

Table of Contents

1. Diesel Engine Operation and Diagnosis James D. Halderman	1
2. Air Induction and Crankcase Ventilation Systems Gus Wright	20
3. Diesel Engine Emissions Gus Wright	41
4. Exhaust Gas Recirculation and Exhaust Aftertreatment Systems Gus Wright	59
5. Onboard Diagnostics for Diesels Gus Wright	97
Index	117

DIESEL ENGINE OPERATION AND DIAGNOSIS

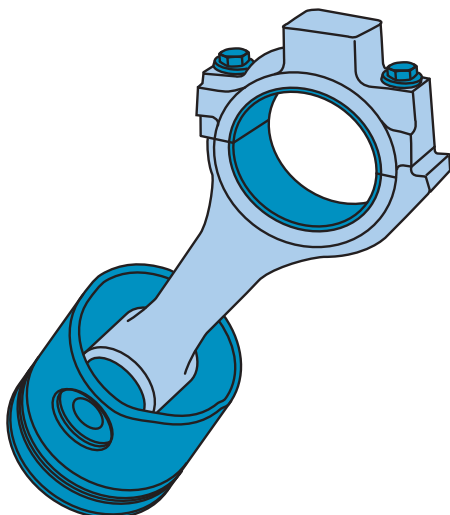


FIGURE 4 A rod/piston assembly from a 5.9 liter Cummins diesel engine used in a Dodge pickup truck.

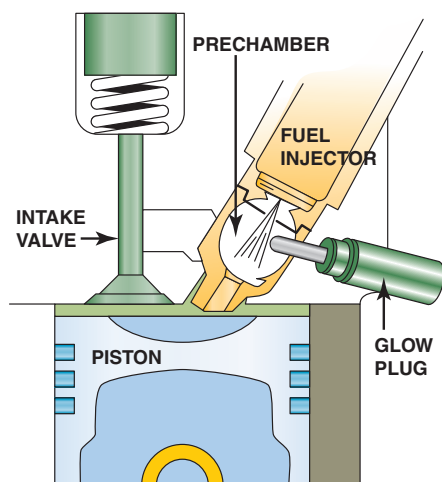


FIGURE 5 An indirect injection diesel engine uses a prechamber and a glow plug.

In a gasoline engine, the speed and power are controlled by the throttle valve, which controls the amount of air entering the engine. Adding more fuel to the cylinders of a gasoline engine without adding more air (oxygen) will not increase the speed or power of the engine. In a diesel engine, speed and power are not controlled by the amount of air entering the cylinders because the engine air intake is always wide open. Therefore, the engine always has enough oxygen to burn the fuel in the cylinder and will increase speed (and power) when additional fuel is supplied.

NOTE: Many newer diesel engines are equipped with a throttle valve. This valve is used by the emission control system and is not designed to control the speed of the engine.

INDIRECT AND DIRECT INJECTION In an **indirect injection** (abbreviated **IDI**) diesel engine, fuel is injected into a small prechamber, which is connected to the cylinder by a narrow opening. The initial combustion takes place in this prechamber. This has the effect of slowing the rate of combustion, which tends to reduce noise. ● **SEE FIGURE 5.**

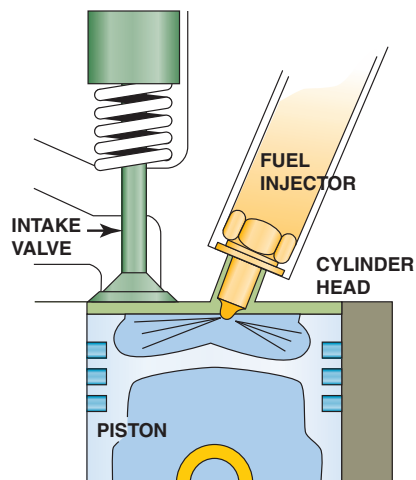


FIGURE 6 A direct injection diesel engine injects the fuel directly into the combustion chamber. Many designs do not use a glow plug.

All indirect diesel injection engines require the use of a glow plug which is an electrical heater that helps start the combustion process.

In a **direct injection** (abbreviated **DI**) diesel engine, fuel is injected directly into the cylinder. The piston incorporates a depression where initial combustion takes place. Direct injection diesel engines are generally more efficient than indirect injection engines, but have a tendency to produce greater amounts of noise. ● **SEE FIGURE 6.**

While some direct injection diesel engines use glow plugs to help cold starting and to reduce emissions, many direct injection diesel engines do not use glow plugs.

DIESEL FUEL IGNITION Ignition occurs in a diesel engine by injecting fuel into the air charge, which has been heated by compression to a temperature greater than the ignition point of the fuel or about 1,000°F (538°C). The chemical reaction of burning the fuel creates heat, which causes the gases to expand, forcing the piston to rotate the crankshaft. A four-stroke diesel engine requires two rotations of the crankshaft to complete one cycle.

- On the intake stroke, the piston passes TDC, the intake valve(s) opens, and filtered air enters the cylinder, while the exhaust valve(s) remains open for a few degrees to allow all of the exhaust gases to escape from the previous combustion event.
- On the compression stroke, after the piston passes BDC, the intake valve(s) closes and the piston travels up to TDC (completion of the first crankshaft rotation).
- On the power stroke, the piston nears TDC on the compression stroke and diesel fuel is injected into the cylinder by the injectors. The ignition of the fuel does not start immediately but the heat of compression starts the combustion phases in the cylinder. During this power stroke, the piston passes TDC and the expanding gases force the piston down, rotating the crankshaft.
- On the exhaust stroke, as the piston passes BDC, the exhaust valve(s) opens and the exhaust gases start to flow out of the cylinder. This continues as the piston travels up to TDC, pumping the spent gases out of the cylinder. At TDC, the second crankshaft rotation is complete.

DIESEL ENGINE OPERATION AND DIAGNOSIS

THREE PHASES OF COMBUSTION

There are three distinct phases or parts to the combustion in a diesel engine.

1. **Ignition delay.** Near the end of the compression stroke, fuel injection begins, but ignition does not begin immediately. This period is called *ignition delay*.
2. **Rapid combustion.** This phase of combustion occurs when the fuel first starts to burn, creating a sudden rise in cylinder pressure. It is this sudden and rapid rise in combustion chamber pressure that causes the characteristic diesel engine knock.
3. **Controlled combustion.** After the rapid combustion occurs, the rest of the fuel in the combustion chamber begins to burn and injection continues. This process occurs in an area near the injector that contains fuel surrounded by air. This fuel burns as it mixes with the air.

FUEL TANK AND LIFT PUMP

PARTS INVOLVED A fuel tank used on a vehicle equipped with a diesel engine differs from the one used with a gasoline engine in the following ways.

- The filler neck is larger for diesel fuel. The nozzle size is 15/16 in. (24 mm) instead of 13/16 in. (21 mm) for gasoline filler necks. Truck stop diesel nozzles for large over-the-road trucks are usually larger, 1.25 in. or 1.5 in. (32 mm or 38 mm) to allow for faster fueling of large-capacity fuel tanks.
- There are no evaporative emission control devices or a charcoal (carbon) canister. Diesel fuel is not as volatile as gasoline and, therefore, diesel vehicles do not have evaporative emission control devices.

The diesel fuel is usually drawn from the fuel tank by a separate pump, called a **lift pump** and delivers the fuel to the injection pump. Between the fuel tank and the lift pump is a **water-fuel separator**. Water is heavier than diesel fuel and sinks to the bottom of the separator. Part of normal routine maintenance on a vehicle equipped with a diesel engine is to drain the water from the water-fuel separator. A float is often used inside the separator, which is connected to a warning light on the dash that lights if the water reaches a level where it needs to be drained. The water separator is often part of the fuel filter assembly. Both the fuel filter and the water separator are common maintenance items.

NOTE: Water can cause corrosive damage and wear to diesel engine parts because it is not a good lubricant. Water cannot be atomized by a diesel fuel injector nozzle and will often “blow out” the nozzle tip.

Many diesel engines also use a *fuel temperature sensor*. The computer uses this information to adjust fuel delivery based on the density of the fuel. ● **SEE FIGURE 7.**

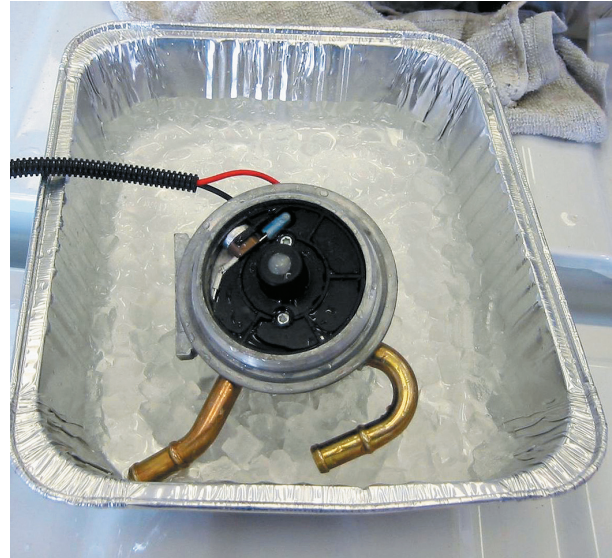


FIGURE 7 A fuel temperature sensor is being tested using an ice bath.

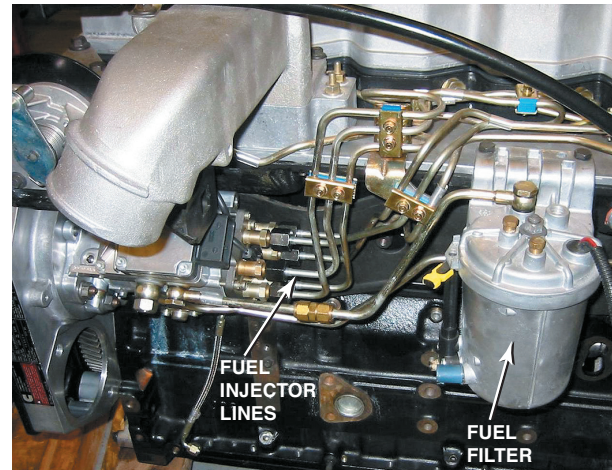


FIGURE 8 A typical distributor-type diesel injection pump showing the pump, lines, and fuel filter.

INJECTION PUMP

NEED FOR HIGH-PRESSURE FUEL PUMP A diesel engine injection pump is used to increase the pressure of the diesel fuel from very low values from the lift pump to the extremely high pressures needed for injection.

- The lift pump is a *low-pressure, high-volume pump*.
- The high-pressure injection pump is a *high-pressure, low-volume pump*.

Injection pumps are usually driven by a gear off the camshaft at the front of the engine. As the injection pump shaft rotates, the diesel fuel is fed from a fill port to a high-pressure chamber. If a distributor-type injection pump is used, the fuel is forced out of the injection port to the correct injector nozzle through the high-pressure line.

● **SEE FIGURE 8.**

DIESEL ENGINE EMISSIONS

TECH TIP

Why Do Diesel Engines Have Lower RPM Limits?

Maximum engine speed is part of the emissions information on diesel engines. You will also note that tachometers in diesel-powered vehicles have a lower RPM limit than gasoline-fueled engines. Diesel engines cannot turn as fast as gasoline engines, because they will not completely burn fuel at high speed. If the maximum engine speed limits are exceeded, diesel engines will produce excessive noxious exhaust emissions. ● SEE FIGURES 24 AND 25.

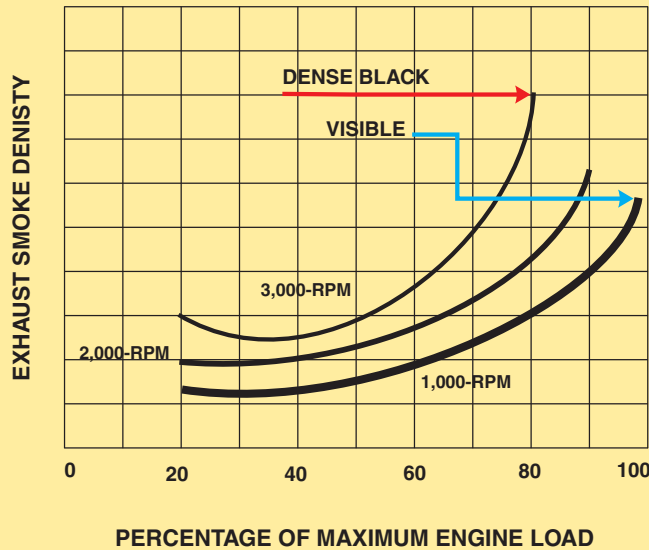


FIGURE 24 This graph illustrates an engine operated at three different RPMs. Note that when the engine operates at a higher RPM, darker exhaust smoke appears sooner. Excessive emissions are produced at high speed and load because diesel combustion events run out of time to complete. RPM limits are imposed on diesel engines to minimize emissions formed when inadequate time is available to completely burn fuel.

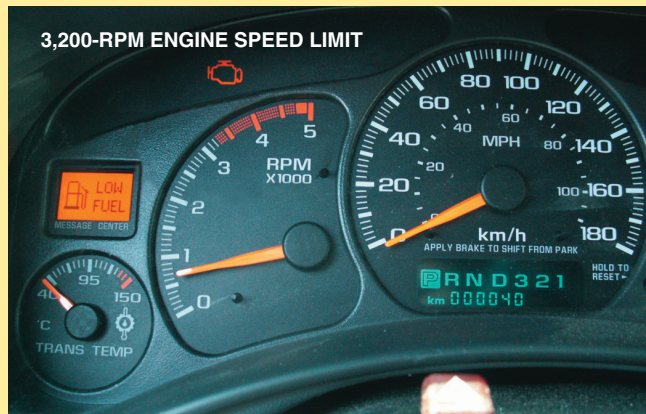


FIGURE 25 Diesel engine maximum RPM is lower than a gas engine due to speed limited combustion. At higher engine speeds, diesel combustion runs out of time to properly distribute, atomize, vaporize, and burn fuel injected near TDC at the end of compression stroke. Exceeding maximum engine speed will produce excessive emissions since inadequate time is available to completely burn fuel.

Resources Board has concluded that diesel soot is responsible for 70% of the state's risk of cancer from airborne toxics. ● SEE FIGURE 26.

SULPHATE (SOx) EMISSIONS When diesel fuel is refined from petroleum that is pumped from the ground, called mineral petroleum, varying quantities of sulphur naturally combine with oil. Burning sulphur contained in fuel produces sulfate (SOx) emissions, which cause air pollution and acid rain. Since the mid-1990s, sulphur content has been progressively reduced to minimize SOx production. In 2007, sulphur content dropped from a high of 500 ppm to a low of 15 ppm, a drop from 0.5% to 0.0015%. Further reductions are scheduled for 2015. Sulphur reduction also enables the use of sophisticated exhaust emissions after treatment systems such as particulate filters, selective catalyst reduction, and NOx adsorbers. High fuel sulphur content will poison these devices rendering them ineffective.

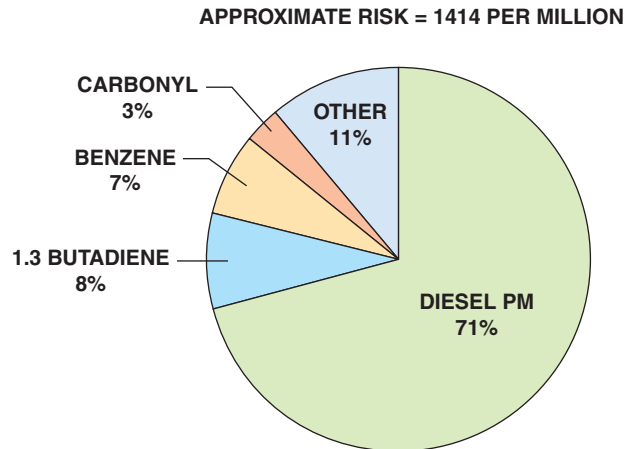


FIGURE 26 Cancer risks attributed to diesel emissions. Carcinogens are carried into the lungs by particulates.

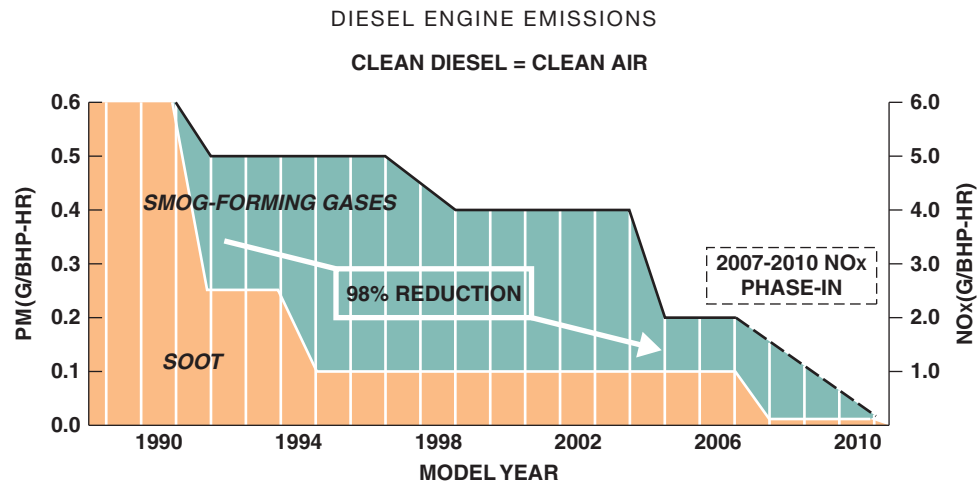


FIGURE 27 Emissions legislation milestones have promoted the development of new engine technology to reduce emissions to the point where they are now almost undetectable.

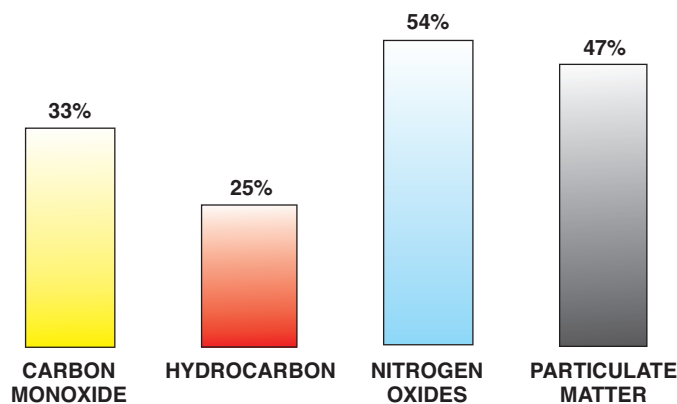


FIGURE 28 The 1980 estimated contributions of diesels to overall emissions from transportation sources. Close to half the emissions were originating from 5% of the vehicles.

EMISSIONS STANDARDS

IS THE DIESEL DIRTY? The public perception of dirty diesel is not without foundation. Emissions legislation for diesels has lagged that of gasoline emissions. Part of the explanation is diesel technology was used primarily in heavy-duty buses and trucks, which make up on average approximately 5% of the number of vehicle registrations in North America. The fewer vehicle numbers meant less attention was given to setting emissions standards. As emissions output dropped from gasoline-fueled vehicles, the proportion of emissions contributions to overall emissions inventories produced by diesels rose. Data from the 1980s and 1990s pointed to over a 50% contribution from all transportation sources originated from diesels. That is 5% of the engines producing half the air pollution from transportation sources. ● **SEE FIGURES 27 AND 28.**

There are a couple of explanations for the disproportionate contribution from diesels to emission inventories. First, the longer distances traveled by heavy-duty diesels and the much higher

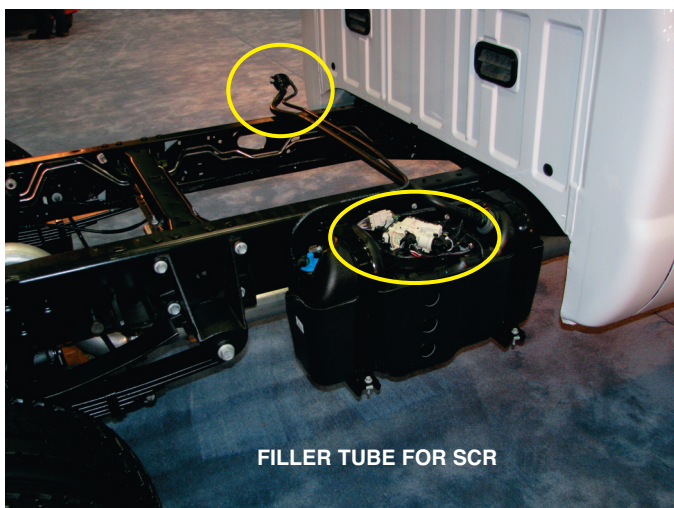
loads carried by these vehicles contributed to the disproportionate emissions produced by heavy-duty diesel-powered vehicles. In fact, 40% of the total accumulated trip distances are made by diesel-powered vehicles such as buses, heavy trucks, delivery vehicles, and the like. In 2005, 23% of fuel used for transportation was diesel fuel. This means diesels travel much farther using less fuel and producing much lower emissions than gasoline powered vehicles for every ton of weight transported per mile.

Second, diesel emissions standards lagged gasoline engine emissions from passenger vehicles. Passenger vehicle emissions controls began to appear on engines beginning in the early 1960s. However, the first emissions standards for diesels were not established until 1970 when limits for peak smoke opacity of no more than 50% were first required for heavy-duty diesels. Not until 1984 was the first diesel emissions standards for NOx established. A particulate matter (PM) standard was first established in 1988. Today's diesels are as clean if not cleaner than gasoline engines producing even lower emissions per ton/mile.

EMISSIONS DECALS Vehicles sold for on-highway use in North America must have an emissions decal affixed to the vehicle or engine. This means before an engine or vehicle can be sold it must pass a standardized emissions test by the EPA for the particular engine family. The decal contains emissions information indicating to what standard the vehicle or engine is certified, as well as important information for the technician about part replacement and adjustment procedures, software calibration files, and other relevant data that could affect emissions production. For example, on a diesel engine, the decal will contain information about valve lash settings, injection timing, fuel rates, and the presence of emissions system components.

Since heavy-duty engines are certified for emissions output in grams per horsepower-hour, decals are affixed to the engine. These engines are used in a variety of chassis configurations so measuring emissions for distance traveled is impractical. Light-duty vehicle emissions are certified by vehicle type and emissions are measured in units for every mile or kilometer traveled. Emissions decals are placed on the chassis in the vicinity of the engine compartment. ● **SEE FIGURES 29 AND 30.**

EXHAUST GAS RECIRCULATION AND EXHAUST AFTERTREATMENT SYSTEMS



FILLER TUBE FOR SCR

FIGURE 46 Electric pump for a 2011 Ford Superduty SCR system. The tank mounted pump pressurizes and drains SCR system lines.

Bayerische Motoren Werke AG VEHICLE EMISSION CONTROL INFORMATION		
Conforms to regulations:	2009 MY	
U.S. EPA: T2B5 LDV	OBD: II	Fuel: Diesel
California: LEV II PC	OBD: II	Fuel: Diesel
No adjustments needed.	DI, 2TC, CAC, EGR, SCR, CSF, DOC	
Group: 9BMXV03.0M57	7 812 057	

FIGURE 47 Emission decal for LD diesel using SCR.

emission-related maintenance cannot occur before 100,000 miles of use (150,000 miles for medium- and heavy-duty engines) or before 100,000 mile intervals thereafter. Because the SCR catalyst in a urea SCR system does not function without the use of a reducing agent, manufacturers must satisfy the following five categories to maintain vehicle compliance according to EPA guidelines if the DEF level is depleted. ● **SEE FIGURES 46 THROUGH 50.**

- A driver warning system (i.e., a dash warning light)
- A driver inducement (i.e., reduced engine power, fuel filler lockout, no restarting after fueling if DEF is depleted)
- Identification of incorrect reducing agent, meaning the system would identify if the reservoir was filled with only water or other liquid
- Tamper-resistant design, meaning the warning system, driver inducement system, and operational system are not easily deactivated (i.e., sensor wiring and dosing injector are not easily disconnected)

- » HIGHER FUEL CONSUMPTION
- » LESS POWER
- » MORE SOOT LOADING OF OIL
- » MORE DPF REGENERATIONS
- » INCREASED FUEL EFFICIENCY
- » INCREASED POWER
- » LESS SOOT LOADING OF OIL
- » FEWER DPF REGENERATIONS

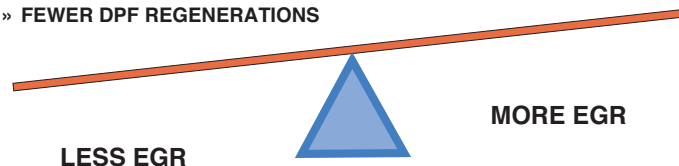


FIGURE 48 Benefits of using SCR. Advanced injection timing and reduced EGR rates increase engine efficiency and durability.



FIGURE 49 The upstream and downstream NOx sensors provide data for OBD-II aftertreatment system monitoring and not closed-loop feedback of metered DEF fluid. Incorrect type of DEF fluid and DEF dosing problems are also diagnosed by the sensors.



FIGURE 50 DEF is added to many light-duty vehicles through a fitting located near the fuel filler door.

- Durable design, in that the system must operate effectively to 120,000 or 150,000 miles depending on certification criteria

Since DEF is a urea-water solution it can freeze at 12°F (−11°C) which requires heating and insulating of the storage tank and lines.

LIQUID SCR COMPONENTS

DIESEL EXHAUST FLUID Diesel exhaust fluid (DEF) is a nontoxic, nonpolluting, nonhazardous, and nonflammable solution. It is also a relatively stable chemically, not harmful to handle, and colorless. A precise 32.5% concentration of urea mixed with 67.5% deionized water forms DEF which is stored in a separate onboard tank and its rate of use is between 1% and 4% of fuel use (50:1). When injected into the exhaust stream as a fine mist upstream from an SCR catalyst, it vaporizes and decomposes (in a process called thermolysis) to form ammonia (NH_3) and carbon dioxide. The ammonia is the end product which converts the NO_x to harmless nitrogen (N_2) and water (H_2O) (through hydrolysis) in the SCR catalyst.

The concentration of urea and water gives DEF the best freeze protection and ensures that both the urea and water will freeze at the same rate, thus preventing the fluid from becoming diluted or overconcentrated as it thaws. Since DEF does freeze, heaters are used in the reservoirs and on lines to ensure rapid delivery in cold weather operation. When the vehicle shuts down, the DEF pump will usually reverse the flow of DEF and pull fluid out of the lines returning it to the reservoir. The EPA permits fault detection systems that allow up to 40 minutes after engine start-up to move DEF to the injector in cold weather to accommodate frozen DEF. ● **SEE FIGURE 51.**

In North America, the American Petroleum Institute has established a performance standard for DEF used in liquid SCR systems. A refractometer to measure its density is best used to evaluate the quality of DEF if there is any contamination suspected. The amount of urea used is carefully metered proportional to the amount of NO_x produced. Current systems dose the exhaust system with urea based on a probability of NO_x in the exhaust system predicted by engine operating factors and software stored in the ECM.

The 2010 and newer systems use an ammonia or NO_x sensor to provide feedback to the ECM regarding the quantity of either NO_x or ammonia in the exhaust stream. These sensors, however, do not form closed-loop feedback with the dosing injector but are only sensitive to detect such problems in the

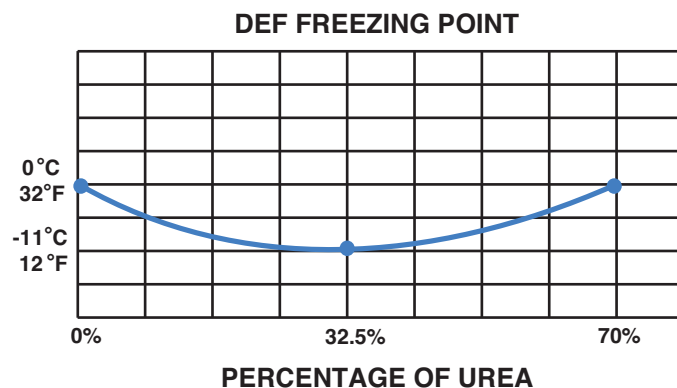


FIGURE 51 The freeze temperature of DEF concentrations.

TECH TIP

Precautions with DEF

There is a temptation to fill a low DEF reservoir with water since it is a colorless fluid. Never add water or any other fluid to the DEF reservoir since the aftertreatment system may be damaged. Adding water to the diesel exhaust fluid tank will change the diesel exhaust fluid concentration levels which may not only affect SCR efficiency but will raise the freezing temperature and change other characteristics of the diesel DEF as well. The potential exists where the SCR system components can be damaged during cold weather operation or lead to a derate condition or even a failure of the engine to start at all.

Long-term storage of DEF in a vehicle (in excess of 6 months) is not recommended since DEF will slowly undergo chemical change. Shelf life is expected to be 18 months. Scheduled testing of the diesel exhaust fluid is recommended to ensure DEF concentration does fall below specification. DEF storage temperature should be maintained between 23°F and 77°F (−5°C and 25°C).

SCR as incorrect fluid or high NO_x levels or excess ammonia which also has a nitrogen constituent. The dosing valve or injector reduces the amount of urea used when the NO_x sensor at the tailpipe outlet detects any slippage or waste of ammonia out the exhaust pipe. Since ammonia is a noxious emission (think cleaning detergent), an ammonia slip catalyst is used to break down ammonia excess through the process of hydrolysis. ● **SEE FIGURES 52 THROUGH 54.**

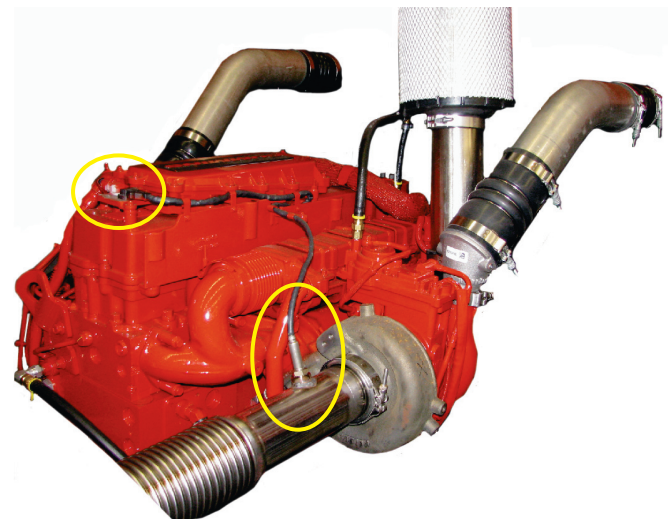


FIGURE 52 The NO_x sensor for use in 2010MY vehicles monitors SCR operation required for OBD-II. This NO_x sensor also requires a module to condition the electrical signal supplied to the exhaust aftertreatment control module. The NO_x sensor is used in either the lean NO_x trap or liquid SCR systems.