Testing Automotive Exhaust Emissions

Abstract

The carbon footprint we are placing on the world around us has become an important topic over the last decade. New regulations are being imposed internationally to regulate greenhouse gas emissions, which is resulting in the need for better emissions testing worldwide. Exhaust emissions testing helps determine how many maleficent compounds form in an engine during combustion. Once this is understood, you can minimize the creation of these gases and design a better engine. In this application note, learn about important concepts to keep in mind when putting together an exhaust emissions test cell, as well as the most efficient ways to use hardware to effectively get all of the data you need. Given the vast amount of engine types, we focus on gasoline internal combustion engine emissions testing, but many of these concepts apply to other engine technologies.

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Introduction to Emissions Test Cells

With the new international focus on more strict emissions testing, the market for combustion engine test cells has flourished. As the need for these cells grows, so does the need for more advanced technology to perform the necessary tests. This technology is often slowly implemented because of the "if it is not broken, don't fix it" mentality. The dyno testing structure has remained relatively stable for the past few decades, meaning there is no pressing need to perform a test cell overhaul and upgrade instrumentation. However, instrumentation has advanced considerably in recent years. Now instrumentation methods can perform vital tests faster, with more accuracy, and with less overhead than traditional testing methods. Modern exhaust emissions test cells use the most advanced methods for data collection to optimize data relevance, allowing you to get the information you need: real-time results that portray the correct data for statistical analysis.

A test cell is an isolated and controlled room in which you can safely analyze and record the properties of a combustion engine. For emissions tests, an engine is usually mounted on a cart in the center of the cell and the intake and exhaust are closely monitored using numerous different testing instruments to accurately record and store exhaust information. These instruments then either process this data or pass it through to a central location known as the operator booth for further processing. Figure 1 provides a basic visual of how all of this looks.

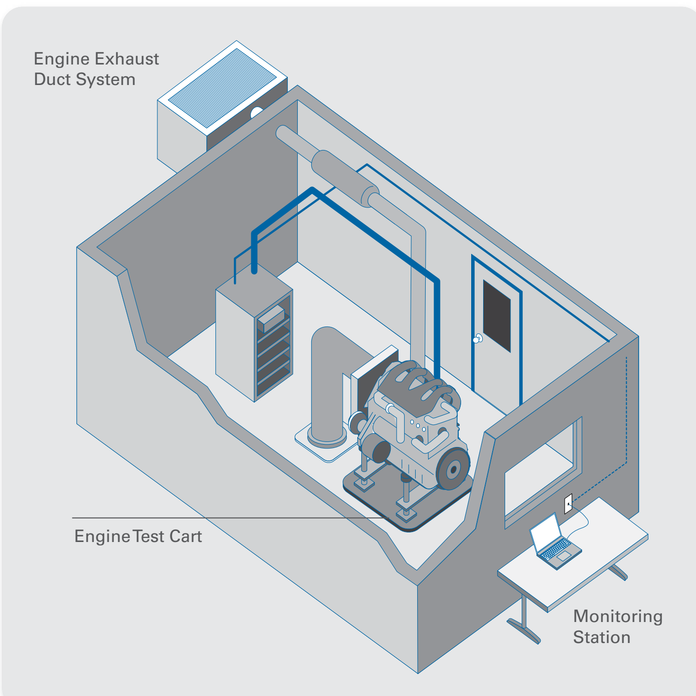

Figure 1. Layout of emissions test cell with operator booth, engine test cart, and exhaust duct system.

Tests that are run in a test cell quantify whether the combustion engine in question is deemed suitable by specific standards. Numerous international standards for greenhouse gas emissions regulate the acceptable limits. In Europe and China, the Euro 4 is the current standard until 2014. China recently adopted the standard in 2010 in the attempt to limit its rising pollution levels. In the United States, the Environmental Protection Agency (EPA) controls the majority of the regulations that specify what the contents of engine exhaust can contain.

International Emissions Standards

There are many international regulatory bodies; however, the Euro 4 and the EPA are the most prevalent among nations and are generally considered the benchmarks. They dictate the total amount of defined pollutants an engine can exhaust into the air. The units used by these specifications are generally defined as grams per mile, or how many grams you can legally disperse per traveled mile of drive time.

Although test cells allow you to measure the concentrations of numerous compounds in the exhaust, most regulatory bodies monitor only five chemicals: nonmethane organic gas (NMOG), nitrous oxides (NOx), carbon monoxide (CO), formaldehyde, and particulate matter (PM). The majority of these compounds are self-explanatory, but it necessary to point out that formaldehyde is used as a metric to measure the amount of hydrocarbon pollution emitted.

The acceptable levels for each compound differ slightly. Table 1 reflects the maximum levels in light-duty vehicles that have been specified as ultralow emission vehicles (as legislated by California state guidelines in the EPA).

Emissions Category	Useful Life Standard	Test Weight (lbs)	NMOG 1(g/mi)	NOx (g/mi)	CO (g/mi)	Formaldehyde (g/mi)	PM (g/mi)b
Transitional Low Emission Vehicle	Intermediate	All	0.125	0.4	3.4	0.015	-
Low Emission Vehicle		All	0.075c	0.2	3.4c	0.015c	-
Ultralow Emission Vehicle		All	0.040	0.2c	1.7	0.008	-
Transitional Low Emission Vehicle	Full	All	0.156	0.6	4.2	0.018	0.08
Low Emission Vehicle		All	0.090c	0.3	4.2c	0.018	0.08c
Ultralow Emission Vehicle		All	0.055	0.3c	2.1	0.011	0.04

Table 1. Light-Duty Vehicle Clean Fuel Fleet Exhaust Emission Standards

1 Note: To classify as a nonmethane organic gas, the compound can be an oxygenated organic gas containing five or fewer carbon atoms or an aromatic containing 12 or fewer carbon atoms. (42 U.S.C. 7581: US Code - Section 7581: Definitions)

The Science Behind Exhaust Emissions Testing

For an engine to work properly, the right ratio of oxygen and gasoline needs to mix to optimize for combustion. If too much oxygen is in the mix, the mixture is qualified as lean. If there is too much gasoline, the mixture is called rich. To keep the reaction stoichiometrically accurate, airflow sensors are located at the intake of the cylinder. To model this, it is necessary to understand what makes up gasoline. It consists of 20 percent octane, 20 percent nonane, 15 percent decane, 15 percent undecane, 8 percent benzene, 10 percent toluene, 10 percent dehydro-m-xylylene, and 2 percent ethylbenzene. All of these compounds react with oxygen in combustion to ideally produce CO_2 and H_20. The reactions for each are as follows:

- Octane: $2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_20$
- Nonane: $C_9H_{20} + 14O_2 \rightarrow 9CO_2 + 10H_20$
- Decane: $2C_{10}H_{22} + 31O_2 \rightarrow 20CO_2 + 22H_20$
- Undecane: $C_{11}H_{24} + 17O_2 \rightarrow 11CO_2 + 12H_20$
- Benzene: $2C_6H_6 + 15O_2 \rightarrow 12CO_2 + 6H_20$
- Toluene: $C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_20$
- Dehydro-m-xylylene: $4C_8H_7 + 39O_2 \rightarrow 32CO_2 + 7H_20$
- Ethylbenzene: $2C_8H_{10} + 21O_2 \rightarrow 16CO_2 + 10H_2O$

Each reaction requires a specific amount of air per fuel component. This ratio is quantified in a term known as air/fuel ratio, and is determined by the mass of air per the mass of the reactant (in this case, gasoline).

Four-stroke combustion engines, as the name implies, require four steps to create mechanical power from the chemical process. For a view of how this reaction occurs within a cylinder, look at Figure 2. The air/gas mixture is first brought in through the intake valve (intake stroke) where the air/fuel ratio is measured. This expands in the cylinder until the piston reaches bottom dead center. The mixture is then compressed until the piston reaches the top of the cylinder and a spark plug ignites the contents (compression stroke). This large force pushes the piston to bottom dead center and turns the crankshaft of the engine (power stroke). In the last step, the products of the reaction are exhausted via the exhaust valve, which then pass into the exhaust system (exhaust stroke). This is the component that we measure in emissions testing.

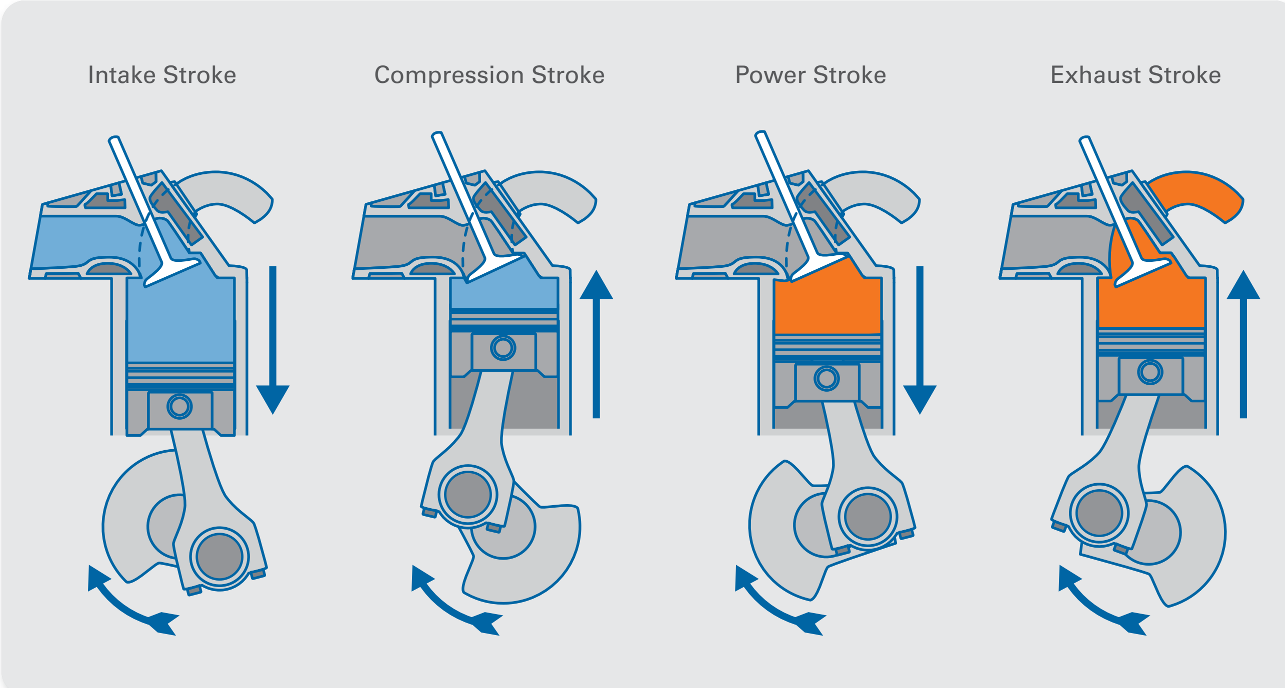

Figure 2. Modern engines use the four-stroke power cycle to convert chemical energy into mechanical energy

In an ideal world, the only by-products of the combustion would be water and carbon dioxide. Unfortunately, this combustion is never as ideal. Frequently, the reactions result in free radicals and environmentally harmful compounds that can have negative effects on the atmosphere if given time to accumulate.

Pollutants and How They Affect the Environment

To fully understand how exhaust can be harmful, you need to understand how each pollutant compound is actually formed.

NOx

Traditionally, oxygen and nitrogen do not react at ambient temperatures. However, when heated to high temperatures, N_2 and O_2 can dissociate. After dissociation, they have the potential to react with each other, potentially undergoing an endothermic reaction to create NOx (NO or NO_2). NOx, if distributed into the atmosphere, eventually forms nitric acid, which is a heavy contributor to acid rain.

Hydrocarbons

Many hydrocarbons have been classified as carcinogens, which is why their emissions are regulated and closely monitored in new engine designs. To claim hydrocarbons as a complete by-product of the combustion reaction is mildly misleading. Hydrocarbons themselves can be better defined as unburned fuel. If some portion of the gasoline does not combust (react with the oxygen) when the spark ignites the fuel in the cylinder, it passes out through the exhaust unburned. In the combustion process, passing hydrocarbons through the exhaust can result from several actions. If the ignition is improperly timed and is ignited before or after the desired angle from top dead center, the reaction will not occur stoichiometrically. Also, non-stoichiometric fuel mixture or a defective catalytic converter can result in high hydrocarbon content.

Particulate Matter

The EPA defines particulate matter as a particle or droplet that is 10 micrometers or smaller. This is the specified size because that is the maximum size that can be absorbed by human lungs. Usually, diesel engines are the biggest culprit of producing particulate matter like ash, sulfates, diesel soot, and metallic abrasion particles. These can result from any different number of factors, but all are considered carcinogens.

CO

Much like hydrocarbons, incomplete combustion can result in carbon monoxide (CO) production. A low air/fuel ratio means there is less air than needed for a full reaction and results in the creation of CO, which in large quantities is toxic to humans and animals.

The Effect of Air/Fuel Mixture on Exhaust Emissions

As the air/fuel ratio changes, the exhaust gas mixtures can change. For example, the more lean your input mixture, the more likely you are to have a high level of hydrocarbons in the product exhaust. Figure 3 provides a diagram explaining more of these relationships.

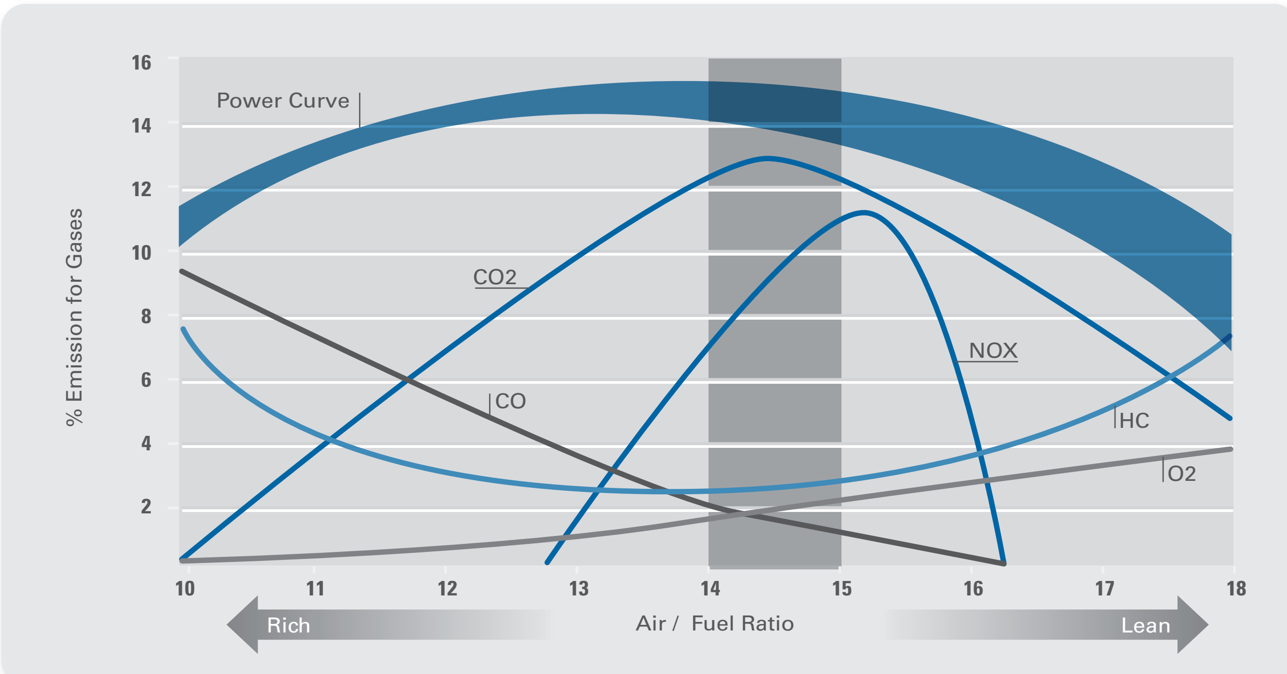

Figure 3. How air-fuel ratio affects NOx, CO, HC, O_2, and CO_2 emissions in an internal combustion engine

Mounting and Control in Test Cells

In an internal combustion engine test cell, the engine is placed on a test cart in the center of the cell and is controlled by an engine dyno that supplies the load and speed for a given test. Each regulatory body generally has a specific set of tests used in these scenarios. For example, the EPA uses the Federal Test Procedure (FTP), which simulates a standard driving course (the test was created by monitoring cars on a standard course). While this application note focuses on acquisition of exhaust emissions, NI VeriStand can be used to perform dyno control, generate test profiles, and log test results within a configurable software environment.

For exhaust emissions testing, there is a piping system for both intake air and exhaust. The intake air is filtered to provide consistent test data. The exhaust air passes into a piping system similar to that in an automotive exhaust system that contains catalytic converters and mufflers. These pipes eventually run into a duct that passes the exhaust into the atmosphere.

Sensors for pressure, temperature, and chemical composition can be mounted along the exhaust pipes to gather information for combustion analysis. Each of these sensors feeds back to a signal conditioning system or instrumentation platform, usually located in a test rack alongside the rest of the test cell instrumentation.

In traditional testing, each emissions test uses its own specialized instrument. For example, a nondispersive infrared analyzer (NDIR) is used to measure CO and CO_2 emissions. This device is placed on the testing rack with the intentions of only measuring carbon emissions. That same device cannot measure hydrocarbons (generally a flame ionization detector is used for hydrocarbons); therefore, these two tests require separate boxed instruments and don't interact. Each sensor feeds data to its respective boxed instrument and the instrument performs onboard processing. Getting all of this information into one central location can be a challenge and usually requires an external measurement system. Many test cell designs incorporate a data acquisition device to measure the scaled voltage outputs and analyze the correlated data using a single PC (Figure 4). The central data acquisition system collects the data then feeds it to the central computer located at the operator's desk. The operator PC, located outside of the test cell, allows for the tester to view all of the data without endangering himself in the process.

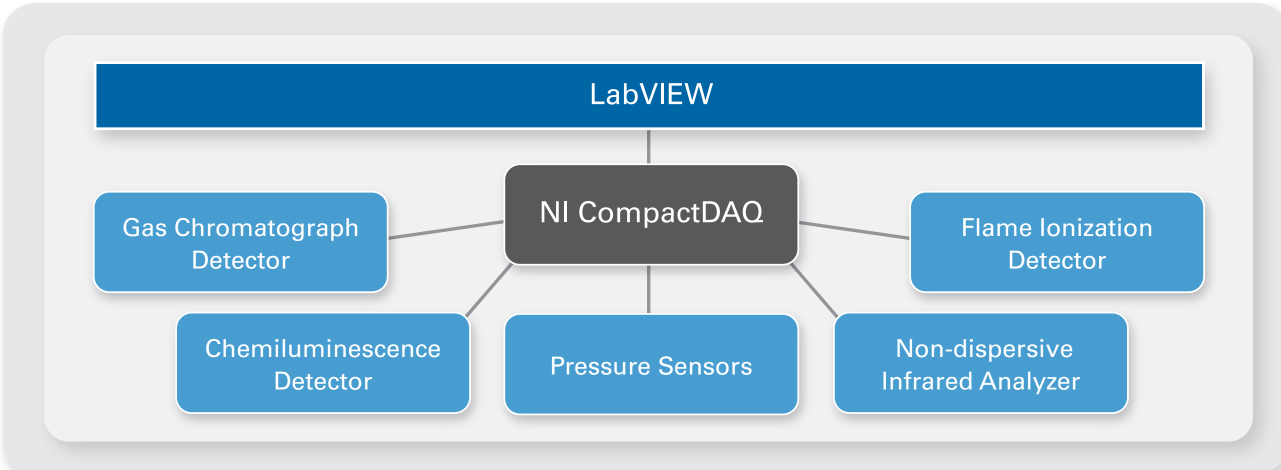

Figure 4. NI CompactDAQ can help simplify emissions testing and organize data from many sources.

Using a modular signal conditioning data acquisition system, like NI CompactDAQ, has the added benefit of measuring analog sensors alongside the specialized instrumentation outputs. You can then easily correlate this data and further process it offline.

Setting Up a Test Cell

The basic requirements for building a test cell are described below; however, it may be more cost-efficient to rent testing space from a leading test facility if a local test cell cannot be sufficiently used to justify startup and maintenance costs.

Room Requirements

A test cell should be 12' to 15' (~3.5-4.5 meters) in length and 10' to 12' (~3-3.5 meters) in width to provide room for housing equipment while not being so large as to create eddy currents in the airflow. The suggested height of the cell is around 10' (3 meters) to optimize airflow.

The engine cart should be centralized, and all cables coming from it should be either routed overhead or in designed trenches in the floor. The operator booth should be outside of the cell in line with the engine crankshaft (to prevent failed engine parts from being projected toward the operator). The booth should have a large wire-reinforced window in front of it to allow the operator a full view of the test. Any switches or controls that will be needed throughout testing should be located outside of the cell at the operator booth. Figure 5 displays how a test cell should look on completed setup.

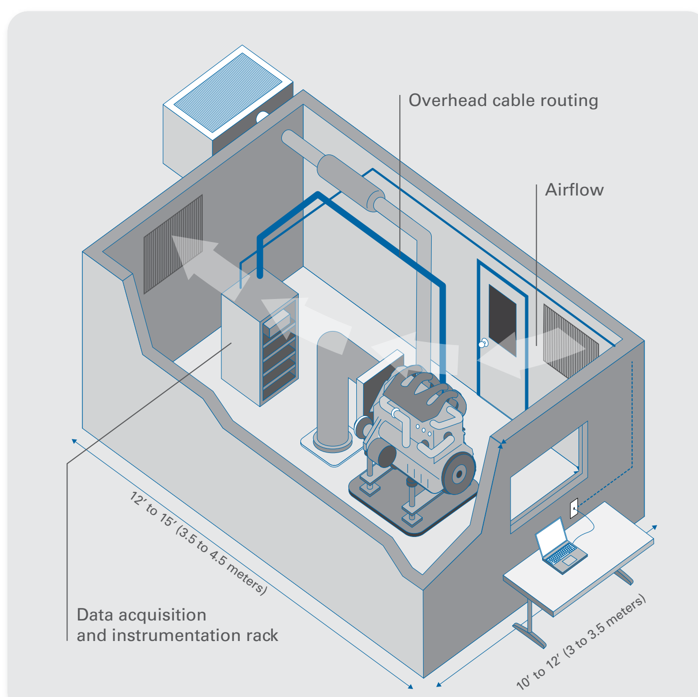

Figure 5. Dimensional Layout of an Emissions Test Cell

Sensors

Beyond the basic setup of the room and engine control, it takes a large amount of analog sensors to collect the emissions data, specifically, temperature, pressure, and airflow measurements in addition to the specialized instrumentation.

Cheap and readily available thermocouples are commonly used for temperature measurements in exhaust emissions test. If you consider the NI CompactDAQ system discussed previously, an NI 9213 thermocouple input module can acquire up to 16 temperature measurements providing the filtering, amplification, cold-junction compensation, and sensor connectivity directly on the module. NI LabVIEW software and DAQ drivers can then perform all of the data processing necessary, such as accounting for cold-junction compensation and using built-in scales to convert the voltage to a temperature.

In addition to temperature, most exhaust emissions test systems require pressure measurement along the exhaust flow piping. In traditional test procedures, a test cell requires a separate set of hardware to perform this task. Once again, using a measurement system like NI CompactDAQ, it is possible to integrate these and synchronize these different measurements in the same system. By adding an NI 9237 simultaneous bridge module to the system, you can add four channels of synchronous pressure measurements per module.

Finally, exhaust emissions test systems require measurement of the flow into and out of the engine. Flowmeters measure how much exhaust is moving through the duct volumetrically. Flowmeters can be easily integrated into a data acquisition system by measuring the frequency of a digital pulse train. Using the NI CompactDAQ example, an NI 9401 digital module can acquire the digital pulse train. In software, the NI-DAQmx driver acquires the raw data and scales it to the volumetric flow of the exhaust.

National Instruments offers both NOx and O2 Sensor Module Kits through the Powertrain Controls product line. Other emissions testing equipment can be purchased through third party vendors. For more specific emissions tests, a standard set of boxed instruments are defined below. These larger instruments are usually located in large racks along the edge of the room and can measure nearly any metric of the combustion exhaust.

For emissions testing, Table 2 shows the most common test equipment you need for your testing racks.

Compound Measured	Compound Measured	How It Works
Nondispersive Infrared Analyzer (NDIR)	■ CO and CO_2	■ Uses infrared radiation that is absorbed by the carbon compounds. Measures the heat emitted.
Chemiluminescence Detector (CLD)	■ NOx	■ Measures NO and NO_2 to determine NOx concentration. The process first converts NO molecules to NO_2. When all NO_2 molecules are then forced back to NO, the compound emits light, which is measured.
Flame Ionization Detector (FID)	■ Total Hydrocarbons (THC)	■ This process burns gas in a hydrogen flame, which farms carbon radicals that are ionized. These ionized particles are discharged at a collector electrode and the current is measured.
Gas Chromatographic Procedure With Flame Ionization Detection (GC FID)	■ Methane (CH4)	■ The gas chromatography column is used to separate out the methane, and the flame ionization detector is used to actually get the methane concentration.
Gravimetric Scale	■ Particulate Matter	■ Uses a very fine scale to actually weigh the particulate filter before and after the testing. This is only useful for diesel engine tests.
Paramagnetic O_2 Detector (PMD)	■ O_2	■ Magnets force oxygen molecules to move. This movement is sensed by a special detector and is proportional to the total molecule concentration.
Mass Spectrometer	■ CO, CO_2, O_2, NOx	■ Ionizes the exhaust and then separates the components using a mass-to-charge ratio. These ions are then identified to determine the total concentration of each component in the compound.

Table 2. See what instrumentation is used in emissions testing and how it works.

As you may have noticed, many dynamic components need to work together for a test to produce the desired results. If any one component does not perform its task, this can cause the validity of the whole test to be voided. This can cause large time delays and cost the tester thousands of dollars. Because of the decentralization of the testing structure with processing on numerous different instruments, it can be difficult to tell whether the results are what you need. To keep this from happening, it is useful to find a method for centralizing your test data.

Using a centralized data acquisition system, like NI CompactDAQ, you can aggregate all of the test data via the analog outputs of the devices and centralize it in one location. Better yet, all of these analog outputs can be processed on the same system that is collecting the temperature, pressure, and flow information. Then, in conjunction with LabVIEW software, you can display and analyze the synchronous data in real time, in one location, so the operator can monitor each component of the test to determine the validity of the data.

Building a Test Cell With the Right Tools

Designing and building a test cell is no small feat, but it can be made easier with the proper tools. As newly imposed restrictions around the world make exhaust emissions testing more difficult, it is more important than ever to achieve tighter results. NI CompactDAQ in conjunction with LabVIEW or NI TestStand provides an ideal platform to bring together all of the collected data to the operator for high-speed processing and analysis.

Additional Resources

- National Instruments Exhaust Emissions Test System – View pricing for an emissions testing system with NI CompactDAQ and LabVIEW and configure it for your application.
- Building optimized systems for your application – Learn more about using a modular system approach with NI CompactDAQ to solve your specific applications needs without paying for unneeded functionality.

Notes

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