Introduction to Combustion Chemistry

The gasoline-powered internal combustion engine takes air from the atmosphere and gasoline, a hydrocarbon fuel, and through the process of combustion releases the chemical energy stored in the fuel. Of the total energy released by the combustion process, about 20% is used to propel the vehicle, the remaining 80% is lost to friction, aerodynamic drag, accessory operation, or simply wasted as heat transferred to the cooling system.

Modern gasoline engines are very efficient compared to predecessors of the late '60s and early '70s when **emissions control** and fuel economy were first becoming a major concern of automotive engineers. Generally speaking, the more efficient an engine becomes, the lower the exhaust emissions from the tailpipe. However, as clean as engines operate today, exhaust emission standards continually tighten. The technology to achieve these ever-tightening emissions targets has led to the advanced closed loop engine control systems used on today's Toyota vehicles. With these advances in technology comes the increased emphasis on maintenance, and when the engine and emission control systems fail to operate as designed, diagnosis and repair.

Understanding the Combustion Process

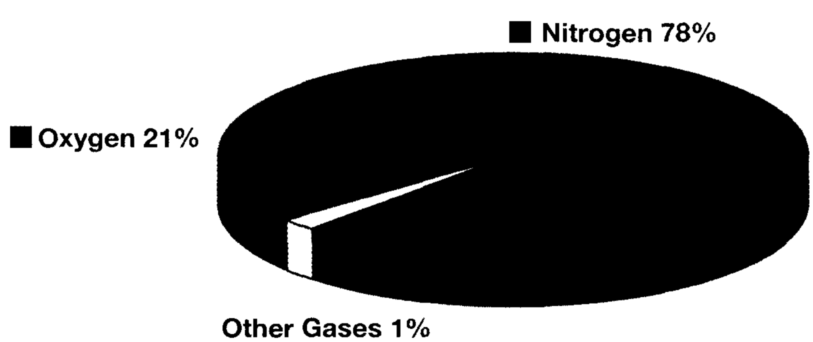
To understand how to diagnose and repair the emissions control system, one must first have a working knowledge of the basic **combustion chemistry** which takes place within the engine. That is the purpose of this section of the program.

The gasoline burned in an engine contains many chemicals, however, it is primarily made up of **hydrocarbons** (also referred to as HC. Hydrocarbons are chemical compounds made up of hydrogen atoms which chemically bond with carbon atoms. There are many different types of hydrocarbon compounds found in gasoline, depending on the number of hydrogen and carbon atoms present, and the way that these atoms are bonded.

Inside an engine, the hydrocarbons in gasoline will not burn unless they are mixed with air. This is where the chemistry of combustion begins. Air is composed of approximately 21% oxygen (02), 78% nitrogen (N2), and minute amounts of other inert gasses.

Atmospheric Make-Up

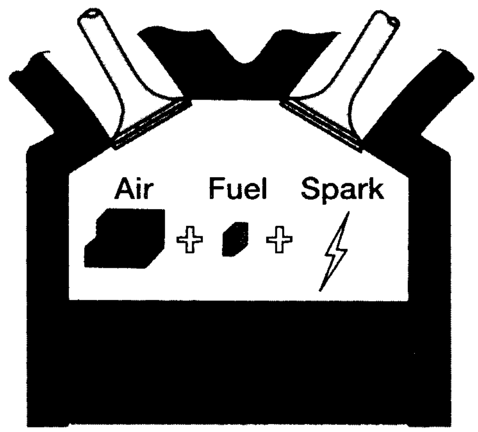
Approximately 99% of "air" is made up of Nitrogen (N_2) and Oxygen (O_2). The "other gases" include Argon (Ar), CO_2, HC, NO_x, SO_2, and trace amounts of other gases.



The hydrocarbons in fuel normally react only with the oxygen during the combustion process to form water vapor (H2O) and carbon dioxide (CO2), creating the desirable effect of heat and pressure within the cylinder. Unfortunately, under certain engine operating conditions, the nitrogen also reacts with the oxygen to form **nitrogen oxides (NOx)**, a criteria air pollutant.

Components of Basic Combustion

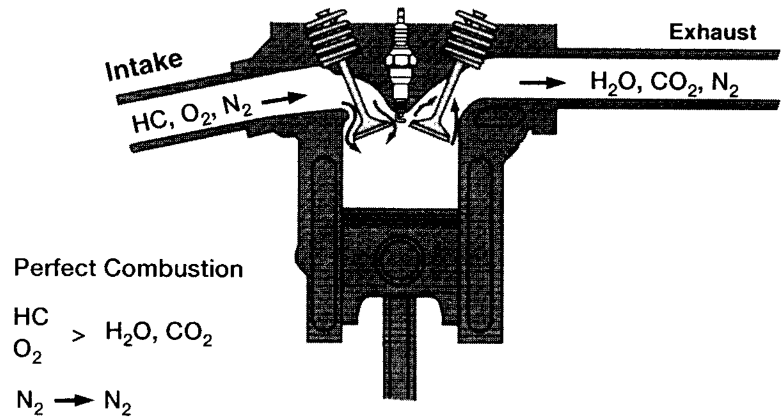
These components, along with other very specific conditions, are needed in order for basic combustion to occur.



The ratio of air to fuel plays an important role in the efficiency of the combustion process. The ideal air/fuel ratio for optimum emissions, fuel economy, and good engine performance is around **14.7 pounds of air for every one pound of fuel**. This "ideal air/fuel ratio" is referred to as **stoichiometry**, and is the target that the feedback fuel control system constantly shoots for. At air/fuel ratios richer than stoichiometry, fuel economy and emissions will suffer. At air/fuel ratios leaner than stoichiometry, power, driveability and emissions will suffer.

"Ideal" Combustion

If "perfect" combustion were to occur, hydrocarbons (HC) would be oxidized into water (H_2O) and carbon dioxide (CO_2). Also, nitrogen (N_2) would pass through uneffected.



Under "Ideal" Combustion Conditions

In a perfectly operating engine with ideal combustion conditions, the following chemical reaction would take place:

- **Hydrocarbons** would react with oxygen to produce **water vapor (H2O**) and **carbon dioxide (CO2)**
- **Nitrogen (N2)** would pass through the engine without being affected by the combustion process.

In essence, only harmless elements would remain and enter the atmosphere. Although modern engines are producing much lower emission levels than their predecessors, they still inherently produce some level of harmful emission output.

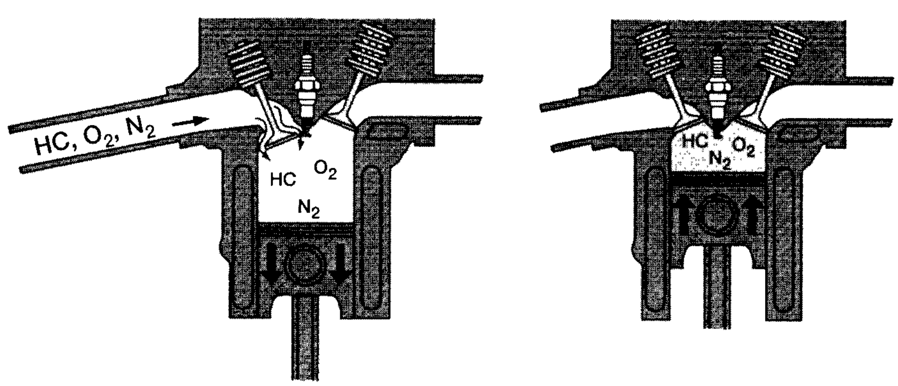
The Four-Stroke Combustion Cycle

During the **Intake Stroke**, air and fuel moves into the low pressure area created by the piston moving down inside the cylinder. The fuel injection system has calculated and delivered the precise amount of fuel to the cylinder to achieve a 14.7 to 1 ratio with the air entering the cylinder.

As the piston moves upward during the **Compression Strok**e, a rapid pressure increase occurs inside the cylinder, causing the air/fuel mixture to superheat. During this time, the antiknock property or **octane rating** of the fuel is critical in preventing the fuel from igniting spontaneously (exploding). This precise superheated mixture is now prime for ignition as the piston approaches Top Dead Center.

Intake and Compression Stroke

During intake, air and fuel is drawn into the cylinder by the downward motion of the piston. During compression, cylinder pressure is increased making the air/fuel charge prime for ignition.

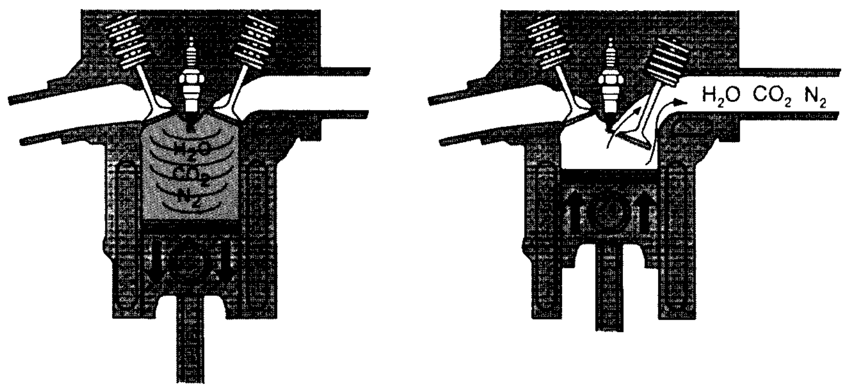


Just before the piston reaches top dead center to start the Power Stroke, the spark plug ignites the air/fuel mixture in the combustion chamber, causing a flame-front to begin to spread through the mixture. During combustion, hydrocarbons and oxygen react, creating heat and pressure. Ideally, the maximum pressure is created as the piston is about 8 to 12 degrees past top dead center to produce the most force on the top of the piston and transmit the most power through the crankshaft. Combustion by-products will consist primarily of water vapor and carbon dioxide if the mixture and spark timing are precise.

After the mixture has burned and the piston reaches bottom dead center, the Exhaust Stroke begins as the exhaust valve opens and the piston begins its return to top dead center. The water vapor, carbon dioxide, nitrogen, and a certain amount of unwanted pollutants are pushed out of the cylinder into the exhaust system.

Power and Exhaust Strcke

During power stroke, the air/fuel charge is ignited and the combustion pressure is exerted on the piston. During exhaust stroke, combustion gases are expelled into the exhaust system.

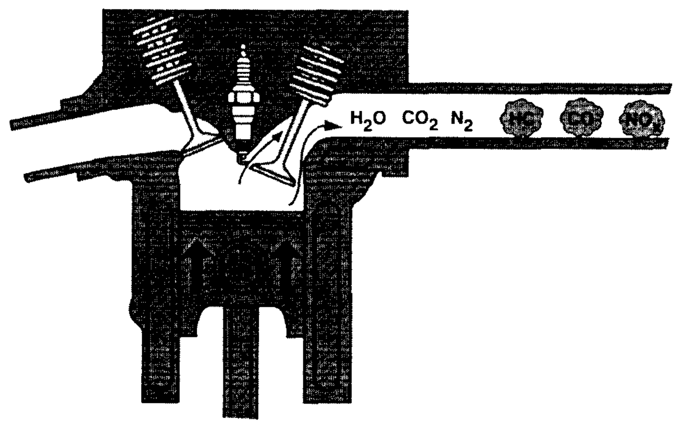


Harmful Exhaust Emissions

As previously mentioned, even the most modern, technologically advanced automobile engines are not "perfect"; they still inherently produce some level of harmful emission output. There are several conditions in the combustion chamber which prevent perfect combustion and cause unwanted chemical reactions to occur. The following are examples of harmful exhaust emissions and their causes.

Exhaust Emissions

Automobile engines inherently produce some level of harmful emission output.



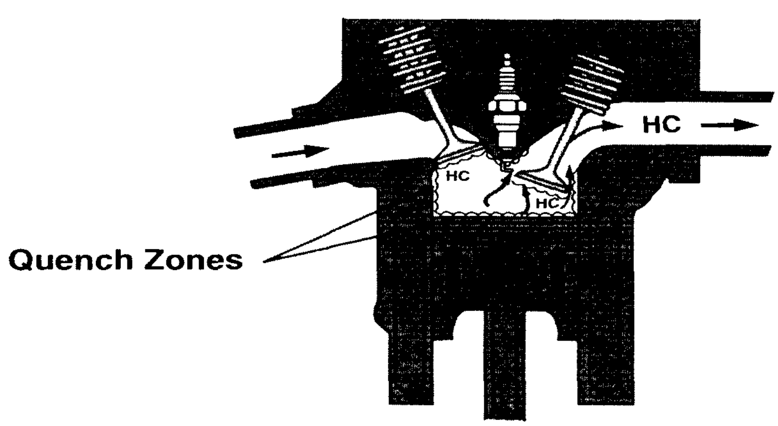
Hydrocarbon (HC) Emission

Hydrocarbons are, quite simply, raw unburned fuel. When combustion does not take place at all, as with a misfire, large amounts of hydrocarbons are emitted from the combustion chamber.

A small amount of hydrocarbon is created by a gasoline engine due to its design. A normal process called wall quenching occurs as the combustion flame front burns to the relatively cool walls of the combustion chamber. This cooling extinguishes the flame before all of the fuel is fully burned, leaving a small amount of hydrocarbon to be pushed out the exhaust valve.

"Quenching"

Quenching occurs when the combustion flame-front is extinguished before all the fuel is burned.



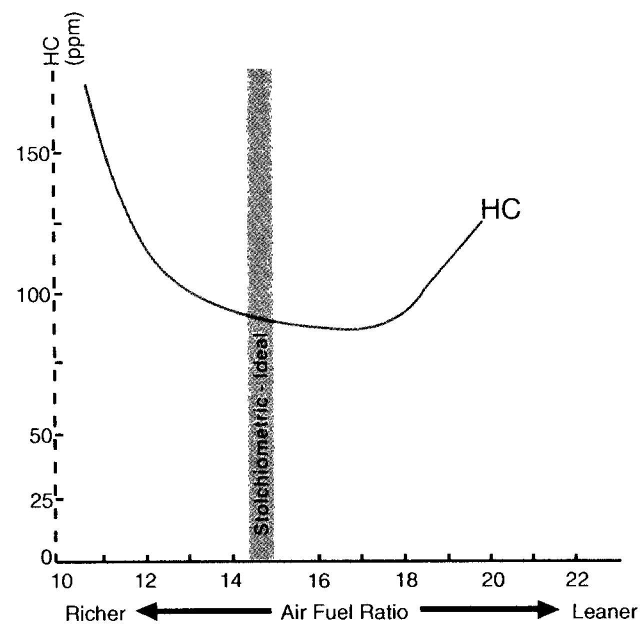
Another cause of excessive hydrocarbon emissions is related to combustion chamber deposits. Because these carbon deposits are porous, hydrocarbon is forced into these pores as the air/fuel mixture is compressed. When combustion takes place, this fuel does not burn, however, as the piston begins its exhaust stroke, these hydrocarbons are released into the exhaust stream.

The most common cause of excessive hydrocarbon emissions is misfire which occurs due to ignition, fuel delivery, or air induction problems. Depending on how severe the misfire, inadequate spark or a noncombustible mixture (either too rich or too lean) will cause hydrocarbons to increase to varying degrees. For example, a total misfire due to a shorted spark plug wire will cause hydrocarbons to increase dramatically. Conversely, a slight lean misfire due to a false air entering the engine, may cause hydrocarbons to increase only slightly.

Excess hydrocarbon can also be influenced by the temperature of the air/ fuel mixture as it enters the combustion chamber. Excessively low intake air temperatures can cause poor mixing of fuel and air, resulting in partial misfire.

Effects of A/F Ratio on Exhaust HC

As shown, exhaust HC production is lowest when A/F ratio is slightly leaner than "ideal"; however, HC's increases dramatically when the mixture becomes too rich or too lean to the point of misfire.

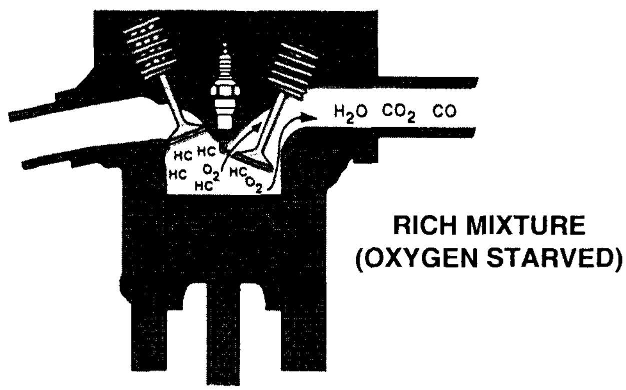


Carbon Monoxide (CO) Emission

Carbon monoxide (CO) is a byproduct of incomplete combustion and is essentially partially burned fuel. If the air/fuel mixture does not have enough oxygen present during combustion, it will not bum completely. When combustion takes place in an oxygen starved environment, there is insufficient oxygen present to fully oxidize the carbon atoms into carbon dioxide (CO2). When carbon atoms bond with only one oxygen atom carbon monoxide (CO) forms.

Oxygen Starved Combustion

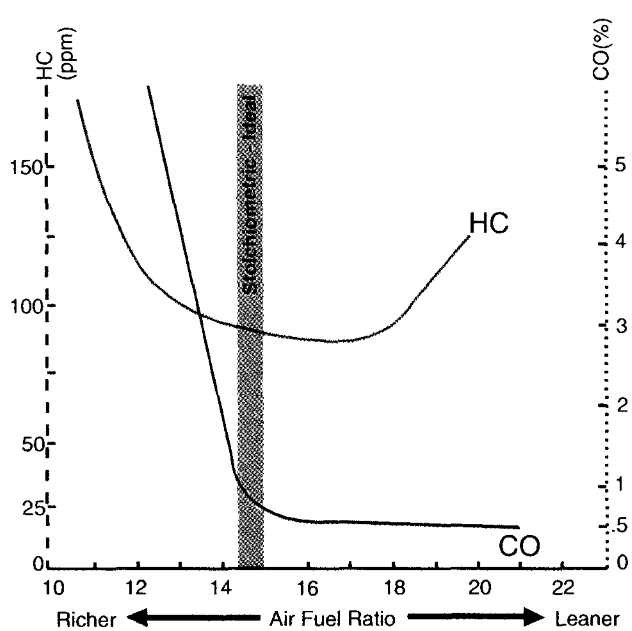
During combustion with rich A/F mixtures, the carbon from HC only partially oxidizes, resulting in carbon monoxide (CO) rather than carbon dioxide (CO_2).



An oxygen starved combustion environment occurs as a result of air/fuel ratios which are richer than stoichiometry (14.7 to 1). There are several engine operating conditions when this occurs normally. For example, during cold operation, warm-up, and power enrichment. It is, therefore, normal for higher concentrations of carbon monoxide to be produced under these operating conditions. Causes of excessive carbon monoxide includes leaky injectors, high fuel pressure, improper closed loop control, etc.

Effects of A/F Ratio on Exhaust CO

Exhaust CO is lowest when A/F ratio is leaner than "ideal"; however, CO increases dramatically with richer mixtures.



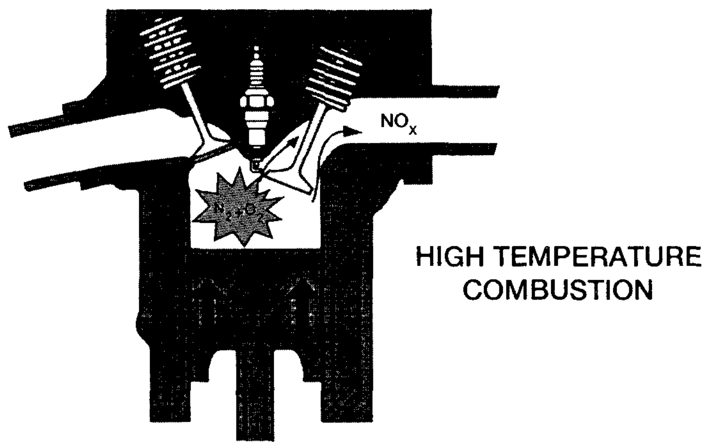
When the engine is at warm idle or cruise, very little carbon monoxide is produced because there is sufficient oxygen available during combustion to fully oxidize the carbon atoms. This results in higher levels of carbon dioxide (CO2) the principal by-product of efficient combustion.

Oxides of Nitrogen (NOx) Emission

High cylinder temperature and pressure which occur during the combustion process can cause nitrogen to react with oxygen to form Oxides of Nitrogen (NOx). Although there are various forms of nitrogen-based emissions that comprise Oxides of Nitrogen (NOx), nitric oxide (NO) makes up the majority, about 98% of all NOx emissions produced by the engine.

High Temperature Combustion

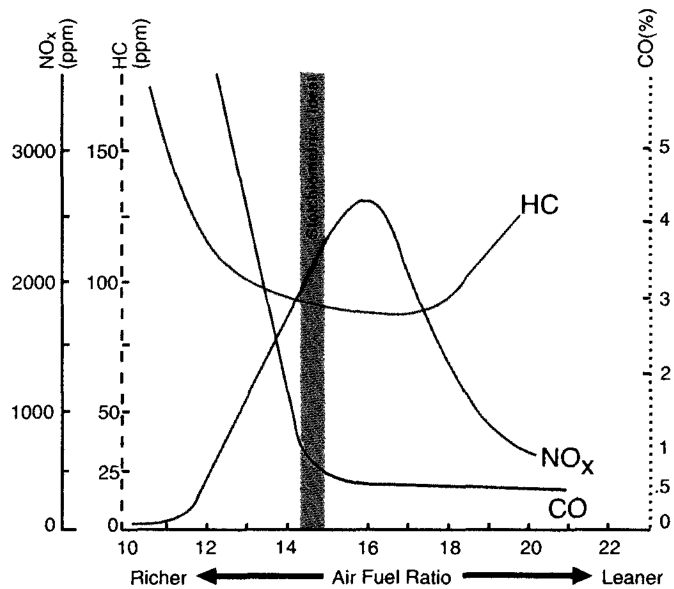
High combustion temperature (typical during heavy load conditions), causes the nitrogen to combine with oxygen to form Oxides of Nitrogen (NO_X).



Generally speaking, the largest amount of NOx is produced during moderate to heavy load conditions when combustion pressures and temperatures are their highest. However, small amounts of NOx can also be produced during cruise and light load, light throttle operation. Common causes of excessive NOx include faulty EGR system operation, lean air/fuel mixture, high temperature intake air, overheated engine, excessive spark advance, etc.

Effects of A/F Ratio on Exhaust NOx

Exhaust NO_x production is highest when A/F ratio is slightly leaner than "ideal". This inverse relationship with HC and CO production poses a problem when attempting to lower all three emission levels at once.



Air/Fuel Mixture Impact on Exhaust Emissions
As you can see in the graph above, HC and CO levels are relatively low near the theoretically ideal 14.7 to 1 air/fuel ratio. This reinforces the need to maintain strict air/fuel mixture control. However, NOx production is very high just slightly leaner than this ideal mixture range. This inverse relationship between HC/CO production and NOx production poses a problem when controlling total emission output. Because of this relationship, you can understand the complexity in reducing all three emissions at the same time.

