CHAPTER 3: Technology

This chapter describes the current state of spark-ignition technology for engines, evaporative emission technology, and compression-ignition technology for marine engines, as well as the emission control technologies expected to be available for manufacturers. Chapter 4 presents the technical analysis of the feasibility of the proposed standards.

3.1 Introduction to Spark-Ignition Engine Technology

The two most common types of engines are gasoline-fueled engines and diesel-fueled engines. These engines have very different combustion mechanisms. Gasoline-fueled engines initiate combustion using spark plugs, while diesel fueled engines initiate combustion by compressing the fuel and air to high pressures. Thus these two types of engines are often more generally referred to as "spark-ignition" and "compression-ignition" (or SI and CI) engines, and include similar engines that used other fuels. SI engines include engines fueled with LPG and CNG.

3.1.1 Four-Stroke Engines

Four-stroke engines are used in many different applications. Virtually all automobiles and many trucks are powered by four-stroke SI engines. Four-stroke engines are also very common in motorcycles, all-terrain vehicles (ATVs), boats, airplanes, and numerous nonroad applications such as lawn mowers, lawn and garden tractors, and generators, to name just a few.

A “four-stroke” engine gets it’s name from the fact that the piston makes four passes or strokes in the cylinder to complete an entire cycle. The strokes are intake, compression, power, and exhaust. Two of the strokes are downward (intake & power) and two of the strokes are upward (compression & exhaust). Valves in the combustion chamber open and close to route gases into and out of the combustion chamber or create compression.

The first step of the cycle is for an intake valve in the combustion chamber to open during the “intake” stroke allowing a mixture of air and fuel to be drawn into the cylinder while an exhaust valve is closed and the piston moves down the cylinder. The piston moves from top dead center (TDC) or the highest piston position to bottom dead center (BDC) or lowest piston position. This creates a vacuum or suction in the cylinder, which draws air and fuel past the open intake valve into the combustion chamber.

The intake valve then closes and the momentum of the crankshaft causes the piston to move back up the cylinder from BDC to TDC, compressing the air and fuel mixture. This is the “compression” stroke. As the piston nears TDC, at the very end of the compression stroke, the air and fuel mixture is ignited by a spark from a spark plug and begins to burn. As the air and fuel mixture burns, increasing temperature and pressure cause the piston to move back down the cylinder, transmitting power to the crankshaft. This is referred to as the “power” stroke. The last stroke in the four-stroke cycle is the “exhaust” stroke. At the bottom of the power stroke, an exhaust valve opens in the combustion chamber and as the piston moves back up the cylinder, the burnt gases are pushed out through the exhaust valve to the exhaust manifold, and the cycle is complete.

3.1.2 Two-Stroke Engines

Two-stroke SI engines are widely used in nonroad applications, especially for recreational vehicles, such as snowmobiles, off-highway motorcycles and ATVs. The basic operating principle of the charge scavenged two-stroke engine (traditional two-stroke) is well understood; in two-strokes the engine performs the operations of intake, compression, expansion and exhaust, which the four-stroke engine requires four strokes to accomplish. Two-stroke engines have several advantages over traditional four-stroke engines for use in recreational vehicles: high power-to-weight ratios; simplicity; ease of starting; and lower manufacturing costs. However, they also have much higher emission rates.

Another difference between two- and four-stroke engines is how the engines are lubricated. Four-stroke engines use the crankcase as a sump for lubricating oil. Oil is distributed throughout the engine by a pump through a series of small channels. Because the crankcase in a two-stroke engine serves as the pump for the scavenging process, it is not possible to use it as an oil sump as is the case for four-stroke engines. Otherwise, gasoline would mix with the oil and dilute it. Instead, lubrication for two-stroke engines is provided by mixing specially-formulated two-stroke oil with the incoming charge of air and fuel mixture. The oil is either mixed with the gasoline in the fuel tank, or metered into the gasoline as it is consumed, using a small metering pump. As the gasoline/oil mixture passes through the carburetor, it is atomized into fine droplets and mixed with air. The gasoline quickly vaporizes, while the less volatile oil forms a fine mist of fine droplets. Some of these droplets contact the crankshaft, piston pin, and cylinder walls, providing lubrication. Most of the oil droplets, however, pass out of the crankcase and into the cylinder with the rest of the incoming charge.

In a two-stroke engine, combustion occurs in every revolution of the crankshaft. Two-stroke engines eliminate the intake and exhaust strokes, leaving only compression and power strokes. This is due to the fact that two-stroke engines do not use intake and exhaust valves. Instead, they have openings, referred to as “ports,” in the sides of the cylinder walls. There are typically three ports in the cylinder; an intake port that brings the air-fuel mixture into the crankcase; a transfer port that channels the air and fuel mixture from the crankcase to the combustion chamber; and an exhaust port that allows burned gases to leave the cylinder and flow into the exhaust manifold. Two-stroke engines route incoming air and fuel mixture first into the crankcase, then into the cylinder via the transfer port. This is fundamentally different from a four-stroke engine which delivers the air and fuel mixture directly to the combustion chamber.

With a two-stroke engine, as the piston approaches the bottom of the power stroke, it uncovers exhaust ports in the wall of the cylinder. The high pressure burned combustion gases blow into the exhaust manifold. At the same time, downward piston movement compresses the fresh air and fuel mixture charge in the crankcase. As the piston gets closer to the bottom of the power stroke, the transfer ports are uncovered, and fresh mixture of air and fuel are forced into the cylinder while the exhaust ports are still open. Exhaust gas is “scavenged” or forced into the exhaust by the pressure of the incoming charge of fresh air and fuel. In the process, however, some mixing between the exhaust gas and the fresh charge of air and fuel takes place, so that some of the fresh charge is also emitted in the exhaust. Losing part of the fuel out of the exhaust during scavenging causes the very high hydrocarbon emission characteristics of two-stroke engines.

At this point, the power, exhaust, and transfer events have been completed. When the piston begins to move up, its bottom edge uncovers the intake port. Vacuum draws fresh air and fuel into the crankcase. As the piston continues upward, the transfer port and exhaust ports are closed. Compression begins as soon as the exhaust port is blocked. When the piston nears TDC, the spark plug fires and the cycle begins again.

3.1.3 Engine Calibration

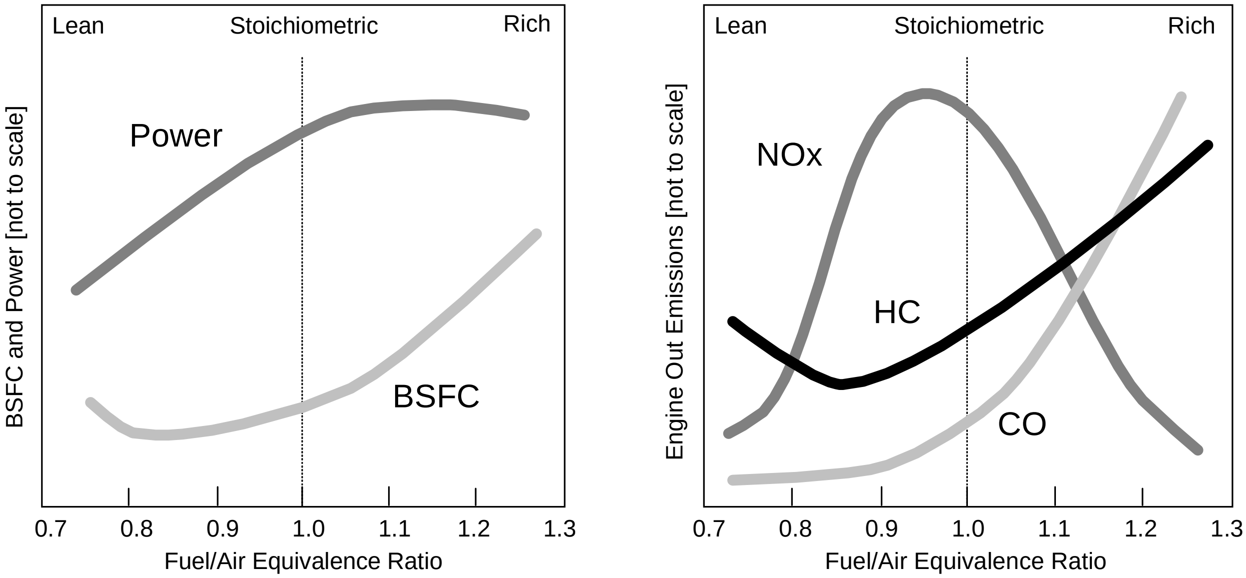
For most current SI engines, the two primary variables that manufacturers can control to reduce emissions are the air and fuel mixture (henceforth referred to as air-fuel ratio) and the spark timing. For highway motorcycles, these two variables are the most common methods for controlling exhaust emissions. However, for many nonroad engines and vehicles, the absence of emission standards have resulted in air-fuel ratio and spark timing calibrations optimized for engine performance and durability rather than for low emissions.

3.1.3.1 Air-fuel ratio

The calibration of the air-fuel mixture affects power, fuel consumption (referred to as Brake Specific Fuel Consumption (BSFC)), and emissions for SI engines. The effects of changing the air-fuel mixture are shown in Figure 3-1.[1] Traditionally, in most nonroad SI applications, manufacturers have calibrated their fuel systems for rich operation for two main advantages. First, by running the engine rich, manufacturers can reduce the risk of lean misfire due to imperfect mixing of the fuel and air and variations in the air-fuel mixture from cylinder to cylinder. Second, by making extra fuel available for combustion, it is possible to get more power from the engine. At the same time, since a rich mixture lacks sufficient oxygen for full combustion, it results in increased fuel consumption rates and higher HC and CO emissions. As can be seen from the figure, the best fuel consumption rates occur when the engine is running lean.

With the use of more advanced fuel systems, manufacturers would be able to improve control of the air-fuel mixture in the cylinder. This improved control allows for leaner operation without increasing the risk of lean misfire. This reduces HC and CO emissions and fuel consumption. Leaner air-fuel mixtures, however, increase NOx emissions due to the higher temperatures and increased supply of oxygen.

Figure 3-1: Effects of Air-fuel Ratio on Power, Fuel Consumption, and Emissions



3.1.3.2 Spark-timing:

For each engine speed and air-fuel mixture, there is an optimum spark-timing that results in peak torque. If the spark is advanced to an earlier point in the cycle, more combustion occurs during the compression stroke. If the spark is retarded to a later point in the cycle, peak cylinder pressure is decreased because too much combustion occurs later in the expansion stroke when it generates little torque on the crankshaft. Timing retard may be used as a strategy for reducing NOx emissions, because it suppresses peak cylinder temperatures that lead to high NOx levels. Timing retard also results in higher exhaust gas temperatures, because less mechanical work is extracted from the available energy. This may have the benefit of warming catalyst material to more quickly reach the temperatures needed to operate effectively during light-load operation.[2] Some automotive engine designs rely on timing retard at start-up to reduce cold-start emissions.

Advancing the spark-timing at higher speeds gives the fuel more time to burn. Retarding the spark timing at lower speeds and loads avoids misfire. With a mechanically controlled engine, a fly-weight or manifold vacuum system adjusts the timing. Mechanical controls, however, limit the manufacturer to a single timing curve when calibrating the engine. This means that the timing is not completely optimized for most modes of operation.

3.1.3.3 Fuel Metering

Fuel injection has proven to be an effective and durable strategy for controlling emissions and reducing fuel consumption from highway gasoline engines. Comparable upgrades are also available for gaseous fuels. This section describes a variety of technologies available to improve fuel metering.

Throttle-body gasoline injection: A throttle-body system uses the same intake manifold as a carbureted engine. However, the throttle body replaces the carburetor. By injecting the fuel into the intake air stream, the fuel is better atomized than if it were drawn through with a venturi. This results in better mixing and more efficient combustion. In addition, the fuel can be more precisely metered to achieve benefits for fuel economy, performance, and emission control.

Throttle-body designs have the drawback of potentially large cylinder-to-cylinder variations. Like a carburetor, TBI injects the fuel into the intake air at a single location upstream of all the cylinders. Because the air-fuel mixture travels different routes to each cylinder, the amount of fuel that reaches each cylinder will vary. Manufacturers account for this variation in their design and may make compromises such as injecting extra fuel to ensure that the cylinder with the leanest mixture will not misfire. These compromises affect emissions and fuel consumption.

Multi-port gasoline injection: As the name suggests, multi-port fuel injection means that a fuel injector is placed at each of the intake ports. A quantity of fuel is injected each time the intake valve opens for each cylinder. This allows manufacturers to more precisely control the amount of fuel injected for each combustion event. This control increases the manufacturer’s ability to optimize the air-fuel ratio for emissions, performance, and fuel consumption. Because of these benefits, multi-port injection is has been widely used in automotive applications for over 15 years.

Sequential injection has further improved these systems by more carefully timing the injection event with the intake valve opening. This improves fuel atomization and air-fuel mixing, which further improves performance and control of emissions.

A newer development to improve injector performance is air-assisted fuel injection. By injecting high pressure air along with the fuel spray, greater atomization of the fuel droplets can occur. Air-assisted fuel injection is especially helpful in improving engine performance and reducing emissions at low engine speeds. In addition, industry studies have shown that the short burst of additional fuel needed for responsive, smooth transient maneuvers can be reduced significantly with air-assisted fuel injection due to a decrease in wall wetting in the intake manifold. On a highway 3.8-liter engine with sequential fuel injection, the air assist was shown to reduce HC emissions by 27 percent during cold-start operating conditions. At wide-open-throttle with an air-fuel ratio of 17, the HC reduction was 43 percent when compared with a standard injector.[3]

3.1.4 Alternate Fuels

2. Gaseous-fuel engines

Engines operating on LPG or natural gas carry compressed fuel that is gaseous at atmospheric pressure. The technical challenges for gasoline related to an extended time to vaporize the fuel don’t apply to gaseous-fuel engines. Typically, a mixer introduces the fuel into the intake system. Manufacturers are pursuing new designs to inject the fuel directly into the intake manifold. This improves control of the air-fuel ratio and the combustion event, similar to the improvements in gasoline injection technology.

3.2 Exhaust Emissions and Control Technologies

3.2.1 Current Two-Stroke Engines

As discussed above, two-stroke engines are typically found in applications where light weight, low cost, simplistic design, easy starting, and high power-to-weight ratio are desirable attributes. Of the engines and vehicles and covered by this proposal, the engines found in recreational vehicles tend to have a high percentage of two-stroke engines. For example, all snowmobiles use two-stroke engines, while 40 percent of off-highway motorcycles are equipped with two-strokes. Approximately 15 percent of all ATVs use two-stroke engines.

California ARB has had exhaust emission standards for off-highway motorcycles and ATVs since 1996. However, the regulations allow the sales and use of non-certified vehicles within the state. Thus, recreational vehicles equipped with two-stroke engines have essentially been unregulated. As a result, two-stroke engines used in recreational vehicles are typically designed for optimized performance and durability rather than low emissions. Current two-stroke engines emit extremely high levels of HC and CO emissions. The scavenging of unburned fuel into the exhaust contributes to the bulk of the HC emissions. Up to 30 percent[b] of the air and fuel mixture (along with lubricating oil) can pass unburned from the combustion chamber to the exhaust, resulting not only in high levels of HC, but also in high levels of particulate matter (PM). As discussed above, two-stroke engines lubricate the engine by mixing specially-formulated two-stroke oil with gasoline. As the gasoline/oil mixture passes through the carburetor, it is atomized into fine droplets and mixed with air. The gasoline quickly vaporizes, while the less volatile oil forms a fine mist of fine droplets. Some of these droplets contact the crankshaft, piston pin, and cylinder walls, providing lubrication. Most of the oil droplets, however, pass out of the crankcase and into the cylinder with the rest of the incoming charge. Much of this oil mist will be trapped in the cylinder and burned along with the gasoline vapor. Since lubricating oil is less combustible than gasoline, some of the oil will survive the combustion process in the cylinder and be passed into the exhaust. In the hot exhaust, the oil may vaporize, however, as the exhaust cools and through mixing with air after it is emitted, the oil vapor recondenses into very fine droplets or particles and enter the atmosphere as PM.

Another major source of unburned HC emissions from two-stroke engines is due to misfire or partial combustion at light loads. Under light load conditions such as idle, the flow of fresh air and fuel into the cylinder is reduced, and substantial amounts of exhaust gas are retained in the cylinder. This high fraction of residual gas leads to incomplete combustion or misfire,

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[b] Hare et al, 1974; Batoni, 1978; Nuti and Martorano, 1985

which is the source of the "popping" sound produced by two-stroke engines at idle and light loads. These unstable combustion events are major sources of unburned HC at idle and light load conditions.[c]

High CO levels from two-stroke engines are a result of operating the engine at rich air and fuel mixture levels to promote engine cooling and enhance performance. Two-stroke engines typically have very low levels of NOx emissions due to relatively cool combustion temperatures. Two-stroke engines have cooler combustion temperatures as a result of two phenomenon: rich air and fuel mixture operation and internal exhaust gas recirculation. Two-stroke engines tend to operate with a rich air and fuel mixture to increase power and to help cool the engine. Because many two-stroke engines are air-cooled, the extra cooling provided by operating rich is a desirable engine control strategy. Combustion with a rich air and fuel mixture results in some incomplete combustion which means less efficient combustion and a lower combustion temperature. High combustion temperature is the main variable in producing NOx emissions. Two-stroke engines also tend to have a high levels of naturally occurring exhaust gas recirculation due to the scavenging process where some of the burned gases are drawn back into the cylinder rather than being emitted out into the exhaust. The addition of burned exhaust gas into the fresh charge of air and fuel mixture in the combustion chamber also results in less complete or efficient combustion, which lowers combustion temperatures and reduces NOx emissions.

HC emissions for recreational vehicle two-stroke engines are approximately 25 times higher than for recreational vehicle four-stroke emissions. CO levels are roughly the same for both types of engines, while NOx levels are 1.5 times lower than four-stroke engine levels. Table 3.2-1 shows two-stroke emission results for several off-highway motorcycles and ATVs tested by and for EPA in grams per kilometer (g/km). Table 3.2-2 shows two-stroke emission results from snowmobiles in grams per horsepower-hour (g/hp-hr).

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[c] Tsuchiya et al, 1983; Abraham and Prakash, 1992; Aoyama et al, 1977

Table 3.2-1
Baseline Two-Stroke Emissions From Off-Highway Motorcycles & ATVs (g/km)

MC or ATV	Manufacturer	Model	Model Year	Eng. Displ.	HC	CO	NOx
ATV	Suzuki	LT80	1998	80 cc	7.66	24.23	0.047
ATV	Polaris	Scrambler 80	2001	90 cc	38.12	25.08	0.057
MC	KTM	125SX	2001	125 cc	33.71	31.01	0.008
MC	KTM	125SX	2001	125 cc	61.41	32.43	0.011
MC	KTM	200EXC	2001	200 cc	53.09	39.89	0.025
MC	Honda	n/a	1993	200 cc	8.00	16.00	0.010
MC	Honda	n/a	1993	200 cc	26.00	28.00	1.010
MC	Honda	n/a	1995	249 cc	12.00	21.00	0.010
MC	Honda	CR250R	1997	249 cc	17.47	36.62	0.004
MC	Honda	n/a	1998	249 cc	23.00	36.00	0.010
MC	KTM	250SX	2001	249 cc	62.89	49.29	0.011
MC	KTM	250EXC	2001	249 cc	59.13	40.54	0.016
MC	KTM	300EXC	2001	298 cc	47.39	45.29	0.0124
Average					34.61	32.72	0.095

Table 3.2-2
Baseline Two-Stroke Emissions From Snowmobiles (g/hp-hr)

Source	Eng. Displ.	HC	CO	NOx	PM
Carroll 1999 (SwRI) YNP	480 cc	115	375	0.69	0.7
White et al. 1997	488 cc	150	420	0.42	1.1
White et al. 1997	440 cc	160	370	0.50	3.4
Hare & Springer 1974	436 cc	89	142	1.40	6.1
Hare & Springer 1974	335 cc	120	235	1.80	2.5
Hare & Springer 1974	247 cc	200	63	3.40	2.6
Wright & White 1998	440 cc	130	380	0.42	n/a
Wright & White 1998	503 cc	105	400	0.73	n/a
ISMA #1	600 cc	110	218	0.86	n/a
ISMA #2	440 cc	95	312	1.62	n/a
ISMA #3	600 cc	106	196	1.30	n/a
ISMA #4	900 cc	95	215	0.84	n/a
ISMA #5	698 cc	92	298	0.34	n/a
ISMA #6	597 cc	100	328	0.30	n/a
ISMA #7	695 cc	88	345	0.24	n/a
ISMA #8	485 cc	148	385	0.56	n/a
ISMA #9	340 cc	104	297	0.84	n/a
ISMA #10	440 cc	95	294	0.56	n/a
ISMA #11	600 cc	94	262	0.81	n/a
ISMA #12	700 cc	102	355	0.69	n/a
ISMA #13	593 cc	67	288	0.57	n/a
ISMA #14	494 cc	105	400	0.43	n/a

ISMA #15	699 cc	92	276	0.50	n/a
Average		111	298	0.86	2.7

3.2.2 Clean Two-Stroke Technologies

Technologies available for reducing two-stroke emissions can be grouped into several categories: calibration improvements; combustion chamber modifications; improved scavenging characteristics; advanced fuel metering systems; and exhaust aftertreatment technologies.

3.2.2.1 Calibration Improvements

The vast majority of two-stroke engines used in recreational vehicles use a carburetor as the means of metering the air and fuel that is supplied to the engine. The carburetion system supplies a controlled mixture of air and fuel to the engine, taking into consideration engine temperature and load and speed, while trying to optimize engine performance and fuel economy. A carburetor is a mechanical fuel atomizing device. It uses the venturi or Bernoulli’s principle, which is based on pressure differences, to draw fuel into the air stream from a small reservoir (known as the “bowl”). A venturi is a restriction formed in the carburetor throat. As air passes through the venturi, it causes an increase in air velocity and creates a vacuum or low pressure. The fuel in the bowl is under atmospheric pressure. The higher pressure fuel will flow to the lower pressure (vacuum) created in the airstream by the venturi. The fuel is atomized (broken into small droplets) as it enters the airstream.

As discussed above in section 3.1.3.1, the calibration of the air-fuel mixture affects power, fuel consumption, and emissions. Traditionally, in most recreational vehicles using two-stroke engines, manufacturers have calibrated their fuel systems for rich operation for two main advantages. First, by running the engine rich, manufacturers can reduce the risk of lean misfire due to imperfect mixing of the fuel and air and variations in the air-fuel mixture from cylinder to cylinder. Second, by making extra fuel available for combustion, it is possible to get more power from the engine. At the same time, since a rich mixture lacks sufficient oxygen for full combustion, it results in increased fuel consumption rates and higher HC and CO emissions.

One means of reducing HC and CO emissions from two-stroke engines is to calibrate the air-fuel ratio for lower emissions. This means leaning the air-fuel mixture, so that there is more oxygen available to oxidize HC and CO. This strategy appears simplistic, but the manufacturer has to not only optimize the air-fuel ratio for emissions, but also allow acceptable performance and engine cooling. This means that the air-fuel ratio must not be leaned to the point of causing lean misfire or substantially reduced power. However, since it is common for manufacturers to set-up their carburetors to operate overly rich, there is opportunity for better optimization of carburetor air-fuel settings to account for performance, engine cooling and lower emissions.

3.2.2.2 Combustion Chamber Modifications

For two-stroke engines, if modifications are made to air-fuel calibrations that result in leaner operation, one of the main concerns is that the combustion temperature will increase and result in engine damage. It is fairly common for two-stroke engines to seize the piston in the cylinder if they operate at too high of combustion temperatures. Piston seizure results when combustion chamber temperatures become excessive and the piston heats-up and expands until it becomes lodged or seizes in the cylinder. Depending on the level of enleanment used to control HC and CO emissions, it may be necessary to also incorporate modifications to the combustion chamber. Combustion chamber and piston configuration can be improved to induce more swirl and squish or turbulent motions during the compression stroke, as well as control the flow direction of the air and fuel mixture as it enters the combustion chamber to minimize short-circuiting (unburned fuel leaving thru the exhaust port). Increasing turbulence in the combustion chamber improves thermal efficiency by increasing the rate of burning in the chamber, which results in lower combustion temperatures. Improved combustion chamber and piston configurations can also minimize the formation of pocket or dead zones in the cylinder volume where unburned gases can become trapped. Many engine designs induce turbulence into the combustion chamber by increasing the velocity of the incoming air-fuel mixture and having it enter the chamber in a swirling motion (known as “swirl”).

3.2.2.3 Improved Scavenging Characteristics

As discussed above, the exhaust and intake events for two-stroke engines overlap extensively, resulting in considerable amounts of unburned gasoline and lubricating oil passing through the engine and out the exhaust into the atmosphere. As the piston moves downward uncovering the exhaust port, a fresh charge of air and fuel enters the combustion chamber under pressure from the transfer port and pushes the burned gases from the previous combustion event out into the exhaust. Since the burned gases are pushed out of the chamber by the intake mixture, some of the fresh air and fuel mixture being introduced into the chamber are also lost through the exhaust port. The ideal situation would be to retain all of the fresh charge in the cylinder while exhausting all of the burned gases from the last cycle. This is difficult in most current two-stroke engine designs, since the cylinder ports and piston timing are generally designed for high scavenging efficiency, in order to achieve maximum power and a smoother idle, which results in higher scavenging losses and emissions. It is possible to reconfigure the cylinder ports to fine tune the scavenging characteristics for lower emissions, but this involves significant trade-offs with engine performance. There are, however, several techniques that can be employed to improve scavenging losses.

Exhaust charge control technology modifies the exhaust flow by introducing one-way control valves in the exhaust, or by making use of the exhaust pressure pulse wave. In order to get increased power out of a two-stroke engine, it is imperative that the engine combust as much air and fuel as possible. Scavenging losses from two-stroke engines (called “short-circuiting”) allow a large percentage of the air and fuel to leave the combustion chamber before they can be combusted. Two-stroke engines used in recreational vehicles all tend to use an exhaust system equipped with an “expansion chamber.” An expansion chamber is typically made of two cones, one diverging and the other converging, with a short straight section of pipe between the two cones. As the exhaust pulse leaves the exhaust port and enters the exhaust pipe, it travels through the diverging cone and expands. The expanded pulse travels through the straight section of pipe and then meets the converging cone. Upon hitting the converging cone, the exhaust pulse wave becomes a sonic wave and travels back into the combustion chamber, pushing some of the burnt exhaust gases and fresh charge of air and fuel that escaped originally.

As part of the Society of Automotive Engineers (SAE) Clean Snowmobile Challenge 2001, a college competition which encourages the development clean snowmobile technologies, Colorado State University (CSU) developed a two-stroke snowmobile engine using a supercharged “reverse uniflow” design. The reverse uniflow design incorporates an exhaust port and a crankcase pressure activated intake valve. After the ignition of the charge occurs at TDC, the high combustion pressures and expanding gases force the piston downward. As the bottom of the piston covers the exhaust port, the pressure in the crankcase increases due to a decreasing volume. The increasing pressure is transmitted to the check-valve diaphragm. As the piston fully uncovers the exhaust port, the exhaust gases are expelled out of the port, and the cylinder pressure goes to approximately atmospheric pressure. Due to the larger pressure in the crankcase (and thus on the diaphragm) as compared to the cylinder, the check-valve opens and the supercharged intake begins to runs into the cylinder. As the intake air is entering the cylinder, expelling the exhaust gases out of the bottom ports, a fuel injector or carburetor provides fuel into the intake air stream. After the piston reaches BDC, and begins to move back upwards, the crankcase pressure decreases. Once the piston moves past the exhaust port, the crankcase pressure returns to approximately atmospheric pressure, and the check-valve completely closes. The piston continues up, compressing the air-fuel mixture until the point that ignition can once again occur, completing the cycle.

3.2.2.4 Advanced Fuel Metering Systems

The most promising technology for reducing emissions from two-stroke engines are advanced fuel metering systems, otherwise known as fuel injection systems. For two-stroke engines, there are two types of fuel injection systems available. The first system is electronic fuel injection (EFI), similar to what exists on automobiles. This system consists of an electronic fuel injector, an electronic fuel pump, pressurized fuel lines and an electronic control unit (ECU) or computer. EFI also requires the use of various sensors to provide information to the ECU so that precise fuel control can be delivered. These sensors typically monitor temperature, throttle position and atmospheric pressure. The use of EFI can provide better atomization of the fuel and more precise fuel delivery than found with carburetors, which can reduce emissions. EFI systems also have the advantage of providing improved power and fuel economy, when compared to a carburetor. However, EFI does not address the high emission resulting from short-circuiting or scavenging losses.

The second type of fuel injection system, known as Direct Injection (DI), does address scavenging losses. DI systems are very similar to EFI systems, since both are electronically controlled systems. The main difference is that DI systems more fully atomize (i.e., break-down into very small droplets) the fuel, which can greatly improve combustion efficiency resulting in improved power and reduced emissions. DI engines pump only air into the cylinder, rather than air and fuel. Finely atomized fuel is then injected into the combustion chamber once all of the ports are closed. This eliminates the short-circuiting of fresh air and fuel into the exhaust port. The biggest problem with DI is that there is very little time for air to be pumped into the cylinder and fuel then injected after all of the ports have closed. This is overcome by the use of numerous engines sensors, a high-speed electronic control module, and software which uses sophisticated control algorithms.

DI systems have been in use for the past several years in some small motorcycle, scooter and marine applications, primarily for personal watercraft (PWC) and outboard engines. There are numerous variations of DI systems, but two primary approaches that are commercially available today: high pressure injection and air-assisted injection. There are a number of companies who have developed high pressure DI systems, but the most successful systems currently belong to FICHT and Yamaha. The FICHT system uses a special fuel injector that is able to inject fuel at very high pressure (e.g., over 250 psi). The fuel injector itself is essentially a piston that is operated by an electromagnet. Fuel enters the injector at low pressure from an electric fuel pump and is forced out of the injector nozzle at high pressure when the piston hammers down on the fuel. The Yamaha system uses a high pressure fuel pump to generate the high fuel pressure. The other DI approach that is most common in various engine applications is the air-assisted injection system which has been developed by Orbital. The Orbital system uses pressurized air to help inject the fuel into the combustion chamber. The system uses a small single cylinder reciprocating air compressor to assist in the injection of the fuel. All three systems are currently used in some marine applications by companies such as Kawasaki, Polaris, Sea-Doo, and Yamaha. The Orbital system is also currently used on some small motorcycle and scooter applications by Aprilla. Certification data from various engines certified with DI have shown HC and CO emission reductions of 60 to 75 percent from baseline emission levels.

There is at least one other injection technology that has had success in small two-stroke SI engines used in lawn and garden applications, such as trimmers and chainsaws. Compression Wave technology, referred to as Low Emission (LE) technology, developed by John Deere, uses a compressed air assisted fuel injection system, similar to the Orbital system, to reduce the unburned fuel charge during the scavenging process of the exhaust portion of the two-stroke cycle. The system has shown the ability to reduce HC and CO emissions by up to 75 percent from baseline levels. Although this technology has not yet been applied to any recreational vehicle engines, it appears to have significant potential, especially because of its simplistic design and low cost. For a detailed description of the LE technology, refer to the Nonroad Small SI regulatory support document.

3.2.2.5 Exhaust Aftertreatment Technologies

There are two exhaust aftertreatment technologies that can provide additional emission reductions from two-stroke engines: thermal oxidation (e.g., secondary air) and oxidation catalyst. Thermal oxidation reduces HC and CO by promoting further oxidation of these species in the exhaust. The oxidation usually takes place in the exhaust port or pipe, and may require the injection of additional air to supply the needed oxygen. If the exhaust temperature can be maintained at a high enough temperature (e.g., 600 to 700°C) for a long enough period, substantial reductions in HC and CO can occur. Air injection at low rates into the exhaust system has been shown to reduce emissions by as much as 77 percent for HC and 64 percent for CO.[d] However, this was effective only under high-power operating conditions, and the high exhaust temperatures required to achieve this oxidation substantially increased the skin temperature of the exhaust pipe, which can be a concern for off-highway motorcycle applications where the operators legs could come in contact with the pipe.

Like thermal oxidation, the oxidation catalyst is used to promote further oxidation of HC and CO emissions in the exhaust stream, and it also requires sufficient oxygen for the reaction to take place. Some of the requirements for a catalytic converter to be used in two-stroke engines include high HC conversion efficiency, resistance to thermal damage, resistance to poisoning from sulfur and phosphorus compounds in lubricating oil, and low light-off temperature. Additional requirements for catalysts to be used in recreational vehicle two-stroke engines include extreme vibration resistance, compactness, and light weight.

Application of catalytic converters to two-stroke engines presents a problem, because of the high concentrations of HC and CO in their exhaust. If combined with sufficient air, these high pollutant concentrations result in catalyst temperatures that can easily exceed the temperature limits of the catalyst. Therefore, the application of oxidation catalysts to two-stroke engines may first require engine modifications to reduce HC and CO and may also require secondary air be supplied to the exhaust in front of the catalyst.

Researchers of Graz University of Technology and the Industrial Technology Research Institute (ITRI) in Taiwan have published data on the application of catalytic converters in small two-stroke moped and motorcycle engines using catalytic converters. The Graz researchers focused on reducing emissions using catalysts, as well as by improving the thermodynamic characteristics of the engines, such as gas exchange and fuel handling systems, cylinder and piston geometry and configurations, and exhaust cooling systems. For HC and CO emissions, they found that an oxidation catalyst could reduce emissions by 88 to 96 percent. Researchers at ITRI successfully retrofitted a catalytic converter to a 125 cc two-stroke motorcycle engine, and demonstrated both effective emissions control and durability.[e] The Manufacturers of Emission Controls Association (MECA)in their publication titled “Emission Control of Two-and Three-

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[d] White, J.J., Carroll,J.N., Hare, C.T., and Lourenco, J.G. (1991), “Emission Control Strategies for Small Utility Engines,” SAE Paper No. 911807, Society of Automotive Engineers, Warrendale, PA, 1991.

[e] Hsien, P.H., Hwang, L.K., and Wang, H.W> (1992), “Emission Reduction by Retrofitting a 125 cc Two-Stroke Motorcycle with Catalytic Converter,” SAE Paper No. 922175, Society of Automotive Engineers, Warrendale, PA, 1992.

wheel Vehicles," published May 7, 1999, state that catalyst technology has clearly demonstrated the ability to achieve significant emissions reductions from two-stroke engines. MECA points to the success of two-stroke moped and motorcycle engines equipped with catalysts that have been operating for several years in Taiwan, Thailand, Austria, and Switzerland.

3.2.3 Current Four-Stroke Engines

Four-stroke engines are the most common engine today. Large nonroad SI engines are exclusively four-stroke. Recreational vehicles are also predominantly four-stroke. Four-stroke engines have considerably lower HC emissions than two-stroke engines, due to the fact that four-stroke engines do not experience short circuiting of raw fuel. CO emissions from four-stroke engines is very similar to two-stroke engines, since CO emissions are the result of inefficient combustion of the air-fuel mixture within the cylinder, typically resulting from rich operation. Since the combustion of fuel within the cylinder of a four-stroke engine is more efficient than that of a two-stroke engine, combustion temperatures are higher, which results in higher NOx emission levels.

The four-stroke engines covered under this proposal are typically either automotive engines (large nonroad SI) or motorcycle-like engines (including ATVs). Large nonroad SI engines, off-highway motorcycles, ATVs, and snowmobiles are unregulated federally. Therefore, while they have relatively low HC emissions compared to two-stroke engines, they can still have high levels of CO (due to rich air-fuel calibration) and NOx. Table 3.2-3 shows baseline emission levels for four-stroke equipped off-highway motorcycles and ATVs.

Table 3.2-3
Baseline Four-Stroke Emissions From Off-Highway Motorcycles & ATVs (g/km)

MC or ATV	Manufacturer	Model	Model Year	Eng. Displ.	HC	CO	NOx
MC	Yamaha	WR250F	20001	249 cc	1.46	26.74	0.110
MC	Yamaha	WR400	1999	399 cc	1.07	20.95	0.112
MC	KTM	400EXC	2001	398 cc	1.17	28.61	0.050
MC	Husaberg	FE501	2001	499 cc	1.30	25.81	0.163
ATV	Kawasaki	Bayou	1989	280 cc	1.17	14.09	0.640
ATV	Honda	300EX	1997	298 cc	1.14	34.60	0.155
ATV	Polaris	Trail Boss	1998	325 cc	1.56	43.41	0.195
ATV	Yamaha	Banshee	1998	349 cc	0.98	19.44	0.190
ATV	Polaris	Sportsman	2001	499 cc	2.68	56.50	0.295
Average					1.39	30.01	0.212

3.2.4 Clean Four-Stroke Technologies

The emission control technologies for four-stroke engines are very similar to those used for two-stroke engines. HC and CO emissions from four-stroke engines are primarily the result of poor in-cylinder combustion. Higher levels of NOx emissions are the result of leaner air-fuel ratios and the resulting higher combustion temperatures. Combustion chamber modifications can help reduce HC emission levels, while using improved air-fuel ratio and spark timing calibrations, as discussed in sections 3.1.3.1 and 3.1.3.2, can further reduce HC emissions and lower CO emissions. The conversion from carburetor to EFI will also help reduce HC and CO emissions. The use of exhaust gas recirculation on large SI engines can reduce NOx emissions, but is not necessarily needed for recreational vehicles, due to their relatively low NOx emission levels. The addition of secondary air into the exhaust can significantly reduce HC and CO emissions. Finally, the use catalytic converters can further reduce all three emissions.

3.2.4.1 Combustion chamber design

Unburned fuel can be trapped momentarily in crevice volumes (especially the space between the piston and cylinder wall) before being released into the exhaust. Reducing crevice volumes decreases this amount of unburned fuel, which reduces HC emissions. One way to reduce crevice volumes is to design pistons with piston rings closer to the top of the piston. HC may be reduced by 3 to 10 percent by reducing crevice volumes, with negligible effects on NOx emissions.[4]

HC emissions also come from lubricating oil that leaks into the combustion chamber. The heavier hydrocarbons in the oil generally don't burn completely. Oil in the combustion chamber can also trap gaseous HC from the fuel and prevent it from burning. For engines using catalytic control, some components in lubricating oil can poison the catalyst and reduce its effectiveness, which would further increase emissions over time. To reduce oil consumption, manufacturers can tighten tolerances and improve surface finishes for cylinders and pistons, improve piston ring design and material, and improve exhaust valve stem seals to prevent excessive leakage of lubricating oil into the combustion chamber.

3.2.4.2 Exhaust gas recirculation

Exhaust gas recirculation (EGR) has been in use in cars and trucks for many years. The recirculated gas acts as a diluent in the air-fuel mixture, slowing reaction rates and absorbing heat to reduce combustion temperatures. These lower temperatures can reduce the engine-out NOx formation rate by as much as 50 percent.[5] HC is increased slightly due to lower temperatures for HC burn-up during the late expansion and exhaust strokes.

Depending on the burn rate of the engine and the amount of recirculated gases, EGR can improve fuel consumption. Although EGR slows the burn rate, it can offset this effect with some benefits for engine efficiency. EGR reduces pumping work since the addition of recirculated gas increases intake pressure. Because the burned gas temperature is decreased, there is less heat loss to the exhaust and cylinder walls. In effect, EGR allows more of the chemical energy in the fuel to be converted to useable work.[6]

For catalyst systems with high conversion efficiencies, the benefit of using EGR becomes proportionally smaller. Also, including EGR as a design variable for optimizing the engine adds significantly to the development time needed to fully calibrate engine models.

3.2.4.3 Secondary air

Secondary injection of air into exhaust ports or pipes after cold start (e.g., the first 40-60 seconds) when the engine is operating rich, coupled with spark retard, can promote combustion of unburned HC and CO in the exhaust manifold and increase the warm-up rate of the catalyst. By means of an electrical or mechanical pump, secondary air is injected into the exhaust system, preferably in close proximity of the exhaust valve. Together with the oxygen of the secondary air and the hot exhaust components of HC and CO, oxidation ahead of the catalyst can bring about an efficient increase in the exhaust temperature which helps the catalyst to heat up quicker. The exothermic reaction that occurs is dependent on several parameters (secondary air mass, location of secondary air injection, engine A/F ratio, engine air mass, ignition timing, manifold and headpipe construction, etc.), and ensuring reproducibility demands detailed individual application for each vehicle or engine design.

Secondary air injection was first used as an emission control technique in itself without a catalyst, and still is used for this purpose in many highway motorcycles and some off-highway motorcycles to meet federal and California emission standards. For motorcycles, air is usually provided or injected by a system of check valves which uses the normal pressure pulsations in the exhaust manifold to draw in air from outside, rather than by a pump.

3.2.4.4 Catalytic Aftertreatment

Over the last several years, there have been tremendous advances in exhaust aftertreatment systems. Catalyst manufacturers are progressively moving to palladium (Pd) as the main precious metal in automotive catalyst applications. Improvements to catalyst thermal stability and washcoat technologies, the design of higher cell densities, and the use of two-layer washcoat applications are just some of the advances made in catalyst technology. There are two types of catalytic converters commonly used: oxidation and three-way. Oxidation catalysts use platinum and/or palladium to increase the rate of reaction between oxygen in the exhaust and unburned HC and CO. Ordinarily, this reaction would proceed very slowly at temperatures typical of engine exhaust. The effectiveness of the catalyst depends on its temperature, on the air-fuel ratio of the mixture, and on the mix of HC present. Highly reactive species such as formaldehyde and olefins are oxidized more effectively than less-reactive species. Short-chain paraffins such as methane, ethane, and propane are among the least reactive HC species, and are difficult to oxidize.

Three-way catalysts use a combination of platinum and/or pallabium and rhodium. In addition to promoting oxidation of HC and CO, these metals also promote the reduction of NO to nitrogen and oxygen. In order for the NO reduction to occur efficiently, an overall rich or stoichiometric air-fuel ratio is requires. The NOx efficiency drops rapidly as the ai-fuel ratio becomes leaner than stoichiometric. If the air-fuel ratio can be maintained precisely at or just rich of stoichiometic, a three-way catalyst can simultaneously oxidize HC and CO and reduce NOx. The window of air-fuel ratios within which this is possible is very narrow and there is a trade-off between NOx and HC/CO control even within this window.

There are several issues involved in designing catalytic control systems for the four-stroke engines covered by this proposal. The primary issues are the cost of the system, packaging constraints, and the durability of the catalyst. This section addresses these issues.

3.2.4.4.1. System cost

Sales volumes of industrial and recreational equipment are small compared to automotive sales. Manufacturers therefore have a limited ability to recoup large R&D expenditures for Large SI and recreational engines. For this reason, we believe it is not appropriate to consider highly refined catalyst systems that are tailored specifically to nonroad applications. For large SI engines, we have based the feasibility of the emission standards on the kind of catalysts that manufacturers have already begun to offer for these engines. These systems are currently produced in very low volumes, but the technology has been successfully adapted to Large SI engines. The cost of these systems will decrease substantially when catalysts become commonplace. This approach is also true for phase 2 ATV standards that may require catalysts for some models. Chapter 4 describes the estimated costs for a nonroad catalyst system.

3.2.4.4.2 Packaging constraints

Large SI engines power a wide range of nonroad equipment. Some of these have no significant space constraints for adding a catalyst. In contrast, equipment designs such as forklifts have been fine-tuned over many years with a very compact fit. The same is even more true for recreational vehicles, such as ATVs and motorcycles.

Automotive catalyst designs typically have one or two catalyst units upstream of the muffler. This is a viable option for most nonroad equipment. However, if there is no available space to add a separate catalyst, it is possible to build a full catalyst/muffler combination that fits in the same space as the conventional muffler. With this packaging option, even compact applications should have little or no trouble integrating a catalyst into the equipment design. The hundreds of catalysts currently operating on forklifts and highway motorcycles clearly demonstrate this.

3.2.5 Advanced Emission Controls

On February 10, 2000, EPA published new "Tier 2" emissions standards for all passenger vehicles, including sport utility vehicles (SUVs), minivans, vans and pick-up trucks. The new standards will ensure that exhaust VOC emissions be reduced to less than 0.1 g/mi on average over the fleet, and that evaporative emissions be reduced by at least 50 percent. Onboard refueling vapor recovery requirements were also extended to medium-duty passenger vehicles. By 2020, these standards will reduce VOC emissions from light-duty vehicles by more than 25 percent of the projected baseline inventory. (See Chapter 4 for a more detailed discussion of the impact of the Tier 2 FRM on VOC inventories.) To achieve these reductions, manufacturers will need to incorporate advanced emission controls, including: larger and improved close-coupled catalysts, optimized spark timing and fuel control, improved exhaust systems.

To reduce emissions gasoline-fueled vehicle manufacturers have designed their engines to achieve virtually complete combustion and have installed catalytic converters in the exhaust system. In order for these controls to work well for gasoline-fueled vehicles, it is necessary to maintain the mixture of air and fuel at a nearly stoichiometric ratio (that is, just enough air to completely burn the fuel). Poor air-fuel mixture can result in significantly higher emissions of incompletely combusted fuel. Current generation highway vehicles are able to maintain stoichiometry by using closed-loop electronic feedback control of the fuel systems. As part of these systems, technologies have been developed to closely meter the amount of fuel entering the combustion chamber to promote complete combustion. Sequential multi-point fuel injection delivers a more precise amount of fuel to each cylinder independently and at the appropriate time increasing engine efficiency and fuel economy. Electronic throttle control offers a faster response to engine operational changes than mechanical throttle control can achieve, but it is currently considered expensive and only used on some higher-price vehicles. The greatest gains in fuel control can be made through engine calibrations -- the algorithms contained in the powertrain control module (PCM) software that control the operation of various engine and emission control components/systems. As microprocessor speed becomes faster, it is possible to perform quicker calculations and to increase response times for controlling engine parameters such as fuel rate and spark timing. Other advances in engine design have also been used to reduce engine-out emissions, including: the reduction of crevice volumes in the combustion chamber to prevent trapping of unburned fuel; "fast burn" combustion chamber designs that promote swirl and flame propagation; and multiple valves with variable-valve timing to reduce pumping losses and improve efficiency. These technologies are discussed in more detail in the RIA for the Tier 2 FRM.[f]

As noted above, manufacturers are also using aftertreatment control devices to control emissions. New three-way catalysts for highway vehicles are so effective that once a TWC reaches its operating temperature, emissions are virtually undetectable.[g] Manufacturers are now working to improve the durability of the TWC and to reduce light-off time (that is, the amount of time necessary after starting the engine before the catalyst reaches its operating temperature and is effectively controlling VOCs and other pollutants). EPA expects that manufacturers will be able to design their catalyst systems so that they light off within less than thirty seconds of engine starting. Other potential exhaust aftertreatment systems that could further reduce cold-start emissions are thermally insulated catalysts, electrically heated catalysts, and HC adsorbers (or traps). Each of these technologies, which are discussed below, offer the potential for VOC reductions in the future. There are technological, implementation, and cost issues that still need to be addressed, and at this time, it appears that these technologies would not be a cost-effective means of reducing nonroad emissions on a nationwide basis.

Thermally insulated catalysts maintain sufficiently high catalyst temperatures by surrounding the catalyst with an insulating vacuum. Prototypes of this technology have demonstrated the ability to store heat for more than 12 hours.[h] Since ordinary catalysts typically cool down below their light-off temperature in less than one hour, this technology could reduce in-use emissions for vehicles that have multiple cold-starts in a single day. However, this technology would have less impact on emissions from vehicles that have only one or two cold-starts per day.

Electrically-heated catalysts reduce cold-start emissions by applying an electric current to the catalyst before the engine is started to get the catalyst up to its operating temperature more

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[f] http://www.epa.gov/otaq/tr2home.htm#Documents. EPA 420-R-99-023

[g] McDonald, J., L. Jones, Demonstration of Tier 2 Emission Levels for Heavy Light-Duty Trucks, SAE 2000-01-1957.

[h] Burch, S.D., and J.P. Biel, SULEV and "Off-Cycle" Emissions Benefits of a Vacuum-Insulated Catalytic Convert, SAE 1999-01-0461.

quickly.[i] These systems require a modified catalyst, as well as an upgraded battery and charging system. These can greatly reduce cold-start emissions, but could require the driver to wait until the catalyst is heated before the engine would start to achieve optimum performance.

Hydrocarbon adsorbers are designed to trap VOCs while the catalyst is cold and unable to sufficiently convert them. They accomplish this by utilizing an adsorbing material which holds onto the VOC molecules. Once the catalyst is warmed up, the trapped VOCs are automatically released from the adsorption material and are converted by the fully functioning downstream three-way catalyst. There are three principal methods for incorporating an adsorber into the exhaust system. The first is to coat the adsorber directly on the catalyst substrate. The advantage is that there are no changes to the exhaust system required, but the desorption process cannot be easily controlled and usually occurs before the catalyst has reached light-off temperature. The second method locates the adsorber in another exhaust pipe parallel with the main exhaust pipe, but in front of the catalyst and includes a series of valves that route the exhaust through the adsorber in the first few seconds after cold start, switching exhaust flow through the catalyst thereafter. Under this system, mechanisms to purge the adsorber are also required. The third method places the trap at the end of the exhaust system, in another exhaust pipe parallel to the muffler, because of the low thermal tolerance of adsorber material. Again a purging mechanism is required to purge the adsorbed VOCs back into the catalyst, but adsorber overheating is avoided. One manufacturer who incorporates a zeolite hydrocarbon adsorber in its California SULEV vehicle found that an electrically heated catalyst was necessary after the adsorber because the zeolite acts as a heat sink and nearly negates the cold start advantage of the adsorber. This approach has been demonstrated to effectively reduce cold start emissions.

3.2.5.1 Multiple valves and variable valve timing

Four-stroke engines generally have two valves for each cylinder, one for intake of the air-fuel mixture and the other for exhaust of the combusted mixture. The duration and lift (distance the valve head is pushed away from its seat) of valve openings is constant regardless of engine speed. As engine speed increases, the aerodynamic resistance to pumping air in and out of the cylinder for intake and exhaust also increases. Automotive engines have started to use two intake and two exhaust valves to reduce pumping losses and improve their volumetric efficiency and useful power output. Some highway motorcycles have used multiple valves for years, especially the high-performance sport motorcycles.

In addition to gains in breathing, 4-valve designs allow the spark plug to be positioned closer to the center of the combustion chamber, which decreases the distance the flame must travel inside the chamber. This decreases the likelihood of flame-out conditions in the areas of the combustion chamber farthest from the spark plug. In addition, the two streams of incoming gas can be used to achieve greater mixing of air and fuel, further increasing combustion efficiency and lowering engine-out emissions.

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[i] Laing, P.M., Development of an Alternator-Powered Electrically-Heated Catalyst System, SAE 941042.

Control of valve timing and lift take full advantage of the 4-valve configuration for even greater improvement in combustion efficiency. Engines normally use fixed-valve timing and lift across all engine speeds. If the valve timing is optimized for low-speed torque, it may offer compromised performance under higher-speed operation. At light engine loads, for example, it is desirable to close the intake valve early to reduce pumping losses. Variable-valve timing can enhance both low-speed and high-speed performance with compromise. Variable-valve timing can allow for increased swirl and intake charge velocity, especially during low-load operating conditions where this is most problematic. By providing a strong swirl formation in the combustion chamber, the air-fuel mixture can mix sufficiently, resulting in a faster, more complete combustion, even under lean air-fuel conditions, thereby reducing emissions.

Variable-valve technology by itself may have somewhat limited effect on reducing emissions, but combining it with optimized spark plug location and exhaust gas recirculation can lead to substantial emission reductions.

3.3 Evaporative Emissions

3.3.1 Sources of Evaporative Emissions

Evaporative emissions from nonroad SI equipment represents a small but significant part of their NMHC emissions. The significance of the emissions varies widely depending on the engine design and application. LPG-fueled equipment generally has very low evaporative emissions because of the tightly sealed fuel system. At the other extreme, carbureted gasoline-fueled equipment with open vented tanks can have very high evaporative emissions. Evaporative emissions can be grouped into five categories:

DIURNAL: Gasoline evaporation increases as the temperature rises during the day, heating the fuel tank and venting gasoline vapors.

RUNNING LOSSES: The hot engine and exhaust system can vaporize gasoline when the engine is running.

HOT SOAK: The engine remains hot for a period of time after the engine is turned off and gasoline evaporation continues.

REFUELING: Gasoline vapors are always present in typical fuel tanks. These vapors are forced out when the tank is filled with liquid fuel.

PERMEATION: Gasoline molecules can saturate plastic fuel tanks and rubber hoses, resulting in a relatively constant rate of emissions as the fuel continues to permeate through these components.

Among the factors that affect emission rates are: (1) fuel metering (fuel injection or carburetor); (2) the degree to which fuel permeates fuel lines and fuel tanks; (3) the proximity of the fuel tank to the exhaust system or other heat sources; (4) whether the fuel system is sealed and the pressure at which fuel vapors are vented; and (5) fuel tank volume.

3.3.1.1 Diurnal and Running Loss Emissions

In an open fuel tank, the vapor space is at atmospheric pressure (typically about 14.7 psi), and contains a mixture of fuel vapor and air. At all temperatures below the fuel's boiling point, the vapor pressure of the fuel is less than atmospheric pressure. This is also called the partial pressure of the fuel vapor. The partial pressure of the air is equal to the difference between atmospheric pressure and the fuel vapor pressure. For example, in an open-vented fuel tank at 60°F, the vapor pressure of typical gasoline would be about 4.5 psi. In this example, the partial pressure of the air would be about 10.2 psi. Assuming that the vapor mixture behaves as an ideal gas, then the mole fractions (or volumetric fractions) of fuel vapor and air would be equal to their respective partial pressures divided by the total pressure; thus, the fuel would be 31 percent of the mixture (4.5/14.7) and the air would be 69 percent of the mixture (10.2/14.7).

Diurnal emissions occur when the fuel temperature increases, which increases the equilibrium vapor pressure of the fuel. For example, assume that the fuel in the previous example was heated to 90°F, where the vapor pressure that same typical fuel would be about 8.0 psi. To maintain the vapor space at atmospheric pressure, the partial pressure of the air would need to decrease to 6.7 psi, which means that the vapor mixture must expand in volume. This forces some of the fuel-air mixture to be vented out of the tank. When the fuel later cools, the vapor pressure of the fuel decreases, contracting the mixture, and drawing fresh air in through the vent. When the fuel is heated again, another cycle of diurnal emissions occurs. It is important to note that this is generally not a rate-limited process. Although the evaporation of the fuel can be slow, it is generally fast enough to maintain the fuel tank in an essentially equilibrium state.

Consider a typical fuel use cycle beginning with a full tank. As fuel is used by the engine, and the liquid fuel volume decreases, air is drawn into the tank to replace the volume of the fuel. (Note: the decrease in liquid fuel could be offset to some degree by increasing fuel vapor pressure caused by increasing fuel temperature.) This would continue while the engine was running. If the engine was shut off and the tank was left overnight, the vapor pressure of the fuel would drop as the temperature of the fuel dropped. This would cause a small negative pressure within the tank that would cause it to fill with more air until the pressure equilibrated. The next day, the vapor pressure of the fuel would increase as the temperature of the fuel increased. This would cause a small positive pressure within the tank that would force a mixture of fuel vapor and air out. In poorly designed gasoline systems, where the exhaust is very close to the fuel tank, the fuel can actually begin to boil. When this happens, large amounts of gasoline vapor can be vented directly to the atmosphere. Southwest Research Institute measured emissions from several large nonroad gasoline engines and found them to vary from about 12 g/day up to almost 100 g/day. They also estimated that a typical large nonroad gasoline engine in the South Coast Air Basin (the area involved in their study) would have an evaporative emission rate of about 0.4 g/kW-hr.

3.3.1.2 Hot Soak Emissions

Hot soak emissions occur after the engine is turned off, especially during the resulting temperature rise. For nonroad engines, the primary source of hot soak emissions is the evaporation of the fuel left in the carburetor bowl. Other sources can include increased permeation and evaporation of fuel from plastic or rubber fuel lines in the engine compartment.

3.3.1.3 Refueling Emissions

Refueling emissions occur when the fuel vapors are forced out when the tank is filled with liquid fuel. At a given temperature, refueling emissions are proportional to the volume of the fuel dispensed into the tank. Every gallon of fuel put into the tank forces out one-gallon of the mixture of air and fuel vapors. Thus, refueling emissions are highest when the tank is near empty. Refueling emissions are also affected by the temperature of the fuel vapors. At low temperatures, the fuel vapor content of the vapor space that is replaced is lower than it is at higher temperatures.

3.3.1.4 Permeation

The polymeric material (plastic or rubber) of which many gasoline fuel tanks and fuel hoses generally have a chemical composition much like that of gasoline. As a result, constant exposure of gasoline to these surfaces allows the material to continually absorb fuel. The outer surfaces of these materials are exposed to ambient air, so the gasoline molecules permeate through these fuel-system components and are emitted directly into the air. Permeation rates are relatively low, but emissions continue at a nearly constant rate, regardless of how much the vehicle or equipment is used. Permeation-related emissions can therefore

3.3.2 Evaporative Emission Controls

Several emission-control technologies can be used to reduce evaporative emissions. The advantages and disadvantages of the various possible emission-control strategies are discussed below. Chapter 4 presents more detail on how we expect manufacturers to use these technologies to meet proposed emission standards for the individual applications.

3.3.2.1 Sealed System with Pressure Relief

Evaporative emissions are formed when the fuel heats up, evaporates, and passes through a vent into the atmosphere. By closing that vent, evaporative emissions are prevented from escaping. However, as vapor is generated, pressure builds up in fuel tank. Once the fuel cools back down, the pressure subsides.

For forklifts, the primary application of Large SI engines, Underwriters Laboratories specifies that units operating in certain areas where fire risk is most significant must use pressurized fuel tanks. Underwriters Laboratories requires that trucks use self-closing fuel caps with tanks that stay sealed to prevent evaporative losses; venting is allowed for positive pressures above 3.5 psi or for vacuum pressures of at least 1.5 psi.[j] These existing requirements are designed to prevent evaporative losses for safety reasons. This same approach for other types of engines would similarly reduce emissions for air-quality reasons.

An alternative to using a pressure relief valve to hold vapors in the fuel tank would be to use a limited flow orifice. However, the orifice size may be so small that there would be a risk of fouling. In addition, an orifice designed for a maximum of 2 psi under worst case conditions may not be very effective at lower temperatures. One application where a limited flow orifice may be useful is if it is combined with an insulated fuel tank as discussed below.

3.3.2.2 Insulated Fuel Tank

Another option for reducing diurnal emissions is insulating the fuel tank. Rather than capturing the vapors in the fuel tank, this strategy would minimize the fuel heating which therefore minimizes the vapor generation. However, significant evaporative emissions would still occur through the vent line due to diffusion even without temperature gradients. A limited-flow orifice could be used to minimize the to loss of vapor through the vent line due to diffusion. In this case, the orifice could be sized to prevent diffusion losses without causing pressure build-up in the tank. Additional control could be achieved with the use of a pressure relief valve or a smaller limited flow orifice. Note that an insulated tank could maintain the same emission control with a lower pressure valve than a tank that was not insulated.

3.3.2.3 Volume Compensating Air Bag

Another concept for minimizing pressure in a sealed fuel tank is through the use of a volume compensating air bag. The purpose of the bag is to fill up the vapor space in the fuel tank above the fuel itself. By minimizing the vapor space, less air is available to mix with the heated fuel and less fuel evaporates. As vapor is generated in the small vapor space, air is forced out of the air bag, which is vented to atmosphere. Because the bag collapses as vapor is generated, the volume of the vapor space grows and no pressure is generated. Once the fuel tank cools as ambient temperature goes down, the resulting vacuum in the fuel tank will open the bag back up. Depending on the size of the bag, pressure in the tank could be minimized; therefore, the use of a volume compensating air bag could allow a manufacturer to reduce the pressure limit on its relief valve.

We are still investigating materials that would be the most appropriate for the construction of these bags. The bags would have to hold up in a fuel tank for years and resist permeation while at the same time be light and flexible. One such material that we are considering is fluoro-silicon fiber. Also, the bag would have to be positioned so that it did not interfere with other fuel system components such as the fuel pick-up or catch on any sharp edges

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[j] UL558, paragraphs 26.1 through 26.4

in the fuel tank.

3.3.2.4 Collapsible Bladder Fuel Tank

Probably the most effective technology for reducing evaporative emissions from fuel tanks is through the use of a collapsible fuel bladder. In this concept, a non-permeable bladder would be installed in the fuel tank to hold the fuel. As fuel is drawn from the bladder, the vacuum created collapses the bladder. Therefore, there is no vapor space and no pressure build up. Because the bladder would be sealed, there would be no vapors vented to the atmosphere. We have received comments that this would be cost prohibitive because it could double costs for smaller fuel tanks. However, bladder fuel tanks are sold today by at least one manufacturer in limited volumes.

3.3.2.5 Charcoal Canister

The primary evaporative emission control device used in automotive applications is a charcoal canister. With this technology, vapor generated in the tank is vented through a charcoal canister. The activated charcoal collects and stores the hydrocarbons. Once the engine is running, purge air is drawn through the canister and the hydrocarbons are burned in the engine. These charcoal canisters generally are about a liter in size and have the capacity to store three days of vapor over the test procedure conditions.

For industrial applications, engines are typically used frequently which would limit the size of canister needed; however, introducing an evaporative canister is a complex undertaking, requiring extensive efforts to integrate evaporative and exhaust emission-control strategies. Large SI engine manufacturers also often sell loose engines to equipment manufacturers, who would also need to integrate the new technology into equipment designs.

3.3.2.6 Floating Fuel and Vapor Separator

Another concept used in some stationary engine applications is a floating fuel and vapor separator. Generally small, impermeable plastic balls are floated in the fuel tank. The purpose of these balls is to provide a barrier between the surface of the fuel and the vapor space. However, this strategy does not appear to be viable for industrial fuel tanks. Because of the motion of the equipment, the fuel sloshes and the barrier would be continuously broken. Even small movements in the fuel could cause the balls to rotate and transfer fuel to the vapor space.

3.3.2.7 Non-permeable Materials

Another source of evaporative emissions is permeation through the walls of plastic fuel tanks and rubber hoses. In highway applications, non-permeable plastic fuel tanks are typically produced by blow molding a layer of ethylene vinyl alcohol between two layers of polyethylene. However, blow molding is expensive and requires high production volumes to be cost effective. Manufacturers of rotationally molded plastic fuel tanks generally have low production volumes and have commented that there is no low permeability material available for their production processes.

Another type of barrier technology for fuel tanks would be to treat the inside of a plastic fuel tanks with sulfur trioxide. This sulfonation process causes a reaction between the sulfur and polyethylene which creates a barrier that reduces gasoline permeation. One study shows reductions in gasoline permeation of 90% through the sulfonation process.[7]

By replacing rubber hoses with non-permeable lines, the evaporative emissions through the fuel and vent hoses can be prevented. An added benefit is that these non-permeable lines are non-conductive and can prevent the buildup of static charges. These non-permeable lines are used in automotive applications.

3.4 CI Recreational Marine Engines

In this section, we discuss how emissions can be reduced from compression-ignition (CI) recreational marine engines. We believe recreational marine diesel engines can use the same technology for reducing emissions that will be used to meet the standards for commercial marine diesel engines.[8] Because of the similarities between recreational and commercial diesel engines, this chapter builds off the technological analysis in the Regulatory Impact Analysis (RIA) for the commercial diesel marine engine rule.[9] This section discusses emissions formation, baseline technology, control strategies for CI recreational marine engines.

3.4.1 Background on Emissions Formation from Diesel Engines

Most, if not all, of compression-ignition recreational marine engines use diesel fuel. For this reason, we focus on recreational marine diesel engines in this section. In a diesel engine, the liquid fuel is injected into the combustion chamber after the air has been heated by compression (direct injection), or the fuel is injected into a prechamber, where combustion initiates before spreading to the rest of the combustion chamber (indirect injection). The fuel is injected in the form of a mist of fine droplets or vapor that mix with the air. Power output is controlled by regulating the amount of fuel injected into the combustion chamber, without throttling (limiting) the amount of air entering the engine. The compressed air heats the injected fuel droplets, causing the fuel to evaporate and mix with the available oxygen. At several sites where the fuel mixes with the oxygen, the fuel auto-ignites and the multiple flame fronts spread through the combustion chamber.

NOx and PM are the emission components of most concern from diesel engines. Incomplete evaporation and burning of the fine fuel droplets or vapor result in emissions of the very small particles of PM. Small amounts of lubricating oil that escape into the combustion chamber can also contribute to PM. Although the fuel-air ratio in a diesel cylinder is very lean, the air and fuel are not a homogeneous charge as in a gasoline engine. As the fuel is injected, the combustion takes place at the flame-front where the fuel-air ratio is near stoichiometry (chemically correct for combustion). At localized areas, or in cases where light-ends have vaporized and burned, molecules of carbon remain when temperatures and pressures in the cylinder become too low to sustain combustion as the piston reaches bottom dead center. Therefore, these heavy products of incomplete combustion are exhausted as PM.

NOx formation requires high temperatures and excess oxygen which are found in a diesel engine. Therefore, the diesel combustion process can cause the nitrogen in the air to combine with available oxygen to form NOx. High peak temperatures can be seen in typical unregulated diesel engine designs. This is because the fuel is injected early to help lead to more complete combustion, therefore, higher fuel efficiency. If fuel is injected too early, significantly more fuel will mix with air prior to combustion. Once combustion begins, the premixed fuel will burn at once leading to a very high temperature spike. This high temperature spike, in turn, leads to a high rate of NOx formation. Once combustion begins, diffusion burning occurs while the fuel is being injected which leads to a more constant, lower temperature, combustion process.

Because of the presence of excess oxygen, hydrocarbons evaporating in the combustion chamber tend to be completely burned and HC and CO are not emitted at high levels. Evaporative emissions from diesel engines are insignificant due to the low evaporation rate of diesel fuel.

Controlling both NOx and PM emissions requires different, sometimes opposing strategies. The key to controlling NOx emissions is reducing peak combustion temperatures since NOx forms at high temperatures. In contrast, the key to controlling PM is higher temperatures in the combustion chamber or faster burning. This reduces PM by decreasing the formation of particulates and by oxidizing those particulates that have formed. To control both NOx and PM, manufacturers need to combine approaches using many different design variables to achieve optimum performance. These design variables are discussed in more detail below.

3.4.2 Marinization Process

Like commercial marine engines, recreational marine engines are not generally built from the ground up as marine engines. Instead, they are often marinized land-based engines. The main difference between recreational and commercial marine engines is the application for which they are designed. Commercial engines are designed for high hours of use. Recreational engines are generally designed for higher power, but less hours of use. The following is a brief discussion of the marinization process, as it is performed by either engine manufacturers or post-manufacture marinizers (PMM).

3.4.2.1 Process common to all marine diesel engines

The most obvious changes made to a land-based engine as part of the marinization process concern the engine’s cooling system. Marine engines generally operate in closed compartments without much air flow for cooling. This restriction can lead to engine performance and safety problems. To address engine performance problems, these engines make use of the ambient water to draw the heat out of the engine coolant. To address safety problems, marine engines are designed to minimize hot surfaces. One method of ensuring this, used mostly on smaller marine engines, is to run cooling water through a jacket around the exhaust system and the turbocharger. Larger engines generally use a thick insulation around the exhaust pipes.

Hardware changes associated with these cooling system changes often include water jacketed turbochargers, water cooled exhaust manifolds, heat exchangers, sea water pumps with connections and filters, and marine gear oil coolers. In addition, because of the greater cooling involved, it is often necessary to change to a single-chamber turbocharger, to avoid the cracking that can result from a cool outer wall and a hot chamber divider.

Marinization may also involve replacing engine components with similar components that are made of materials that are more carefully adapted to the marine environment. Material changes include more use of chrome and brass including changes to electronic fittings to resist water induced corrosion. Zinc anodes are often used to prevent engine components, such as raw-water heat exchangers, from being damaged by electrolysis.

3.4.2.2 Process unique to recreational marine diesel engines

Other important design changes are related to engine performance. Especially for planing hull vessels used in recreational and light duty commercial marine applications, manufacturers strive to maximize the power-to-weight ratio of their marine engines, typically by increasing the power from a given cylinder displacement. The most significant tool to accomplish this is the fuel injection system: the most direct way to increase power is to inject more fuel. This can require changes to the camshaft, cylinder head, and the injection timing and pressure.

Design limits for increased fuel to the cylinder are smoke and durability. Modifications made to the cooling system also help enhance performance. By cooling the charge, more air can be forced into the cylinder. As a result, more fuel can be injected and burned efficiently due to the increase in available oxygen. In addition, changes are often made to the pistons, cylinder head components, and the lubrication system. For instance, aluminum piston skirts may be used to reduce the weight of the pistons. Cylinder head changes include changing valve timing to optimize engine breathing characteristics. Increased oil quantity and flow may be used to enhance the durability of the engine.

Depending on the stage of production and the types of changes made, the marinization process can have an impact on the base engine’s emission characteristics. In other words, a land-based engine that meets a particular set of emission limits may no longer meet these limits after it is marinized. This can be the case, for example, if the fuel system is changed to enhance engine power or if the cooling system no longer achieves the same degree of engine cooling as that of the base engine. Because marine diesel engines are currently unregulated, engine manufacturers have been able to design their marine engines to maximize performance. Especially for recreational marine engines, manufacturers often obtain power/weight ratios much higher than for land-based applications.

Recreational engine manufacturers strive for higher power/weight ratios than are necessary for commercial marine engines. Because of this, recreational marine engines use technology we projected to be used by commercial marine engines to meet the Tier 2 emissions standards such as raw-water aftercooling and electronic control. However, this technology is used to gain more power rather than to reduce emissions. The challenge presented by the proposed emission control program will be to achieve the emission limits while maintaining favorable performance characteristics.

3.4.3 General Description of Technology for Recreational Marine Diesel Engines

We believe that the proposed standards can be met using technology that has been developed for and used on land-based nonroad and highway engines. The Regulatory Impact Analysis for the commercial marine rule includes a lengthy description of emission control technology for diesel marine engines. Table 3.4-1 outlines this description. By combining the strategies shown below, manufacturers can optimize the emissions and performance of their engines. A more detailed analysis of the application of several of these technologies to recreational marine engines is discussed in Chapter 4. The costs associated with applying these systems are considered in Chapter 5.

Table 3.4-1: Emission Control Strategies for Marine Diesel Engines

Technology	Description	HC	CO	NOx	PM
Combustion optimization:	timing retard–reduce peak cylinder temperatures by shortening the premixed burning phase	↑	↑	↓↓	↑↑
	reduced crevice volume–such as raising the top piston ring	↓	↓	↔	↓
	geometry–match piston crown geometry to injector spray	↓	↓	↓	↓
	increased compression ratio–raises cylinder pressures	↓	↓	↑	↓
	increased swirl–control of air motion for better mixing	↓	↓	↑,↔	↓
Advanced fuel injection controls	increased injection pressure–better atomization of fuel	↓	↓	↑,↔	↓
	nozzle geometry–optimize spray pattern	↓	↓	↓	↓
	valve-closed orifice–minimize leakage after injection	↓	↔	↔	↓
	rate shaping–inject small amount of fuel early to begin combustion to reduce premixed burning	↔	↔	↓	↔
	common rail–high pressure rail to injectors, excellent control of fuel rate, pressure, and timing	↓	↓	↓	↓
Improving charge air characteristics	turbocharging–increases available oxygen in the cylinder but heats intake air	↓	↓	↑	↓
	jacket-water aftercooling–uses engine coolant to cool charged air which increases available oxygen in cylinder	↔	↔	↓	↔
	raw-water aftercooling–uses ambient water to cool charge air; more effective than jacket-water aftercooling; may result in additional maintenance such as changing anodes	↔	↔	↓↓	↔
Electronic control	better control of fuel system including rate, pressure, and timing especially under transients; can use feedback loop	↓	↓	↓	↓
Exhaust gas recirculation	hot EGR–recirculated exhaust gas reduces combustion temperatures by absorbing heat and slowing reaction rates	↑	↑	↓	↑
	cooled EGR–reduces volume of recirculated gases so to allow more oxygen in the cylinder	↔	↔	↓↓	↑,↔
	soot removal–soot in recirculated gases may cause durability problems at high EGR rates; gas filter or trap; oil filter	↔	↔	↔	↓
Exhaust aftertreatment devices	oxidation catalyst–oxidizes hydrocarbons and soluble organic fraction of PM; will be poisoned by high levels of sulfur	↓	↓	↔	↓
	particulate trap–collect PM; regenerate at high temperature	↓	↓	↔	↓
(would require “dry” exhaust)	selective catalytic reduction–uses a catalyst and a reducing agent such as ammonia	↔	↔	↓	↔
Water emulsification	water is mixed with fuel or injected into the cylinder; water has a high heat capacity and will lower in-cylinder temperatures	↔	↔	↓	↔

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