Vibration Reduction: Kato et al. [25] compared boxer engines with linear and V-type engines to find that the boxer engine significantly reduced the vibration transmitted to the vehicle body. This is mainly due to the motion of the pistons, which cancel out each other's forces [27,28,29].

Noise Reduction: Maclean et al. [30] explored the acoustic properties of boxer engines and concluded that their design led to lower vibration-induced noise levels, making them especially suitable for premium and sports car models where noise and vibration are key factors driving experiences [31,32,33].

3.3 Using Materials to Fill the Gap Between the Engine and the Surrounding Walls

The space between the engine and surrounding areas (engine cabin walls and vehicle chassis) can be redesigned to reduce noise and vibration. One method is the use of sound-damping materials to fill the gap between the engine and its surrounding walls.

Damping Materials: MD Rao [34] studied the use of viscoelastic materials and the passive damping technology in cars and airplanes to reduce vibrations. These materials effectively absorb noise and vibrations that would otherwise be transmitted to the vehicle, thereby improving overall ride quality and reducing engine noise [35].

Thermal Insulation: W. Nice [36] investigated the use of insulating materials, such as ceramics foams, to fill the gap between the engine and the surrounding walls. This not only reduces noise but also improves thermal management, which is crucial for high-performance engines [37].

Active Structural Acoustic Control: In addition to using materials that absorb noise, using active structural acoustic control (ASAC) to reduce noise inside the cabin is also an attractive choice. According to Misol et al. [38], using ASAC in a medium-class car can reduce noise up to 15 dB [39].

3.4 Using Biodiesel or Mixed Fuels

The use of biodiesel and other mixed fuels in ICEs reduces greenhouse gas emissions and improves fuel sustainability. Biodiesel is derived from renewable sources such as vegetable oils and offers a cleaner alternative to conventional diesel fuels.

Biodiesel Benefits: According to K. Dincer [40], biodiesel can significantly reduce carbon monoxide, particulate matter, and sulfur oxide emissions. However, it does not address challenges such as engine compatibility, fuel stability, and engine wear.

Mixed Fuels: Chauhan et al. [41,42] explored the use of mixed fuels, combining biodiesel with traditional diesel or petrol, to improve engine performance and reduce environmental impact. They found that using a mixture of biodiesel and conventional fuels could maintain engine efficiency while reducing the emission of harmful pollutants.

Reducing the viscosity of biodiesel: Balat et al. [43] research showed that biodiesel is stickier (or higher viscosity) than traditional fuel like diesel. The authors proposed several methods to address this problem: Dilution, micro-emulsification, pyrolysis, and transesterification. Among all of these methods, transesterification is the most common and can generate methyl ester, which shortens ignition delay and increases combustion duration.

3.5 Combining the Advantages of Diesel and Petrol Engines

The development of hybrid engine technologies that combine the benefits of both diesel and petrol engines combines the fuel efficiency and high torque of diesel engines with the smooth operation and low emissions of petrol engines.

Dual-Fuel Engine Technology: GA Karim [44] explored dual-fuel engine configurations, which enable an engine to run on both diesel and petroleum, allowing for optimized fuel efficiency in various driving conditions. The use of petrol in low-load conditions makes the engine smoother, while diesel provides high torque for heavy-duty applications.

Compression Ignition with Spark Assistance: Benajes et al. [45,46,47] investigated a combination of compression ignition (diesel) and spark ignition (petrol) in a single engine, known as a "dual-mode engine." The engine could switch between modes based on load, which maximizes fuel efficiency and performance. This approach, however, requires complex control systems and refinement in engine design to optimize for both fuel types [48].

4. Results

4.1 Increased Air Flow

Figure 3 plots different engines' horsepower. The Y-axis is the maximum horsepower, and the X-axis shows the air intake volume per minute from smallest to largest values. The intake volume per minute of 4-stroke engines (all engines in the chart are 4-stroke engines) can be calculated through the following formula:

Intake Volume (L/min) = Displacement*RPM/2 (1) *Source: Poulin, 2006.*

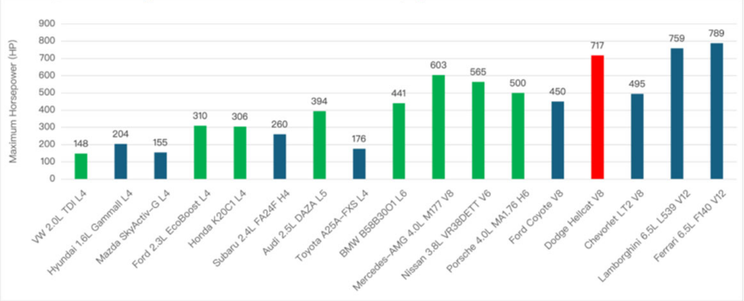

Figure 3. Horsepower of Different Engines (Blue Bars: Natural Aspirated Engines, Green Bars: Turbocharged and Twin-turbo Engines, Red Bar: Supercharged Engines).

The naturally aspirated engines are represented by blue bars, the green bars represent turbocharged engines, and the red bar represents the only supercharged engine. The highest horsepower (unit: HP) is from the Ferrari 6.5 L F140 V12 engine, which has up to 789 HP (The Ultimate Engine, 2023). The lowest horsepower (150 HP) is from the Volkswagen 2.0 L TDI L4. The average horsepower of all 17 engines included in Figure 3 is 424 HP, and the average intake volume is 12297 L/min. Among all the naturally aspirated engines, the average horsepower is 411 HP, and the average intake volume is 14572 L/min. Among all the turbocharged engines, the average horsepower is 402 HP, and the average intake volume is 9234 L/min. Among all the supercharged engines, the average horsepower is 717 HP, and the average intake volume is 18600 L/min. By comparing the average horsepower and intake volume, turbocharged engines have similar horsepower and less intake volume. This is because turbocharged engines can intake air with higher pressure and density, which leads to a better air-fuel ratio and higher combustion efficiency. Therefore, increasing air flow can improve engine power.

4.2 Boxer Engine Noise

Figure 4 shows the noise of these engines at 100 km/h in dB. The orange bars in Figure 4 show internal noise, and the green bars show external noise. Since most noise data is shown as a range, the numbers are the average noise. From Figure 4, it is clear that almost all of the surveyed engines create more external noise than internal noise.

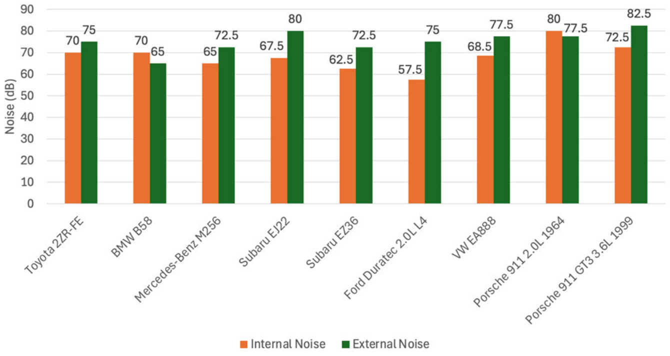

Figure 4. Average Internal and External Noise of Different Engines.

It is an unexpected result that the boxer engines (EJ22, EZ36, 911 2.0 L 1964, and GT3 3.6 L 1999) do not appear quieter than other engines with similar sizes. This could be attributed to the operating principle of the internal combustion engines. Although boxer engines exhibit less vibration than other kinds of engines, vibrations are not the only source of noise. Explosions inside the cylinders, exhaustion, and friction also contribute to noise. As a result, boxer engines do not have a significant impact on reducing noise.

4.3 Sound Absorption Materials

Figure 5 shows the measured noise reduction of selected materials. We calculated noise reduction with the formula.

$\text{Noise Reduction} = 10 \times \text{log10}[1/(1-a)]$ (2) Source: Rienstra & Hirschberg, 2021.

Using data from the same reference (a is the sound absorption coefficient). While the other four materials' noise reduction is around 5 dB, the lead board can achieve an average of 37.5 dB (the original data was 35-40 dB).

Figure 6 shows the thicknesses of each material that achieve the noise reduction shown in the previous graph. The first three materials all need 60 mm to achieve the greatest effect, and the polyurethane foam only needs 20 mm [27]. EPDM (combined with Ethylene, Propylene, Diene, Monomer) rubber and neoprene both have a low porosity, and the ceramic foam and polyurethane foam both have high porosity [33]. However, the lead board only needs 2 mm to achieve 37.5 dB of noise reduction, which is the highest among all five materials.

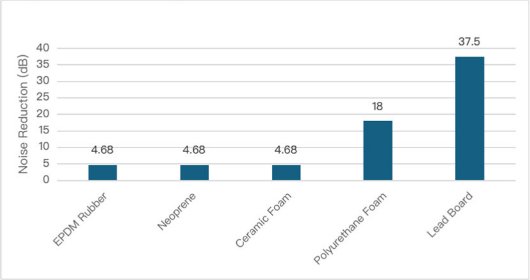

Figure 5. Noise Reduction of Various Materials

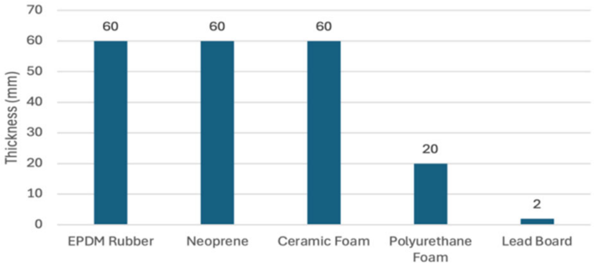

Figure 6. Minimum Thickness Materials to Generate the Noise Reduction Amount Showed in Figure 5.

4.4 Biodiesel

There is no specific correlation between different biodiesels and engine performance, but there is still some meaningful qualitative analysis. According to Table 1, R33 fuel, which consists of 26% HVO, 7% FAME, and 67% diesel, can reduce 20% CO2 emission (Bioenergy International, 2018), and E85 (85% ethanol+15% petrol) can make a vehicle emit less than 140 g/km CO2. Also, E10 (10% ethanol + 90% petrol) leads to 0-3% more fuel consumption, and B20 (20% biodiesel + 80% diesel) can increase fuel economy and reduce carbon emissions. ULSD+RME can result in a full load performance reduction of 5%, and ULSD+HVO can result in a full load performance reduction 1%. Under medium and low load, both fuels reduce CO and HC emissions, and NOx emissions are nearly identical to common diesels. The chance of wall impingement (the fuel sprays on the wall of the cylinders and is not fully mixed with the air) is to be critical with B20 but more with B25, B50, and B100. NOx emission increases with all biodiesel blends (B20: 15.6% and B100: 22.8%). B15 is the optimum blend based on the change in NOx emission and no wall impingement.

Table 1. Different Engines and the Effect After Using Different Kinds of Biodiesel.

Engine Info	Biodiesel Info	Effect
VW	R33 (26% HVO, 7% FAME, 67% diesel)	-20% CO2
Benz	E20 (20% ethanol+80% petrol) or E10 (10% ethanol+90% petrol)	E10 leads to 0-3% more fuel consumption, E20 has a significantly higher octane number (>100)
Renault	E85 (85% ethanol+15% petrol) or B30 (30% biodiesel+70% diesel)	emit <140g/km CO2
Chevrolet Cruze Diesel	B20 (20% biodiesel and 80% diesel)	increase fuel economy, reduce carbon emissions

4.5 Dual-Fuel Engine

In this section, we compare dual-fuel engines with single-fuel (or commonplace) engines. Figure 7 compares the horsepower of one dual-fuel V6 engine and three common V6 engines. Dual-Fuel engines are marked as red bars, and common engines are the blue bars. The Ford 3.5 L EcoBoost engine has the largest power of 365 Hp, which shows that the dual-fuel engine is more powerful.

Similarly, Figure 8 compares the horsepower of dual- and single-fuel V8 engines. According to Figure 8, which includes one dual-fuel engine and three common engines in V8 size, the dual-fuel Scania engine has 470 HP, exhibiting less horsepower than the other engines in the figure. From the results in Figures 7 and 8, there is no convincing evidence that supports the idea that dual-fuel engines are more powerful than common engines. However, it is important to note that both dual-fuel engines can use compressed natural gas (CNG) or liquified natural gas (LNG), which can increase fuel economy and reduce emissions.

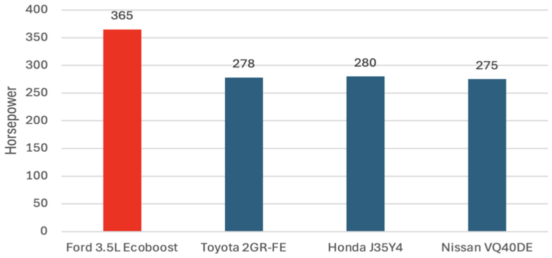

Figure 7. Maximum Horsepower of Selected V6 Engines

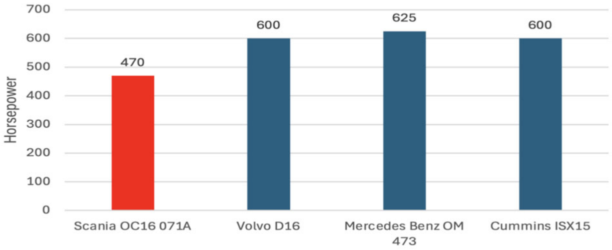

Figure 8. Maximum Horsepower of V8 Engines

This result is likely because of the fuel used in dual-fuel engines. Dual-fuel engines switch between petrol or diesel and natural gas. When they are using natural gas, which has less energy density, the resulting energy output is less than when using traditional fossil fuels. Moreover, dual-fuel engines are designed to maximize power while using both fuel types. Therefore, the peak power will be less than that of a single-mode engine. In conclusion, dual-fuel engines can generally improve fuel economy, and some of them will be more powerful than common engines of similar size.

5. Discussion

Our results quantify the improvement of promising technologies in ICE performance. First, according to Figure 4, boxer engines are effective at reducing vibration generated by pistons, but not other sources of noise. As a result, the majority of boxer engines are not quieter than other types of engines. Also, dual-fuel engines do not yield more power than other engines of similar sizes. According to Figure 7, Ford's EcoBoost engine has more power than other engines of a similar size, but the Scania engine in Figure 8 does not exhibit the same boost in power. However, increasing engine air intake can greatly improve power. Additionally, turbocharging and supercharging can further improve the horsepower due to their optimal air-fuel ratios. Furthermore, although using biodiesel does not increase power and performance, it can improve ICEs by making them more environmentally friendly. Most biodiesel mixtures can increase fuel economy and reduce carbon emissions, but some biodiesel may cause wall impingement, so finely controlling combustion is necessary. Finally, for noise reduction, the use of a thin lead board around the engine cabin can significantly reduce engine noise due to lead's strong absorption of noise. Also, using ASAC technology inside the passenger cabin can reduce internal noise.

Our qualitative analyses could lead to inherently inaccurate predictions of how these technologies perform. For example, certain kinds of biodiesel may show effects in different aspects: B20 biodiesel can increase fuel economy when used in a Chevrolet engine, but has a high wall impingement chance in other engines. Additionally, these technologies do not consider the performance of the ICEs under extreme temperature and moisture conditions. We propose that the development of mechanisms that reduce performance in adverse conditions is equally as critical. It is important to note that these technologies do not include economic factors such as the cost of manufacturing and to the consumer.

6. Conclusions

Data was obtained through the cited literature references and analyzed with Microsoft Excel. First, we found several engines' data that included their size, horsepower, air intake method, and volume. We ranked their air intake from smallest to largest and created a chart that compares their horsepower. Through this method, we found that the intake volume of the engine and the horsepower have a generally positive correlation, while supercharging and turbocharging can greatly increase the horsepower with a relatively small intake volume. Afterwards, we aimed to address the noise problem of engines by researching sound absorption materials that were specifically engineered for ICE vehicles. Furthermore, we compared the internal and external noise of several boxer engines and non-boxer engines with the same methodology. To obtain information about biodiesels and their impact on engines, we identified representative engines that use biodiesel. Finally, we used dual-fuel engine data and compared their performance with conventional engines of similar sizes.

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