The Optimization of Diesel Engine Efficiency using Modern Innovations

Matthew Sabag

ENC2256

September 24, 2025

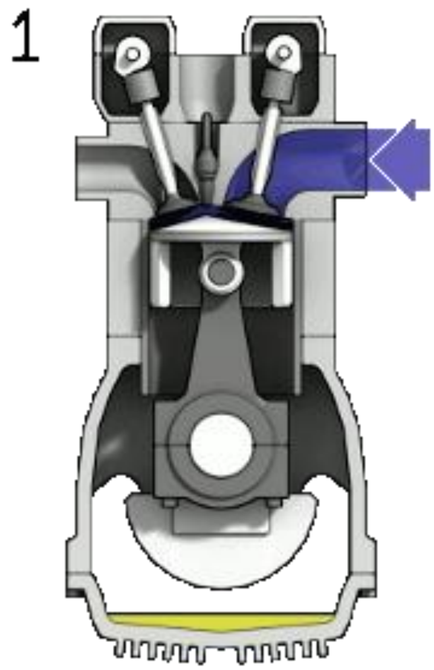
Section 1 – Abstract

Diesel engines have come a long way since the dawn of their existence. Diesels specifically are typically known for being used in heavy-duty situations and usually involve inefficient processes that lead to unprecedented amounts of contamination and pollution being released to the atmosphere. Since the first prototype by Rudolf Diesel in 1897, engineers have spent decades upon decades coming up with creative and innovative technology to enhance their practicality (Cummins, 2023). The purpose of this paper is to understand the fundamentals of a diesel engine by discussing necessary components and additive technology that helps improve its efficiency. This discussion will primarily cover an introductory-level preface to diesel engine systems and how these systems operate by defining relevant terms and explaining 4-stroke combustion cycles. The discussion will then transition to addressing several innovations that have created a substantial impact on the magnitude of efficiency that these engines are capable of. Next, the topic of analysis will be the results that some of these effective components yield, with a concluding paragraph that summarizes the contents of this work and the potential these innovations bring for the future.

Section 2 – Introduction

Diesel engines, similarly to traditional petrol engines, fall under the category of internal combustion engines, or ICE, and also are categorized with 4-stroke engines. These types of engines are called 4-stroke engines because it takes 4 strokes of the piston-cylinder system to complete one combustion cycle. In the first stroke, a piston is inside of a cylinder housing with an open air intake valve. The piston pulls down, creating a low pressure vacuum, sucking cool air and completing the first stroke. After the first stroke and before the second, the intake valve closes, and the piston rises up again. This creates a sealed chamber for the piston to compress the oxygen-rich cool air while also injecting high pressure fuel into the chamber just before the compression. The third stroke is known as the power stroke, when the oxygen-fuel mixture ignites and combusts, creating a high-pressure high-temperature event that produces power. With the piston in the relative bottom position, the remaining waste gases, or exhaust gas, is then pushed out through an exhaust valve that opens by the extension of the piston. This puts the piston back at the relative top of the cylinder in which the intake valve opens again and the process is repeated. This operation of the 4-stroke cycle is represented by *Figure 1*. In this figure, the piston-cylinder system is depicted through the 4-stroke cycle.

Figure 1: 4-Stroke Internal Combustion Engine Diagram



(Zephyris, 2010)

It is imperative to understand how power is delivered. When the piston moves from its relative top position, or top dead center (TDC), to its relative bottom position, or bottom dead center (BDC), the piston rotates a shaft that runs in the axis that goes into or out of the page, called the crankshaft. The ratio of the TDC to the BDC is called the compression ratio. The crankshaft is the main shaft that drives power to all other functions of the vehicle. The first priority is for the crankshaft to deliver power to the camshafts, which are above the cylinders. Camshafts hold camlobes that rotate with the shaft, attached at specific angles and with specific shapes to open and close the valves with proper timing for the intake and exhaust processes. It is important to note that these valves require stiff springs to close the valves after the camlobes have opened them to ensure that the combustion chamber is sealed completely and properly. Attached at the crankshaft with the piston arm is a counterweight that provides balance and reduces engine vibration for a smoother experience. The key difference between gasoline engines and diesel is that gasoline engines have a spark plug that ignites the fuel after the compression stroke to initiate the power stroke, whereas diesel engines rely solely on the high-pressure high-temperature of the air-fuel mixture to combust.

Section 3 – Innovations

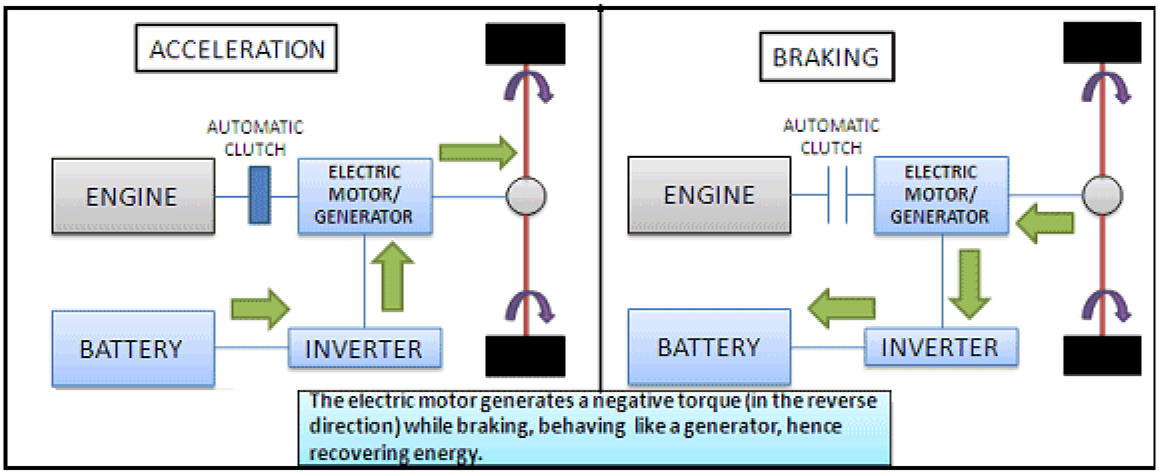
3a. Transmission, Aerodynamics, and Regenerative Braking

The transmission is where the power output of the engine delivered by the crankshaft goes next. In this crucial component, different gear ratios are engaged using a clutch plate to shift from gear to gear. With these different gear ratios, different power outputs are available at variable revolutions per minute (RPMs) from the engine, emphasizing the correlation between the combustion cycle and fuel efficiency. Downspeeding is a process that engages a system in which the rear axle has a fast axle ratio, meaning that the axle spins faster than the drivetrain. This, in turn, slows down the engine turnover speed, or lowers the RPM and increases fuel efficiency (NACFE, 2025). This system is only compatible with Automatic Manual Transmissions, or AMTs. This transmission system uses electrical components and fuel mapping to optimize the timing to shift from gear to gear, unlike manual transmissions that require the driver to manually do so. Since downspeeding reduces the strain of operation of the engine, it produces less greenhouse gas emissions (GHGs), less noise, and reduces wear on engine components. While most heavy-duty diesel vehicles are tailored for a relatively flat range of torque across all RPMs, dual clutch transmissions utilize a secondary clutch to automatically pre-engage another gear to swiftly shift from gear to gear with minimal energy loss. This technology is only available for AMTs as a single manual clutch is incapable of recreating the energy savings of a dual clutch transmission (Buysse et al., 2021).

Another detail to pay attention to when considering fuel efficiency and operating costs is resistance. Aerodynamic drag is the resistance felt by the vehicle from the surrounding or incoming air. Many variables play a role in air friction, however, it is possible to optimize particular variables to achieve minimal air resistance. The main variables when taking drag into consideration are cross-sectional area, aerodynamic geometry, and coefficient of drag. Cross-sectional area is the face-on area of the front of the vehicle. The smaller the area, the less air that contacts the surface which reduces the friction between them. Aerodynamic geometry involves the shape of the vehicle after making contact with the incoming air. The smooth flow of air is just as important as the cross-sectional area. If the airflow becomes turbulent, this can create unpredictable high and low pressure systems that can slow the vehicle down. A vehicle with a low aerodynamic profile and minimal disturbance is ideal for this type of research and development. Coefficient of drag is calculated through the use of computer simulations and tested materials under ideal conditions to measure the resistive force between the material of a surface and the air making contact. This term is a loose combination of both aerodynamic geometry and cross-sectional area into one.

Regenerative braking is an innovative concept that can only be implemented to hybrid vehicles or completely electric vehicles. All vehicles require some sort of energy output or power delivery to rotate the axles and drive the vehicle. When accelerating, power is directly delivered to the wheels. However, when decelerating, power can actually be delivered from the axle back into the battery. It makes thermodynamic sense to consider a system that draws energy from a source to power a mechanism, supplying kinetic energy, and transforming that excess kinetic energy back into electrical potential energy back into the battery. Engineers and researchers use intensive computer simulation software to test and calculate how effective regenerative braking technology is (Buysse et al., 2021). *Figure 2* represents the direction of power flow in a hybrid system.

Figure 2: Power Delivery during Acceleration and Regenerative Braking during Deceleration



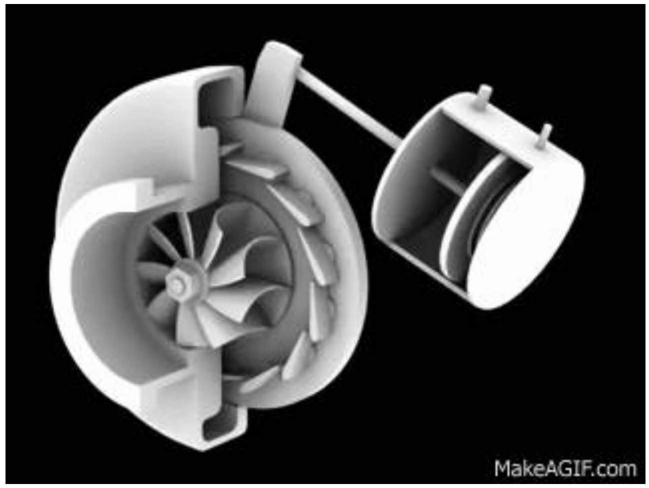
(Clemson University Vehicular Electronics Laboratory, 2015)

When the vehicle is accelerating, the battery is delivering power to the axle(s) and the clutch must be engaged. When the vehicle is decelerating, or braking, the battery is receiving power with the clutch disengaged. The key components for this system to be successful are the electric motor and the inverter. In an electric vehicle (EV), there is no existing clutch nor is there any engine so that power input contribution is discounted.

3b. Turbochargers

Turbocharger technology has been around for quite some time now, giving engineers time to research, experiment, and improve their efficiency. Turbochargers, or turbos for short, use the flow of waste exhaust gas to spin a fan. This fan is connected through a shaft to another fan in a separately sealed pipe for additional cool air intake. The exhaust air flow induces a torque on the turbo shaft, generating pressure and supplying more oxygen-rich air for the engine to consume. Turbos are a cost-effective method to increase the efficiency and performance of diesel engines. Traditional turbos are becoming less and less efficient compared to modern day turbochargers. The first innovation to this area is Variable Geometry Turbochargers, or VGTs. VGTs use extendable pins on the intake side of the turbo to open or close the intake as seen in *Figure 3*.

Figure 3: Variable Geometry Turbocharger Diagram



(MakeAGIF, 2014)

It can be extremely beneficial towards the fuel efficiency of an engine to vary the amount of air that is supplied to the engine to ensure a complete combustion. VGTs can limit the amount of air that goes into the system, or they can allow total airflow to take place. Typically, more air means more combustion and more power, but combustion and power are not always the objective. To stay efficient, VGTs precisely open and close based on the output of the Electronic Control Unit, or ECU. The ECU receives O_2 sensor readings from the exhaust manifold, where the waste gas is received post-combustion. From this, the ECU understands that the combustion process is not ideal and commands the VGT to constrict the airway (Heavy Duty Parts Company, 2024). Variable Geometry Turbochargers, in comparison to Fixed Geometry Turbochargers (FGTs), are highly functional and effective when prioritizing efficiency (Dahham et al., 2022).

Another innovation under the category of turbochargers is electric turbocharging, or e-turbos. This technology acknowledges that turbochargers require some time to spool, or charge up, to generate the high pressure from the turbine. This event is called turbolag. E-turbos eliminate turbolag by using an electric motor to automatically spool the turbo to its required operating RPM. This technology puts an end to the time wasted waiting for the turbo to spool, which improves responsiveness and can influence the efficiency of the diesel system by supplying cool air when necessary by the engine’s intake requirement for better combustion (Morgan, 2024). When the engine is running on low RPM, the turbo struggles to spool to an RPM that satisfies the engine’s demand. With an integrated e-turbo, the electric power source helps the turbo spool and generate the necessary pressure for near-immediate power from the turbocharger, bypassing the otherwise initial delay.

Two-stage turbocharging is yet another turbocharger innovation that provides exceeding results in efficiency. Two-stage turbo setups include two individual turbochargers connected in series to ensure a uniform flow of air delivered to the combustion chamber. These two-stage structures can deliver smooth, compressed air to improve the fuel economy of a motor as well as comply with environmental regulations (Morgan, 2024).

3c. Fuel Injection, Valve Timing, and Combustion

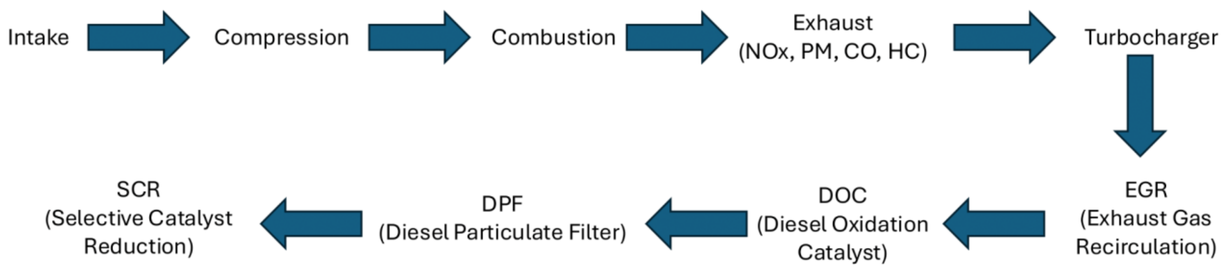
Fuel injection is a key factor in mitigating unused fuel after combustion and to improve overall fuel efficiency. Many systems have been set forth in motion, starting with piezoelectric injectors. These types of injectors take advantage of the piezoelectric effect to induce an electric charge from some materials under mechanical stress. With this effect, engineers have developed a fuel injection mechanism that has greater precision over how much fuel is injected. With more precise amounts of fuel and other known dimensions, fuel efficiency is improved through more complete combustion and reduces the amount of any left over waste as a byproduct of the combustion process (Express Diesel USA, 2025). High-pressure common rails is another innovation that pressurizes the fuel to extremely high pressures to ensure a more even distribution of fuel into each cylinder. The high-pressure fuel is injected as a vapor which mixes better with the air, promoting a more powerful and even combustion as well (Moldovan, 2017). Additive gases such as water vapor and hydrogen gas also have their benefits in the combustion chamber. Hydrogen gas is combustible and highly reactive. Under the conditions of high-pressure and high-temperature, as well as being mixed with diesel fuel, hydrogen injection is a highly promising method of reducing dependence on diesel fuel and increases thermal efficiency of the motor, reduces particulate matter (PM) emissions, and enhances engine performance. Similarly, injecting water vapor, which seems counterintuitive, has its benefits. Injecting water vapor into the combustion chamber drastically reduces engine temperatures because of water's thermally conductive properties. The presence of water vapor also limits the formation of harmful gases by creating an environment for a neutralizing chemical reaction to occur and exit as waste through the exhaust (Akbalık & Arpa, 2024).

Valves contribute greatly to the efficiency and performance of an engine. Variable Valve Actuation (VVA) or Variable Valve Timing (VVT) integrate technology that is comparable to Honda's patented VTEC. In concept, this technology uses more than one set of camlobes to operate the engine at different desired outputs. Smaller camlobes, for instance, would keep the valves open for less time, restricting airflow. Alternatively, larger camlobes would leave the valves open for longer, allowing more air to flow in and out of the chamber. Instead of depending on a separate mechanical part such as two sets of camlobes, researchers and engineers have developed camless valve systems that utilize either hydraulic, electromagnetic, or pneumatic systems to engage and disengage individual valves (Dahham et al., 2022). With this tech, specialists can program variable timings with more precision into valve systems. VVA systems are also capable of warming up engine components faster, reducing the risk of engine malfunction, reducing wear on most parts by bringing them to operating temperatures faster, and reducing emissions. This innovation can also mitigate emissions from circumstances that are otherwise pollution-heavy such as low-load bearing, idle situations, or even highway conditions (Huchel, 2023).

The combustion chamber itself can also be designed to optimize fuel consumption and undergo a complete and thorough combustion cycle. By changing the shape of the combustion chamber itself, such as a more oval or squared cross-section may increase the mixing of vaporized fuel and air, depending on specific engine designs. Using computational fluid dynamics (CFD) in computer simulations, scientists run tests to see which types of shapes and geometrical features on the piston head induce a more thorough mixing of the air and fuel. When the two fluids combine together efficiently, a more ideal, complete combustion takes place, eliminating excess wasted fuel or other unwanted particles in the emission of exhaust (Express Diesel USA, 2025). More research suggests that new examination of compression ratio, the ratio of TDC to BDC, can prove beneficial in the process of optimizing diesel cycle efficiency. Extensive testing and experimentation indicate that there is a positive correlation between compression ratio (CR) and Brake Thermal Efficiency (BTE) (Dahham et al., 2022).

3d. Exhaust Aftertreatment

Figure 4: Combustion Cycle and Exhaust Aftertreatment Process



Directly after combustion, the exhaust gas travels through the exhaust manifold into the turbocharger. The positioning of the turbo is critical to reduce turbo lag and to maximize turbo performance output. After the waste exhaust gas is used in the turbocharger to increase cool air intake into the engine, some of the gas travels to the EGR system and the rest continues. Here, the exhaust gas is reused and put back into the combustion chamber for a second time to ensure that there is no unused wasted fuel in the exhaust gas and to decrease the formation of NOx particles (Akbalık & Arpa, 2024). Onto the next component of the exhaust system, the gas enters an oxidation catalyst known as DOC. This is a type of catalytic converter that is inexpensive, effective, and requires no maintenance. This catalytic converter uses elements that are abundant in exhaust gas to initialize chemical reactions that remove hydrocarbons, carbon monoxide, and PM from the gas (EPA, 2010). Diesel Particulate Filters, or DPFs, use air filters to remove larger particulate matter from the exhaust gas. This helps remove soot from the gas itself and also reduces the rate at which PM deposits accumulate, potentially preventing damage to certain exhaust components. Selective Catalyst Reduction, or SCR, is the final component of a diesel exhaust system before the gas is released into the atmosphere. SCRs use urea-based technology to convert harmful NOx into harmless N_2 and H_2O (Heavy Duty Parts Company, 2024). Another form of exhaust treatment is Nanomaterial coatings. These nanomaterials are activated carbon, activated carbon with magnesium oxide, and nickel-carbon nanotubes (CNTs). These composites of material react with the exhaust gas, extracting impurities and further filtering any harmful particles. The particles that are effectively mitigated are NOx, CO_2, SO_2, CO, HC, and PM. (Nasr et al., 2025).

3e. Materials and Fuels

Engineers understand that to improve the efficiency of a vehicle, it's not always about making the engine more powerful, but making the load lighter. Researchers are constantly changing and evolving the design and material of engine components, even engines as a whole themselves. Using the right materials can decrease the overall weight of the vehicle, improve fuel efficiency as a whole by having less weight to move around, positively affect performance and handling, and additionally alleviate mechanical stress from major functional parts (Express Diesel USA, 2025).

Alternative fuel options are also an opportunistic way to cleanly fuel the future of diesel engines. High sulfur concentrations in diesel fuel contribute massively to the emissions they produce. Chemical analysts and researchers have developed new, cleaner fuel sources that are compatible with diesel engines. An example of this would be Ultra Low Sulfur Diesel (ULSD) and biodiesel. ULSD is a fuel source that emits significantly less GHG elements that are harmful into the atmosphere. Biodiesel originates from organic material. For organic material to exist, it must act as an environmental carbon sink, extracting carbon from the natural processes of nature (Moldovan, 2017). This shows how natural fuel sources are becoming exceedingly more available, cost-effective, and eco-friendly.

Section 4 – Results

Table 1: Top Three Most Effective Innovations

Technology or Innovation	Efficiency Increase	Source
Turbocharging (VGT & Two-Stage)	15% (VGT) 17% (Two-Stage)	(Dahham et al., 2022)
Aftertreatment Exhaust	80.77% CO Absorption @ 100% Activated Carbon	(Nasr et al., 2025)
High Pressure Common Rail	25% Increase in Power and Torque	(G2DieselProducts, 2025)

As seen from *Table 1*, turbochargers play a significant role in the increase of the overall thermal efficiency of an engine. With staggering improvements up to 17%, turbochargers are likely the most cost-effective path to follow when manufacturing commercial diesel systems. Aftertreatment systems are crucial when considering environmental regulations and implications. Many systems are in place in the exhaust to ensure that any impurities are removed such as EGR, DOC, DPF, and SCR. These systems work together to effectively strip the exhaust gas of its harmful elements and release the waste gas that has a very minimal impact on the environment. High pressure fuel rails are complex components that elegantly perform the specific task of ensuring that each cylinder receives the same amount of fuel, with sharp precision. This system can transform a traditional diesel engine by improving its power output and torque range by up to 25%. As time passes and engineering technology becomes more abundant and widespread, it becomes increasingly difficult to revolutionize the ICE world dramatically by such staggering improvements to efficiency like these innovations do.

Section 5 – Conclusion and Creative Potential

Diesel engines have evolved substantially over the decades. Millions of dollars have been invested by major manufacturers, pioneering the future of diesel engine systems through creative innovations. This work has discussed the fundamentals of internal combustion engines and the 4-

stroke cycle, diving deeper into different technologies that work hand in hand to produce a machine more efficient than ever. Components for increased efficiency that apply directly to the engine and intake systems have demonstrated the potential for growth that these machines have. After the combustion cycle occurs, even ‘wasted’ exhaust gas has a purpose and is used to compress more air into the intake, revolutionizing the understanding of the word “efficiency.” Many mechanisms, components, and moving parts work with precise timing and accuracy, always evolving with so much more room for improvement and further innovation.

References

Akbalık, Zafer, and Orhan Arpa. "Enhancing Diesel Engine Efficiency and Emission Control: A Study on Hydrogen and Water Vapor Injection - Sciencedirect." ScienceDirect, December 29, 2024. https://www.sciencedirect.com/science/article/abs/pii/S0360319924055952.

Buysse, Claire, Ben Sharpe, & Oscar Delgado. "Efficiency Technology Potential for Heavy-Duty Diesel Vehicles in the United States through 2035." International Council on Clean Transportation, December 20, 2021. https://theicct.org/publications/efficiency-tech-potential-hdvs-us-2035-nov21.

Cummins. "History of Diesel Engines." Cummins Inc., April 4, 2023. https://www.cummins.com/news/2023/04/04/history-diesel-engines.

CVEL. "Automotive Electronics | Regenerative Braking." Clemson Vehicular Electronics Laboratory: Regenerative Braking, 2015. https://cecas.clemson.edu/cvel/auto/systems/regenerative_braking.html.

Dahham, Rami Y., Haiqiao Wei, and Jiaying Pan. "Improving Thermal Efficiency of Internal Combustion Engines: Recent Progress and Remaining Challenges." MDPI, August 26, 2022. https://www.mdpi.com/1996-1073/15/17/6222.

EPA. "Diesel Oxidation Catalyst | General Information." Technical Bulletin, May 2010. https://www.epa.gov/sites/default/files/2016-03/documents/420f10031.pdf.

Express Diesel USA. "Top Diesel Engine Innovations to Watch in 2025." Express Diesel USA, April 10, 2025. https://expressdieselusa.com/blogs/fuel-injectors-and-pumps/top-diesel-engine-innovations-to-watch-in-2025.

G2 Diesel Products. "Common Rail Injectors 101: Everything You Need to Know." G2 DIESEL PRODUCTS, May 15, 2025. https://www.g2dieselproducts.com/blog-resources/common-rail-injectors.

Heavy Duty Parts Co. "Diesel Engine Innovations: The Future of Power and Efficiency." Heavy Duty Parts Company, December 1, 2024. https://heavydutypartscompany.com/diesel-engine-innovations-the-future-of-power-and-efficiency/.

Huchel, Brian. "Diesel Engine Research Leading to Better Efficiency, Emissions Standards on the Roads." Purdue University - News, July 19, 2023. https://www.purdue.edu/newsroom/2023/Q3/diesel-engine-research-leading-to-better-efficiency-emissions-standards-on-the-roads/.

MakeAGIF. "VGT Turbocharger Cutaway Animation." MakeAGif, 2014. https://makeagif.com/i/gFgsoy.

Moldovan, Paul. "Diesel Engines: Is Old Technology Actually Green Technology?" USC Viterbi School of Engineering, November 13, 2017. https://illumin.usc.edu/diesel-engines-is-old-technology-actually-green-technology/.

Morgan, Paul. “Optimising Engine Performance through Turbocharger Innovation.” Riviera, December 18, 2024. https://www.rivieramm.com/news-content-hub/news-content-hub/optimising-engine-performance-through-turbocharger-innovation-83339.

NACFE. “Engine Downspeeding.” NACFE, October 2015. https://nacfe.org/research/technology/powertrain/downspeeding/.

Nasr, Gamal E M, Magdy A Baiomy, A Z Taieb, Mayada E Abdel Razek, and Mohamed Refai. “Assessment of the Performance of Ni Carbon Nanotube Nano Composite Coatings and Activated Carbon for Diesel Exhaust Treatment.” Scientific reports, February 6, 2025. https://pmc.ncbi.nlm.nih.gov/articles/PMC11802834/.

Zephyris. “File:4StrokeEngine Ortho 3D Small.Gif - Wikimedia Commons.” Wikipedia Commons, August 29, 2010. https://commons.wikimedia.org/wiki/File:4StrokeEngine_Ortho_3D_Small.gif.