PROFESSIONAL TECHNICIAN SERIES Part of Pearson Automotive’s Professional Technician Series, the fifth edition of Automotive Engine Performance represents the future of automotive textbooks. The series is a full-color, media-integrated solution for today’s students and instructors. The series includes textbooks that cover all eight areas of ASE certification, plus additional titles covering common courses.

The series is also peer reviewed for technical accuracy.

UPDATES TO THE FIFTH EDITION Text was updated with the following features:

- Many new full color line drawings and photos were added to this edition to help bring the subject to life.
- Updated throughout and correlated to the latest ASE/NATEF tasks.
- New Case Studies included in this edition that includes the “three Cs” (Complaint, cause and correction).
- New OSHA hazardous chemical labeling requirements added to Chapter 2.
- Atkinson Cycle engine design added to Chapter 3.
- Scope testing of MAF sensors added to Chapter 23.
- Additional content on gasoline direct injection (GDI) added to Chapter 28.
- Fiat Chrysler Multiair System information added to Chapter 30.
- Tier 3 Emission Standards added to Chapter 31.
- Unlike other textbooks, this book is written so that the theory, construction, diagnosis, and service of a particular component or system are presented in one location. There is no need to search through the entire book for other references to the same topic.

ASE AND NATEF CORRELATED NATEF-certified programs need to demonstrate that they use course material that covers NATEF and ASE tasks. All Professional Technician textbooks have been correlated to the appropriate ASE and NATEF task lists. These correlations can be found in two locations:

- As an appendix to each book.
- At the beginning of each chapter in the Instructor’s Manual.

A COMPLETE INSTRUCTOR AND STUDENT SUPPLEMENTS PACKAGE All Professional Technician textbooks are accompanied by a full set of instructor and student supplements. Please see page vi for a detailed list of supplements.

A FOCUS ON DIAGNOSIS AND PROBLEM SOLVING

The Professional Technician Series has been developed to satisfy the need for a greater emphasis on problem diagnosis. Automotive instructors and service managers agree that students and beginning technicians need more training in diagnostic procedures and skill development. To meet this need and demonstrate how real-world problems are solved, “Real World Fix” features are included throughout and highlight how real-life problems are diagnosed and repaired.

The following pages highlight the unique core features that set the Professional Technician Series book apart from other automotive textbooks.
LEARNING OBJECTIVES AND KEY TERMS appear at the beginning of each chapter to help students and instructors focus on the most important material in each chapter. The chapter objectives are based on specific ASE and NATEF tasks.

TECH TIPS feature real-world advice and “tricks of the trade” from ASE-certified master technicians.

SAFETY TIPS alert students to possible hazards on the job and how to avoid them.

CASE STUDY present students with actual automotive scenarios and show how these common (and sometimes uncommon) problems were diagnosed and repaired.

FREQUENTLY ASKED QUESTIONS are based on the author’s own experience and provide answers to many of the most common questions asked by students and beginning service technicians.
NOTE: Most of these “locking nuts” are grouped together and are commonly referred to as prevailing torque nuts. This means that the nut will hold its tightness or torque and not loosen with movement or vibration.

NOTES provide students with additional technical information to give them a greater understanding of a specific task or procedure.

CAUTION: Never use hardware store (nongraded) bolts, studs, or nuts on any vehicle steering, suspension, or brake component. Always use the exact size and grade of hardware that is specified and used by the vehicle manufacturer.

CAUTIONS alert students about potential damage to the vehicle that can occur during a specific task or service procedure.

WARNING
Do not use incandescent trouble lights around gasoline or other flammable liquids. The liquids can cause the bulb to break and the hot filament can ignite the flammable liquid, which can cause personal injury or even death.

WARNINGS alert students to potential dangers to themselves during a specific task or service procedure.

THE SUMMARY, REVIEW QUESTIONS, AND CHAPTER QUIZ at the end of each chapter help students review the material presented in the chapter and test themselves to see how much they’ve learned.
# SUPPLEMENTS

## RESOURCES IN PRINT AND ONLINE

*Automotive Engine Performance*

<table>
<thead>
<tr>
<th>NAME OF SUPPLEMENT</th>
<th>PRINT</th>
<th>ONLINE</th>
<th>AUDIENCE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instructor Resource Manual</td>
<td>✔</td>
<td></td>
<td>Instructors</td>
<td>NEW! The Ultimate teaching aid: Chapter summaries, key terms, chapter learning objectives, lecture resources, discuss/demonstrate classroom activities, and answers to the in text review and quiz questions.</td>
</tr>
<tr>
<td>TestGen</td>
<td>✔</td>
<td></td>
<td>Instructors</td>
<td>Test generation software and test bank for the text.</td>
</tr>
<tr>
<td>PowerPoint Presentation</td>
<td>✔</td>
<td></td>
<td>Instructors</td>
<td>Slides include chapter learning objectives, lecture outline of the test, and graphics from the book.</td>
</tr>
<tr>
<td>Image Bank</td>
<td>✔</td>
<td></td>
<td>Instructors</td>
<td>All of the images and graphs from the textbook to create customized lecture slides.</td>
</tr>
<tr>
<td>NATEF Correlated Task Sheets - For Instructors</td>
<td>✔</td>
<td></td>
<td>Instructors</td>
<td>Downloadable NATEF task sheets for easy customization and development of unique task sheets.</td>
</tr>
<tr>
<td>NATEF Correlated Task Sheets - For Students</td>
<td>✔</td>
<td></td>
<td>Students</td>
<td>Study activity manual that correlates NATEF Automobile Standards to chapters and pages numbers in the text. Available to students at a discounted price when packaged with the text.</td>
</tr>
<tr>
<td>CourseSmart eText</td>
<td>✔</td>
<td></td>
<td>Students</td>
<td>An alternative to purchasing the print textbook, students can subscribe to the same content online and save up to 50% off the suggested list price of the print text. Visit <a href="http://www.coursesmart.com">www.coursesmart.com</a></td>
</tr>
</tbody>
</table>

All online resources can be downloaded from the Instructor’s Resource Center: [www.pearsonighered.com/irc](http://www.pearsonighered.com/irc)
chapter 28

GASOLINE DIRECT-INJECTION SYSTEMS

LEARNING OBJECTIVES

After studying this chapter, the reader will be able to:

1. Discuss how to troubleshoot a gasoline direct-injection system.
2. Explain how a gasoline direct-injection system works.
3. Describe the differences between port fuel-injection and gasoline direct-injection systems.
4. List the various modes of operation of a gasoline direct-injection system.

This chapter will help you prepare for Engine Repair (A8) ASE certification test content area “C” (Fuel, Air Induction, and Exhaust Systems Diagnosis and Repair).

KEY TERMS

- Gasoline direct injection (GDI) 436
- Spark ignition direct injection (SIDI) 436
- Homogeneous mode 438
- Stratified mode 438


**DIRECT FUEL INJECTION**

Several vehicle manufacturers such as Audi, Mitsubishi, Mercedes, BMW, Toyota/Lexus, Mazda, Ford, and General Motors are using gasoline direct injection (GDI) systems, which General Motors refers to as a spark ignition direct injection (SIDI) system. A direct-injection system sprays high-pressure fuel, up to 2,900 PSI, into the combustion chamber as the piston approaches the top of the compression stroke. With the combination of high-pressure swirl injectors and modified combustion chamber, almost instantaneous vaporization occurs. This combined with a higher compression ratio allows a direct-injected engine to operate using a leaner-than-normal air–fuel ratio, which results in improved fuel economy with higher power output and reduced exhaust emissions. ● SEE FIGURE 28–1.

**ADVANTAGES OF GASOLINE DIRECT INJECTION** The use of direct injection compared with port fuel injection has many advantages including:

- Improved fuel economy due to reduced pumping losses and heat loss
- Allows a higher compression ratio for higher engine efficiency
- Allows the use of lower-octane gasoline
- The volumetric efficiency is higher
- Less need for extra fuel for acceleration
- Improved cold starting and throttle response
- Allows the use of greater percentage of EGR to reduce exhaust emissions
- Up to 25% improvement in fuel economy
- 12% to 15% reduction in exhaust emissions

**DISADVANTAGES OF GASOLINE DIRECT INJECTION**

- Higher cost due to high-pressure pump and injectors
- More components compared with port fuel injection
- Due to the high compression, a NOx storage catalyst is sometimes required to meet emission standards, especially in Europe. (● SEE FIGURE 28–2.)
- Uses up to six operating modes depending on engine load and speed, which requires more calculations to be performed by the Powertrain Control Module (PCM).
**GASOLINE DIRECT-INJECTION SYSTEMS**

**LOW-PRESSURE SUPPLY PUMP** The fuel pump in the fuel tank supplies fuel to the high-pressure fuel pump at a pressure of approximately 60 PSI. The fuel filter is located in the fuel tank and is part of the fuel pump assembly. It is not usually serviceable as a separate component; the engine control module (ECM) controls the output of the high-pressure pump, which has a range between 500 PSI (3,440 kPa) and 2,900 PSI (15,200 kPa) during engine operation. ● SEE FIGURES 28–2 AND 28–3.

**HIGH-PRESSURE PUMP** In a General Motors system, the engine control module (ECM) controls the output of the high-pressure pump, which has a range between 500 PSI (3,440 kPa) and 2,900 PSI (15,200 kPa) during engine operation. The high-pressure fuel pump connects to the pump in the fuel tank through the low-pressure fuel line. The pump consists of a single-barrel piston pump, which is driven by the engine camshaft. The pump plunger rides on a three-lobed cam on the camshaft. The high-pressure pump is cooled and lubricated by the fuel itself. ● SEE FIGURE 28–4.

**FUEL RAIL** The fuel rail stores the fuel from the high-pressure pump and stores high-pressure fuel for use to each injector. All injectors get the same pressure fuel from the fuel rail.

**FUEL PRESSURE REGULATOR** An electric pressure-control valve is installed between the pump inlet and outlet valves. The fuel rail pressure sensor connects to the PCM with three wires:
- 5 volt reference
- ground
- signal

The sensor signal provides an analog signal to the PCM that varies in voltage as fuel rail pressure changes. Low pressure results in a low-voltage signal and high pressure results in a high-voltage signal.

**FIGURE 28–3** A typical direct-injection system uses two pumps—one low-pressure electric pump in the fuel tank and the other a high-pressure pump driven by the camshaft. The high-pressure fuel system operates at a pressure as low as 500 PSI during light load conditions and as high as 2,900 PSI under heavy loads.

**FIGURE 28–4** A typical camshaft-driven high-pressure pump used to increase fuel pressure to 2,000 PSI or higher.
The PCM uses internal drivers to control the power feed and ground for the pressure control valve. When both PCM drivers are deactivated, the inlet valve is held open by spring pressure. This causes the high pressure fuel pump to default to low-pressure mode. The fuel from the high-pressure fuel pump flows through a line to the fuel rail and injectors. The actual operating pressure can vary from as low as 500 PSI (3,440 kPa) at idle to over 2,000 PSI (13,800 kPa) during high speed or heavy load conditions. See Figure 28–5.

**NOTE:** Unlike a port fuel-injection system, a gasoline direct injection system varies the fuel pressure to achieve greater fuel delivery using a very short pulse time, which is usually less than one millisecond. To summarize:

- **Port Fuel Injection** = constant fuel pressure but variable injector pulse-width.
- **GDI** = almost constant injector pulse-width with varying fuel pressure.

**GASOLINE DIRECT-INJECTION FUEL INJECTORS**

Each high-pressure fuel injector assembly is an electrically magnetic injector mounted in the cylinder head. In the GDI system, the PCM controls each fuel injector with 50 to 90 volts (usually 60 to 70 volts), depending on the system, which is created by a boost capacitor in the PCM. During the high-voltage boost phase, the capacitor is discharged through an injector, allowing for initial injector opening. The injector is then held open with 12 volts. The high-pressure fuel injector has a small slit or six precision-machined holes that generate the desired spray pattern. The injector also has an extended tip to allow for cooling from a water jacket in the cylinder head. See Chart 28–1 for an overview of the differences between a port fuel-injection system and a gasoline direct-injection system.

**MODES OF OPERATION**

The two basic modes of operation include:

1. **Stratified mode.** In this mode of operation, the air–fuel mixture is richer around the spark plug than it is in the rest of the cylinder.

2. **Homogeneous mode.** In this mode of operation, the air–fuel mixture is the same throughout the cylinder.

There are variations of these modes that can be used to fine-tune the air–fuel mixture inside the cylinder. For example, Bosch, a supplier to many vehicle manufacturers, uses the following six modes of operation:

- **Homogeneous mode.** In this mode, the injector is pulsed one time to create an even air–fuel mixture in the cylinder. The injection occurs during the intake stroke. This mode is used during high-speed and/or high-torque conditions.

- **Homogeneous lean mode.** Similar to the homogeneous mode except that the overall air–fuel mixture is slightly lean for better fuel economy. The injection occurs during the intake stroke. This mode is used under steady, light-load conditions.

- **Stratified mode.** In this mode of operation, the injection occurs just before the spark occurs resulting in lean combustion, reducing fuel consumption.

- **Homogeneous stratified mode.** In this mode, there are two injections of fuel:
The first injection is during the intake stroke.
The second injection is during the compression stroke. As a result of these double injections, the rich air-fuel mixture around the spark plug is ignited first. Then, the rich mixture ignites the leaner mixture. The advantages of this mode include lower exhaust emissions than the stratified mode and less fuel consumption than the homogeneous lean mode.

Homogeneous knock protection mode. The purpose of this mode is to reduce the possibility of spark knock from occurring under heavy loads at low engine speeds. There are two injections of fuel:
The first injection occurs on the intake stroke.
The second injection occurs during the compression stroke with the overall mixture being stoichiometric. As a result of this mode, the PCM does not need to retard ignition timing as much to operate knock-free.

Stratified catalyst heating mode. In this mode, there are two injections:
The first injection is on the compression stroke just before combustion.
The second injection is after combustion occurs to heat the exhaust. This mode is used to quickly warm the catalytic converter and to burn the sulfur from the NOx catalyst.

Gasoline direct-injection (GDI) systems use a variety of shapes of piston and injector locations depending on make and model of engine. Three of the most commonly used designs include:

- Spray-guided combustion. In this design, the injector is placed in the center of the combustion chamber and injects fuel into the dished-out portion of the piston. The shape of the piston helps guide and direct the mist of fuel in the combustion chamber. See Figure 28–6.
- Swirl combustion. This design uses the shape of the piston and the position of the injector at the side of the combustion chamber to create turbulence and swirl of the air-fuel mixture. See Figure 28–7.
- Tumble combustion. Depending on when the fuel is injected into the combustion chamber helps determine how the air-fuel mixture is moved or tumbled. See Figure 28–8.
An engine equipped with gasoline direct injection could use the system to start the engine. This is most useful during idle stop mode when the engine is stopped while the vehicle is at a traffic light to save fuel. The steps used in the Mazda start-stop system, called the *smart idle stop system (SISS)*, allow the engine to be started without a starter motor and include the following steps:

**STEP 1** The engine is stopped. The normal stopping position of an engine when it stops is 70 degrees before top dead center, plus or minus 20 degrees. This is because the engine stops with one cylinder on the compression stroke and the PCM can determine the cylinder position, using the crankshaft and camshaft position sensors.

**STEP 2** When a command is made to start the engine by the PCM, fuel is injected into the cylinder that is on the compression stroke and ignited by the spark plug.

**STEP 3** The piston on the compression stroke is forced downward forcing the crankshaft to rotate counterclockwise or in the opposite direction to normal operation.

**STEP 4** The rotation of the crankshaft then forces the companion cylinder toward the top of the cylinder.

**STEP 5** Fuel is injected and the spark plug is fired, forcing the piston down, causing the crankshaft to rotate in the normal (clockwise) direction. Normal combustion events continue allowing the engine to keep running.
GASOLINE DIRECT-INJECTION SERVICE

NOISE ISSUES Gasoline direct-injection systems operate at high pressure and the injectors can often be heard with the engine running and the hood open. This noise can be a customer concern because the clicking sound is similar to noisy valves. If a noise issue is the customer concern, check the following:

- Check a similar vehicle to determine if the sound is louder or more noticeable than normal.
- Check that nothing under the hood is touching the fuel rail. If another line or hose is in contact with the fuel rail, the sound of the injectors clicking can be transmitted throughout the engine, making the sound more noticeable.
- Check for any technical service bulletins (TSBs) that may include new clips or sound insulators to help reduce the noise.

CARBON ISSUES Carbon is often an issue in engines equipped with gasoline direct-injection systems. Carbon can affect engine operation by accumulating in two places:

- **On the injector itself.** Because the injector tip is in the combustion chamber, fuel residue can accumulate on the injector, reducing its ability to provide the proper spray pattern and amount of fuel. Some injector designs are more likely to be affected by carbon than others. For example, if the injector uses small holes, these tend to become clogged more than an injector that uses a single slit opening where the fuel being sprayed out tends to blast away any carbon. ★ SEE FIGURE 28–10.

- **The backside of the intake valve.** This is a common place for fuel residue and carbon to accumulate on engines equipped with gasoline direct injection. The accumulation of carbon on the intake valve can become so severe that the engine will start and idle, but lack power to accelerate the vehicle. The carbon deposits restrict the airflow into the cylinder enough to decrease engine power.

**NOTE:** Lexus engines that use both port and gasoline direct-injection injectors do not show intake valve deposits. It is thought that the fuel being sprayed onto the intake valve from the port injector helps keep the intake valve clean.

**CARBON CLEANING.** Most experts recommend the use of Techron®, a fuel system dispersant, to help keep carbon from accumulating. The use of a dispersant every six months or every 6,000 miles has proven to help prevent injector and intake valve deposits.

If the lack of power is discovered and there are no stored diagnostic trouble codes, a conventional carbon cleaning procedure will likely restore power if the intake valves are coated.

**FIGURE 28–10** There may become a driveability issue because the gasoline direct-injection injector is exposed to combustion carbon and fuel residue.

SUMMARY

1. A gasoline direct-injection system uses a fuel injector that delivers a short squirt of fuel directly into the combustion chamber rather than in the intake manifold, near the intake valve on a port fuel-injection system.
2. The advantages of using gasoline direct injection instead of port fuel injection include:
   - Improved fuel economy
   - Reduced exhaust emissions
   - Greater engine power
3. Some of the disadvantages of gasoline direct-injection systems compared with a port fuel-injection system include:
   - Higher cost
   - The need for NOx storage catalyst in some applications
   - More components
4. The operating pressure can vary from as low as 500 PSI during some low-demand conditions to as high as 2,900 PSI.
5. The fuel injectors are open for a very short period of time and are pulsed using a 50 to 90 volt pulse from a capacitor circuit.

6. GDI systems can operate in many modes, which are separated into the two basic modes:
   • Stratified mode
   • Homogeneous mode

7. GDI can be used to start an engine without the use of a starter motor for idle-stop functions.

8. GDI does create a louder clicking noise from the fuel injectors than port fuel-injection injectors.

9. Carbon deposits on the injector and the backside of the intake valve are a common problem with engines equipped with gasoline direct-injection systems.

**REVIEW QUESTIONS**

1. What are two advantages of gasoline direct injection compared with port fuel injection?
2. What are two disadvantages of gasoline direct injection compared with port fuel injection?
3. How is the fuel delivery system different from a port fuel-injection system?
4. What are the basic modes of operation of a GDI system?

**CHAPTER QUIZ**

1. Where is the fuel injected in an engine equipped with gasoline direct injection?
   a. Into the intake manifold near the intake valve
   b. Directly into the combustion chamber
   c. Above the intake port
   d. In the exhaust port

2. The fuel pump inside the fuel tank on a vehicle equipped with gasoline direct injection produces about what fuel pressure?
   a. 5 to 10 PSI  
   b. 10 to 20 PSI  
   c. 20 to 40 PSI  
   d. 50 to 60 PSI

3. The high-pressure fuel pumps used in gasoline direct-injection (GDI) systems are powered by ________.
   a. Electricity (DC motor)
   b. Electricity (AC motor)
   c. The camshaft
   d. The crankshaft

4. The high-pressure fuel pump pressure is regulated by using ________.
   a. An electric pressure-control valve
   b. A vacuum-biased regulator
   c. A mechanical regulator at the inlet to the fuel rail
   d. A non-vacuum biased regulator

5. The fuel injectors operate under a fuel pressure of about ________.
   a. 35 to 45 PSI  
   b. 90 to 150 PSI  
   c. 500 to 2,900 PSI  
   d. 2,000 to 5,000 PSI

6. The fuel injectors used on a gasoline direct-injection system are pulsed on using what voltage?
   a. 12 to 14 volt
   b. 50 to 90 volt
   c. 100 to 110 volt
   d. 200 to 220 volt

7. Which mode of operation results in a richer air-fuel mixture near the spark plug?
   a. Stoichiometric
   b. Homogeneous
   c. Stratified
   d. Knock protection

8. Some engines that use a gasoline direct-injection system also have port injection.
   a. True
   b. False

9. A gasoline direct-injection system can be used to start an engine without the need for a starter.
   a. True
   b. False

10. A lack of power from an engine equipped with gasoline direct injection could be due to ________.
    a. Noisy injectors
    b. Carbon on the injectors
    c. Carbon on the intake valves
    d. Both b and c