

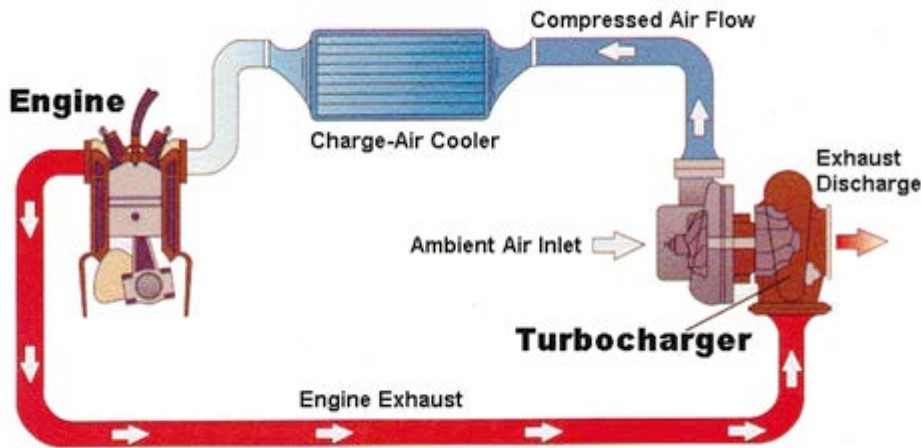
## Powertrain Efficiency Technologies

### **Turbochargers**

Turbochargers increasingly are being used by automakers to make it possible to use downsized gasoline engines that consume less fuel but still deliver the power of the larger-displacement engines they replace.

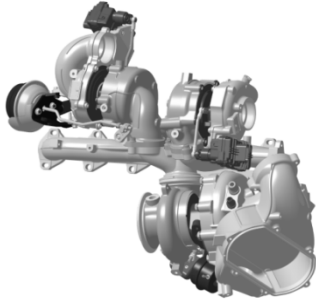
A turbocharger is a device driven by exhaust gases that increases engine power by pumping air into the combustion chambers. Forcing air into an engine's intake manifold at higher-than-atmospheric pressure allows more fuel to be burned, which results in higher output. The turbocharger employs two encased fans mounted on either end of a common shaft. The engine's exhaust gases are routed through one fan (a turbine), which rotates the shaft at several hundred-thousand rpm. This in turn spins the opposite fan (a compressor), which compresses the air entering the engine's intake manifold.

Turbochargers often work in tandem with an intercooler, which serves to cool the compressed air before it enters the engine. Compressing the air heats it, which makes it less dense and negates some of the positive effect. Intercoolers typically are simple radiators through which the intake air passes to shed some heat, increasing the density before combustion.



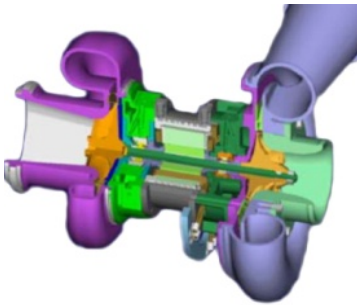
**Figure. Turbocharger system for a gasoline engine.**

Multi-stage turbocharging systems have been developed to increase engine performance and improve fuel economy over a wider range of engine speeds. Two-stage turbos use two fans: one for low speeds and another for high speeds. A small turbine is activated at low engine rpm and a larger one at high rpm. Three-stage turbocharging systems are also available. One turbo manufacturer's three-stage turbocharging system consists of two small high-pressure variable turbine geometry turbochargers integrated with one larger low-pressure water-cooled turbocharger.



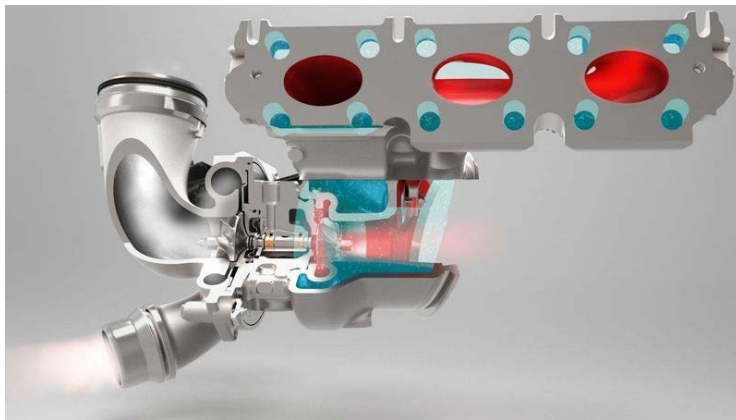
**Figure. Regulated three-stage turbocharger system.**

Electric turbochargers have been developed to help increase efficiency and eliminate delayed boost response (i.e., “turbo lag”) at low engine speeds. Electric turbochargers are powered by an electric motor instead of exhaust gases. Since these systems increase power consumption, electric turbochargers require more power than a conventional 12-volt automotive electrical system alone can provide. Electric turbochargers currently being developed use a 48-volt hybrid electrical system to power the electric compressor (see section on 48V Hybrid Technology).



**Figure. Electric turbocharging.**

Turbochargers with a lightweight turbine housing made of aluminum (instead of steel) have also been developed. Water cooling enables use of lightweight material and thus a significant weight reduction by nearly 30% while simultaneously providing cost and system benefits.



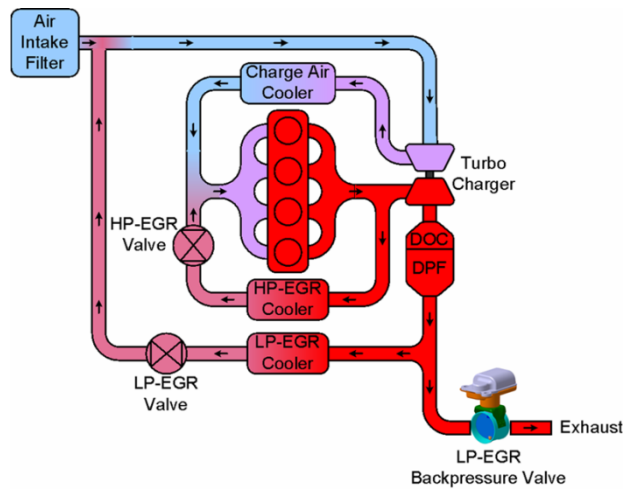
**Figure. Water-cooled turbocharger with aluminum turbine housing.**

## Exhaust Gas Recirculation

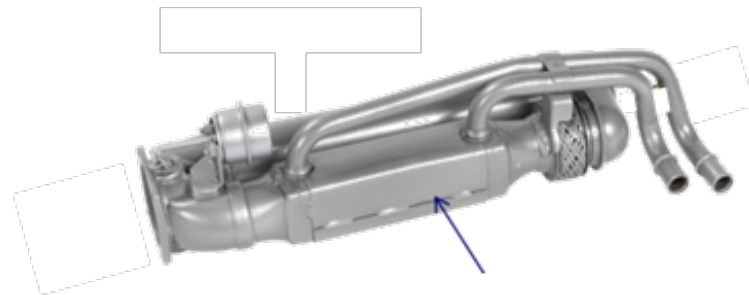
Exhaust gas recirculation (EGR) systems divert some of the engine-out exhaust gas and mixes it back into the fresh intake air stream. Mixing exhaust with the intake air lowers combustion temperatures and rates. This improves emissions by reducing the formation of NO<sub>x</sub>. It also reduces the knock limit, providing better fuel economy through higher compression ratios and/or spark advance (in a spark-ignition engine). Cooling the exhaust before mixing it into the intake stream in a special heat exchanger further improves emissions and the knock limit.

Cooled dual-loop EGR systems have been developed to cover the entire engine map. In a turbocharged engine, the low-pressure loop EGR system, located downstream of the turbo, mitigates knock at low speeds and high load, while the high-pressure loop upstream of the turbo improves fuel economy at high speed and high load.

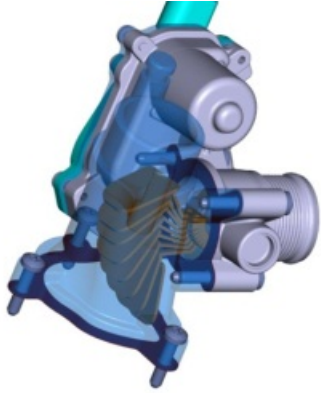
Cooled EGR could improve a vehicle's average fuel economy from 2% to 5%, as measured on current vehicle test cycles used for regulatory compliance.



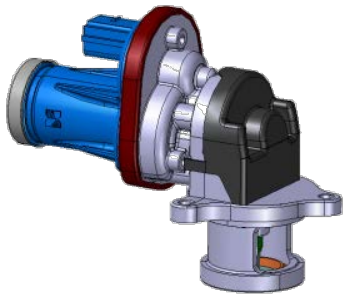
**Figure. EGR system for a diesel engine.**



**Figure. EGR cooler.**



**Figure. Low-pressure EGR valve.**



**Figure. High-pressure EGR valve.**

## Fuel Injection Technologies

Fuel injection is the introduction of fuel in an internal combustion engine by the means of an injector. Diesel engines use fuel injection by design. In gasoline engines, fuel injection replaced carburetors starting in the 1970s because it can be more precisely controlled, thus resulting in more efficient use of fuel and fewer emissions.

Most modern gasoline engines are either port fuel injection or direct fuel injection. Port fuel injection (PFI) injects fuel into the intake ports just upstream of each cylinder's intake valve rather than at a central point within an intake manifold. Many modern electronic fuel injection systems utilize PFI; however, in newer gasoline engines, direct injection systems are beginning to replace PFI ones. In a gasoline direct injection (GDI) engine, fuel is injected into the combustion chamber as opposed to injection before the intake valve.

Direct fuel injection technology enables gasoline engines to achieve greater fuel efficiency and increased power output. Gasoline direct injection permits more fine-tuned control of the amount of fuel injected, as well as control of injection timing independently from valve timing. GDI engines can reduce CO<sub>2</sub> emissions in a number of ways, including better “breathing” efficiency, higher engine compression ratio, the potential for lean operation, and reduction of pumping losses. Gasoline direct injection offers CO<sub>2</sub> emissions reductions ranging from 5% to 20%, depending on how it is implemented and the base engine to which it is compared.

GDI engines, however, can also result in higher particulate emissions, mainly due to limited mixing of fuel and air within the combustion chamber. There are ways to design and calibrate the GDI system that will dramatically reduce particulate emissions. For example, it is now well known that wall-guided (side-mounted) direct injection can create much higher particulate emissions than spray-guided (center-mounted) direct injection, as fuel injected with wall-guided systems can impinge upon the cylinder wall. Spray-guided injection directs fuel straight down the cylinder and minimizes particulate formation.

Common rail direct fuel injection is a direct fuel injection system for gasoline and diesel engines. Solenoid or piezoelectric injectors make possible fine electronic control over the fuel injection time and quantity, and the higher pressure that the common rail technology makes available provides better fuel atomization. GDI systems can be designed with multiple injections (e.g., up to eight injections) per cylinder stroke to precisely meter fuel and match the power demand curve of the engine.



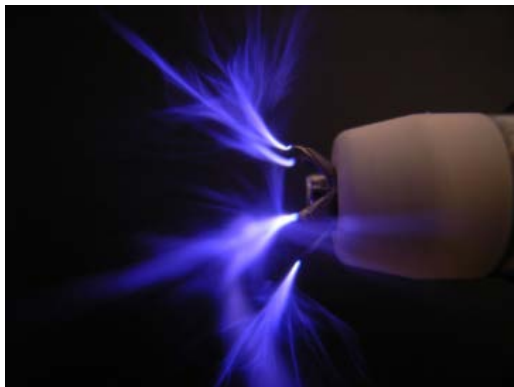
**Figure. Solenoid direct injectors.**



**Figure. Piezo common rail injectors.**

Recent design enhancements to fuel injectors include micron-sized laser-drilled spray holes. The laser-drilling process provides automakers with the precision and customization needed for engines to meet strict emissions requirements (e.g., tighter PM standards and particle number standards) by improving fuel atomization and reducing spray penetration.

To facilitate ignition of lean air-fuel mixtures, manufacturers have developed combustion efficiency technologies such as corona volume discharge ignition, which extends a spark-ignition engine's lean operating combustion limit. Unlike conventional systems, which initiate combustion by a spark, this technology generates an extended corona discharge in the combustion chamber and, under such conditions, even extremely lean fuel-air mixes are reliably ignited. Corona ignition can lower gasoline consumption and CO<sub>2</sub> emissions, reduce NO<sub>x</sub> emissions, and improve smooth operation of the engine.



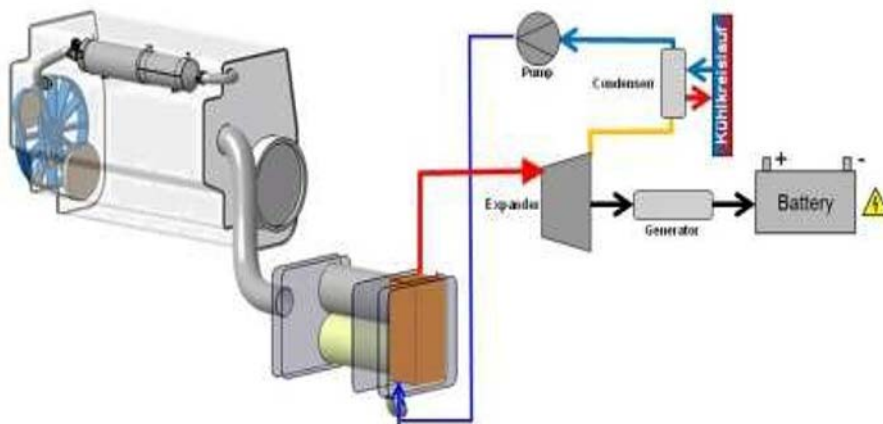
**Figure. Corona ignition.**

## Waste Heat Recovery

In a typical internal combustion engine, approximately 30% of the fuel energy is used for actual vehicle propulsion, while more than 70% is lost, about half of it through the vehicle's exhaust system. A waste heat recovery system turns thermal losses in the exhaust pipe into energy. This technology can produce either electrical energy or mechanical energy reintroduced on the crankshaft. Recovering energy from the engine exhaust could improve overall vehicle fuel economy by more than 5%.

### Rankine Cycle Waste Heat Recovery

In transportation, Rankine cycle systems vaporize a pressurized fluid due to a steam generator located in the exhaust pipe. As a result of the heating by exhaust gases, the fluid is turned into steam/vapor. The pressure then drives the expander of the Rankine engine, which could be a turbine as well as a volumetric expander. This expander can be either directly tied to the crankshaft of the thermal engine or linked to an alternator to generate electricity. The fluid used in Rankine cycle engines can be a "humid" fluid (such as water) or a "dry" organic fluid. The choice of the fluid depends in particular on the operating temperature of the system.



**Figure. Rankine cycle waste heat recovery.**

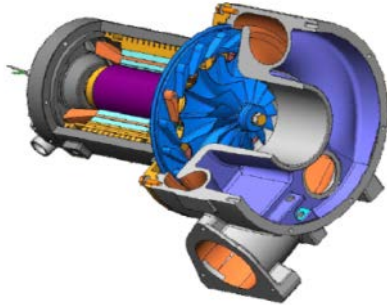
### Turbo Compounding

Turbo compounding is a type of waste heat recovery that uses a turbine run off exhaust gases to provide additional power to the crankshaft via gearing or a hydrodynamic coupling, or to power an electric generator that distributes energy via a power electronics module. Turbo compounding is a way to take advantage of wasted exhaust gases to provide more power to the engine.

Like a turbocharger, the turbo-compound approach recovers waste exhaust energy, but, instead of powering a compressor, the turbine wheel is connected to the crankshaft through a series of gears. Turbo compounding works with or without a conventional turbocharger upstream.

Production cars could use the electrical energy recovered by turbo compounding to eliminate engine-driven alternators. In hybrid applications, turbo compounding is an efficient way to charge batteries and to power electric-drive motors.

Turbo compounding recovers energy downstream of the turbocharger but upstream of emission controls, thus reducing the available heat used for rapid heat-up of catalysts. On the other hand, Rankine cycle waste heat recovery can recover heat downstream of exhaust emission controls, thus allowing for faster catalyst light-off.



**Figure. Turbo compounding cut-away.**

### Thermoelectric Generators

Thermoelectric generators (TEGs) are solid-state devices – thermoelectric material that is sandwiched together within cylindrical-shaped cartridges – that convert heat extracted from hot exhaust gases into electrical power, which can then be used to power the electrical systems in a car or recharge the battery. TEGs are comprised of an array of thermoelectric couples. When placed across a temperature gradient (between a heat source and a heat sink), these couples produce a voltage that drives a current through an electrical circuit.

Today’s conventional vehicles power auxiliary accessories with engine-driven alternator/generators that can decrease fuel economy. As electrical demand increases for accessories, such as communication systems, navigation systems, and stability controls, it increases the drag on the engine. This increased demand for electric power provides a perfect opportunity to improve efficiency by producing electricity directly from engine waste heat.



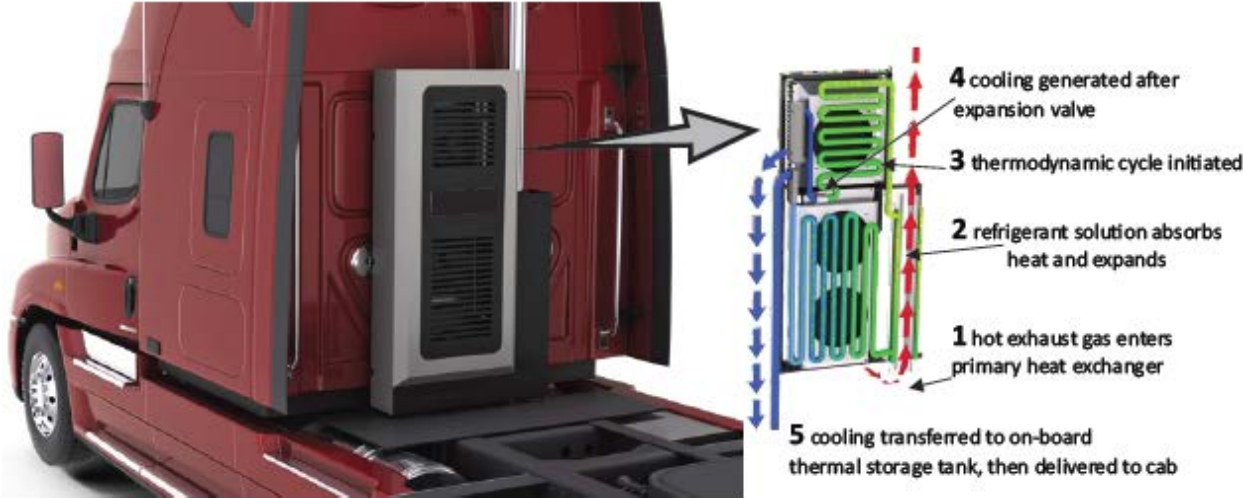
**Figure. Thermoelectric generators.**

### Thermal Compressors

Another type of waste heat recovery technology is a new type of “thermal compressor.” This thermal compressor utilizes the waste exhaust gases to drive a refrigeration cycle – the exhaust gas passes through a cylindrical heat exchanger where a non-ozone depleting refrigerant absorbs heat, then expands, creating pressurization. The modest temperatures and pressures are controlled to cycle the pressurized refrigerant solution through an expansion valve where below-freezing temperatures are generated. This cold condition is then cycle through a separate thermal loop and thermal storage tank where it is eventually transferred to the end application.



The high power output of the thermal compressor can provide cooling in motion for transportation applications to eliminate the need for engine-driven A/C compressors. The technology is able to pre-warm fluids and components to reduce cold-start fuel consumption. One type of application for this technology is as an auxiliary power unit (APU) for over-the-road Class 8 heavy trucks. The technology can generate enough power to provide overnight heating and cooling capacity of more than eight hours for long-haul drivers.

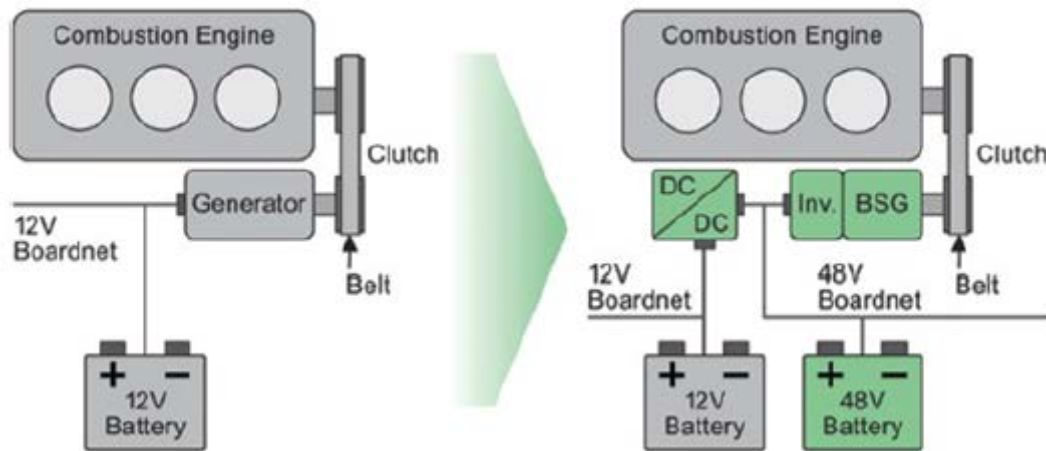


**Figure. Thermal compressor unit installed on a Class 8 truck.**

## 48V Hybrid Technology

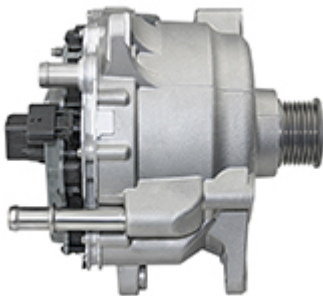
Demand for greater on-board electrical capacity is driving plans for higher voltage automotive systems. 48-volt hybrid technology combines a dual-voltage setup with the advantages of start-stop technology. It effectively captures a vehicle's braking energy, provides more power for a growing list of electrical devices, and simultaneously boosts fuel efficiency – possibly by as much as 15%.

The 48-volt configuration, supported by a number of automotive suppliers, calls for a conventional 12-volt network using a lead-acid battery like those employed in most conventional vehicles. However, it adds an extra layer: a 48-volt lithium-ion battery with a separate 48-volt network. The 12-volt network handles traditional loads, such as lighting, ignition, entertainment, and audio systems. The 48-volt system supports active chassis systems and regenerative braking, and allows for further electrification of components such as turbochargers, fluid pumps, air conditioning compressors, cooling fans, and power steering.



**Figure. Basic layout differences of 48V and 12V electrical systems.**

Advanced start-stop systems have been developed that use an induction motor in a 48-volt belt-driven starter-generator (BSG). When the engine is running, the motor, acting as a generator, will charge a separate battery. When the engine needs to be started, the motor then applies its torque via the accessory belt and cranks the engine instead of using the starter motor. The separate battery is also recharged via a regenerative braking system. In addition to the start-stop function, a BSG system can enhance fuel economy even during highway driving by cutting off the fuel supply when cruising or decelerating.



**Figure. 48V belt-driven starter-generator module with integrated power inverter.**