Control of Emissions from Marine SI and Small SI Engines, Vessels, and Equipment

Final Regulatory Impact Analysis

Chapter 4
Feasibility of Exhaust Emission Control

Assessment and Standards Division
Office of Transportation and Air Quality
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CHAPTER 4: Feasibility of Exhaust Emission Control

Section 213(a)(3) of the Clean Air Act presents statutory criteria that EPA must evaluate in determining standards for nonroad engines and vehicles including marine vessels. The standards must "achieve the greatest degree of emission reduction achievable through the application of technology which the Administrator determines will be available for the engines or vehicles to which such standards apply, giving appropriate consideration to the cost of applying such technology within the period of time available to manufacturers and to noise, energy, and safety factors associated with the application of such technology." This chapter presents the technical analyses and information that form the basis of EPA's belief that the exhaust emission standards are technically achievable accounting for all the above factors.

The exhaust emission standards for Small SI engines and Marine SI engines are summarized in the Executive Summary. This chapter begins with a current state of technology for spark-ignition (SI) engines and the emission control technologies expected to be available for manufacturer and continues with a presentation of available emissions data on baseline emissions and on emission reductions achieved through the application of emission control technology. In addition, this chapter provides a description of new test procedures including not-to-exceed requirements.

4.1 General Description of 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 use other fuels. SI engines include engines fueled with liquid petroleum gas (LPG) and compressed natural gas (CNG).

4.1.1 Basics of Engine Cycles

Spark ignition engines may be of two-stroke or four-stroke which refers to the number of piston strokes per combustion cycle. Handheld Small SI equipment typically use two-stroke engines while larger non-handheld equipment use four-stroke engines. Outboard and personal watercraft (OB/PWC) engines, until the advent of recent environmental regulations, were generally two-stroke engines. They are now a mix of two- and four-stroke engines. Sterndrive and inboard (SD/I) engines are primarily SI four-stroke engines.

4.1.1.1 Two-Stroke Engines

“Two-stroke” refers to the number of piston strokes per combustion cycle. These two strokes, compression and expansion, occur in one revolution of the crankshaft. During the expansion stroke the piston moves downward. As the piston nears its lowest position, the intake and exhaust ports are opened. While these ports are open, a fresh charge of fuel and air is pushed into the cylinder which, in turn, helps force the burned gases from the previous cycle out of the exhaust port. During the compression stroke, the intake and exhaust ports close and the fresh charge is compressed. As the piston approaches its highest position, a spark-plug ignites the fresh charge to generate combustion. The force from the combustion acts on the piston to move it downward, thereby causing the expansion stroke and generating power.

In traditional two-stroke engine designs, the engines are crankcase-scavenged and carbureted with intake and exhaust ports on the cylinder walls. The advantage of this engine design is simplicity (low number of moving parts) and a high power to weight ratio of the engine. In this design, the carburetor meters fuel into the intake air which is then routed to the crankcase. The motion of the drive shaft then pressurizes the charge. Oil is typically blended into the fuel to provide cylinder and reciprocating assembly lubrication. When the piston lowers, it exposes the intake port on the side of the cylinder wall which allows the pressurized fuel/air charge to enter the cylinder. At the same time, the exhaust port is exposed allowing burned gases to escape the cylinder. Because both ports are open at the same time, some of the fresh charge can exit the exhaust port. These fuel losses are known as “short-circuiting” or “scavenging” losses and can result in 25 percent or more of the fuel passing through the cylinder unburned. As the piston moves up, the intake and exhaust ports are covered and combustion is initiated.

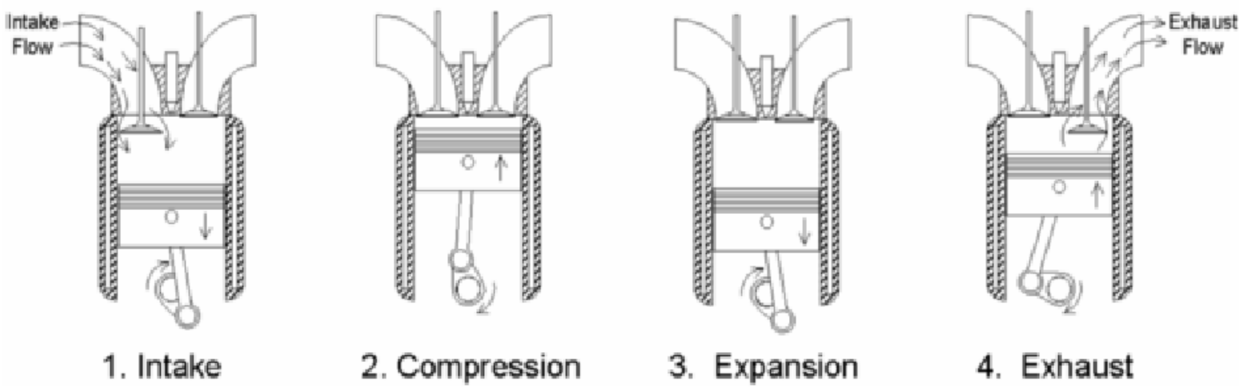
An emerging technology for reducing emissions and scavenging losses from two-stroke engines is direct-injection. This is used primarily on larger outboard and personal watercraft engines (37 kW and up) to meet exhaust emission standards. In a direct-injected engine, charge air is used to scavenge the exhaust gases. Once the exhaust valve closes, fuel is injected into the charge air and ignited with a spark-plug. Because the exhaust valve is closed during most or all of the injection event, short-circuiting losses are minimized. Also, because the fuel is not used to lubricate the crankcase, oil does not need to be blended into the fuel. As a result, much less oil is used.

4.1.1.2 Four-Stroke Engines

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

A “four-stroke” engine gets its 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, expansion or power, and exhaust. Two of the strokes are downward (intake & expansion) and two of the strokes are upward (compression & exhaust). The four strokes are completed in two revolutions of the crankshaft. Valves in the combustion chamber open and close to route gases into and out of the combustion chamber or create compression.

Figure 4.1-1: 4-Stroke Cycle



The first step of the cycle is for an intake valve 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 displacement of the piston draws air and fuel past the open intake valve into the cylinder.

During the compression stroke, the intake valve closes and the momentum of the crankshaft moves the piston up the cylinder from BDC to TDC, compressing the air and fuel mixture. As the piston nears TDC, at the very end of the compression stroke, the air and fuel mixture is ignited by a spark plug and the air and fuel mixture begins to burn. As the air and fuel mixture burns, pressures and temperatures increase and the products of combustion expand in the cylinder, which causes the piston to move back down the cylinder, transmitting power to the crankshaft during the expansion or power stroke. Near the bottom of the expansion stroke, an exhaust valve opens and as the piston moves back up the cylinder, exhaust gases are pushed out through the exhaust valve to the exhaust manifold to complete the exhaust stroke, finishing a complete four-stroke cycle.

4.1.2 Exhaust Emissions from Nonroad SI Engines

Hydrocarbon (HC) and carbon monoxide (CO) emissions are products of incomplete combustion. The level of CO exhaust emissions is primarily a function of the air-to-fuel ratio at which an engine is operated. Hydrocarbon emissions formation mechanisms are somewhat more complex, and appear to be primarily related to:

1. Quenching of the air/fuel mixture at the walls of the combustion chamber
2. Filling of crevice volumes with the air/fuel mixture that remains unburned due to flame quenching at the entrance to the crevice
3. Lubricant absorption and desorption of fuel compounds
4. Partial combustion during an operating cycle or even complete misfiring of the air/fuel mixture during the cycle
5. Entrainment and incomplete combustion of lubricant

As a result, a number of design and operational variables have an impact on HC emissions, including air-to-fuel ratio; combustion chamber design and geometry; homogeneity of the air/fuel charge; intake port geometry and the degree of induced air/fuel charge motion; ignition energy, dwell, and timing; the effectiveness of the cooling system; and oil consumption.

NOx emissions from SI engines are primarily emissions of nitric oxide (NO). Nitrogen in the intake air reacts with oxygen at high temperatures primarily via the Zeldovich mechanism to form NO. Thus variables that impact combustion temperatures can have a significant impact on NO formation and NOx exhaust emissions. These include air-to-fuel ratio, spark timing and the quantity of residual exhaust gases carried over between engine firing cycles (either through external exhaust gas recirculation or inefficient cylinder scavenging).

Particulate matter (PM) emissions from SI engines consists primarily of semi-volatile organic compounds from the engine lubricant together with elemental-carbon soot formed from pyrolysis of fuel and lubricant during combustion.

4.1.2.1 Air-to-fuel ratio

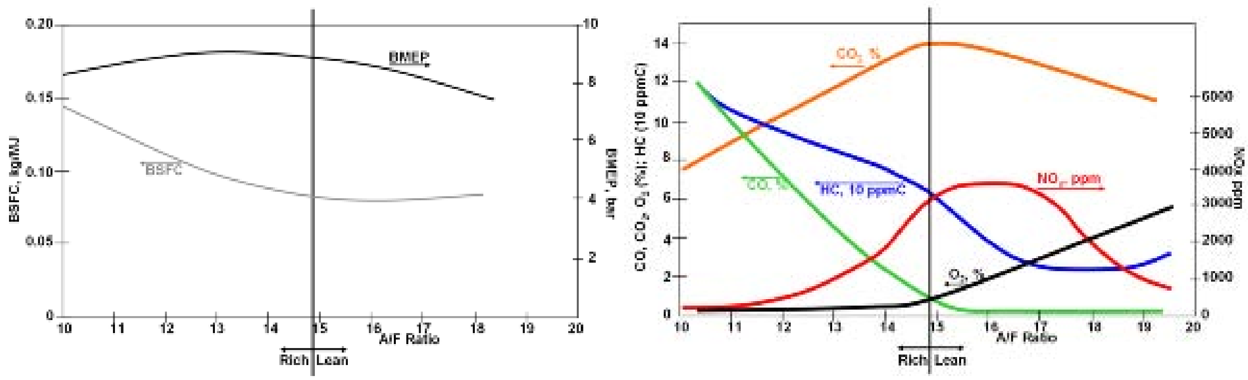
The calibration of engine air-to-fuel ratio affects torque and power output, fuel consumption (often indicated as Brake Specific Fuel Consumption or BSFC), engine temperatures, and emissions for SI engines. The effects of changing the air-to-fuel ratio on emissions, fuel consumption and torque (indicated as Brake Mean Effective Pressure or BMEP, which is torque corrected for engine volumetric displacement) are shown in Figure 3-1.[1]

In the past, manufacturers have calibrated fuel systems of nonroad SI engines for rich operation. This was done in part to 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. Rich operation at between approximately 12.5:1 and 13:1 air-to-fuel ratio also generally increased engine torque output (figure 4.1-1) and prevented lean air-to-fuel ratio excursions during application of transient loads to the engine. Rich operation also has been used to reduce piston, combustion chamber, cylinder and exhaust port temperatures, thus reducing the thermal load on the cooling system, a particularly important issue with air-cooled engines. Operation at air-to-fuel ratios richer than approximately 13:1 or 13.5:1 can limit the effectiveness of, or pose design challenges for, post-combustion catalytic exhaust emission controls for HC and CO emissions but work well for catalytic reduction of NOx. At the same time, because a rich mixture lacks sufficient oxygen for complete 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 of the stoichiometric air-to-fuel ratio (approximately 14.6:1 air-to-fuel ratio for typical gasolines), but lean operational limits are bounded by the onset of abnormal combustion (e.g., lean misfire and combustion knock), the ability to pick up load, and exhaust port temperatures (particularly with air-cooled engines). Many air-cooled engines are limited by heat-rejection to operation that starts approximately at stoichiometry for light loads, and is rich of stoichiometry as load is increased.

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 that is closer to a stoichimetric air-to-fuel ratio without increasing the risk of abnormal combustion. This can be enhanced through careful selection of intake port geometry and combustion chamber shape to induce turbulence into the air/fuel cylinder charge. The leaner air-to-fuel ratios (e.g., operating just rich of stoichiometry) resulting from advanced fuel systems and intake charge turbulence can significantly reduce HC and CO emissions and fuel consumption, and can provide more oxygen in the exhaust for improved catalytic control of HC and CO. Leaner air-to-fuel ratios, however, can increase NOx emissions due to higher combustion temperatures, particularly for engines that are not equipped with exhaust catalysts. More advanced fuel systems would allow tailoring of the air to fuel ratio to allow good transient response and to add enrichment at higher load conditions for engine and catalyst protection and to reduce engine-out NOx emissions. High-load enrichment is particularly important for air-cooled engines, since high-load operation at leaner air-to-fuel ratios could also increase hydrocarbon emissions and PM emissions if the higher cylinder temperatures encountered result in a significant increase in cylinder-bore distortion and lubricating oil consumption.

Figure 4.1-2: Effects of Air-to-Fuel Ratio on Torque Output, Fuel Consumption and Emissions for Naturally Aspirated Spark Ignition Engines.



4.1.2.2 Spark-timing

For each engine speed and air-fuel mixture, there is an optimum spark-timing that results in peak torque ("Maximum Brake Torque" or "MBT" timing). If the spark is advanced from MBT, more combustion occurs during the compression stroke. If the spark is retarded from MBT, peak cylinder pressure is decreased because too much combustion occurs later in the expansion stroke generating less useable torque. 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.

4.1.3 Marinization

Gasoline sterndrive and inboard (SD/I) engines are generally derived from land-based counterparts. Engine marinizers buy automotive engine blocks and modify them for use on boats. Because of the good power/weight ratio of gasoline engines, most SD/I engines are not modified to produce more power than the base engines were originally designed to produce. In some airboat applications, aircraft engines are used.

4.1.3.1 Typical SD/I marinization process

Marine SI engines are typically built from base engines designed for use in cars and trucks. Currently, the vast majority of base engines are General Motor (GM) engines that range in size from a 3.0 L in-line four cylinder engine to an 8.1 L V8 engine and range in power from about 100 to 300 kW. These engines are sold without front accessory drives or intake and exhaust manifolds. Also, no carbureted versions of these engines are offered; they are either sold with electronic fuel injection, or no fuel system at all. Relatively small numbers of custom blocks and Mazda rotary engines are also used.

Marinizers convert the base engines into marine engines in the following ways:

- Choose and optimize the fuel management system.
- Configure a marine cooling system.
- Add intake and exhaust manifolds, and accessory drives and units.

Fuel and air management: Historically, Marine SI engines have been carbureted. Today this technology seems to be going away but is still offered as cheaper alternative to electronic fuel injection. Less than half of new engines are sold with carburetors. GM does not offer carburetors or their associated intake manifolds because they are not used in the higher volume, automotive applications. Therefore, marinizers who produce carbureted engines must purchase the fuel systems and intake manifolds elsewhere.

The 3.0 L and 4.3 L base engines are offered with throttle body fuel injection systems as an option. All of the larger engines are offered with multi-port fuel injection as an option. Although GM offers a base marine calibration for its electronic control module, it also offers software allowing marinizers to perform their own engine calibrations. For most engines sold, the marinizers will alter the calibrations to optimize engine operation. Except for some small market niches, the marinizers do not calibrate the engines for more power.

Cooling system: Marine SI engines are generally packaged in small compartments without much air flow for cooling. In addition, Coast Guard safety regulations require that surface temperatures be kept cool on the engine and exhaust manifold. Typically, marine exhaust systems are designed with surface temperatures below 93°C (200°F). To do this, manufacturers use ambient (raw) water to cool the engine and exhaust. Most sterndrive and inboard engines use raw water to cool the engine. This water is then used, in a water jacket, to cool the exhaust manifold. Finally, the water is dumped into the exhaust stream.

Most Marine SI engines are cooled with raw water. This means that ambient water is pumped through the engine, to the exhaust manifold, and mixed with the exhaust. The exhaust/water mixture is then dumped under water. Mixing the water with exhaust has three advantages:

- cools the exhaust and protects rubber couplings in sterndrives
- acts as a muffler to reduce noise
- helps tune the exhaust back pressure

An alternative to raw water cooling is fresh water cooling. In a fresh water system, raw water is used to cool the recirculated engine coolant (“fresh water”). The raw water is generally still used to cool the exhaust manifold and exits the engine with the exhaust. However, some systems use the engine coolant to cool the exhaust manifold.

Some gasoline engines, mostly inboards, have fresh water cooling systems which provide two advantages. 1) Engine corrosion problems are reduced, especially when the boat is used in saltwater. Fresh water systems keep saltwater, which can be corrosive, out of the engine. Because salt emulsifies at about 68°C, thermostats in fresh water systems are set around 60-62°C. 2) Marinizers can achieve much better control of the engine temperature. By reducing variables in engine operation, combustion can be better optimized.[3]

There are trade-offs with using a fresh water system. The fresh water system costs more because of the added pump and heat exchanger. Also, this system is not as efficient for cooling the engine as pumping raw water directly to the engine

Other additions: As mentioned above, marinizers add intake manifolds to carbureted engines. As part of the cooling system, marinizers must add water jacketed exhaust manifolds, pumps, and heat exchangers. SD/I engines may also have larger oil pans to help keep oil temperatures down. Because of the unique marine engine designs, marinizers also add their own front accessory drive assembly. Finally, sterndrive engines also must be coupled with the lower drive unit.

4.1.3.2 High performance SD/I marinization process

There is a niche in the SD/I market where customers are willing to sacrifice engine durability for a high power to weight ratio. Marinizers who address this niche do so by increasing the fueling of the engine, optimizing the spark-timing for power, increasing the peak engine speed (rpm), and modifying the exhaust manifold for better tuning. In some cases, the marinizers may actually increase the displacement of the engine by boring out the cylinders. Other components such as camshafts and pistons may also be modified. Superchargers may also be added. As an example, GM's largest base engine for this market is rated at 309 kW. One high performance SD/I engine with a bored cylinder, a high performance fuel injection calibration, and a supercharger achieves more than 800 kW.

4.1.4 Gaseous Fuels

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 do not 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.

4.2 General Description of Exhaust Emission Control Technologies

HC and CO emissions from spark-ignition engines are primarily the result of poor in-cylinder combustion. This is intensified in carbureted two-stroke engines with the very high HC emissions due to short-circuiting losses. 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 4.1.2.1 and 4.1.2.2, can further reduce HC emissions and lower CO emissions. The conversion from carburetor to electronic fuel injection will also help reduce HC and CO emissions. Exhaust gas recirculation could be used to reduce NOx emissions. 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.

4.2.1 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 do not 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.

4.2.2 Fuel injection

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 with multi-cylinder engines. 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, and because the fuel "wets" the intake manifold, 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.

Port gasoline injection: As the name suggests, port (single cylinder) or multi-port (multi-cylinder-port) fuel injection means that a fuel injector is placed in close proximity to each of the intake ports. The intake manifold, if used, flows only air. Sequentially-timed systems inject a quantity of fuel each time the intake valve opens for each cylinder, but multi-port injection systems can also be "batch fired" (all injectors pulsed simultaneously on a multicylinder engine) or continous (e.g., the Bosch CIS automotive systems of the 1970's and 80's). Port injection 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 decades.

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.[5]

4.2.3 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.[6] 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 of SI engines because the addition of nonreactive recirculated gases forces larger throttle openings for the same power output. Because the burned gas temperature is decreased, there is also 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.[7]

Electronic EGR control: Many EGR systems in today's automotive applications utilize a control valve that requires vacuum from the intake manifold to regulate EGR flow. Under part-throttle operation where EGR is needed, engine vacuum is sufficient to open the valve. However, during throttle applications near or at wide-open throttle, engine vacuum is too low to open the EGR valve. While EGR operation only during part-throttle driving conditions has been sufficient to control NOx emissions for vehicles in the past, more stringent NOx standards and emphasis on controlling off-cycle emission levels may require more precise EGR control and additional EGR during heavy throttle operation to reduce NOx emissions. Automotive manufacturers now use electronic control of EGR. By using electronic solenoids to directly open and close the EGR valve or by modulating the vacuum signal to vacuum actuated valves, the flow of EGR can be precisely controlled.

Stratified EGR: Another method of increasing the engine's tolerance to EGR is to stratify the reicirculated gases in the cylinder. This stratification allows high amounts of dilution near the spark plug for NOx reduction while making undiluted air available to the crevices, oil films, and deposit areas so that HC emissions may be reduced. Stratification may be induced radially or laterally through control of air and mixture motion determined by the geometry of the intake ports. Research on a one cylinder engine has shown that stratified EGR will result in much lower fuel consumption at moderate speed and load (6 percent EGR at 2400 rpm, 2.5 bar BMEP) while maintaining low HC and NOx emissions when compared to homogeneous EGR.[8]

For catalyst systems with high conversion efficiencies, the benefit of using EGR becomes proportionally smaller, although it can offer cost savings by reducing catalyst rhodium loadings. Including EGR as a design variable for optimizing the engine can add significantly to the development time needed to fully calibrate the electronic controls of engines or vehicles.

4.2.4 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.

In addition to gains in volumetric efficiency, four-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-quenching 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.

Control of valve timing and lift take full advantage of the four-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 less 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. Automotive engines with valve timing have also replaced external EGR systems with “internal EGR” accomplished via variable valve overlap, generally with improved EGR rate control over external systems and improved engine-out NOx emissions.

4.2.5 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, or by using a passive venturi or check-valve, 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, net oxidizing conditions 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.[9]

Secondary air injection can also be used in continuous operation with rich-jetted carbureted engines to a achieve an exhaust chemistry just rich of stoichiometry to improve the efficiency of 3-way catalysts.[10,11]

4.2.6 Catalytic Aftertreatment

Over the last several years, there have been tremendous advances in exhaust aftertreatment systems. Catalyst manufacturers have increased the use of palladium (Pd), particularly for close-coupled positions in automotive catalyst applications.[12] 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.[13] Current Pd catalysts are capable of withstanding prolonged exposure to temperatures approaching 1100°C.[14] The light-off temperature of these advanced catalysts is in the range of 250 to 270°C.

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 more difficult to oxidize.

Three-way catalysts use a combination of platinum and/or palladium 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 slightly-rich of stoichiometric air-fuel ratio is required. 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. The window can be broadened somewhat through the use of oxygen storage components, such as cerium oxide, within the catalyst washcoating. Cerium oxide also promotes CO and HC removal via steam reformation with water vapor in the exhaust, and the hydrogen liberated by these reactions promotes further NOx reduction.

Manufacturers are developing catalysts with substrates that utilize thinner walls in order to design higher cell density, low thermal mass catalysts for close-coupled applications (improves mass transfer at high engine loads and increase catalyst surface area). The cells are coated with washcoat which contain the noble metals which perform the catalysis on the exhaust pollutants. The greater the number of cells, the more surface area with washcoat that exists, meaning there is more of the catalyst available to convert emissions (or that the same catalyst surface area can be put into a smaller volume). Cell densities of 900 cells per square inch (cpsi) have already been commercialized, and research on 1200 cpsi catalysts has been progressing. Typical cell densities for conventional automotive catalysts are 400 to 600 cpsi.

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

4.2.6.1 System cost

Sales volumes of recreational vessels are small compared to automotive sales and while sales of Small SI engines <19kW are similar, the price of equipment is much less than automotive. Manufacturers therefore have a limited ability to recoup large R&D expenditures for these applications. For these reasons, we believe it is not appropriate to consider highly refined catalyst systems that are tailored specifically to nonroad applications. Catalyst manufacturers have assured us that automotive-type catalysts can easily be built to any size needed for Small SI and marine applications. We are considering catalyst packaging designs that do not require the manufactures to incur the costs of reworking the entire exhaust system and, for Marine SI engines, the lower power unit. The cost of these systems will decrease substantially when catalysts become commonplace. Chapter 6 describes the estimated costs for nonroad catalyst systems for Small SI and Marine SI engines.

4.2.6.2 Differences in emission control system application and design by engine category

One challenge in the use of catalytic control for Small SI and Marine SI engines lies in acceptable design and packaging of the exhaust catalysts onto a wide variety of different types of equipment. This section discusses specific issues related to these applications.

4.2.6.2.1 Small SI Class I engines

Class I engines typically are equipped with integral exhaust and fuel systems and are air-cooled. Significant applications include walk-behind lawn mowers (largest segment), pressure washers, generator sets and pumps. There are both overhead valve (OHV) and side-valve (SV) engines used in Class I, but side-valve engines are the predominant type in Class I, particularly in lawn mower applications. They currently represent about 60 percent of Class I sales. Exhaust catalyst design for Class I engines must take into account several important factors that differ from automotive applications:

1. Air-cooled engines run rich of stoichiometry to prevent overheating when under load. Because of this, CO and HC emissions can be high. Catalyst induced oxidation of a high

percentage of available reactants in the exhaust in the presence of excess oxygen (i.e., lean of stoichiometric conditions) can result in highly exothermic exhaust reactions and increase heat rejection from the exhaust. For example, approximately 80 to 90 percent of the energy available from catalyst-promoted exhaust reactions is via oxidation of CO.

2. Air-cooled engines have significant HC and NOx emissions that are typically much higher on a brake-specific basis than water-cooled automotive engine types. Net heat available from HC oxidation and NOx reduction at rich of stoichiometric conditions is considerably less than that of oxidation of CO at near stoichiometric or lean of stoichiometric conditions due to the much lower concentrations of NO and HC in the exhaust relative to CO.
3. Most Class I engines do not have 12-volt DC electrical systems to power auxiliaries and instead are pull start. Electronic controls relying on 12-volt DC power would be difficult to integrate onto Class I engines without a significant cost increase.
4. Most Class I engines use inexpensive stamped mufflers with internal baffles. Mufflers are typically integrated onto the engine and may or may not be placed in the path of cooling air from the cooling fan.
5. The regulatory emission test cycles (A-cycle, B-cycle), manufacturer's durability cycles and some limited in-use operation data indicate that emissions control should focus primarily on light and part load operation for the highest volume applications (lawnmowers).

These factors would lead to exhaust catalyst designs for small engines that should differ somewhat from those of light duty gasoline vehicle exhaust catalyst designs. Design elements specific to Class I Phase 3 exhaust catalysts would include:

1. Catalyst substrate volume would be sized relatively small so as to be space-velocity limited. Catalyst volume for Class I Phase 3 engines would be approximately 18 to 50 percent of the engine cylinder displacement, depending on cell count, engine-out emission levels, and oil consumption. Catalyst substrate sizes would be compact, with typical catalyst substrate volumes of approximately 2 to 5 cubic inches. This would effectively limit mass transport to catalyst sites at moderate-to-high load conditions and reduce exothermic reactions occurring when exhaust temperature is highest. This is nearly the opposite of the case of typical automotive catalyst designs. Automotive catalyst volume is typically 50 to 100 percent of cylinder displacement, with the chief constraints on catalyst volume being packaging and cold-start light-off performance.
2. Catalyst precious metal loading (Pt-platinum, Pd-palladium, Rh-rhodium) would be kept relatively low, and formulations would favor NOx and HC selectivity over CO selectivity. We estimate that typical loading ratios for Phase 3 would be approximately in the range of 40 to 50 g/ft3 (approximately 50 percent of typical automotive loadings at light-duty vehicle Tier 2 emission levels) and can be Pt:Rh, Pd:Rh or tri-metallic. Tri-metallic platinum group metal (PGM) loadings that replace a significant fraction of Pt with Pd would be less selective for CO oxidation and would also reduce the cost of the catalyst. Loading ratios would be similar or higher in Rh than what is typically used for automotive applications (20-25 percent of the total PGM mass in Small SI) to improve NOx selectivity, improve rich of stoichiometry HC reactions and reduce CO selectivity.

3. Catalysts would be integrated into the muffler design. Incorporating the catalyst into the muffler would reduce surface temperatures, and would provide more surface area for heat rejection. This is nearly the opposite of design practice used for automotive systems, which generally try to limit heat rejection to improve cold-start light-off performance. The muffler design for Class I Phase 3 engines would have somewhat higher surface area and somewhat larger volume than many current Class I muffler designs in order to promote exhaust heat rejection and to package the catalyst, but would be similar to some higher-end "quiet" Class I muffler designs. Appropriately positioned stamped heat-shielding and touch guards would be integrated into Class I Phase 3 catalyst-muffler designs in a manner similar to many Class I Phase 2 mufflers. A degree of heat rejection would be available via forced convection from the cooling fan, downstream of cooling for the cylinder and cylinder head. This is the case with many current muffler designs. Heat rejection to catalyst muffler surfaces to minimize "hot spots" can also be enhanced internally by turning the flow through multiple chambers and baffles that serve as sound attenuation within the muffler, similar to the designs used with catalyst-equipped lawn mowers sold in Sweden and Germany.
4. Many Class I Phase 3 catalysts would include passive secondary air injection to enhance catalyst efficiency and allow the use of smaller catalyst volumes. Incorporation of passive secondary air allows halving of catalyst substrate volume for the same catalyst efficiency over the regulatory cycle. A system for Class I Phase 3 engines would be sized small enough to provide minimal change in exhaust stoichiometry at high load conditions so as to limit heat rejection, but would be provide approximately 0.5 to 1.0 points of air-to-fuel ratio change at conditions of 50 percent of peak torque and below in order to lower HC emissions effectively in engines operating at air-to-fuel ratios similar to those of current Class I Phase 2 engines. Passive secondary air systems are preferred. Mechanical or electrical air pumps are not necessary. Passive systems include stamped or drawn venturis or ejectors integrated into the muffler, some of which may incorporate an air check-valve, depending on the application. Pulse-air injection is also a form of passive secondary air injection. Pulse air draws air into the exhaust port through a check-valve immediately following the closure of the exhaust valve. Active secondary air (air pump) systems were not considered in this analysis since they may be cost prohibitive for use in Class I applications due to the need for a mechanical accessory drive or 12-volt DC power.
5. Catalyst durability in side valve engines can be enhanced through two catalyst design ideas. First, the use of a pipe catalyst upstream of the main catalyst brick can “catch” the oil in the exhaust thereby limiting the amount seen in the catalyst and thereby catalyst poisoning. Second, the catalyst brick can be lengthened to allow poisoning to some degree yet allow for catalyst conversion for the regulatory life of the engine.
6. Class I engines are typically turned off via a simple circuit that grounds the input side of the ignition coil. Temperature fail-safe capability could, if appropriate, be incorporated into the engine by installing a bimetal thermal switch in parallel with the ignition grounding circuit used for turning the engine off. The switch can be of the inexpensive bimetal disc type in wide-spread use in numerous consumer products (furnaces, water-heaters, ovens, hair dryers, etc.). To reduce cost, the bimetal switch could be a non-contact switch mounted to the engine immediately behind the muffler, similar to the

installation of bimetal sensors currently used to actuate automatic chokes on current Phase 2 Class I lawn mower engines.

4.2.6.2.2 Small SI Class II engines

Almost all Class II engines are air-cooled. Unlike Class I engines, Class II engines are not typically equipped with integral exhaust systems and fuel tanks. Significant applications include lawn tractors (largest segment), commercial turf equipment, generator sets and pumps. Overhead valve engines have largely replaced side-valve engines in Class II, with the few remaining side-valve engines certifying to the Phase II standards using emissions credits or being used in snow thrower type applications where the HC+NOx standards do not apply. Class II engines are typically built more robustly than Class I engines. They often use cast-iron cylinder liners, may use either splash lubrication or full-pressure lubrication, employ high volume cooling fans and in some cases, use significant shrouding to direct cooling air. Exhaust catalyst design practice for Class II engines will differ depending on the level of emission control. Class II engine designs are more suitable for higher-efficiency emission control systems than most Class I engine designs. The design factors are somewhat similar to Class I:

1. Class II engines are mostly air-cooled, and thus must run rich of stoichiometry at high loads. The ability to operate at air-to-fuel ratios rich of stoichiometry at high load may be more critical for some Class II engines than for Class I engines due to the longer useful life requirements in Class II. The larger displacement Class II engines have better efficiency combustion and some engines incorporate more advanced fuel metering and spark control than is typical in Class I, in order to meet the more stringent Class II Phase 2 emission standards (12.1 g/kW-hr HC+NOx in Class II versus 16.1 g/kW-hr in Class I). The heat energy available from CO oxidation is typically somewhat less than the case in Class I because of slightly lower average emission rates.
2. Class II engines have HC and NOx emissions that are generally in more equal portions, or have the potential to be, in the total regulated HC+NOx emissions and lower CO emissions than is the case for Class I engines.
3. Most Class II engines are equipped with 12-volt DC electrical systems for starting. Electronic controls relying on 12-volt DC power could be integrated into Class II engine designs. Low-cost electronic engine management systems are extensively used in motor scooter applications in Europe and Asia. Both Kohler and Honda have introduced Class II engines in North America that use electronic engine management systems.
4. Class II engines use inexpensive stamped mufflers with internal baffles similar to Class I, but the mufflers are often not integrated onto the engine design and may be remote mounted in a manner more typical of automotive mufflers. Class II mufflers are often not placed in the direct path of cooling air from the cooling fan.
5. As with Class I, the regulatory cycles (A-cycle, B-cycle), manufacturer's durability cycles and some limited in-use operation data indicate that emissions control should focus primarily on light and part load operation for the high volume sales of garden tractor equipment.

Taking these factors into account would point towards exhaust catalyst designs that differ from those of light duty gasoline exhaust catalysts and differ in some cases from Class I systems. Elements specific to Class II Phase 3 emission control system design using carburetor fuel systems would include:

1. Catalyst substrate volume would be sized relatively small so as to be space-velocity limited. Catalyst volume for Class II Phase 3 engines would be approximately 33-50 percent of the engine cylinder displacement, depending on cell count, engine-out emission levels, oil consumption and the useful life hours to which the engine's emissions are certified. Catalyst substrate sizes would be very compact within typical mufflers used in Class II, with typical catalyst substrate volumes of approximately 8 to 10 cubic inches (based on sales weighting within useful life categories). This would effectively limit mass transport to catalyst sites at moderate-to-high load conditions and reduce exothermic reactions occurring when exhaust temperature is highest.
2. Catalyst precious metal loading would be kept relatively low, and formulations would favor NOx and HC selectivity over CO selectivity to minimize heat concerns. We estimate that typical loading ratios for Phase 3 would be approximately in the range of 30 to 50 g/ft3 (approximately 50 percent of typical automotive loadings) and could be Pt:Rh, Pd:Rh or tri-metallic. Tri-metallic PGM loadings that replace a significant fraction of Pt with Pd would be less selective for CO oxidation and would also reduce the cost of the catalyst. Loading ratios would be similar or higher in Rh than what is typically used for automotive applications (20-25 percent of the total PGM mass in Small SI).
3. Catalysts would be integrated into the muffler design. Incorporating the catalyst into the muffler would reduce surface temperatures relative to the use of a separate catalyst component. The catalyst for Class II Phase 3 engines would be integrated into mufflers that are similar in volume to today's Class II Phase 2 mufflers. Appropriately positioned stamped heat-shielding and touch guards would be integrated into Class II Phase 3 catalyst-muffler designs in a manner similar to current product. Class II engines typically have a much higher volume of cooling air available downstream of the cylinder than Class I engines. Heat rejection from the cylinder and cylinder head increases the temperature of the cooling air, but it is still sufficiently below the temperature of exhaust system components to allow its use for forced cooling. Thus a degree of heat rejection would be available via forced convective cooling of exhaust components via the cooling fan. However, this would require some additional ducting to supply cooling air to exhaust system surfaces along with careful layout of engine and exhaust components within the design of the equipment that it is used to power. Integrated catalyst-mufflers can also use exhaust energy for ejector cooling (see chapter 6). Heat rejection to catalyst muffler surfaces to minimize "hot spots" can also be enhanced internally by turning the flow through multiple chambers and baffles that serve as sound attenuation within the muffler.
4. Some applications may include secondary air injection to enhance catalyst efficiency. Incorporation of passive secondary air allows halving of catalyst substrate volume for the same catalyst efficiency over the regulatory cycle. In many cases, this may not be necessary due to the lower engine-out emissions of Class II engines. In cases where secondary air is used, it could either be a passive system similar to the previously described Class I systems, or an active system with an engine driven pump. Pump drive for active systems could be either 12-volt DC electric or via crankcase pulse, and pump

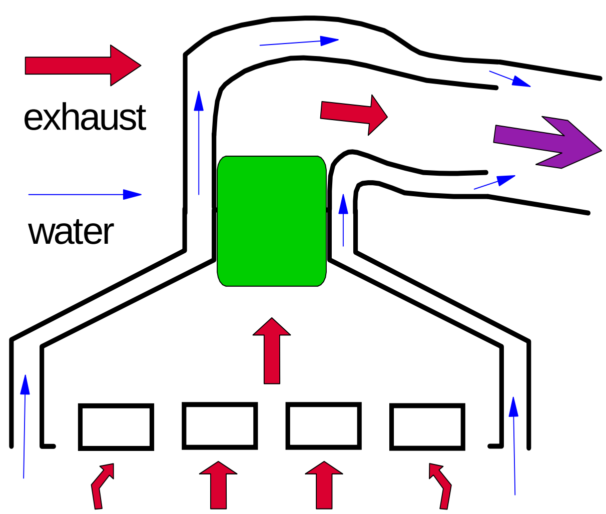
actuation could be actively controlled using an electric solenoid or solenoid valve. The use of active systems is an option but seems unlikely. The most likely control scenario for Class II would be a combination of engine out emission control, use of a small catalyst, and no use of secondary air.

Higher catalyst efficiency, considerably lower exhaust emissions levels, and improved fuel consumption are possible with Class II engines, but heat rejection and safety considerations might necessitate the use of electronic engine management and open-loop fuel injections systems. In such a case, the design and integration of the emission control system would more closely resemble automotive applications with the use of electronic engine management and larger catalyst volumes with higher precious metal loadings.

4.2.6.2.3 Marine SI

Due to the design of marine exhaust systems, fitting a catalyst into the exhaust system raises unique application issues for many boat/engine designs. Often boat builders will strive to minimize the space taken up in the boat by the engine compartment. In addition, these exhaust systems are designed, for safety reasons, to avoid hot surface temperatures. For most Marine SI engines, the surface temperature is kept low by running raw water through a jacket around the exhaust system. This raw water is then mixed with the exhaust before being passed out of the engine. To avoid a major redesign of the exhaust system, the catalyst must be placed upstream of where the water and exhaust mix. In addition, the catalyst must be insulated and/or water-jacketed to keep the surface temperatures of the exhaust low.

Figure 4.2-1: Placement of Marine Catalyst



As discussed later in this chapter, testing has been performed on prototype systems where small catalysts have been placed in the exhaust manifolds of SD/I engines. Figure 4.2-1 illustrates one installation design. For outboard engines, this packaging arrangement would be less straightforward because of the very short exhaust path between the cylinder exhaust ports and where the cooling water and exhaust mix. However, it may be possible to engineer a packaging solution for outboards as well similar to that shown for SD/I in Figure 4.2-1.

Several marine engine manufacturers are now producing engines with water jacketed catalysts in the exhaust. As discussed later in this chapter, one manufacturer has certified personal watercraft engines with catalysts packaged in the exhaust system. These are small oxidation catalysts used in conjunction with two-stroke engines. Two manufacturers are selling marine generators with catalysts. Also, one SD/I engine marinizer has recently added an engine with catalysts in the exhaust to its product line.

Another issue is maintaining high enough temperatures with a water-jacketed catalyst for the catalyst to react properly. The light-off temperature of these advanced catalysts is in the range of 250 to 270°C which was low enough for the catalysts to work effectively in our laboratory tests. However, it could be necessary for manufacturers to retard the spark timing at idle and low load for some engines to maintain this minimum temperature in the catalyst.

The matching of the catalyst to the engine may have to be compromised to fit it into the exhaust manifold. However, significant reductions are still achievable. One study on a 4.3 liter automotive engine looked at three different Pd-only catalyst displacements. The smallest of these catalysts had a displacement ratio of 0.12 to 1. The HC+NOx downstream of the catalyst was measured to be from 1.2 to 2.6 grams per mile, depending on the severity of the catalyst aging.[15] This is equivalent to about 1.5 to 3.2 g/kW-hr based on highway operation.[16] This work suggests that significant reductions are achievable with an "undersized" catalyst. As discussed later in this chapter, significant reductions in exhaust emissions have been demonstrated for catalysts packaged in SD/I exhaust systems.

4.2.6.3 Catalyst Durability

Two aspects of marine applications that could affect catalyst durability are thermal load and vibration. Because the catalyst would be coupled close to the exhaust ports, it would likely see temperatures as high as 750 to 850°C when the engine is operated at full power. The bed temperature of the catalyst would be higher due to the reactions in the catalyst. However, even at full power, the bed temperature of the catalyst most likely would not exceed the exhaust temperature by more than 50-100°C. In our laboratory testing, we minimized the temperature at full load by operating the engine with a rich air-fuel mixture. The temperatures seen were well within the operating range of new Pd-only catalysts which are capable of withstanding prolonged exposure to temperatures approaching 1100°C.[17]

In on-highway applications, catalysts are designed to operate in gasoline vehicles for more than 100,000 miles. This translates to about 4,000-5,000 hours of use on the engine/catalyst. We estimate that, due to low annual hours of operation, the average useful life of Small SI and Marine SI engines is only a fraction percent of this value. This suggests that catalysts designed for automotive use should be durable over the useful life of a Small SI and Marine SI engines. Use of catalysts in automotive, motorcycle, and hand-held equipment applications suggests that catalysts can be packaged to withstand the vibration in the exhaust manifold. As discussed later in this chapter, catalysts have recently been demonstrated, through in-use testing, to be durable over the useful lives of SD/I marine vessels.

4.2.6.4 Water Reversion

Another aspect of marine applications that could affect catalyst durability is the effect of water contact with the catalyst. There is concern that, in some designs, water could creep back up the exhaust passages, due to pressure pulses in the exhaust, and damage the catalyst and oxygen sensor. This damage could be due to thermal shock from cold water coming into contact with a hot catalyst or due to salt deposition on the catalyst. One study was performed, using a two-stroke outboard equipped with a catalyst, to investigate the effect of water exposure on a catalyst.[18] The results of this study are summarized in Table 4.2-1.

Table 4.2-1: Summary of Marine Catalyst Durability Study

Issue	Investigation	Result
high catalyst temperatures	- compared base catalyst to catalysts aged for 10 hrs at 900 and 1050°C	- little change in conversion efficiency observed
saltwater effects	- soaked catalysts in two seawater solutions and compared to base catalyst - used intake air with a salt-water mist	- large drop in conversion efficiency observed - no effect on catalyst
fresh water effects	- soaked catalyst in fresh water and compared to base catalyst - flushed out catalyst with fresh water that was soaked in saltwater	- little change in conversion efficiency observed - washing catalyst removes salt and restores some performance
thermal shock of hot catalyst with cold water	- as part of the catalyst soaking tests, 900°C catalysts were soaked in both salt and fresh water	- no damage to the catalysts was reported
deterioration factor	- operated engine with catalyst for 300 hours of E4 operation	- 20% loss in conversion efficiency for a 2-stroke engine

The above study on catalysts in marine applications was performed supplemental to an earlier study.[19] The earlier study also showed that immersing the catalysts in saltwater would hurt the conversion efficiency of the catalyst, but that operating in a marine environment would not. In addition, this earlier study showed that much of the efficiency loss due to salt on the catalyst could be reversed by flushing the catalyst with water. This paper also showed that with the catalyst activated, temperatures at full power were less than at mid power because the space velocity of the exhaust gases at rated speed was high enough to reduce the conversion efficiency of the catalyst.

A study of water reversion was performed on a vessel powered by a sterndrive engine.[20] However, it was found that the water found in the exhaust system upstream of where the exhaust and water mix was due to condensation. This condensation was a result of cool surfaces in the exhaust pipe due to the water-jacketing of the exhaust. This study found that the condensation could be largely resolved by controlling the exhaust cooling water temperature with a thermostat. Since that time, data has been collected on a number of catalyst-equipped SD/I vessels operated either in salt or fresh-water. This data, which showed no significant catalyst deterioration, is discussed later in this chapter. These engines were designed to prevent water reversion by placing the catalyst near the engine and away from the water/exhaust mixing point. In addition, some of the prototype designs used either a water dam or mist barrier to help limit any potential water reversion.

4.2.7 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. 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.[21]

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.[22] 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, offers 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.[23] 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 quickly.[24] 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.

4.3 Feasibility of Small SI Engine Standards

We are establishing new, more stringent HC+NOx standards for Small SI engines (<19kW) used in nonhandheld, terrestrial applications (we are also setting a CO std for Small SI engines used in marine applications that is discussed in Section 4.4). The standards differ by engine size. Class I engines have a total cylinder displacement of < 225cc. Class II engines have a total displacement of ≥225cc. We are also making changes to the emission certification protocols for durability testing and test fuel specifications for both classes. The new certification requirements will improve emissions performance of these engines over their regulatory lifetime and better align the test fuel with in-use fuel characteristics.

Table 4.3-1 shows the existing Phase 2 exhaust emission standards for Class I and II small spark ignition engines as well as the new Phase 3 standards. The Phase 3 standards represent a nominal 35-40 percent reduction from current standards.

Table 4.3-1: Comparison of Phase 2 and Phase 3 Standards for Small Spark-Ignition Engines

Engine Class	Phase 2 Standards (HC+NOx g/kW-hr)	Phase 3 Standards (HC+NOx g/kW-hr)	Percent Reduction (%)
Class I (<225 cc)	16.1	10.0	38
Class II (≥225cc)	12.1	8.0	34

The following sections present the technical analyses and information that support our view that the Phase 3 exhaust emission requirements are technically feasible. We begin with a review of the current state of compliance with the Phase 2 standards relative to the Phase 3 standards and conclude with a more in depth assessment of the technical feasibility of the requirements for Class I gasoline-fueled engines, Class II single-cylinder gasoline-fueled engines, Class II multi-cylinder gasoline-fueled engines, and both classes of gaseous-fueled (e.g., liquid propane gas) engines.

4.3.1 Current Technology and 2008 Certification Test Data

In the 2008 model year manufacturers certified engines to the Phase 2 standards using a variety of engine designs and emission control technology. Table 4.3-2 shows manufacturers' projected engine sales by technology type. For Class I engines, side-valve designs represent the majority of sales, although there are also a significant number of overhead-valve sales. An extremely small number of engines used catalyst-based emission control technology. Class II is dominated by overhead-valve engine designs. A limited number of these engines used catalyst technology, electronic fuel injection, or were water cooled.

Table 4.3-2: 2005 Engine Sales by Technology Market Mix

Engine Technology	Class I	Class II
Side Valve	66%	2%
Overhead Valve	34%	98%
With Catalyst	0.003%	0.4%
With Other (Electronic Fuel Injection and/or water cooled)	0	1%

Looking at the industry from an engine family rather than a sales perspective, shows that 68 and 212 engine families were emission certified in Class I and II, respectively for 2008. The range of technology types is shown in Table 4.3-3. The majority of engine families in Class I are overhead-valve, carbureted engines, with only 14 families using side-valve, carbureted designs (the side-valve engines still account for the bulk of Class I sales). Five families utilized catalytic exhaust aftertreatment.

Table 4.3-3: 2005 Small Spark-Ignition Engine Technology Types and Number of Engine Families

	Side-Valve		Overhead Valve					
Engine Class	Single-Cylinder Carburetor	Single-Cylinder Carburetor w. Catalyst	Single-Cylinder Carburetor	Single-Cylinder Carburetor w. Catalyst	Multi-Cylinder Carburetor	Multi-Cylinder Carburetor w. Catalyst	Multi-Cylinder Fuel Injection	Multi-Cylinder Fuel Injection w. Catalyst
I	yes (14)	no	yes (48)	yes (4)	no	no	no	no
II	yes (2)	yes (0)	yes (43)	no	yes (105)	yes (6)	yes (6)	yes (8)

In Class II, the majority of the engine families use multi-cylinder (predominately v-twins) designs incorporating overhead-valve technology. Most of these multi-cylinder families utilized carburetors, with a few using catalytic exhaust aftertreatment, fuel injection, or electronic engine controls. There are relatively fewer single-cylinder engine families using the older, less sophisticated side-valve technology. None of these engines were certified with catalytic aftertreatment.

Figures 4.3-1 and 4.3-2 present the 2008 certification results at full life for Class I and II engine families, respectively, by technology type.[1] One striking feature of these figures, especially Figure 4.3-2, is that there are a number of engine families displaying emission levels well above the existing, i.e., Phase 2, standards. Generally, these families represent somewhat older technology, low production engines that have been certified using preexisting emission credits. Under the conditions of the final Phase 3 rules, these engine families will be unable to be certified using existing credits. As a consequence, we expect these families will be eliminated in favor of newer designs when the Phase 3 standards become effective.

Looking at the remaining engine families, several families were certified at levels necessary to comply with the Phase 3 standards. Also, a number of families are very close to the requisite emission levels. This suggests that, even accounting for the relative increase in stringency associated with our certification protocols, a number of families will either not need to do anything or require only modest reductions in their emission performance to meet the new standards.

[1] The data presented in Figure 4.3-1 and Figure 4.3-2 are consistent with the 2008 certification data used for the cost analysis in Chapter 6. This data does not include certification data from the nearly 90 Chinese manufacturers that have started certifying nonhandheld engines with EPA in the last few years. (As noted in Chapter 6, EPA has chosen not include data from Chinese manufacturers because we have no information on actual sales of their engines in the United States. Based on discussions with nonhandheld engine manufacturers that have been certifying with EPA for over ten years now, it is our understanding that sales of nonhandheld engines from Chinese manufacturers are relatively small at this time.) The certification levels of the engines certified by Chinese manufacturers generally fall within the same range as the engines presented in Figure 4.3-1 and Figure 4.3-2.

Figure 4.3-1:Class I HC+NOx Full Life Certification Results for 2008

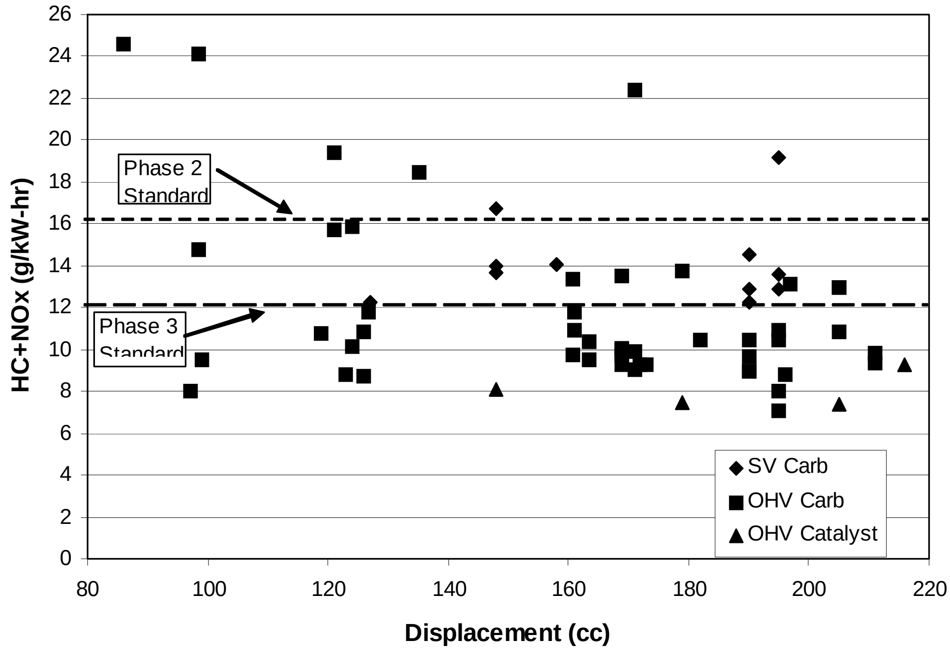
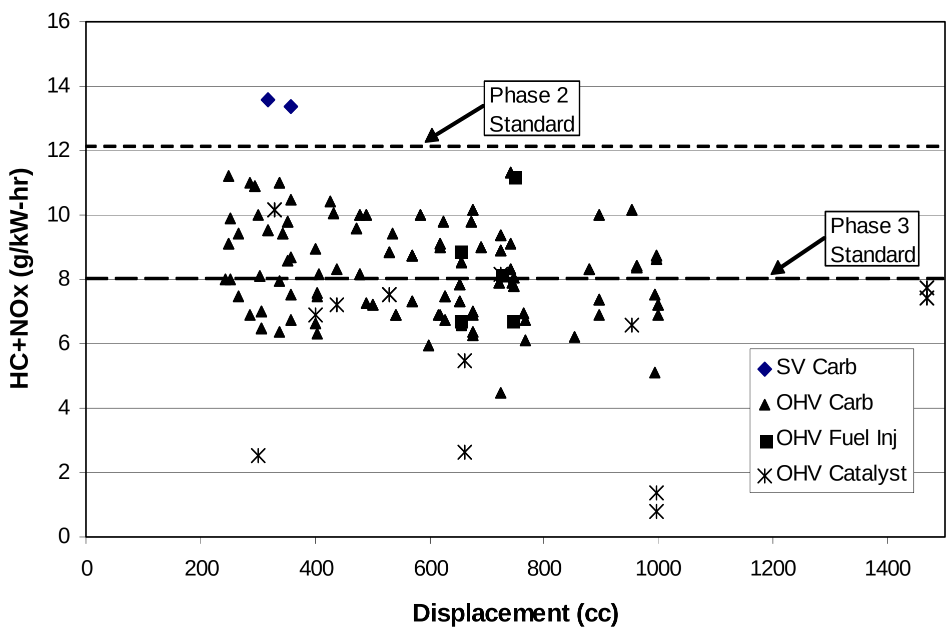


Figure 4.3-2: Class II HC+NOx Full Life Certification Results for 2008



4.3.2 Technology Assessment and Demonstration

As described above, a number of engine families already are certified to emission levels that likely would comply with the Phase 3 standards. However, many engine families clearly will have to do more to improve emission performance. Generally, we believe the new requirements will require many engine manufacturers to adopt exhaust aftertreatment technology using catalyst-based systems. Other likely changes include improved engine designs and fuel delivery systems. Finally, adding electronic controls or fuel injection systems may obviate the need for catalytic aftertreatment for some engine families, with the most likely candidates being multi-cylinder engine designs.

Many of the technical design considerations for adapting advanced emission controls to Small SI engines were presented in Section 4.2. These included redirected air from the cooling fan, redirected exhaust flow through multiple chamber and baffles within the catalyst muffler, or other design considerations. (These are also the kinds of design elements that engine manufacturers will need to consider for safe and durable emission control systems.) In the remainder of this section we describe the specific results of our emission control assessment based on engine testing of exhaust catalyst systems, as well as a more specific discussion of other potential emission reduction technology for certain engine types such as electronic engine controls and fuel injection. The results of our safety assessment are described later in section 4.8 of this chapter.

4.3.2.1 Overview of Technology Assessment

Our feasibility assessment began by evaluating the emissions performance of current technology for Small SI engines and equipment. These initial efforts focused on developing a baseline for emissions and general engine performance so that we could assess the potential for new emission standards for engines and equipment in this category. This process involved laboratory and field evaluations of the current engines and equipment. We reviewed engineering information and data on existing engine designs and their emissions performance. We also reviewed patents of existing catalyst/muffler designs for Class I engines. We engaged engine manufacturers and suppliers of emission control-related engine components in discussions regarding recent and expected advances in emissions performance beyond that required to comply with the current Phase 2 standards. Finally, we purchased catalyst/muffler units that were already in mass production by an original equipment manufacturer for use on European walk-behind lawn mowers and conducted engineering and chemical analysis on the design and materials of those units.

We used the information and experience gathered in the above effort along with the previous catalyst design experience of our engineering staff to design and build prototype catalyst-based emission control systems that were capable of effectively and safely achieving the Phase 3 requirement based on dynamometer and field testing. We also used the information and the results of our engine testing to assess the potential need for improvements to engine and fuel system designs, and the selective use of electronic engine controls and fuel injection on some engine types. A great deal of this effort was conducted in association with our more exhaustive study regarding the efficacy and safety of implementing advanced exhaust emission controls on Small SI engines, as well as new evaporative requirements for these engines.[25] In other testing, we evaluated advanced emission controls on a multi-cylinder Class II engine with electronic fuel injection.[26]

In designing our engine testing program, we selected engines certified to the Phase 2 emission standards that were expected to remain compliant with those standards for the duration of their useful life based on our low-hour emission testing and the manufacturer's declared deterioration factor from the certification records for that engine family. We also selected engine families that represented: 1) a cross section of Class I and Class II side-valve and overhead-valve technologies; and 2) higher sales volume families. Each engine was maintained based on the manufacturer's specifications.[2] The results of our specific technical feasibility assessment are presented below.

4.3.2.2 Class I Gasoline-Fueled Engines

We tested six side-valve and six overhead-valve Class I engines that used gasoline fuel with prototype catalyst/muffler control systems. The primary design target for selecting the catalyst configuration, e.g., volume, substrate, platinum group metal (PGM), was to achieve emission levels below the limit of 10 g/kW-hr HC+NOx for this class at 125 hours of engine operation. That time period represents the useful life requirement for the most common application in this category, i.e., residential walk-behind lawn mowers. A maximum of about 7 g/kW-hr HC+NOx was set as the low-hour performance target with a catalyst system to allow for engine and emission control degradation over the engine's useful life. This level assumes a certification cushion at low hours of 1 g/kW-hr HC+NOx and a multiplicative deterioration factor of 1.3. Secondary design targets were primarily safety related and included minimizing CO oxidation at moderate to high load conditions to maintain exhaust system surface temperatures comparable to those of the original Phase 2 compliant systems. The test engine, size, and salient catalyst features are shown in Table 4.3-4.

Table 4.3-5 presents the results of our catalyst testing on Class I engines.[27,28] Three of the engines were tested at high hours. The high-hour results for the remaining engines were projected from their low-hour emission performance. We projected high-hour emission results for these engines by applying the multiplicative deterioration factor from the manufacturer's Phase 2 certification application to the low-hour emission test results. The certification deterioration factors ranged from 1.097 to 1.302 g/kW-hr HC+NOx. [3] As shown, each of the engines achieved the requisite emission limit of 10 g/kW-hr HC+NOx at the end of their useful lives.

[2] The specific test engines were generally used in residential lawn mower and lawn tractor applications. These applications were chosen for field testing as part of our safety study because they represented certain potentially unique and challenging safety concerns connected with operation and storage in environments with combustible debris.

[3] These results were taken from the 2005 certification results.

Table 4.3-4: Class I Test Engine and Control Technology Description

Engine ID	Displace-ment (L)	Valve Train	Fuel Metering	Passive (Venturi) Secondary Air?	Catalyst Type	Catalyst Volume	Catalyst Cell Density	PGM Loading (mass/catalyst volume, Pt:Pd:Rh ratio)
236	0.20	Side	Carburetor	Yes	Metal monolith	44 cc	200 cpsi	30 g/ft^3, 4:0:1
246	0.20	Side	Carburetor	Yes	Metal monolith	44 cc	200 cpsi	30 g/ft^3, 4:0:1
248	0.20	Side	Carburetor	Yes	Metal monolith	44 cc	200 cpsi	30 g/ft^3, 0.33:3.66:1
249	0.20	Side	Carburetor		Wire-mesh	60 cc	N/A	proprietary, 0:0:1
6820	0.19	Side	Carburetor	Yes	Cordierite Ceramic Monolith	40 cc	400 cpsi	30 g/ft^3, 5:0:1
258	0.19	Side	Carburetor	Yes	Cordierite Ceramic Monolith	40 cc	400 cpsi	30 g/ft^3, 5:0:1
241	0.19	Overhead	Carburetor	Yes	Cordierite Ceramic Monolith	40 cc	400 cpsi	30 g/ft^3, 5:0:1
255	0.19	Overhead	Carburetor	Yes	Coated tube pre-catalyst, Metal monolith main-body catalyst	20 mm dia. X 73 mm long exhaust tubing, 22 cc metal monolith	Tube: 2 channels (annular shape), Main body: 200 cpsi	Tube: Proprietary Main body: 30 g/ft^3, 3:1:1
2982	0.19	Overhead	Carburetor	Yes	Metal monolith	34 cc	100 cpsi	50 g/ft^3, 5:0:1
243	0.16	Overhead	Carburetor	Yes	Cordierite Ceramic Monolith	30 cc	400 cpsi	30 g/ft^3, 5:0:1
244	0.16	Over-head	Carburetor	Yes	Metal monolith	44 cc	200 cpsi	30 g/ft^3, 1:3:1
245	0.16	Overhead	Carburetor	Yes	Metal monolith	44 cc	200 cpsi	30 g/ft^3, 3:1:1

Table 4.3-5: Class I Emission Results with Advanced Catalytic Control Technology

Engine	Age (hours)[1]	HC+NOx (g/kW-hr)
236	10-20	4.9 ± 0.6[2]
	Projected High	**6.1**
246	10-20	5.6
	Projected High	**7.0**
248	10-20	4.6
	Projected High	**5.7**
249	10-20	6.3
	Projected High	**7.8**
6820	Not Tested	na
	>110	**9.4**
258	10-20	6.7
	>110	**8.2**
241	10-20	3.9 ± 0.2
	>110	**6.6 ± 0.2**
255	10-20	5.0
	Projected High	**6.5**
2982	10-20	4.9 ± 0.3
	>110	**7.0 ± 0.4**
243	10-20	7 ± 1
	Projected High	**7.7**
244	10-20	7.2
	Projected High	**7.9**
245	10-20	5.6
	Projected High	**6.1**

[1] Projected high hour results estimated by multiplying the low hour test results by the manufacturer's certification deterioration rate.
[2] "±" values represent the 95% confidence intervals of 3 tests using a 2-sided t-test.

The above method for projecting high-hour emission results using a certification deterioration factor assumes that the catalyst system will control engine-out emissions to the same extent, i.e., proportional reduction, over the useful life of the engine. For some engines this may not always be the case depending on oil consumption, air-to-fuel ratio and other factors that may change the effectiveness of the catalyst over time.[4] Our approach also did not explicitly account for the fact that manufacturers will generally design the engine and catalyst to provide some certification cushion. It appears that most of the engines in Tables 4.3-5 would accommodate the above design considerations. However, the projected high-hour results are uncomfortably close to the 10 g/kW-hr HC+NOx standard for engine number 6820. In these cases, such factors can be accounted for by the engine manufacturer in the engine family's research and design phase by either improving the durability of the engine (see the discussion below) or designing the catalyst to account for degradation in catalyst effectiveness over time, e.g, more precious metal loading, larger catalyst volume, dividing the catalyst into two separate pieces within the exhaust stream, etc.

The technical feasibility of the Phase 3 standard for Class I engines is supported by a number of Small SI engine manufacturers.[29,30,31,32] Also, a manufacturer of emission controls specifically indicated the types of hardware that may be needed to comply with new standards.[33] That manufacturer concluded that, depending on the application and engine family, either catalyst or electronic engine controls should be able to achieve emission standards as low as 9 g/kW-hr HC+NOx. As demonstrated above, we believe the standard of 10 g/kW-hr HC+NOx can be achieved using catalysts only. However, based on our engineering judgment, we agree that it may be possible to achieve the standard with the sole use of electronic engine controls because of the more precise management of air-fuel mixtures and ignition spark timing offered by that technology.

We conducted a design and process Failure Mode and Effects Analysis study to assess the safety of implementing advanced exhaust emission controls on Small SI engines.[34] That work, which was based in part on our engine test program, suggests that manufacturers of Class I may need to improve the durability of basic engine designs, ignition systems, or fuel metering systems for some engines in order to comply with the emission regulations at full useful life. Some of these emission-related improvements may include:

1. Adding a fuel filter or improving the needle and seat design in the carburetor to minimize fuel metering problems caused by debris from the fuel tank;
2. Improving intake manifold design or materials to reduce air leaks;
3. Upgrading the ignition system design for better ignition spark reliability and durability;
4. Improving design and manufacturing processes for carburetors to reduce the production variability in air-fuel mixtures; and

[4] Catalyst performance degradation can occur from thermal sintering and catalyst poisoning due to oil consumption. Catalyst performance can also improve as engine air-to-fuel ratio slowly drifts towards stoichiometry over the useful life of the engine. Air-cooled engines are typically designed with air-to-fuel ratio calibrations that take into account lean-drift with extended operation, and are designed with a sufficiently rich air-to-fuel ratio to prevent net-lean operation at high hours that could result in engine damage or deteriorating engine performance.

5. Enhancing exhaust manifold design for better reliability and durability.

4.3.2.3 Class II Single-Cylinder Gasoline-Fueled Engines

Class II single-cylinder engines that use gasoline fuel are currently certified and sold under the Phase 2 standard in both side-valve and overhead-valve configurations. In 2008, only 2 out of 107 Class II single-cylinder engine families used side-value designs. Manufacturers certified these families under the averaging provisions of the applicable regulations with emission credits that were generated by (low emitting) overhead-valve engines. We believe that the Phase 3 standard will reduce the number of emission credits available for the certification of side-valve technology. As a result, we assume that a number of the remaining Class II side-valve engines may be phased out of applicable manufacturer's product line in the future.

Based on the above, we did not directly assess the technical feasibility of the standard for side-valve Class II engines in our test program. Instead we assessed only single-cylinder, overhead-valve Class II engines with prototype catalyst/muffler control systems. The primary design target for selecting the catalyst configuration for these engines, e.g., volume, substrate, design and PGM loading, was to achieve emission levels well below the limit of 8 g/kW-hr HC+NOx for this class to accommodate the longer useful life of many of these engines. The emission regulations allow useful lives ranging from 250 to1000 hours. For two of the engines families, we selected emission control technology with a target of meeting a 3.5 g/kW-hr HC+NOx. This included the use of electronic engine and fuel controls to improve the management of air-fuel mixtures and ignition spark timing that allow, among other advantages, the use of larger catalyst volumes and higher precious metal loading. Secondary design targets were primarily safety related and included minimizing CO oxidation at moderate to high load conditions to maintain exhaust system surface temperatures comparable to those of the original Phase 2 compliant systems. The test engines, size, salient catalyst parameters, and use of electronic engine controls are shown in Table 4.3-6.

Table 4.3-6: Class II Single-Cylinder Test Engine and Control Technology Description

Engine	Displacement (L)	Useful Life	Fuel Metering	Catalyst Type	Catalyst Volume	Catalyst Cell Density	Catalyst Loading
142	0.40	500 hour	Carburetor	Cordierite Ceramic Monolith	250 cc	400 cpsi	40 g/ft^3, 5:0:1[1]
231	0.50	250 hour	Electronic Fuel Injection	Metal monolith	280 cc	200 cpsi	70 g/ft^3, 0:5:1
251	0.50	250 hour	Carburetor	Cordierite Ceramic Monolith	250 cc	400 cpsi	40 g/ft^3, 5:0:1
253	0.50	250 hour	Carburetor	Cordierite Ceramic Monolith	250 cc	400 cpsi	40 g/ft^3, 5:0:1
254	0.59	250 hour	Carburetor	Cordierite Ceramic Monolith	250 cc	400 cpsi	40 g/ft^3, 5:0:1
232	0.49	1,000 hour	Electronic Fuel Injection	Metal monolith	250 cc	200 cpsi	40 g/ft^3, 5:0:1

[1] Metal loading expressed as a ratio of platinum:palladium:rhodium.

Table 4.3-7 shows the results of our catalyst testing on single cylinder Class II engines. Only one of the engines was tested at high hours. As explained above for the Class I engines, the high-hour results for the remaining engines were projected from their low-hour emission performance. We projected high-time emission results for these engines by applying the multiplicative deterioration factor from the manufacturer's Phase 2 certification application to the low-hour emission test results. The certification deterioration factors ranged from 1.033 to 1.240 g/kW-hr HC+NOx.[5] As shown, each of the engines achieved the requisite emission limit of 8 g/kW-hr HC+NOx.

[5] These results were taken from the 2005 certification results.

Table 4.3-7: Class II Single-Cylinder Emission Results with Advanced Catalytic Control Technology

Engine	Age (hours)[1]	HC+NOx (g/kW-hr)
231 (w/ EFI)	10-40	1.8 ± 0.4[2]
	Projected High	**2.2**
232 (w/ EFI)	10-40	2.2 ± 0.1
	Projected High	**2.3**
251	10-40	3.1 ± .3
	Projected High	**3.8**
253	10-40	4.5 ± 0.1
	Projected High	**5.6**
254	10-40	4.0 ± 0.3
	Projected High	**4.5**
142	50	2.5 ± 0.6
	500	**2.8**

[1] Projected high-hour results estimated by multiplying the low-hour test results by the manufacturer's 2005 certification deterioration rate.
[2] "±" values represent the 95% confidence intervals of 3 tests using a 2-sided t-test.

Again, as with Class I engines, the technical feasibility of the Class II standard was supported by a number of Small SI engine manufacturers.[35363738] Also, a manufacturer of emission controls specifically indicated the types of hardware that may be needed to comply with new standards.[39] That manufacturer concluded that, depending on application and engine family, a catalyst and electronic engine controls should be capable of achieving emission standards as low as 7 g/kW-hr HC+NOx. Also, as described above, that same manufacturer concluded that, again depending on the application and engine family, either catalyst or electronic engine controls should be able to achieve emission standards as low as 9 g/kW-hr HC+NOx. Our standard of 8 g/kW-hr HC+NOx is in between these two regions. Therefore, based solely on that manufacturer's conclusions, complying with the standard may require control technology ranging from either a catalyst or electronic engine controls, or a combination of both.

Based on the above information, especially our testing as discussed previously, we conclude that catalysts do not necessarily need to be used in conjunction with electronic engine controls to achieve our standard of 8 g/kW-hr HC+NOx. Either one of those technologies appear sufficient. In fact, market forces may cause some manufacturers to shift to electronic controls in the absence of more stringent emission standards. Nonetheless, we can not discount the possibility that both technologies may be used by some manufacturers to meet the standard on single-cylinder Class II engines. (See section 4.2.3.4 for more on electronic engine control and fuel injection.)

The design and process Failure Mode and Effects Analysis study mentioned previously suggests that manufacturers of Class II may need to improve the durability of basic engine designs, ignition systems, or fuel metering systems for some engines in order to comply with the emission regulations at full useful life.[40] Some of these emission-related improvements may include:

1. Reducing the variability in air-fuel mixtures with tighter manufacturing tolerances for fuel metering components; and
2. Improving the ignition system design for better ignition spark reliability and durability.

4.3.2.4 Class II Multi-Cylinder Gasoline-Fueled Engines

Gasoline-fueled Class II multi-cylinder engines are very similar to their single-cylinder counterparts. Beyond the difference in the number of cylinders, several more Class II multi-cylinder engine families are currently certified with catalysts and electronic engine control technology (either with or without a catalyst). Because of the direct similarities and the use of more sophisticated emission control-related technology on some engine families, we find that our conclusions regarding the technical feasibility of the 8 g/kW-hr HC+NOx standard for single-cylinder Class II engines is directly transferable to multi-cylinder Class II engines.

Nonetheless, we also tested two twin-cylinder gasoline-fueled Class II engines from different engine families by the same manufacturer.[41] The engines were basically identical except for their fuel metering systems, i.e., carbureted or electronic fuel injection. We tested both without modification and tested the electronic fuel injected engine with a catalyst system that we developed. All the tests were conducted when the engines had accumulated 10-15 total hours of operating time.

The results of this testing are shown in Table 4.3-8. As was done for the Class I and II single-cylinder engines discussed earlier, we projected emission levels at the end of each engine's useful life using the multiplicative deterioration factors for each engine family as reported in the manufacturer's Phase 2 certification application. As shown, the carbureted engine is projected to have end of life emissions of approximately 9.1 g/kW-hr. Based on our experience with single-cylinder engines, compliance with the new standard may require the use of a catalyst for this engine family. The unmodified engine with electronic fuel injection is projected to achieve about 7.3 g/kW-hr. This engine is very close to complying with the standard and will most likely require only additional fuel-air mixture and injection timing calibration changes for compliance.

Table 4.3-8: Class II Multi-Cylinder
Emission Results with Advanced Catalytic Control Technology
(V-Twin, Approximately 0.7 Liter Displacement, 3-Way Catalyst)

Engine Configu r-ation	Fuel Metering	Age (hours)[1]	HC+NOx (g/kW-hr)	Catalyst Type	Catalyst Volume	Catalyst Cell Density	Catalyst Loading
OEM	Carburet	10-40	7.2	--	--	--	--
		Projected	**9.1**	--	--	--	--
OEM	EFI	10-40	5.9	--	--	--	--
		Projected	**7.3**	--	--	--	--
OEM w/	EFI	10-40	1.8	Cordierite	700cc	400 cpsi	60 g/ft[3],
catalyst		**Projected**	2.2	same	same	same	same

[1] Projected high-hour results estimated by multiplying the low-hour test results by the manufacturer's 2004 certification deterioration rate.
[2] Metal loading expressed as a ratio of platinum:palladium:rhodium.

Finally, the combination of electronic fuel injection and catalytic exhaust aftertreatment clearly has the potential to reduce emissions well below the Phase 3 standard as shown in the table.

We also evaluated emission control technology for twin-cylinder Class II engines, and by analogy all multi-cylinder engines, as part of our safety study.[42] Here again we did not find any unique challenges in designing catalyst-based control systems for these multi-cylinder engines relative to the feasibility of complying with the exhaust standards under normal engine operation. However, we did conclude that these engines may present unique concern with the application of catalytic control technology under atypical operation conditions. More specifically, the concern relates to the potential consequences of combustion misfire or a complete lack of combustion in one of the two or more cylinders when a single catalyst/muffler design is used. (A single muffler is typically used in Class II applications.) In a single-catalyst system, the unburned fuel and air mixture from the malfunctioning cylinder would combine with hot exhaust gases from the other, properly operating cylinder. This condition would create high temperatures within the muffler system as the unburned fuel and air charge from the misfiring cylinder combusts within the exhaust system. This could potentially destroy the catalyst.

One solution is simply to have a separate catalyst/muffler for each cylinder. Another solution is to employ electronic engine controls to monitor ignition and either put the engine into "limp-mode" or shut the engine down until the condition clears on re-start or until necessary repairs are made, if appropriate. For engines using carburetors, this would effectively require the addition of electronic controls. For engines employing electronic fuel injection that may need to also employ a small catalyst, it would require that the electronic controls incorporate ignition misfire detection if they do not already utilize the inherent capabilities within the engine management system.

We expect some engine families will use electronic fuel injection to meet the Phase 3 standard without employing catalytic aftertreatment. As described earlier, engine families that already use these fuel metering systems and are reasonably close to complying with the requirement are likely to need only additional calibration changes to the engine management system for compliance. In addition, we expect that some engine families which currently use carbureted fuel systems will convert directly to electronic fuel injection. Manufacturers may adopt this strategy to couple achieving the standard without a catalyst and realizing other advantages of using fuel injection such as easier starting, more stable and reliable engine operation, and reduced fuel consumption. A few engine manufacturers have confidentially confirmed their plans to use electronic fuel injection on some engine families in the future as part of an engine management strategy in lieu of using catalysts.

Our evaluation of electronic fuel injection systems that could be used to attain the new standard found that a rather simple, low cost system should be sufficient. We demonstrated this proof of concept as part of the engine test program we conducted for our safety study. In that program, we fitted two single-cylinder Class II engines with an electronic control unit and fuel system components developed for Asian motor-scooters and small-displacement motorcycles. The sensors for the system were minimized to include a throttle position sensor, air charge temperature sensor, oil temperature sensor, manifold absolute pressure sensor, and a crankshaft position sensor. This is in contrast to the original equipment manufacturer (OEM) fuel injection systems currently used in some two-cylinder Class II engine applications that employ more sophisticated and expensive automotive-based components.

Regarding the electronic control unit and fuel system components referenced above and in previous sections, at least two small engine manufacturers have developed simplified, compact, low-cost electronically controlled fuel injection systems for small motorcycles and scooters.[4344] One manufacturer has also developed a general purpose small engine with electronic engine speed control technology that eliminates the need for a battery.[45,46] These manufacturers have generally reported a number of benefits for these advanced systems, including lower emissions and better fuel economy.

4.3.2.5 Class II Gaseous-Fueled Engines

Engine manufacturers and equipment manufacturers certify engines to run on liquid propane gas (LPG) or compressed natural gas (CNG) in a number of applications including indoor floor buffers which require low CO emissions. The technology to reduce emissions to the Phase 3 levels is catalyst due the fact that most engines run closer to stoichiometry than gasoline engines and further enleanment to reduce emissions may not be feasible. Due to the high amount of NOx compared with HC, as seen from engine data in the certification database, the catalysts may need to be designed to reduce NOx and oxidize a limited amount of CO. The EPA 2008 Certification Database lists 6 multi-cylinder engine families in the Class II 1000 useful life category as having catalysts. Due to this fact, it is assumed that gaseous engines do not have the same concerns with multi-cylinder engines and catalysts as gasoline engines.

4.4 Feasibility of Outboard/Personal Watercraft Marine Engine Standards

Outboard and personal watercraft (OB/PWC) engines are subject to exhaust emission standards which require approximately a 75 percent reduction in hydrocarbon emissions compared to conventional carbureted, crankcase-scavenged two-stroke engines. Because of the emission credit program included in these requirements, manufacturers are able to sell a mix of old and new technology engines to meet the standards on average.

We are finalizing new exhaust emission standards for OB/PWC engines based on the emissions results achievable from the newer technology engines. These technologies have primarily been two-stroke direct injection and four-stroke engine designs. For a few model years, one manufacturer certified PWC engines with catalytic aftertreatment. This section presents emission data for 2004 model year outboard and personal watercraft engines and includes a description of the various emission control technologies used. In addition, the possibility of using catalytic aftertreatment on OB/PWC engines is discussed.

4.4.1 OB/PWC Certification Test Data

When engine manufacturers apply for certification to exhaust emission standards, they submit exhaust emission test data. In the case of the OB/PWC engines, the emission standards are based on the sum of hydrocarbons and oxides of nitrogen (HC+NOx). Manufacturers submit emission test data on HC and NOx to demonstrate their emission levels. Although carbon monoxide (CO) emissions are not currently regulated, manufacturers submit data on CO emissions as well.

Three primary technologies are used on Marine SI engines: conventional two-stroke engines, direct injection two-stroke engines, and four-stroke engines. Conventional two-stroke engines are primarily carbureted, but larger engines may have indirect fuel injection systems as well (IDI). Four stroke engines come in carbureted, throttle-body fuel injected (TBI), and multi-port fuel injection (MPI) versions. These technologies are discussed in more detail in Section 4.4.2.

4.4.1.1 HC+NOx Certification Data

Figure 4.4-1 presents HC+NOx certification levels for 2006 model year outboard engines and compares this data to the existing and new exhaust emission standards. These certification levels are based on test data over the ISO E4 duty cycle with an adjustment for emissions deterioration over the regulatory useful life. The certification data set includes engines well above and below the emission standard. Manufacturers are able to certify to the standard by meeting it on average. In other words, clean engines generate emission credits which offset the debits incurred by the engines emitting above the standard. Figure 4.4-2 presents only the data from engines that meet the 2006 standard. As shown in these figures, two-stroke direct injection engines and four-stroke engines easily meet the 2006 standard.

Figure 4.4-1: 2006 MY Outboard HC+NOx Certification Levels

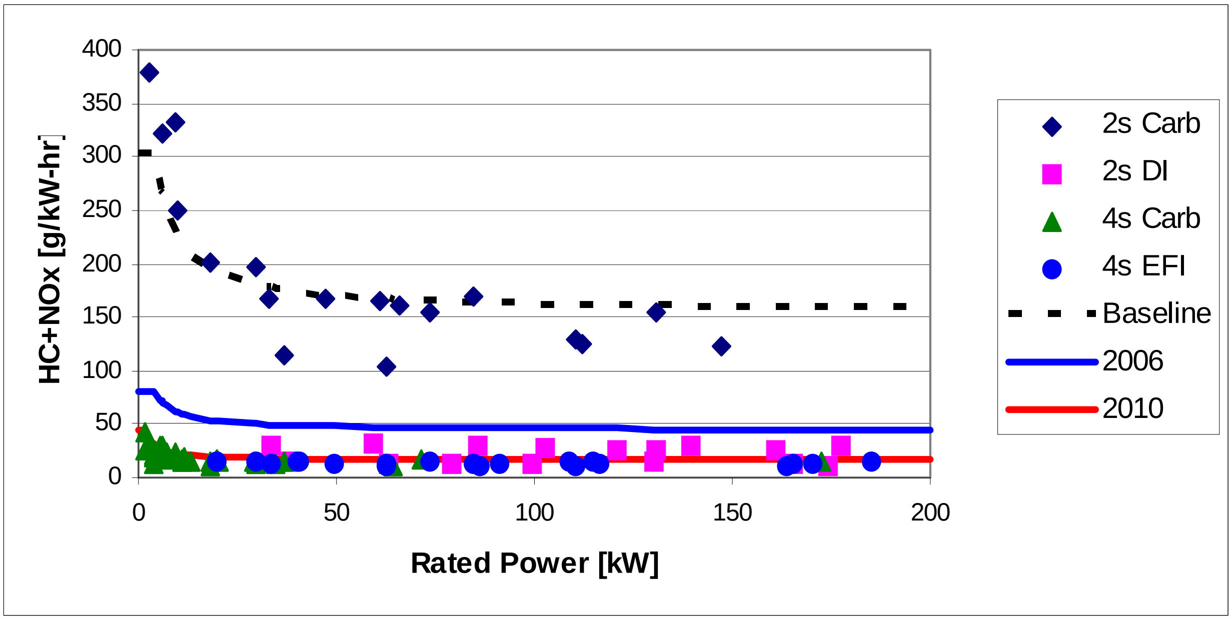
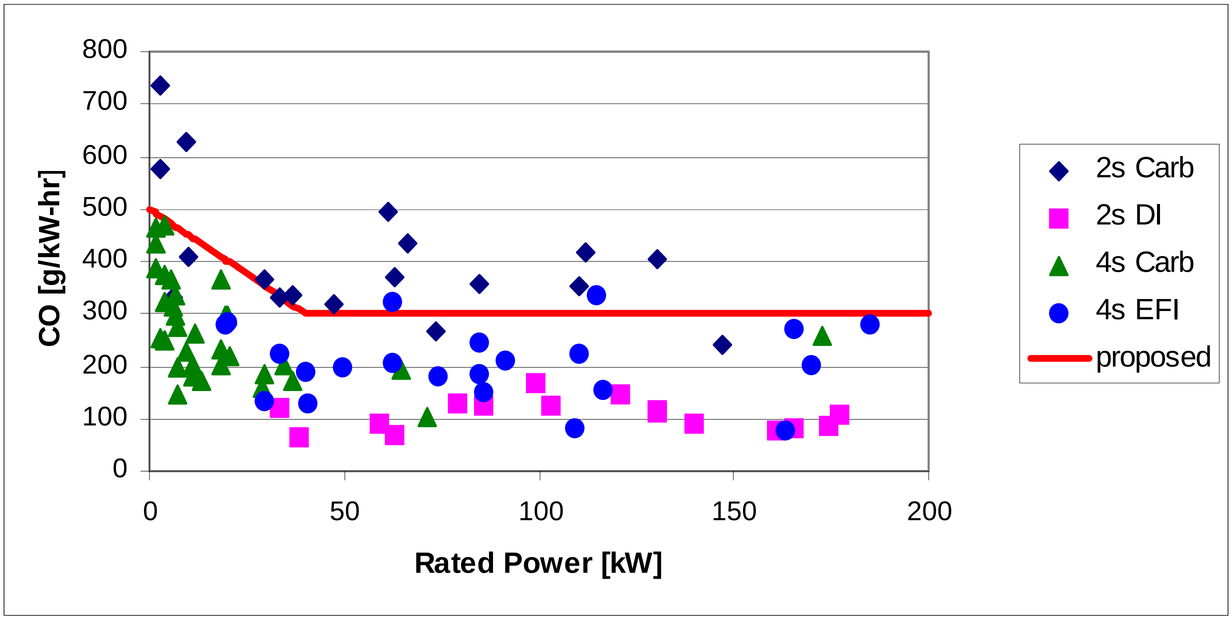


Figure 4.4-2: 2006 MY New Technology Outboard HC+NOx Certification Levels



Figures 4.4-3 and 4.4-4 present similar data for personal watercraft engines. These engines

use similar technology, but the HC+NOx emissions are a little higher on average, presumably due to higher average power densities for PWC engines. This difference in emissions is reflected in the new HC+NOx standards.

Figure 4.4-3: 2006 MY Personal Watercraft HC+NOx Certification Levels

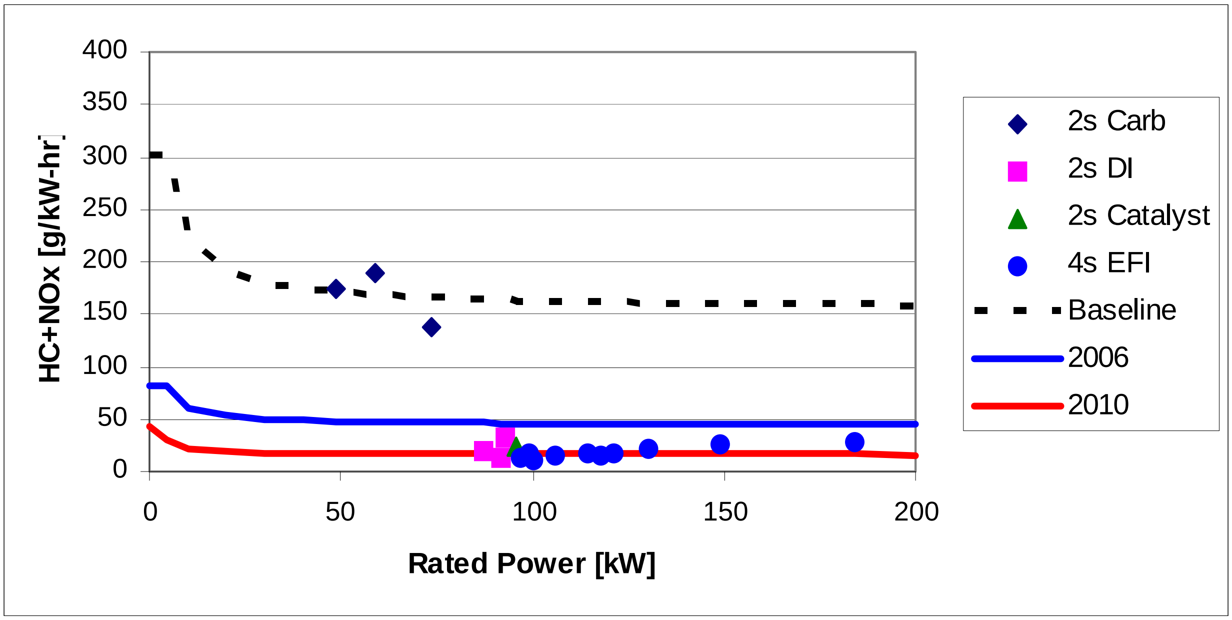
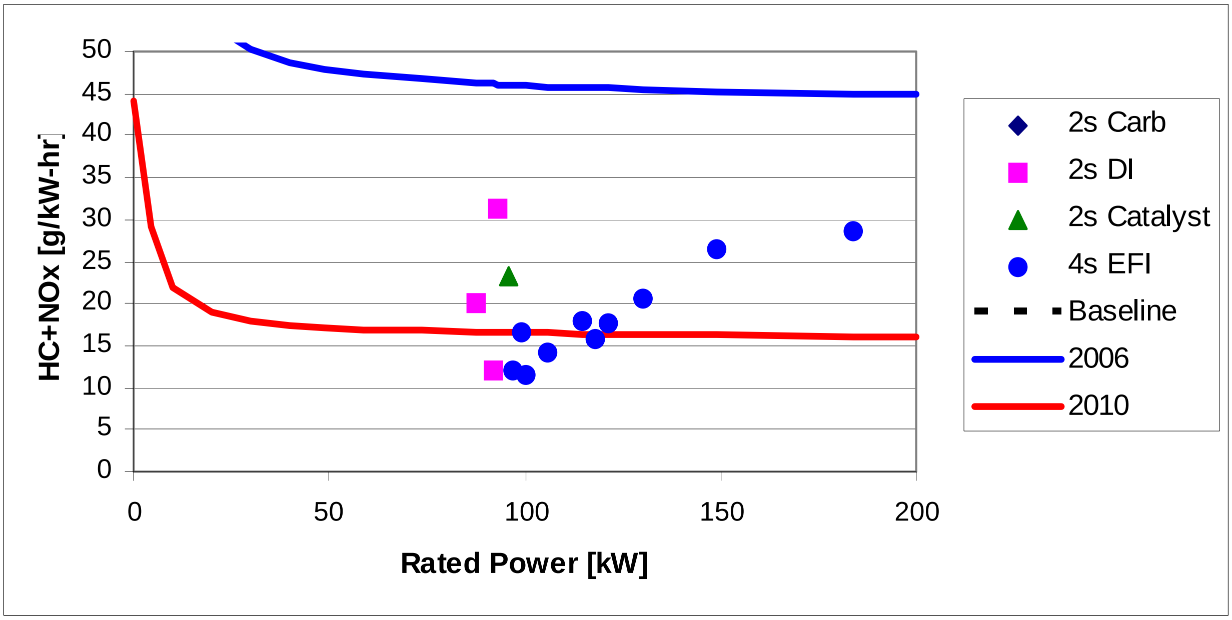


Figure 4.4-4: 2006 MY New Technology PWC HC+NOx Certification Levels



4.4.1.2 CO Certification Data

Although no exhaust emission standards for CO are currently in place for Marine SI engines, the technological advances associated with the HC+NOx standards have resulted in lower CO emissions for many engines. Figures 4.4-5 and 4.4-6 present reported CO exhaust emission levels for certified outboard and personal watercraft engines. These engines use similar technology as outboard engines and show similar emission results.

Figure 4.4-5: Reported CO Emission Levels for 2006 MY Outboard Engines

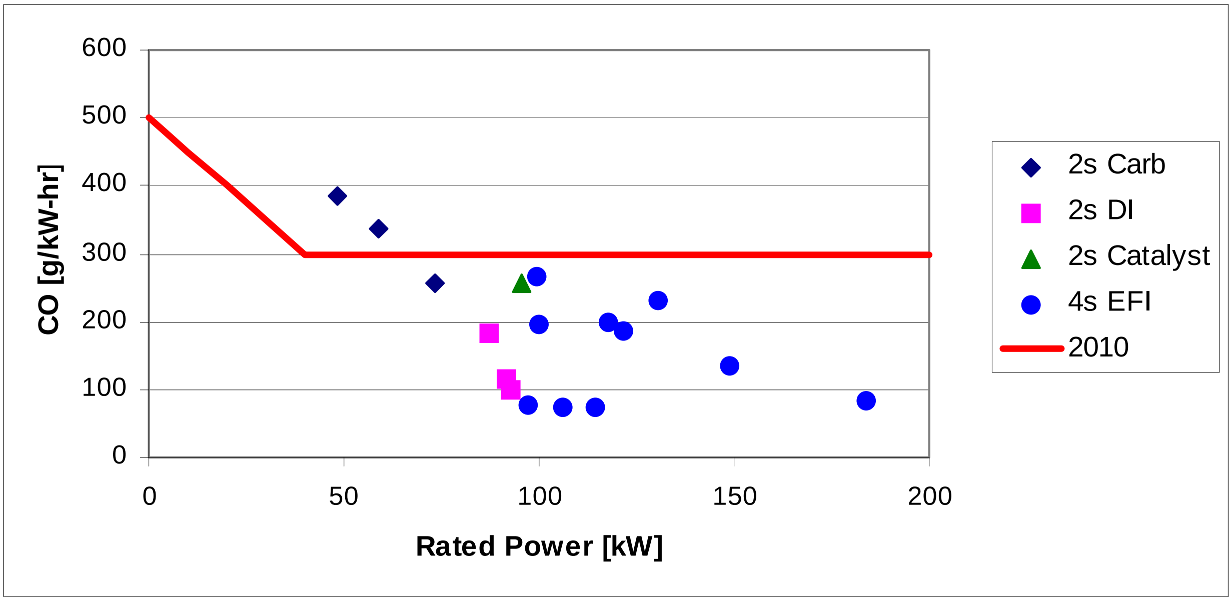
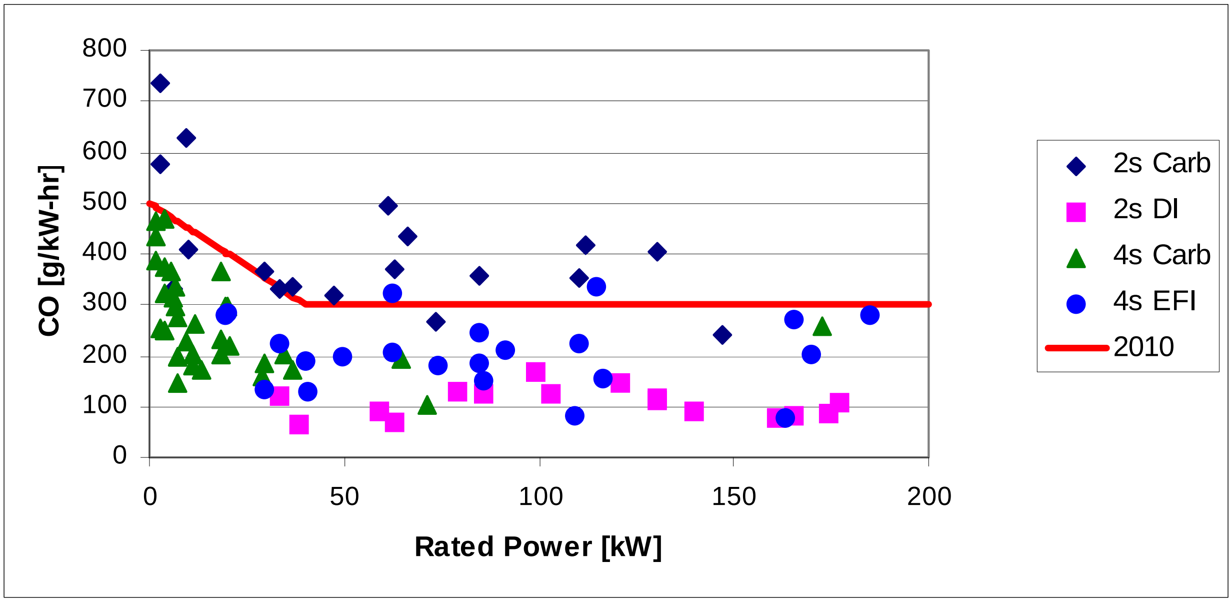


Figure 4.4-6: Reported CO Emission Levels for 2006 MY PWC Engines



4.4.2 OB/PWC Emission Control Technologies

This section discusses the how general technologies discussed above apply to outboard and PWC applications and discusses specific OB/PWC technology.

4.4.2.1 Conventional Two-Stroke Engines

As discussed earlier in this chapter, hydrocarbon emissions from two-stroke engines are primarily the result of short-circuiting losses where unburned fuel passes through the engine and out the exhaust during cylinder charging. Even with an indirect injection system, the air and fuel are mixed prior to entering the cylinder. Therefore, even though there is better metering of fuel and air than with a carbureted engine, short-circuiting losses still occur. Because of the very rich and cool conditions, little NOx is formed. As shown in Figures 4.4-1 and 4.4-2, HC emissions can range from 100 to 400 g/kW-hr. CO is formed as a product of incomplete combustion. As a result, CO emissions range from 200 to 500 g/kW-hr from these engines.

4.4.2.2 Direct Injection Two-Stroke Engines

The primary advantage of direct-injection (DI) for a two-stroke is that the exhaust gases can be scavenged with fresh air and fuel can be injected into the combustion chamber after the exhaust port closes. As a result, hydrocarbon emissions, fuel economy, and oil consumption are greatly improved. Some users prefer direct-injection two-stroke engines over four-stroke engines due to the higher power to weight ratio. Today, this technology is used on engines with power ratings ranging from 35 to 220 kW. One manufacturer has recently stated its plans to manufacture DI two-stroke engines as low as 7.4 kW.

Most of the DI two-stroke engines currently certified to the current OB/PWC emissions standards have HC+NOx emissions levels somewhat higher than certified four-stroke engines. These engines also typically have lower CO emissions due to the nature of a heterogeneous charge. By injecting the fuel directly into a charge of air in the combustion chamber, localized areas of lean air/fuel mixtures are created where CO is efficiently oxidized. PM emissions may be higher for DI two-stroke engines than for four-stroke engines because oil is burned in the combustion chamber and because of localized rich areas in the fuel injection stream.

Recently, one manufacturer has introduced a newer technology DI two-stroke engine that has comparable HC+NOx emission results as many of the certified four-stroke engines.[47] This engine makes use of a low-pressure fuel injection nozzle that relies on high swirl to produce uniform fuel flow rates and droplet sizes. Also, significant improvements have been made in oil consumption. As with the older DI two-stroke designs, CO emissions are much lower than comparable four-stroke engines. What is unique about this design is that the manufacturer has reported lower PM emissions than for a comparable four-stroke engine.

4.4.2.3 Four Stroke Engines

Manufacturers currently offer four-stroke Marine SI engines with power ratings ranging from 1.5 to 224 kW. These engines are available with carburetion, throttle-body fuel injection, or multi-point fuel injection. Carbureted engines are offered from 1.5 to 60 kW while fuel injected engines are offered from 22 to 224 kW. One manufacturer has stated that the fuel injection systems are too expensive to use on the smaller engine sizes. Most of the four-stroke outboard engines above 19 kW have HC+NOx emissions below 16 g/kW-hr and many have emissions below 13 g/kW-hr. CO emissions for these engines range from 150 to 250 g/kW-hr. Based on the certification data, whether the engine is carbureted or fuel injected does not have a significant effect on combined HC+NOx emissions. For PWC engines, the HC+NOx levels are somewhat higher. However, many of the four-stroke PWC engines are below 16 g/kW-hr. CO emissions for these engines are similar as those for four-stroke outboards.

4.4.2.4 Catalysts

Figure 4.4-7: PWC Engine with Catalyst

One manufacturer has certified two PWC engine models with oxidation catalysts. One engine model uses the oxidation catalyst in conjunction with a carburetor while the other uses throttle-body fuel injection. The engine with throttle-body fuel injection has an HC+NOx emission rate of 25 g/kW-hr which is significantly below the EPA 2006 standard. In this application, the exhaust system is shaped in such a way to protect the catalyst from water and is nearly as large as the engine (see Figure 4.4-7). Manufacturers have recently begun efforts to develop a three-way catalyst system for PWC engines used in jet boats.

Catalysts have not yet been packaged into the exhaust system of production outboard marine engines. In current designs, water and exhaust are mixed in the exhaust system to help cool the exhaust and tune the engine. Water often works its way up through the exhaust system because the lower end in under water and due to pressure pulses. As discussed above, salt-water can be detrimental to catalyst performance and durability. In addition, the lower unit of outboards are designed to be as thin as possible to improve the ability to turn the engine on the back of the boat and to reduce drag on the lowest part of the unit. Certainly, the success of packaging catalysts in sterndrive and inboard boats in recent development efforts (see below) suggests that catalysts may be feasible for outboards. However, this has not yet been demonstrated and significant development efforts would be necessary.

4.5 Feasibility of Sterndrive/Inboard Marine Engine Standards

We are establishing exhaust emission standards for spark-ignition sterndrive and inboard (SD/I) engines. These new emission standards are supported by data collected on SD/I engines equipped with catalysts. This section presents exhaust emission data from baseline SD/I engines as well as data from SD/I engines equipped with lean calibrations, exhaust gas recirculation, and catalytic control.

4.5.1 Baseline SD/I Emissions Data

The vast majority of SD/I engines are four-stroke reciprocating piston engines similar to those used in automotive applications. The exceptions are small sales of air boats using aircraft piston-type engines and at least one marinizer that uses rotary engines. More than half of the new engines sold are equipped with electronic fuel injection while the rest still use carburetors. The majority of the electronic fuel injection systems are multi-port injection; however, throttle-body injection is also widely used, especially on smaller engines.

Table 4.5-1 presents baseline emissions for four-stroke SD/I engines built up from automotive engine blocks.[48,49,50,51,52,53,54] All these data were collected during laboratory tests over the ISO E4 duty cycle. Five of these engines are carbureted, one uses throttle-body fuel injection, and four use multi-port fuel injection. One of the multi-port fuel injected engines was tested with three calibrations. Note that without emissions calibrations performed specifically for low emissions, the HC+NOx emissions are roughly equal for the carbureted and fuel injected engines. Using the straight average, HC+NOx from the carbureted engines is 15.6 g/kW-hr while it is 16.0 g/kW-hr from the fuel injected engines (15.1 g/kW-hr if the low HC calibration outlier is excluded).

Table 4.5-1: Baseline SD/I Exhaust Emission Data

Engine #	Power [kW]	Fuel Delivery System	HC [g/kW-hr]	NOx [g/kW-hr]	CO [g/kW-hr]
1	79	carburetor	11.2	8.0	281
2	91	carburetor	4.4	13.9	98
3	121	carburetor	8.5	6.0	247
4	153	multi-port electronic fuel injection	4.9	11.7	111
5	158	carburetor	7.3	6.0	229
6	167	carburetor	8.0	5.7	174
7	196	carburetor	4.4	10.3	101
8	159	throttle-body fuel injection	2.9	8.7	42
9	185	multi-port electronic fuel injection	5.2	9.7	149
9	181	#9, low CO calibration	5.8	11.7	48
9	191	#9, low HC calibration	3.3	18.2	72
10	219	multi-port electronic fuel injection	4.7	9.4	160
11	229	multi-port electronic fuel injection	2.7	13.1	44

A distinct class of SD/I engines are the high-performance engines. These engines are similar to SD/I engines except that they are designed for high power output at the expense of engine durability. This high power output is typically achieved through higher fuel and air rates, larger combustion chambers, and through higher peak engine speeds. In most cases, custom engine blocks are used. Even in the engines that use an automotive block, few stock automotive engine components are used. Table 4.5-2 presents emission data collected by EPA on five high-performance engines.[55,56,57] This data also includes data submitted by a high performance engine manufacturer in its public comments on the proposed rule.[58]

Table 4.5-2: Baseline High Performance SD/I Exhaust Emission Data [g/kW-hr]

Power [kW]	Fuel Delivery System	HC	NOx	CO	BSFC
391	multi-port electronic fuel injection	14.7	3.8	243	354
550	carburetor	13.2[a]	8.4	253	376
634	multi-port electronic fuel injection, supercharger	16.9	9.1	135	348
778	throttle-body fuel-injection, supercharger, intercooler	7.6	4.9	349	448
802	multi-port electronic fuel injection, supercharger	16.1	9.4	102	299
466	electronic fuel injection	15.4[a]	3.2	257	--
410	electronic fuel injection	14.8[a]	3.9	325	--
466	electronic fuel injection, low emission calibration[b]	4.3	10.8	104	--

[a] HC concentration at idle was out of measurement range
[b] 15% load factor at idle

4.5.2 Exhaust Gas Recirculation Emission Data

We collected data on three engines over the ISO E4 marine test cycle with and without the use of exhaust gas recirculation (EGR).[59,60,61] The first engine was a 6.8 L Ford heavy-duty highway engine. Although this was not a marine engine, it uses the same basic technology as SD/I engines. The second and third engines were the 7.4 L and 4.3 L SD/I engines used in the catalyst development program described below. These engines are marinized versions of GM heavy-duty highway engines. The baseline emissions from the 7.4 L engine are a little different than presented below in the catalyst discussion because engine head was rebuilt prior to the catalyst development work.

This test data suggests that, through the use of EGR on a SD/I marine engine, a 40-50 percent reduction in NOx (30-40 percent reduction in HC+NOx) can be achieved. EGR was not applied at peak power in this testing because the throttle is wide open at this point and displacing fresh air with exhaust gas at this mode of operation would reduce power. We also did not apply EGR at idle because the idle mode does not contribute significantly to the cycle weighted NOx.

Table 4.5-3: Exhaust Emission Data Using EGR on the E4 Marine Duty Cycle

EGR Scenario	HC [g/kW-hr]	NOx [g/kW-hr]	CO [g/kW-hr]	Power [kW]	BSFC [g/kW-hr]
6.8 L Engine: baseline	2.7	13.4	26.5	145	326
with EGR	2.7	7.1	24.3	145	360
7.4 L Engine: baseline	4.5	8.4	171	209	349
with EGR	4.5	4.8	184	209	356
4.3 L Engine: baseline	4.9	11.7	111	153	329
with EGR	4.2	5.3	92	148	350

4.5.3 Catalytic Control Emission Data

4.5.3.1 Engine Testing

In a joint effort with the California Air Resources Board (ARB), we contracted with Southwest Research Institute to perform catalyst development and emission testing on a SD/I marine engine.[62] This test program was performed on a 7.4 L electronically controlled Mercruiser engine with multi-port fuel injection. Figure 4.5-1 illustrates the three primary catalyst packaging configurations used in this test program. The upper right-hand picture shows a catalyst packaged in a riser extension which would be placed between the lower exhaust manifold and the exhaust elbow. This riser had the same outer dimensions as the stock riser extension produced by Mercury Marine. The upper left-hand picture shows a catalyst packaged in the elbow. The lower picture shows a larger catalyst that was packaged downstream of the exhaust elbow. All of these catalyst configurations were water jacketed to prevent high surface temperatures.

Figure 4.5-1: Three Catalyst Configurations Used in SD/I Test Program

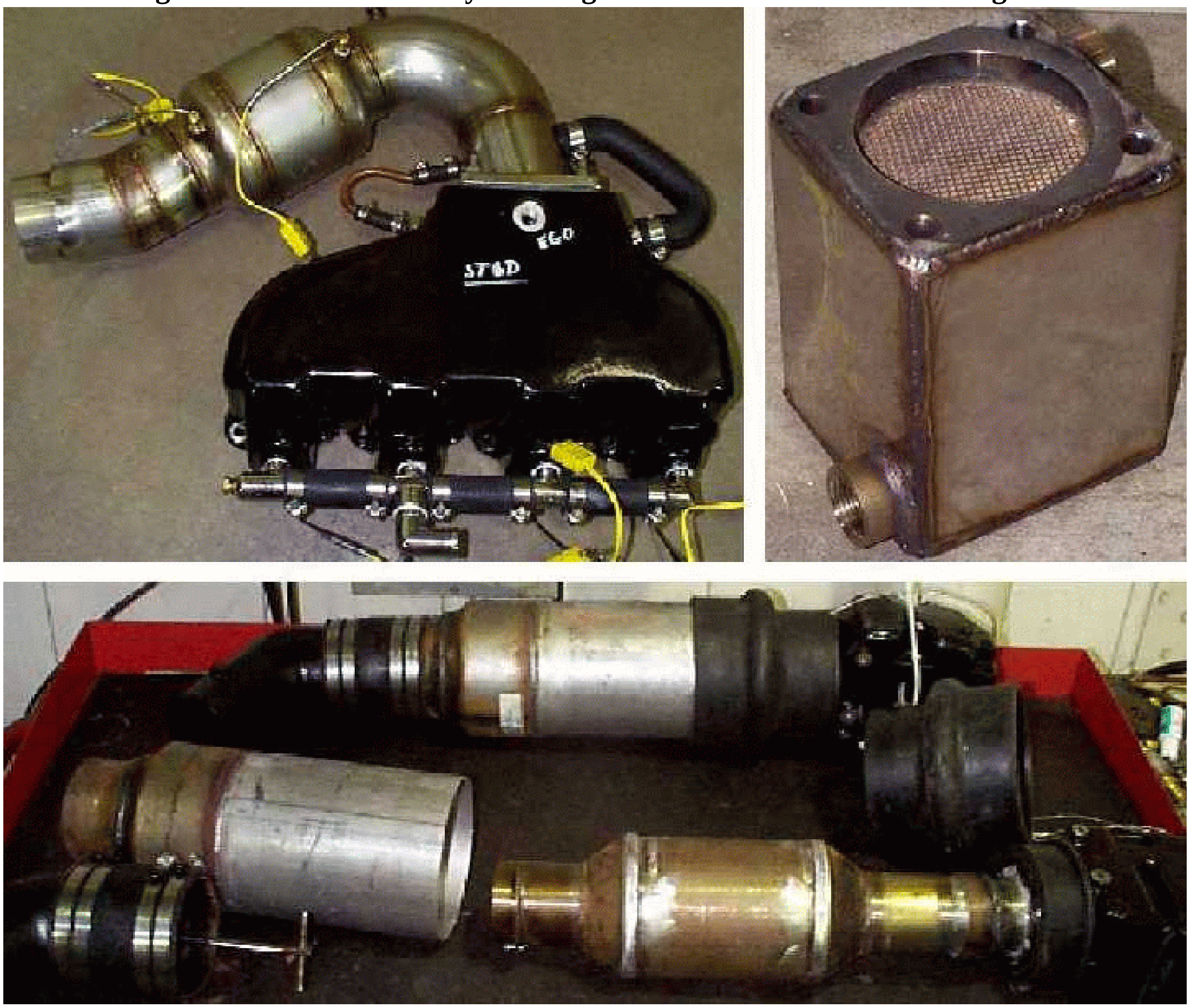


Table 4.5-4 presents the exhaust emission results for the baseline test and three catalyst packaging configurations. In each case a pair of catalysts were used, one for each exhaust manifold. For the riser catalyst configuration, we tested the engine with two cell densities, 60 and 300 cells per square inch (cpsi), to investigate the effects of back-pressure on power. The catalysts reduced in HC+NOx in the range of 42 to 77 percent and reduced CO in the range of 46 to 54 percent. There were no significant impacts on power, and fuel consumption actually improved due to the closed-loop engine calibrations necessary to optimize the catalyst effectiveness. At the full power mode, we left the engine controls in open-loop and allowed it to operate rich to protect the catalysts from over-heating.

Table 4.5-4: Exhaust Emission Data on a 7.4 L SD/I Engine with Various Catalysts

Catalyst Scenario* (cell density, volume, location)	HC [g/kW-hr]	NOx [g/kW-hr]	CO [g/kW-hr]	Power [kW]	BSFC [g/kW-hr]
baseline (no catalyst)	4.7	9.4	160	219	357
60 cpsi, 0.7 L, riser	2.5	5.7	81	214	345
300 cpsi, 0.7 L, riser	1.7	1.9	87	213	349
400 cpsi, 1.3 L, elbow	2.8	1.1	81	217	337
200 cpsi, 1.7 L, downstream	2.1	1.2	83	221	341

*Multiply volume by two for total catalyst volume per engine.

Additional reductions in HC+NOx and CO can be achieved by using EGR in addition to a catalyst. However, the added benefit of EGR is small compared to the emission reductions achieved by the catalysts. Regardless, the use of EGR could give manufacturers some flexibility in the design of their catalyst. In the catalyst testing work described above on the 7.4 L SD/I marine engine, each of the catalyst configurations were tested with and without EGR. Table 4.5-5 presents these test results.

Table 4.5-5: Exhaust Emission Data on a 7.4 L SD/I Engine with Catalysts and EGR

Catalyst Scenario* (cell density, volume, location)	HC+NOx [g/kW-hr]		CO [g/kW-hr]	
	catalyst	catalyst + EGR	catalyst	catalyst + EGR
60 cpsi, 0.7 L, riser	8.2	6.8	81	74
300 cpsi, 0.7 L, riser	3.6	2.8	87	77
400 cpsi, 1.3 L, elbow	3.9	3.3	81	76
200 cpsi, 1.7 L, downstream	3.3	2.5	83	73

*Multiply volume by two for total catalyst volume per engine.

4.5.3.2 Freshwater Boat Testing

The catalyst testing described above was a first step in developing and demonstrating catalysts that can reduce emissions from Marine SI engines. However, this program only looked at catalysts operating in a laboratory. Additional efforts have been made to address issues with using catalyst in marine applications by operating engines in boats with catalysts. When the California Air Resources Board finalized their catalyst-based emission standards for SD/I engines, they agreed to further assessment of the durability of catalyst used in boats through technology review.

To that end, ARB, industry and the U.S. Coast Guard recently performed a cooperative in-boat demonstration program designed to demonstrate the feasibility of using catalysts in SD/I applications.[63,64] This testing included four boats, two engine types, and four catalysts. The catalysts were packaged in the exhaust emission manifold in such a way that they were water-jacketed and capable of fitting within the existing boat design. Each of the boats were operated by the U.S. Coast Guard for 480 hours on a fresh water lake. This service accumulation period, which was intended to represent the useful life of typical SD/I engines, began in December of 2003 and was completed in September of 2004. Table 4.5-6 presents a description of the boats that were used in the test program.

Table 4.5-6: Vessel Configurations for Full Useful Life Catalyst Testing

Boat	Engine	Catalyst Type	Catalyst Volume*	Catalyst Cell Density
Inboard Straight-Drive Ski Boat	5.7 L, V-8	metallic	1.4 L	300 cpsi
Inboard V-Drive Runabout	5.7 L, V-8	ceramic	1.7 L	400 cpsi
22 ft, Sterndrive Bowrider	5.7 L, V-8	metallic	1.4 L	200 cpsi
19 ft. Sterndrive Runabout	4.3 L, V-6	ceramic	0.7 L	400 cpsi

*Multiply volume by two for total catalyst volume per engine.

Exhaust emissions were measured for each catalyst before and after the durability testing.[65] No significant deterioration was observed on any of the catalysts. In fact, all of the 5.7 L engines were below the standard of 5 g/kW-hr HC+NOx even after the durability testing. Although the zero hour emissions for the 4.3 L engine were less than half of the HC+NOx standard, the final emissions for the 4.3 L engine were 15 percent above the HC+NOx standard. However, it should be noted that the 4.3L engine was determined to have excessive fuel delivered to one cylinder bank and low compression in one of the cylinders. These problems did not appear to be related to the catalyst installations and would account for the increase in emissions even without catalyst deterioration. Once the calibration on this engine was corrected, a level of 5 g/kW-hr HC+NOx was achieved. In addition, no deterioration was observed in the oxygen sensors which were installed upstream of the catalysts.

Significant carbon monoxide emission reductions were achieved, especially at lower power modes. At wide-open-throttle, the engines operated in open-loop to prevent the exhaust valves from overheating. Additional reductions in CO could be achieved through better fuel air ratio control. For instance, although the engines in this test program were fuel injected, batch injections were used. In other words, all of the fuel injectors for each bank were firing at the same time rather than timing the fuel injection with the valve timing for each individual cylinder. Because of this strategy, the engine would need to be calibrated somewhat rich. The next generation of electronics for these engines are expected to have more sophisticated control which would allow for optimized timing for each fuel injector.

Table 4.5-7: Vessel Configurations for Full Useful Life Catalyst Testing

Boat	Catalyst Aging	HC [g/kW-hr]	NOx [g/kW-hr]	CO [g/kW-hr]
5.7 L engine 4.3 L engine	baseline (no catalyst) baseline (no catalyst)	5.4 4.9	6.7 11.7	193 111
Inboard Straight-Drive Ski Boat	0 hours 480 hours	1.7 2.1	1.0 1.7	100 117
Inboard V-Drive Runabout	0 hours 480 hours	1.8 1.7	0.5 1.0	87 102
22 ft, Sterndrive Bowrider	0 hours 480 hours	1.8 1.5	0.5 0.9	74 93
19 ft. Sterndrive Runabout	0 hours 480 hours*	1.9 2.9	0.5 2.1	106 116

* after calibration corrected

4.5.3.3 Saltwater Boat Testing

Two test programs were initiated to investigate the feasibility of using catalysts on boats used in saltwater. In the first program, a small boat with a catalyst was operated over a set of operation conditions, developed by industry, to represent the worst case conditions for water reversion. In the second test program, three boats were equipped with catalysts and operated for an extended period similar to the fresh water testing.

4.5.3.3.1 Safety, Durability, and Performance Testing

We contracted with SwRI to test catalysts on a sterndrive engine before and after operation on a boat in saltwater.[66] The purpose of the testing was to determine if the catalyst would be damaged by water reversion in the exhaust manifold. This testing was performed on a 19 foot runabout with a 4.3 L sterndrive engine. On previous testing on this boat without a catalyst, SwRI found that the only water collected in the exhaust manifold was due to condensation. They were able to prevent this condensation by fitting the water jacket around the exhaust system with a thermostat to keep the manifold walls from becoming too cool.

The 4.3 L engine was fitted with a pair of riser catalysts similar to the one illustrated in Figure 4.5-1. These catalysts had a cell density of 300 cpsi and a combined volume of 1.4 L. The catalysts were water-jacketed to maintain low surface temperatures and, to prevent any possible water reversion, cones were inserted in the exhaust elbows. These cones were intended to increase the difficulty for water to creep up the inner walls of the exhaust manifold. The water jacketing system was fitted with a 82°C thermostat to keep the manifold wall temperatures above the dew point of the exhaust gas (~50°C) thereby preventing water condensation in the exhaust manifold.

Prior to testing, the catalysts were aged using a rapid aging cycle designed to represent 50,000 miles of vehicle operation. SwRI estimated that this would likely be more severe than would be seen over the useful life of an SD/I engine. The engine was then tested for emissions, in a test cell, with and without the aged catalysts installed in the exhaust manifold risers. In addition to adding the catalysts, the engine fueling was optimized using closed-loop electronic emission control.

After the baseline emission tests, the catalysts were installed on a 19 foot runabout equipped with a similar 4.3 L engine used in the emissions test cell. The boat was operated on saltwater over a number of safety, durability, and performance tests that were developed by industry for heat soak, water ingestion, and engine exhaust back-pressure. In addition, SwRI operated the boat over tests that they designed to represent operation and use that would most likely induce water reversion. After this boat testing, the catalyst was returned to the laboratory for a repetition of the baseline emission tests.

Table 4.5-8 presents the baseline, aged catalyst, and post boat operation catalyst emission test results. No significant deterioration of the catalysts were observed. Prior to boat testing, the aged catalysts achieved a 75 percent reduction in HC+NOx and a 36 percent reduction in CO. After the boat operation in saltwater, the catalysts achieved a 73 percent reduction in HC+NOx and a 34 percent reduction in CO. As described in Chapter 3, if saltwater had reached the catalyst, there would have been a large reduction in catalyst efficiency. No salt deposits were observed on the catalysts when they were removed from the boat.

Table 4.5-8: Exhaust Emission Data on a 4.3 L SD/I Engine with Catalysts

Catalyst Scenario	HC [g/kW-hr]	NOx [g/kW-hr]	CO [g/kW-hr]	Power [kW]	BSFC [g/kW-hr]
open-loop, no catalyst	4.9	11.7	111	153	329
closed-loop, no catalyst	4.5	10.4	101	153	327
aged catalyst pre boat	2.1	2.0	70	154	321
aged catalyst post boat	2.2	2.3	73	150	327

4.5.3.3.2 Extended Period In-Use Testing

We engaged in a test program with the California Resources Board, United States Coast Guard, National Marine Manufacturers Association, the Texas Department of Parks and Wildlife, and Southwest Research Institute to evaluate three additional engines with catalysts in vessels operating on salt-water. Early in the program, two of the three manifolds experienced corrosion in the salt-water environment resulting in water leaks and damage to the catalyst. These manifolds were rebuilt with guidance from experts in the marine industry and additional hours were accumulated on the boats. Although the accumulated hours are well below the 480 hours performed on fresh water, the completed operation showed no visible evidence of water reversion or damage to the catalysts. Table 4.5-9 presents initial exhaust emission results for the three engines, equipped with catalysts, included in this test program.

Table 4.5-9: Baseline Emission Data for Engines/Catalysts in Saltwater Test Program

Catalyst Scenario	HC [g/kW-hr]	NOx [g/kW-hr]	CO [g/kW-hr]	Power [kW]	BSFC [g/kW-hr]
Maxum, 4.3L V6, ceramic catalysts	2.1	0.7	136	150	345
Sea Ray, 5.7L V8, metal catalysts	1.3	0.3	114	191	351
Malibu, 5.7L V8, ceramic catalysts	0.5	0.4	107	194	348

4.5.3.4 Production Engines

At the time of proposal, only one manufacturer was selling inboard Marine SI engines equipped with catalysts. These engines are being sold nationwide. The engines are based on 5.7L automotive blocks and use electronically controlled fuel injection, twin catalysts, and onboard diagnostics. The manufacturer, Indmar, has also performed extended durability testing in a saltwater environment. Test data from this engine is presented in Table 4.5-10, with and without an applied deterioration factor.[67] One advantage that Indmar has promoted with this engine is very low CO at part throttle. Part throttle operation is associated with lower boat speeds where the risk of CO poisoning is highest. The measured CO over the marine duty cycle is primarily due to emissions at wide open throttle, where the engine goes to open loop rich operation to protect the exhaust valves from overheating.

Table 4.5-10: Exhaust Emission Data on a 5.7L Production SD/I Engine with Catalysts

	HC [g/kW-hr]	NOx [g/kW-hr]	CO [g/kW-hr]
measured test results	1.8	2.0	46.6
with deterioration factor applied	2.0	2.3	51.8

At this time, three manufacturers have certified engines, equipped with catalysts, to the 5 g/kW-hr HC+NOx California standards for SD/I engines. Table 4.5-11 presents the certification data available from the California Air Resources Board’s Off-Road Certification Database.[68]

Table 4.5-11: Catalyst-Equipped SD/I Engines Certified in California

Manufacturer	Engine Disp. [liters]	Rated Power [kW]	HC+NOx [g/kW-hr]
Indmar	5.7	230	3.7
	5.7	230	4.6
Mercury Marine	1.6	75	4.2
	3.0	101	2.7
	5.0	194	1.8
	5.7	246	3.4
	8.1	280	2.8
	8.1	317	4.6
Volvo Penta	5.0	239	3.3
	8.1	298	2.6

4.5.3.5 CO Emissions Reductions at Low versus High Power

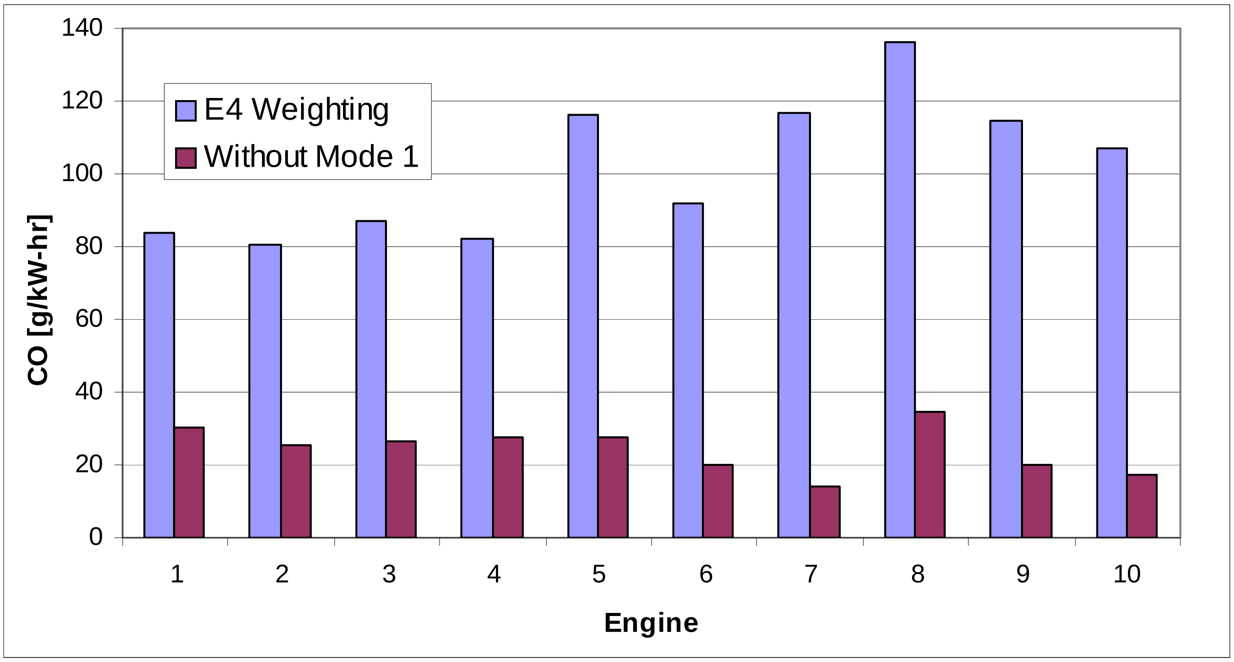
Under stoichiometric or lean conditions, catalysts are effective at oxidizing CO in the exhaust. However, under very rich conditions, catalysts are not effective for reducing CO emissions. SD/I engines often run at high power modes for extended periods of time. At these temperatures, engine marinizers must calibrate the engine to run rich as an engine protection strategy. If the engine were calibrated for a stoichiometric air-fuel ratio at high power, high temperatures could lead to failures in exhaust valves and cylinder heads.

All of the data presented above on SD/I engines equipped with catalysts were based on engines that used open-loop engine control at high power. As a result, the catalysts achieved little reduction in HC and CO at full power (test mode 1). However, NOx reductions were achieved at mode 1 because NOx is effectively reduced under rich conditions.

The catalysts were effective in reducing CO in modes 2 through 5 of the test procedure. In these lower power modes, the engines described above saw CO reductions on the order of 80 percent. However, the weighted values over the test cycle only show about a 50 percent reduction in CO because of the high contribution of mode 1 to the total weighted CO value. Studies have shown that there is a higher risk of operator exposure to CO at lower boat speeds[69] which would correspond to lower engine power modes. This suggests that CO reductions at lower power modes may be more beneficial than CO reductions at full power.

To look at the effect of mode 1 on the cycle weighted CO levels, we performed an analysis in which we recalculated the CO level for ten catalyst-equipped SD/I engines without mode 1. To determine the weighted value without mode 1, the weighting factor for mode 1 was set to zero percent and the weighting factors for modes 2 and 3 were each increased so that weighting factors would sum to 100 percent. Figure 4.5-2 compares the CO emissions with and without including mode 1 for these engines. Although mode 1 is only weighted as 6 percent of the test cycle, but makes up the majority of the cycle weighted CO value. Based on this analysis, the weighed CO level would be 70-90 percent lower if mode 1 were not included in the test procedure.

Figure 4.5-2: CO Emissions for SD/I Engines Equipped with Catalysts with and without Including Mode 1 in the Weighted Results



4.6 Feasibility of Standard for Marine Generator Sets

Currently, SI marine generator sets are regulated as Small SI or Large SI engines, depending on their size. Most SI marine generators are less than 25 hp and are therefore classified as Small SI engines. Generator sets in marine applications are unique in that they use liquid-cooled engines. Liquid cooling allows manufacturers to minimize the temperature of hot surfaces on marine generators, thereby reducing the risk of fires on a boat. For marine applications, liquid cooling is practical because of the nearly unlimited source of cooling water around the boat.

Another safety issue that has become apparent in recent years is carbon monoxide poisoning on boats. Studies have shown that exhaust emissions from engines on boats can lead to user exposure of high levels of carbon monoxide.[70] The marine industry, Coast Guard, American Boat and Yacht Council, and other stakeholders have been meeting regularly over the past several years in an attempt to mitigate the risk of CO poisoning in boating.[71,72] Mitigation strategies that have been discussed at these meetings include labeling, education, diverting the exhaust flow with smoke stacks, CO detectors, low CO emission technologies, and emission standards.

The vast majority of gasoline marine generators are produced by two engine manufacturers. Recently, these two manufacturers have announced that they are converting their marine generator product lines over to low CO engines.[73,74] They have stated that this is to reduce the risk of CO poisoning and that this action is a result of boat builder demand. Both manufacturers are using a combination of closed-loop electronic fuel injection and catalytic control. To date, both of these manufacturers have certified some low CO engines and have stated their intent to convert their full product lines in the near future. These manufacturers also make use of the electronic controls to monitor catalyst function. Table 4.6-1 presents the 2005 model year certification levels for these engines.

Table 4.6-1: 2005 MY Certification Levels for Low CO Marine Generator Engines

Engine Manufacturer	Power [kW]	Emission Control System	HC+NOx [g/kW-hr]	CO [g/kW-hr]
Kohler Power Systems	10.2	throttle-body injection, O_2 sensor, catalyst	7.2	5.2
Westerbeke	7.5 17.9	throttle-body injection, O_2 sensor, catalyst throttle-body injection, O_2 sensor, catalyst	2.0 4.4	0.01 0.0

In-use testing has been performed on two marine generator engine equipped with catalysts. These engines were installed on rental houseboats and operated for a boating season. Testing was first performed with low hours of operation; 108 hours for the 14 kW engine and 159 hours for the 20 kW.[75] The CO performance was reported to be "impressive with exhaust stack CO emissions of approximately 200 ppm for a fully warmed generator." The emissions measured around the boat were much lower due to dilution. According to the manufacturer, no significant deterioration has been found in the emission performance of the catalysts. Note that the manufacturer recommends changing the catalysts at 2000 hours and inspecting for CO at 1000 hours.

4.7 Test Procedures

We are making several technical amendments to the existing exhaust emission test procedures for Small SI and OB/PWC engines. These amendments are part of a larger effort to develop uniform test procedures across all of our programs. We including SD/I engines in these test procedures. In addition we are establishing not-to-exceed requirements for Marine SI engines. These new procedures are discussed in this section.

4.7.1 SD/I Certification Test Procedure

We are using the same certification duty cycle and test procedures for all Marine SI engines, including sterndrives and inboards. Table 4.5-6 presents the certification test duty cycle. This duty cycle is commonly referred to as the E4 duty cycle and was developed using operational data on outboard and sterndrive marine gasoline engines.[76] In addition, the E4 duty cycle is recommended by the International Standards Organization for use with all spark-ignition pleasurecraft less than 24 meters in length.[77] Although some Marine SI engines may be used for commercial activities, these engines would not likely be made or used differently than those used for pleasure.

Table 4.7-1: SI Marine Certification Steady-State Test Duty Cycle

Mode	% of Maximum Test Speed (MES)	% of Maximum Torque at MES	% of Maximum Power[a] at MES	Weighting Factor
1	100	100	100	0.06
2	80	71.6	57.2	0.14
3	60	46.5	27.9	0.15
4	40	25.0	10.1	0.25
5	idle	0[b]	--	0.40

[a] % power = (% speed) × (% torque)
[b] 15% of maximum torque at MES for high-performance engines

For high-performance engines, the above test procedure is modified slightly. These engines typically have substantial auxiliary loads and parasitic losses even when the vessel does not need propulsion power. In addition, these engines are not designed to operate at a low load idle and survey data suggests that operators do not spend significant time at zero power idle.[78] To account for this, for high-performance engines, we revised the test torque at idle speed to be 15 percent of maximum torque at maximum test speed.

4.7.2 SI Marine Not-To-Exceed Requirements

EPA is concerned that if a marine engine is designed for low emissions on average over a low number of discrete test points, it may not necessarily operate with low emissions in-use. This is due to a range of speed and load combinations that can occur on a vessel which do not necessarily lie on the test duty cycle. For instance, the test modes on the E4 duty cycle lie on an average propeller curve. However, a propulsion engine may never be fitted with an "average propellor." In addition, a light planing hull boat may operate at much lower torques than a heavily loaded boat.

It is our intent that an engine operate with low emissions under all in-use speed and load combinations that can occur on a boat, rather than just the discrete test modes in the five-mode duty cycle. To ensure this, we have requirements that extend to typical in-use operation. We are establishing not-to-exceed (NTE) requirements similar to those established for marine diesel engines. Under this approach, manufacturers would design their engines to comply with a not-to-exceed limit, tied to the standard, for HC+NOx and CO, within the NTE zone. In the cases where the engine is included in averaging, banking, and trading of credits, the NTE limits would be tied to the family emission limits. We would reserve the right to test an engine in a lab or installed in a boat to confirm compliance to this requirement.

We believe there are significant advantages to taking this approach. The test procedure is very flexible so it can represent the majority of in-use engine operation and ambient conditions. Therefore, the NTE approach takes all of the benefits of a numerical standard and test procedure and expands it to cover a broad range of conditions. Also, laboratory testing makes it harder to perform in-use testing because either the engines would have to be removed from the vessel or care would have to be taken that laboratory-type conditions can be achieved on the vessel. With the NTE approach, in-use testing and compliance become much easier because emissions may be sampled during normal vessel use. Because this approach is objective, it makes enforcement easier and provides more certainty to the industry of what is expected in use versus over a fixed laboratory test procedure.

Even with the NTE requirements, we believe it is still important to retain standards based on the steady-state duty cycle. This is the standard that we expect the certified marine engines to meet on average in use. The NTE testing is more focused on maximum emissions for segments of operation and should not require additional technology beyond what is used to meet the new standards. We believe basing the emission standards on a distinct cycle and using the NTE zone to ensure in-use control creates a comprehensive program. In addition, the steady-state duty cycles give a basis for calculating credits for averaging, banking, and trading.

We believe that the same technology that can be used to meet the standards over the five-mode certification duty cycle can be used to meet the NTE caps in the NTE zone. We therefore do not expect the NTE standards to cause marinizers to need additional technology. We do not believe the NTE concept results in a large amount of additional testing, because these engines should be designed to perform as well in use as they do over the steady-state five-mode certification test.

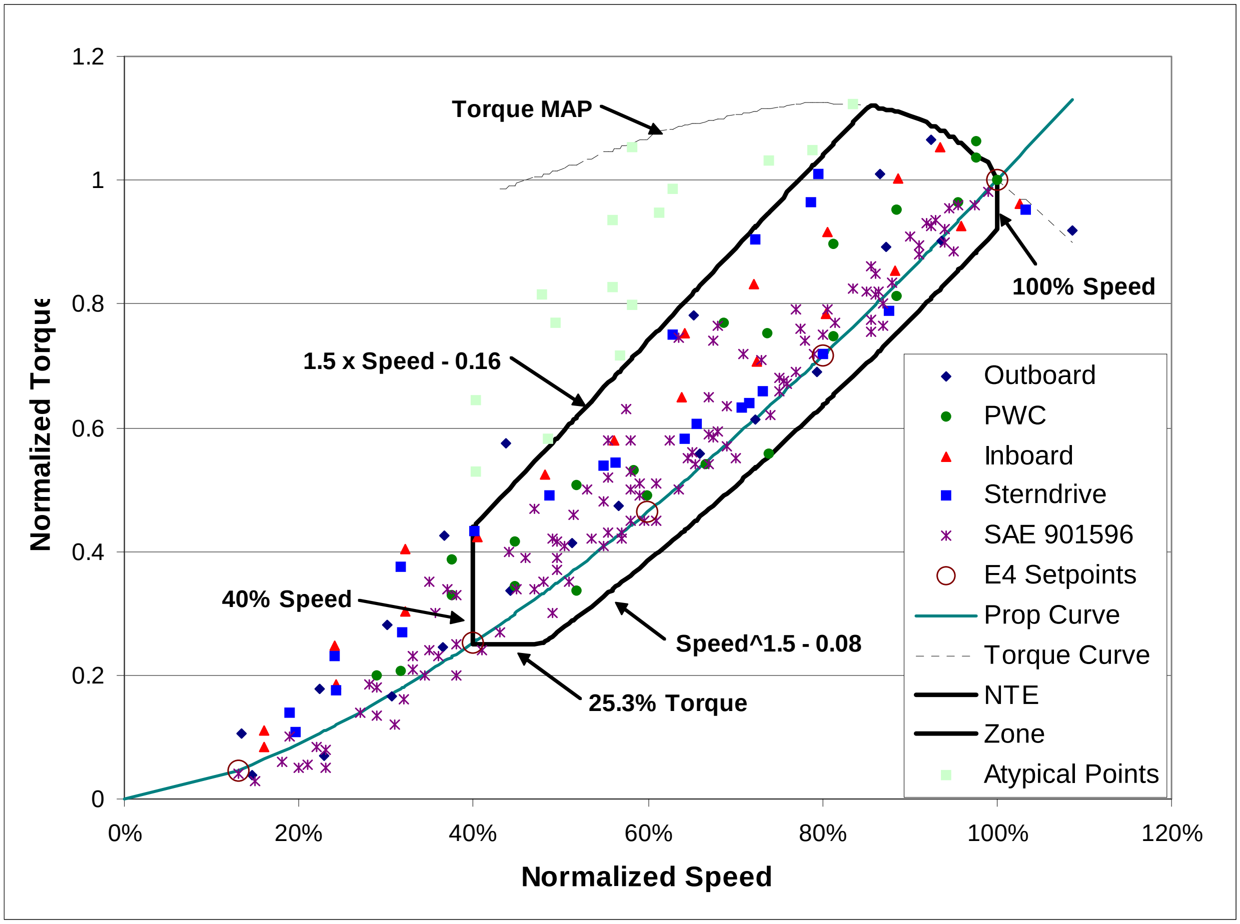
4.7.2.1 Shape of the NTE Zone

The NTE zone is intended to capture typical in-use operation for marine vessels. We used two data sources to define this operation. The first data source was the collection of data on marine engine operation that was used to develop the ISO E4 steady-state duty cycle.[79] Speed and torque data were collected on 33 outboards and three sterndrives. This data showed that the marine engines generally operated along a propeller curve with some variation due to differences in boat design and operation. A propeller curve defines the relationship between engine speed and torque for a marine engine and is generally presented in terms of torque as a function of engine speed in RPM raised to an exponent. The paper uses an exponent of 1.5 as a general fit, but states that the propeller curves for Marine SI applications range from exponents of 1.15 to 2.0.

The second source of data was a study of marine engine operation recently initiated by the marine industry.[80] In this study, sixteen boats were tested in the water at various engine speeds. These boats included seven sterndrives, three inboards, four outboards, and two personal watercraft. To identify the full range of loads at each engine speed, boats were operated both fully loaded and lightly loaded. Boats were operated at steady speeds to identify torque at each speed. In some cases, the operation was clearly unsafe or atypical. We did not include these operating points in our analysis. An example of atypical operation would be with a boat so highly loaded that it was operating in an unstable displacement mode with its bow sticking up into the air.

Figure 4.7-1 presents test data from the two studies as well as the NTE zone for Marine SI engines. This zone includes operation above and below the theoretical propeller curve used in the E4 duty cycle. Operation below 25 percent of rated speed is excluded because brake-specific emissions at low loads becomes very high due to low power in the denominator. This approach is consistent with the marine diesel NTE zone. The upper and lower borders of the NTE zone are designed to capture all of the typical operation that was observed in the two studies. The curve functions for these boarders are presented in Figure 4.7-1.

Figure 4.7-1: NTE Zone and Marine Engine Operation Data



When testing the engine within the NTE zone, only steady-state operation would be considered. It is unlikely that transient operation is necessary under the NTE concept to ensure that emissions reductions are achieved. We designed the NTE zone to contain the operation near an assumed propeller curve that the steady-state duty cycle represents. We believe that the vast majority of the operation in the NTE zone would be steady-state. When bringing a boat to plane, marine engine operation would be transient and would likely be above the NTE zone. However we do not have enough information to quantify this. Also we do not believe that the NTE zone should be extended to include areas an engine may see under transient operation, but not under steady-state operation. For this reason, we do not believe that adding transient operation to the NTE requirements is necessary at this time. We would revise this opinion in the future if there were evidence that in-use emissions were increased due to insufficient emission control under transient operation

4.7.2.2 Modal Emission Test Data within the NTE Zone

The NTE zone has emissions caps which represent a multiplier times the weighted test result used for certification. Although ideally the engine should meet the certification level throughout the NTE zone, we understand that a cap of 1.0 times the standard is not reasonable because there is inevitably some variation in emissions over the range of engine operation. This is consistent with the concept of a weighted modal emission test such as the E4 duty cycle.

In developing the emission caps in the NTE zone, we collected modal HC+NOx and CO emission data on a large number of OB, PWC, and SD/I engines. Because limited modal data is available in published literature,[81,82,83] most of the modal data on outboards and personal watercraft was provided confidentially by individual manufacturers. Data on SD/I engines with catalysts was collected as part of the catalyst development efforts discussed earlier in this chapter.[84,85,86,87] Our analysis focuses only on engines using technology that could be used to meet the new standards. The modal data is presented in Figures 4.7-2 through 4.7-9 in terms of the modal emission rate divided by the weighted E4 average for that engine. Each color bar represents a different engine. Because of the large volume of data and differences in engine operation and emissions performance, data is presented separately for carbureted 4-stroke, fuel-injected 4-stroke, and direct-injected 2-stroke OB/PWC, and for catalyst-equipped SD/I engines.

Figures 4.7-2 and 4.7-4 present normalized HC+NOx modal data for carbureted and EFI 4-stroke OB/PWC engines. Note that most of the data points are near or below the E4 weighted average (represented by bars near or below 1.0). This is largely due to the exclusion of idle operation from the NTE zone compared to the E4 duty cycle that is 40 percent weighted at idle. As mentioned above, idle is excluded because brake-specific emissions become very large at low power due to a low power figure in the denominator (g/kW-hr). Especially for the carbureted engines, higher normalized HC+NOx emissions are observed at the low power end of the NTE zone (40 percent speed, 25 percent torque). As shown in Figures 4.7-3 and 4.7-5, a similar trend is observed with normalized CO emissions from these engines.

Figure 4.7-2: Normalized Modal HC+NOx for Carbureted 4-Stroke OB/PWC

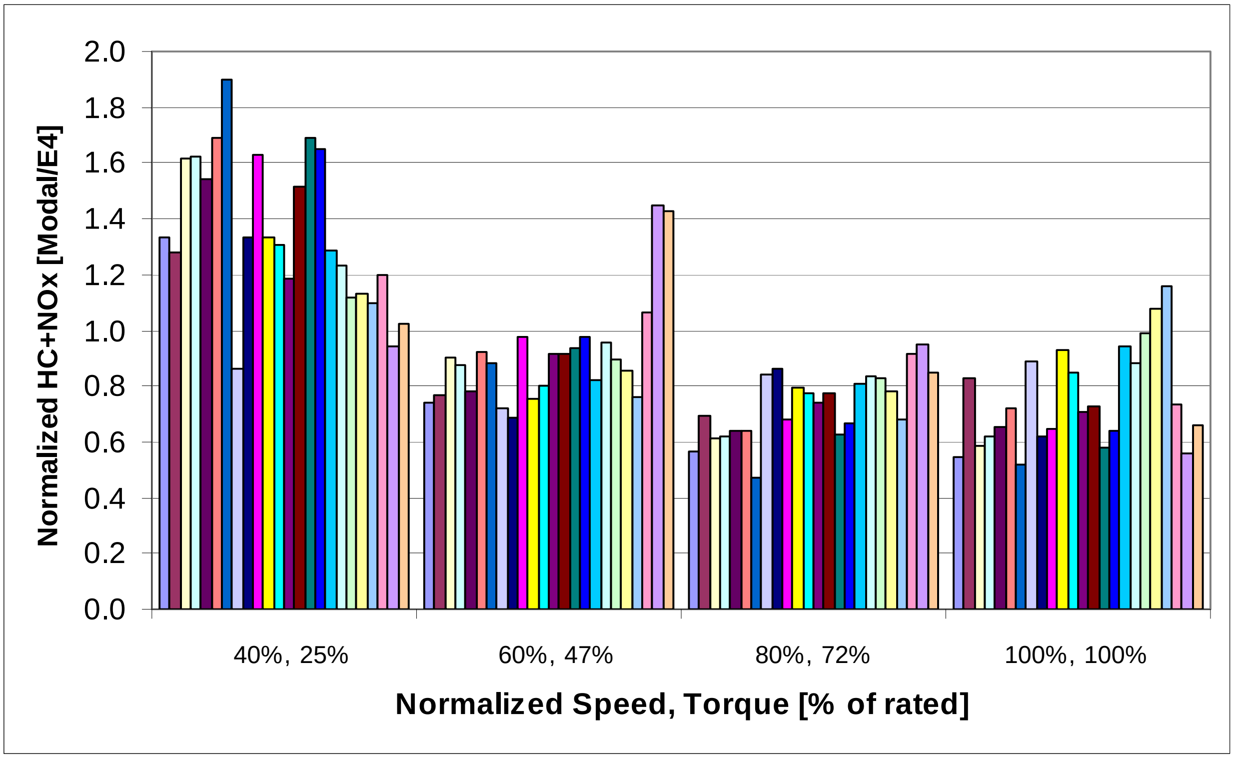


Figure 4.7-3: Normalized Modal CO for Carbureted 4-Stroke OB/PWC

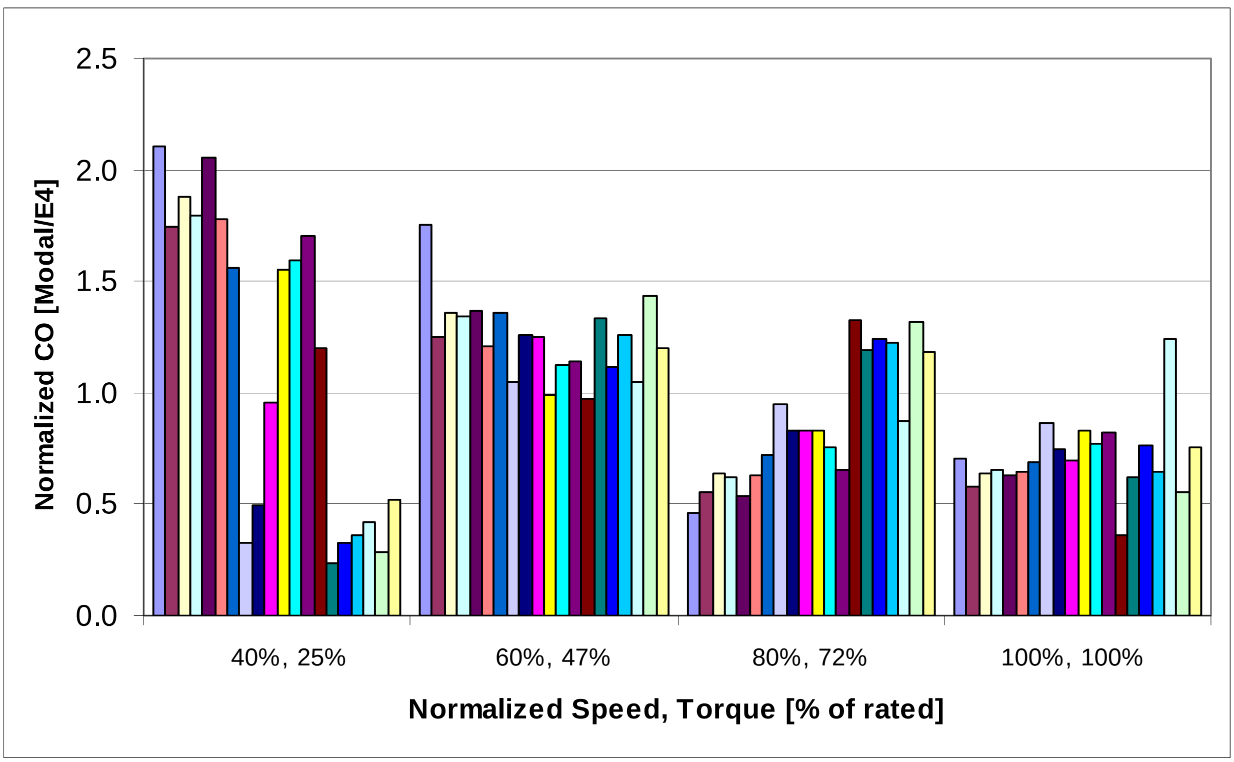


Figure 4.7-4: Normalized Modal HC+NOx for EFI 4-Stroke OB/PWC

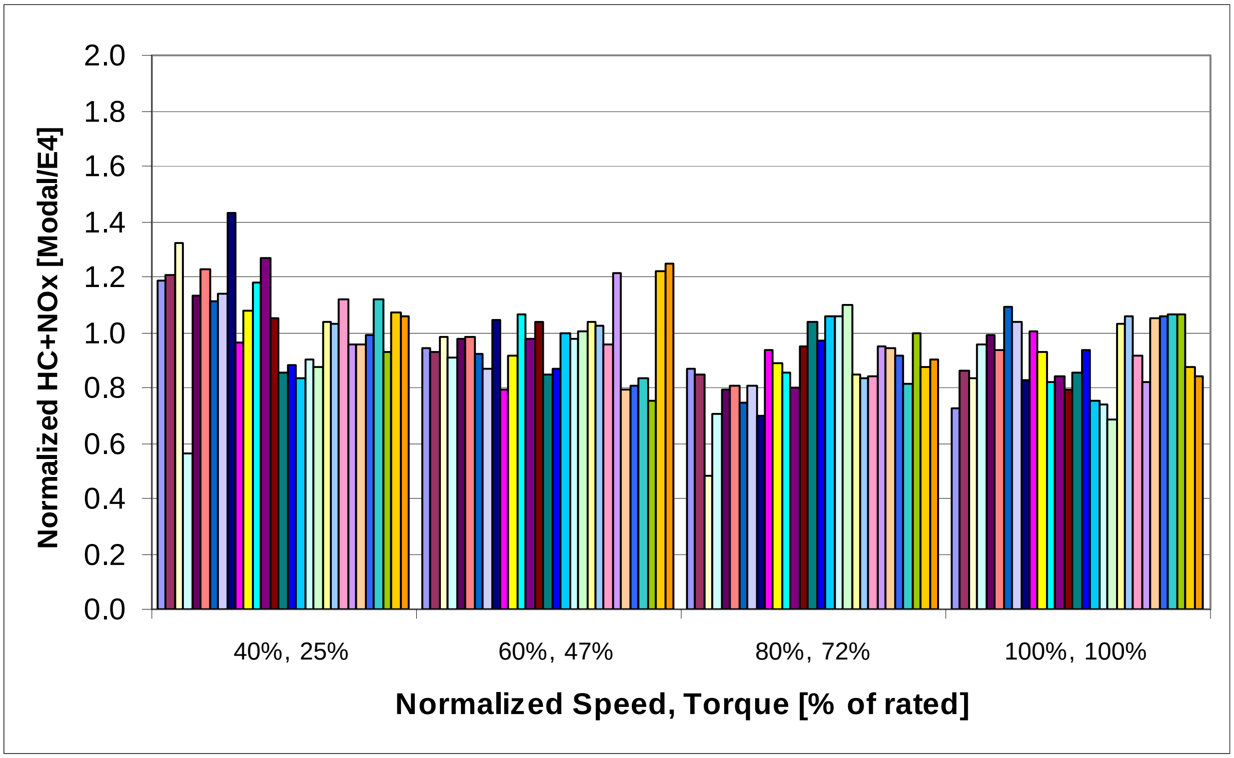
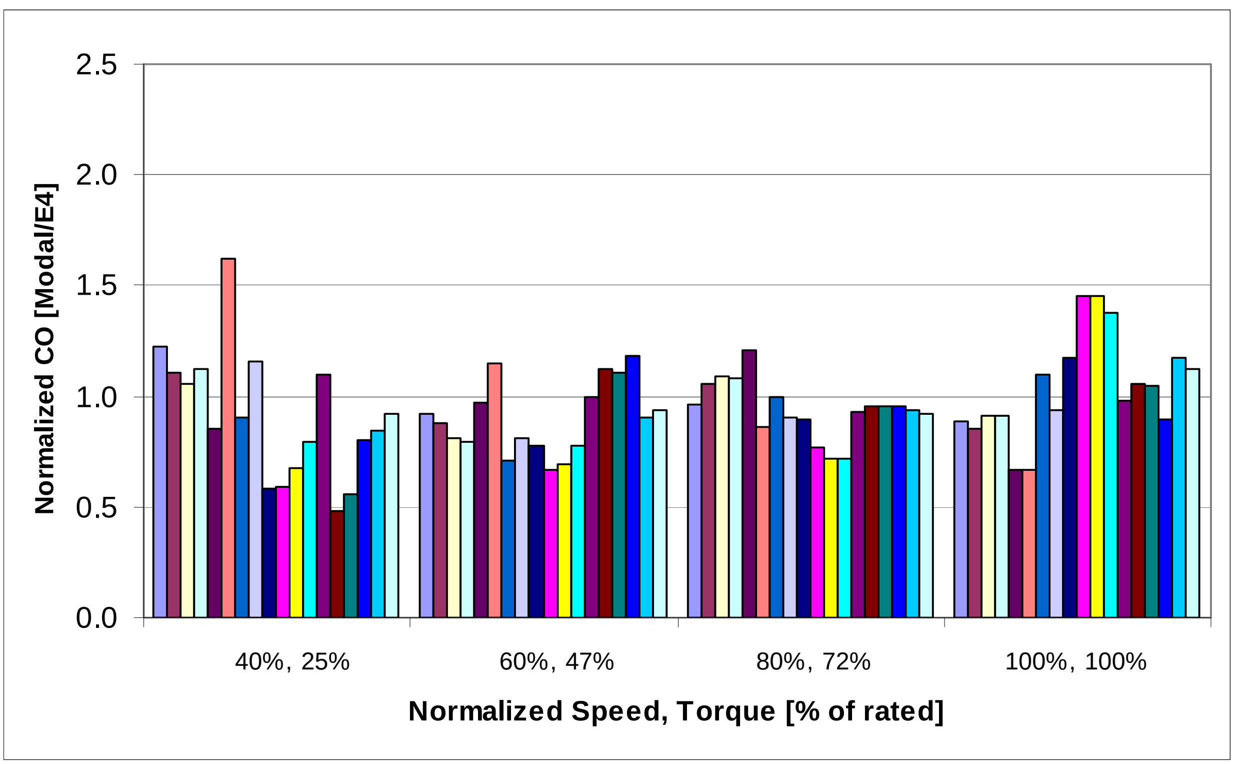


Figure 4.7-5: Normalized Modal CO for EFI 4-Stroke OB/PWC



Figures 4.7-6 through 4.7-9 present normalized HC+NOx and CO modal data for direct-injected 2-stroke OB/PWC engines. Based on the data collected, there appear to be two distinct types of direct-injection 2-stroke engines. One manufacturer uses a higher pressure fuel system with a unique combustion chamber design for low emissions. Because the modal variation in emission results are significantly different for the two engine designs, we designate them headings of Type 1 and Type 2 engines and look at them separately for the purposes of this analysis. As shown in Figure 4.7-6 and 4.7-7, Type 1 engines tend to have relatively high HC+NOx at low power, then fairly low emissions over the rest of the modes. For CO, these engines show much less variability between modes. For Type 2 engines, HC+NOx is below the E4 average in the mid-speed range as shown in Figure 4.7-8. However, there is a wide degree of variation in how these engines behave at low and high speed. Most of these engines seem to have high normalized HC+NOx emissions either at low or at high speed. Figure 4.7-9 presents CO values for Type 1 engines. These engines tend to have high CO at full power with decreasing CO at lower power modes.

Figure 4.7-6: Normalized Modal HC+NOx for Type 1 DI 2-Stroke OB/PWC

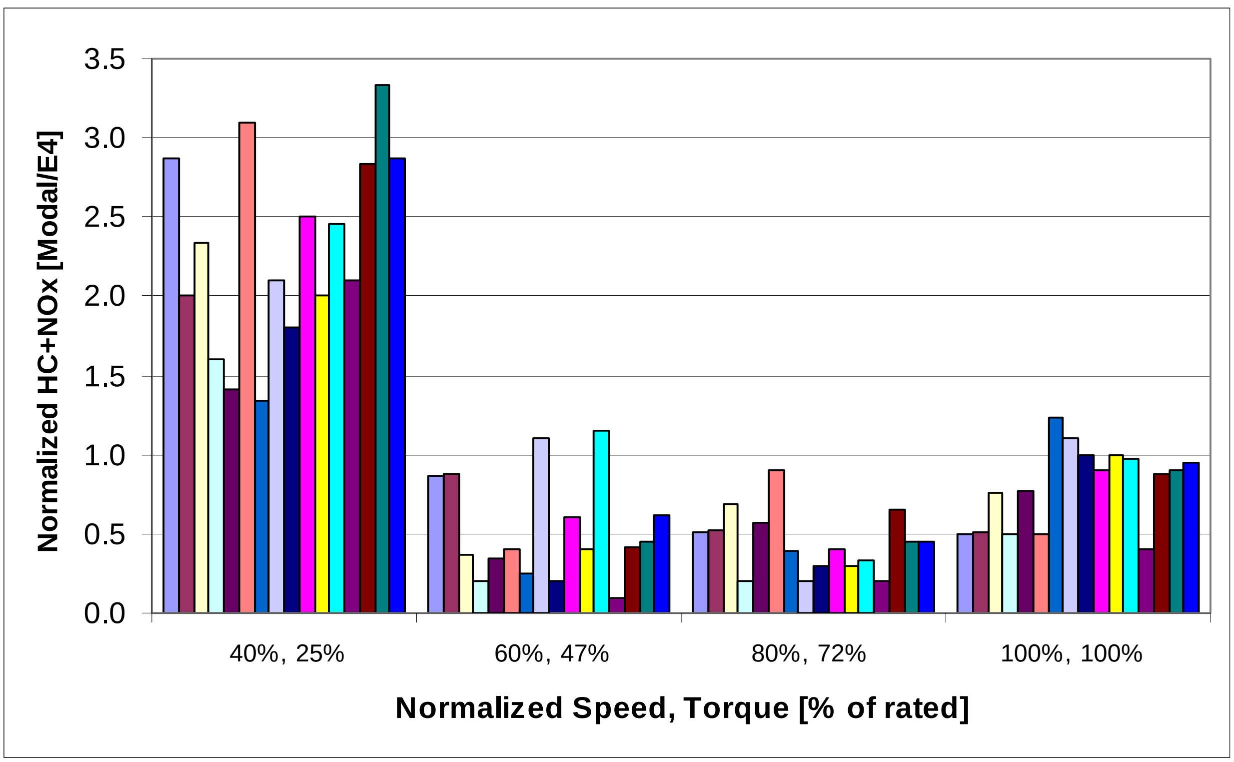


Figure 4.7-7: Normalized Modal CO for Type 1 DI 2-Stroke OB/PWC

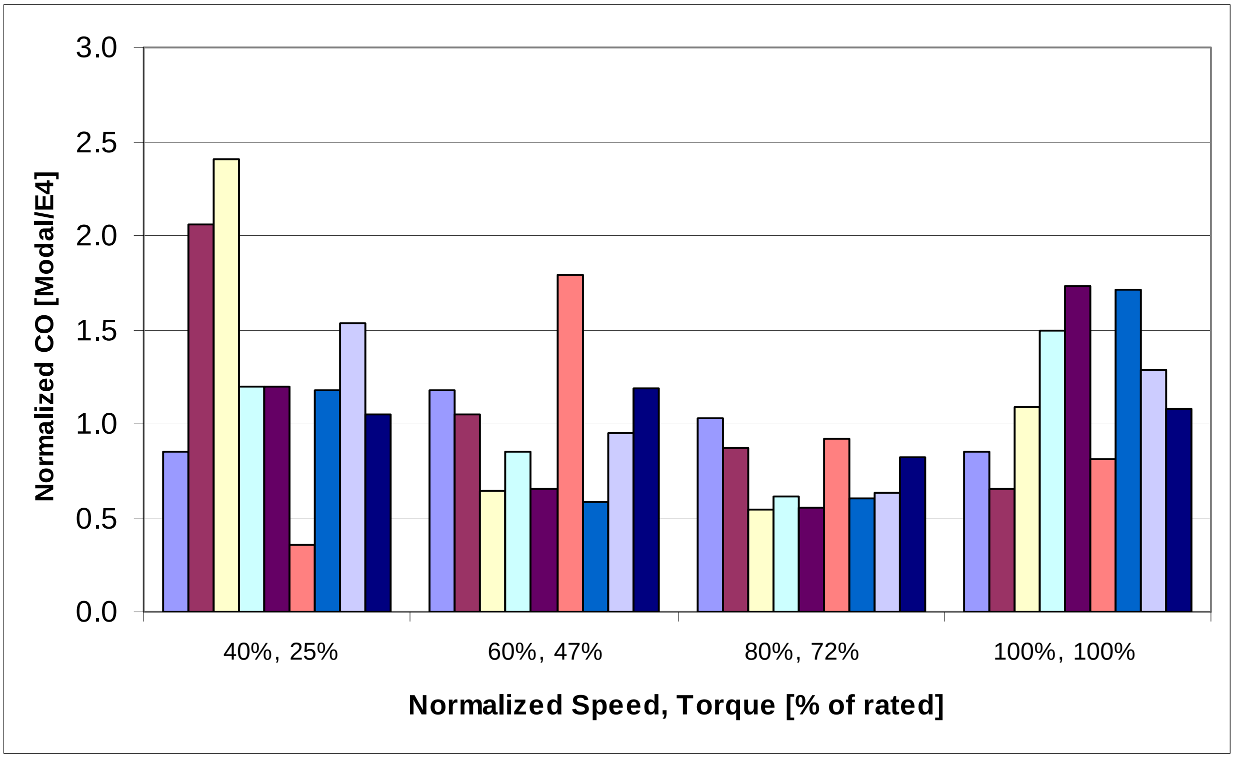


Figure 4.7-8: Normalized Modal HC+NOx for Type 2 DI 2-Stroke OB/PWC

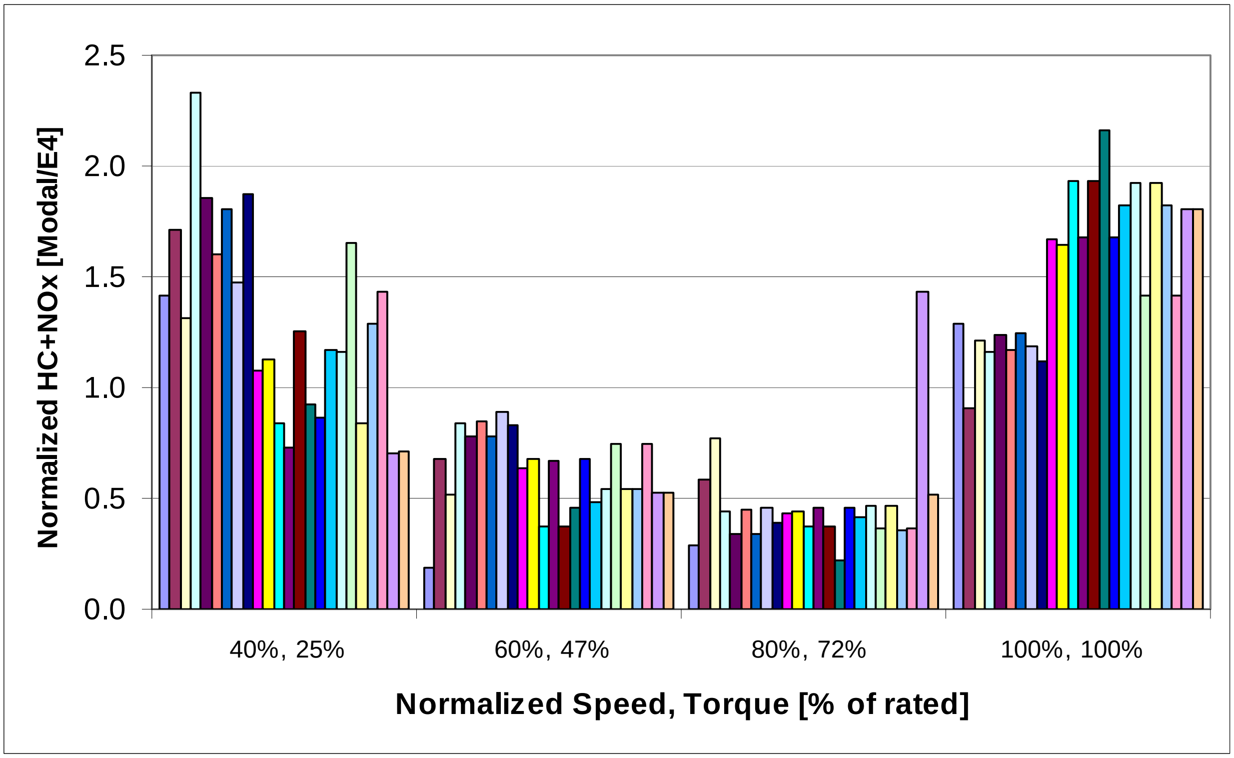
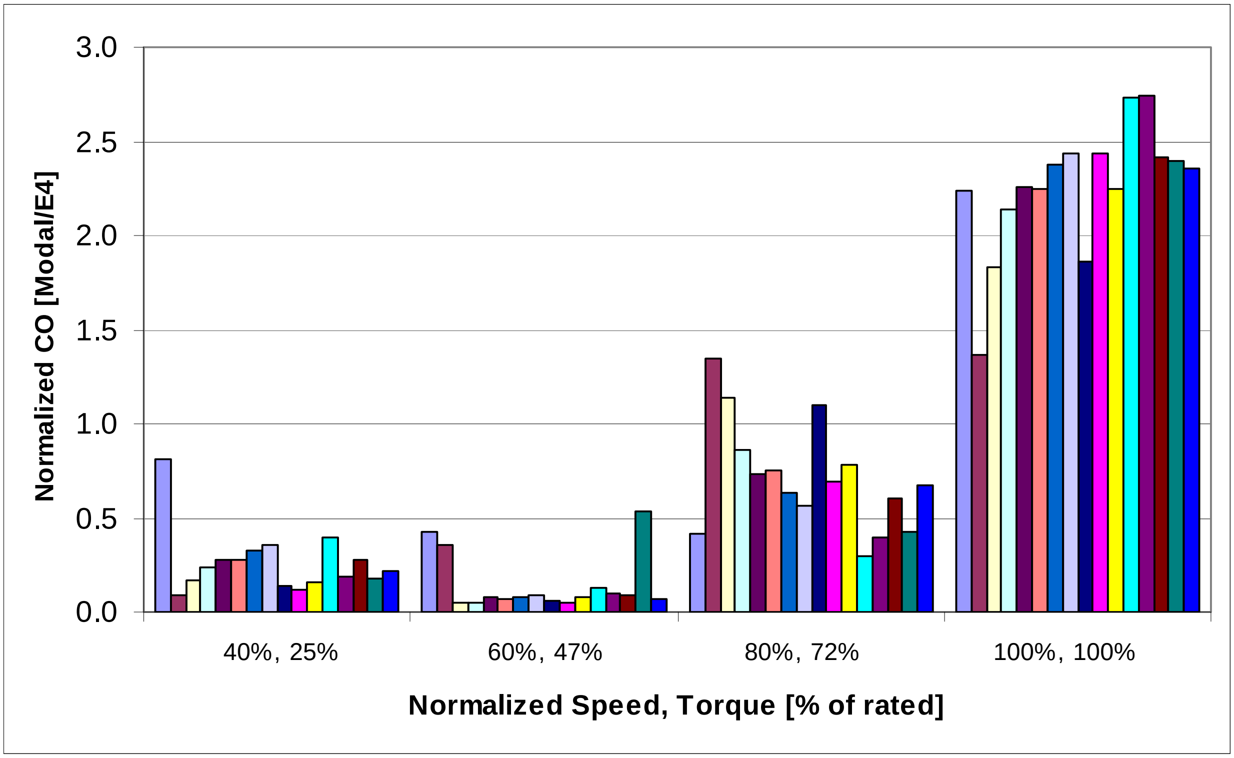


Figure 4.7-9: Normalized Modal CO for Type 2 DI 2-Stroke OB/PWC



Figures 4.7-10 and 4.7-11 present normalized HC+NOx and CO modal data for SD/I engines equipped with catalysts. All of these engines demonstrated HC+NOx emissions below the E4 average in the mid-speed range. However, some of these engines show somewhat higher normalized HC+NOx emissions at either the low-power or full power mode. These differences are likely a function of catalyst design and location as well as air/fuel calibration. At wide open throttle, all of these engines were calibrated to run rich as an engine protection strategy, so emission reductions at this mode are due to NOx reductions in the catalyst. Because these engines are designed to run rich at full power, high CO emissions were observed at this mode. For the rest of the power range, CO emissions were generally below the E4 average for these engines. As part of the catalyst development work for SD/I engines, one engine was tested over 26 modes, most of which are contained in the NTE zone.[88] This engine was tested in its baseline configuration (open-loop fuel injection) as well as with three catalyst configurations. The three catalyst configurations included one close-coupled to the engine (in the riser), one a little farther downstream (in the exhaust elbow), and a larger catalyst external to the existing exhaust manifold. This data provided insight into how exhaust emissions throughout the NTE zone for Marine SI engines compare to the modal test data on the theoretical propeller curve. This data is presented in Appendix 4A.

Figure 4.7-10: Normalized Modal HC+NOx for SD/I with Catalysts

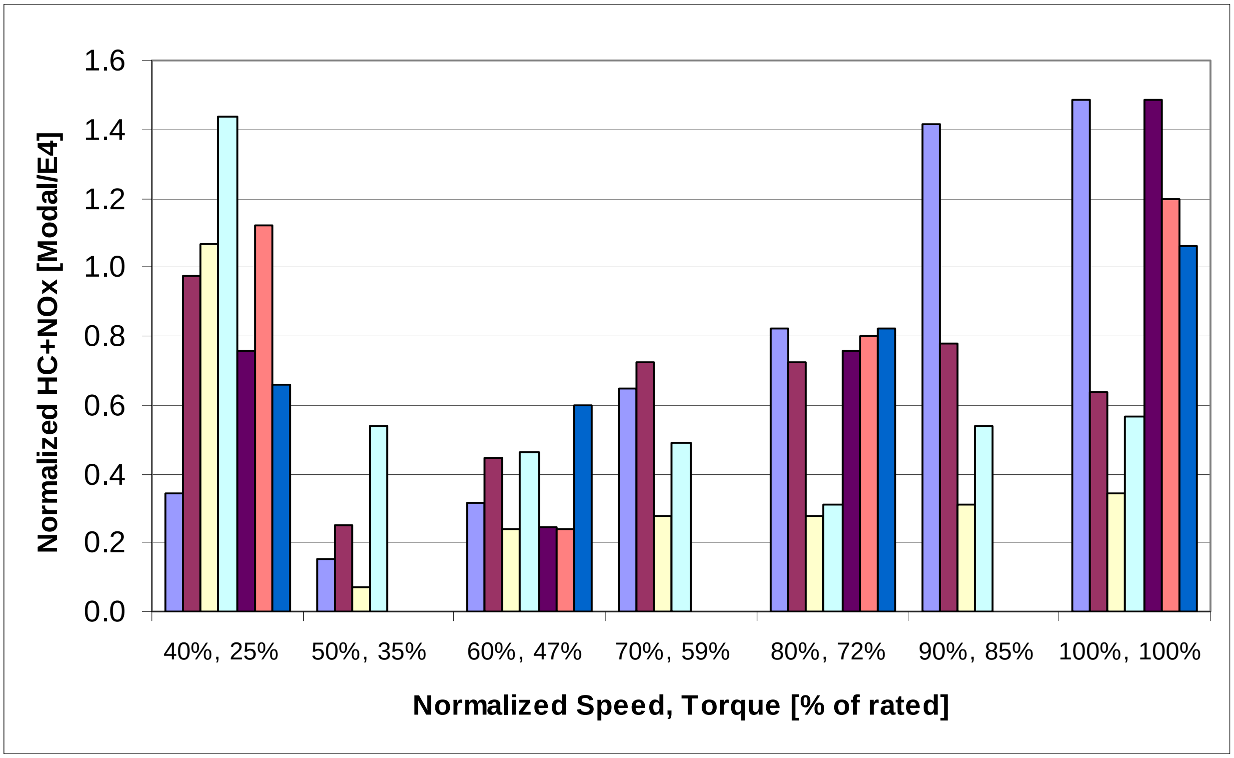
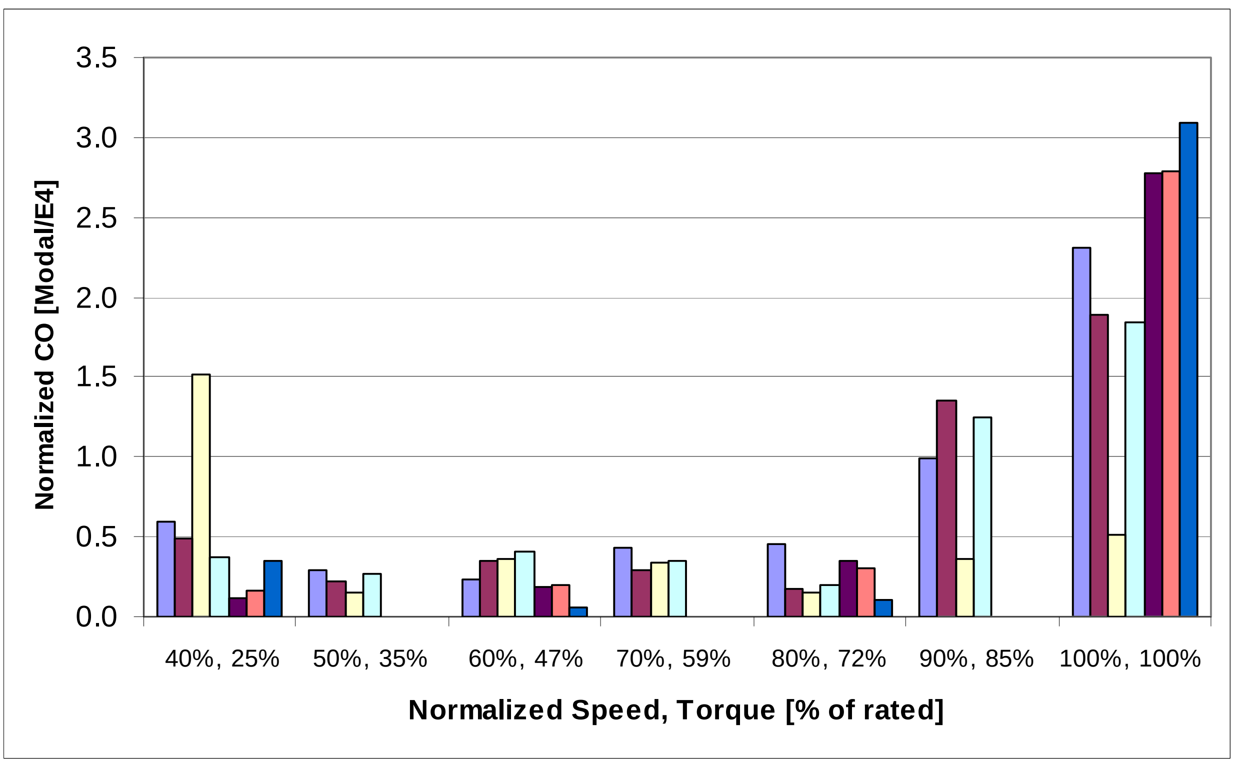


Figure 4.7-11: Normalized Modal CO for SD/I with Catalysts



4.7.2.3 NTE Zones and Standards

As described above, the emissions characteristics of marine engines are largely dependent on technology type. Four-stroke engines tend to have relatively constant emission levels throughout the NTE zone. In contrast, two-stroke engine tend to have high variability in emissions, not only within the NTE zone but between different engine designs as well. Catalyst-equipped engines tend to have relatively flat emissions profiles, in the NTE zone, when operating in closed-loop engine control mode. However, at higher engine power, the engines are calibrated to operate with a rich fuel-air ratio, in open-loop control, to protect the exhaust valves and catalyst from high exhaust temperatures. This reduces the catalyst efficiency at high power for oxidizing HC and CO.

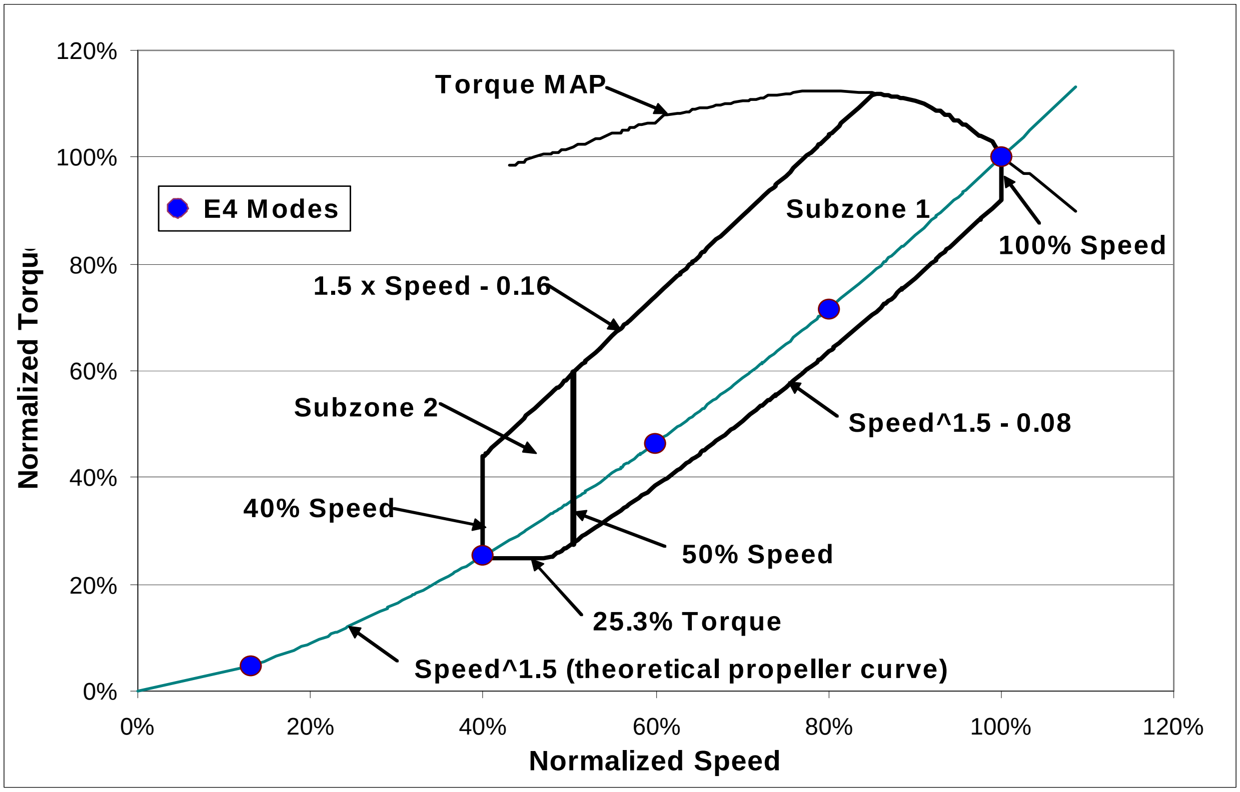
Since the NPRM was published, we have worked with engine manufacturers to better understand the design constraints, operation, and emissions characteristics of marine engines. Based on this understanding, and the emission data presented above, we decided to develop different NTE standards for three distinct types of engines; 4-stroke, 2-stroke, and catalyst-equipped. These standards are discussed below.

We used the modal data presented above and the data on additional operation points presented in Appendix 4A to develop NTE limits. These limits are presented as a multiplier times the Family Emission Limit (FEL) developed using the 5-mode test procedure. The limits represent the levels that can be met by the majority of the marine engines tested. In the case of engines that have modal emissions that are somewhat higher than the NTE limits, we believe that these engines can be calibrated to meet these limits. In addition, the limits are based on the FELs chosen by manufacturers at certification. Therefore, manufacturers would have the option of increasing their FELs, in some cases, to bring otherwise problem engines into compliance with the NTE limits.

4.7.2.3.1 4-Stroke Engines

The emissions data, presented above, for 4-stroke marine engines suggests that brake-specific emissions rates are relatively constant throughout the NTE zone. One exception is slightly higher HC+NOx emissions at low power. To account for this, we are subdividing the NTE zone to have a low power subzone below 50 percent of maximum test speed. In this low power subzone, the HC+NOx NTE limit is 1.6, while it is 1.4 for the remainder of the NTE zone. The CO NTE limit is 1.5 throughout the NTE zone. Figure 4.7-12 presents the NTE zone and subzones. These limits would apply to all non-catalyzed four-stroke marine engines.

Figure 4.7-12: 4-Stroke Engine NTE Zone and Subzones



4.7.2.3.2 2-Stroke Engines

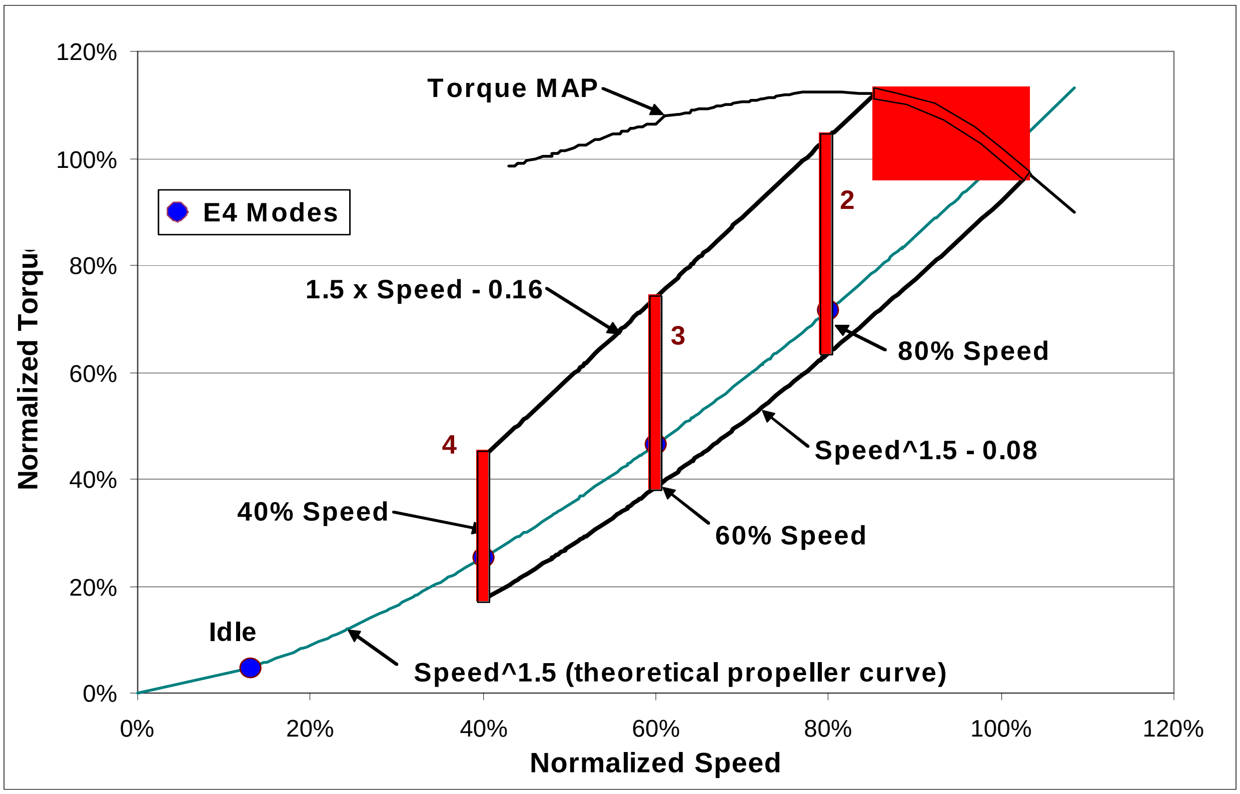
The emissions data presented above, for 2-stroke direct-injection marine engines suggests that these engines have high variability in emissions, not only within the NTE zone but between different engine designs as well. Due to this variability, we do not believe that a flat (or stepped) limit in the NTE zone could be effectively used to establish meaningful standards for these engines. At the same time, we believe that NTE standards are valuable for facilitating in-use testing. Therefore, we developed a weighted NTE approach specifically for these engines. In the long term, we may consider further emission reduction based on catalytic control applied to OB/PWC engines. In this case, we would revisit the appropriateness of the weighted NTE approach in the context of those standards.

Under the weighted NTE approach, emissions data is collected at five test points. These test points are idle, full power, and the speeds specified in modes 2-4 of the 5-mode duty cycle. Similar to the 5-mode duty cycle, the five test points are weighted to achieve a composite value. This composite value must be no higher than 1.2 times the FEL for that engine.

The difference in this approach, from the 5-mode duty cycle, is that the test torque is not specified. During an in-use test, the engine would be set to the target speed and the torque value would be allowed to float. In addition, at wide open throttle, the engine speed would be based on actual performance on the boat. Because in-use engines installed in boats do not generally operate on the theoretical propeller curve used to define the 5-mode duty cycle, this NTE approach helps facilitate NTE testing.

At each test mode, limits are placed on allowable engine operation. These limits are generally based on the NTE zone presented above for 4-stroke engines, but there are two exceptions. First, the lower torque limit at 40 percent speed is lowered slightly to better ensure that an engine on an in-use boat is capable of operating within the NTE zone. Second, the speed range is extended at wide-open throttle for the same reason. Figure 4.7-13 presents this approach.

Figure 4.7-13: 2-Stroke Engine Weighted NTE Concept



During laboratory testing, any point within each of the four non-idle subzones may be chosen as test points. These test points do not necessarily need to lie on a propeller curve. It should be noted that the actual power measured would be used in the calculation of the weighted brake-specific emissions.

4.7.2.3.3 Catalyst-Equipped Engines

SD/I engines are anticipated to make use of three-way catalysts to meet the new exhaust emission standards. These catalysts are most effective when the fuel-air ratio in the exhaust is near stoichiometry. Engine manufacturers use closed-loop control to monitor and maintain the proper fuel-air ratio in the exhaust for optimum catalyst efficiency. However, at high power, engine manufacturers must increase the fueling rate to reduce the temperature of the exhaust. Otherwise, if the exhaust temperature becomes too high, exhaust valves and catalysts may be damaged. During rich, open-loop operation at high power, the catalyst is oxygen-limited and less effective at oxidizing HC and CO. To address the issue of open-loop catalyst efficiency, we created a high power subzone in the NTE zone for catalyst-equipped engines.

The majority of SD/I engines are based on engine blocks produced by General Motors. To determine the appropriate threshold for the high power-subzone, we used temperature data supplied by General Motors.[89] This data was consistent with confidential data supplied by engine marinizers on engine control strategies for catalyst-equipped SD/I engines. Figure 4.7-14 presents the stoichiometric limits for engine protection, based on the General Motors study, for three different engine designs.

Figure 4.7-14: GM Study-Stoichiometric Limits for Engine Protection

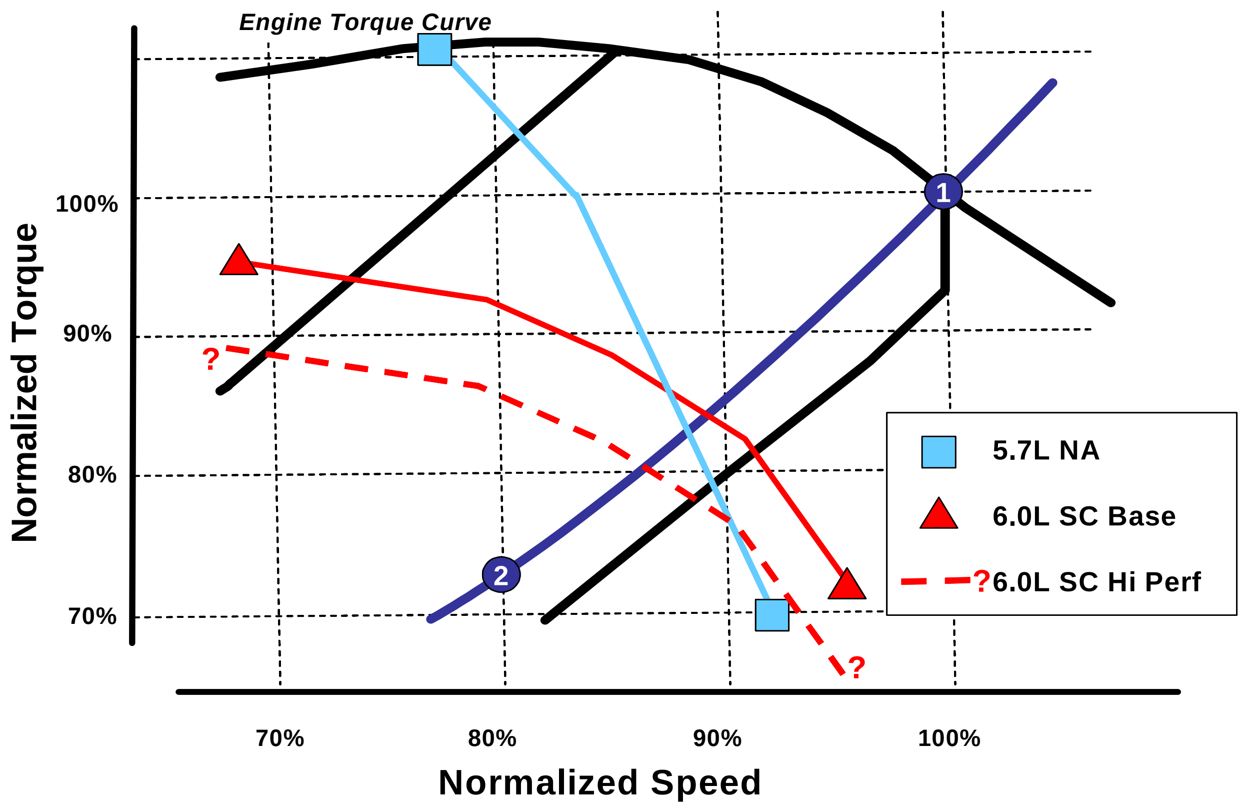


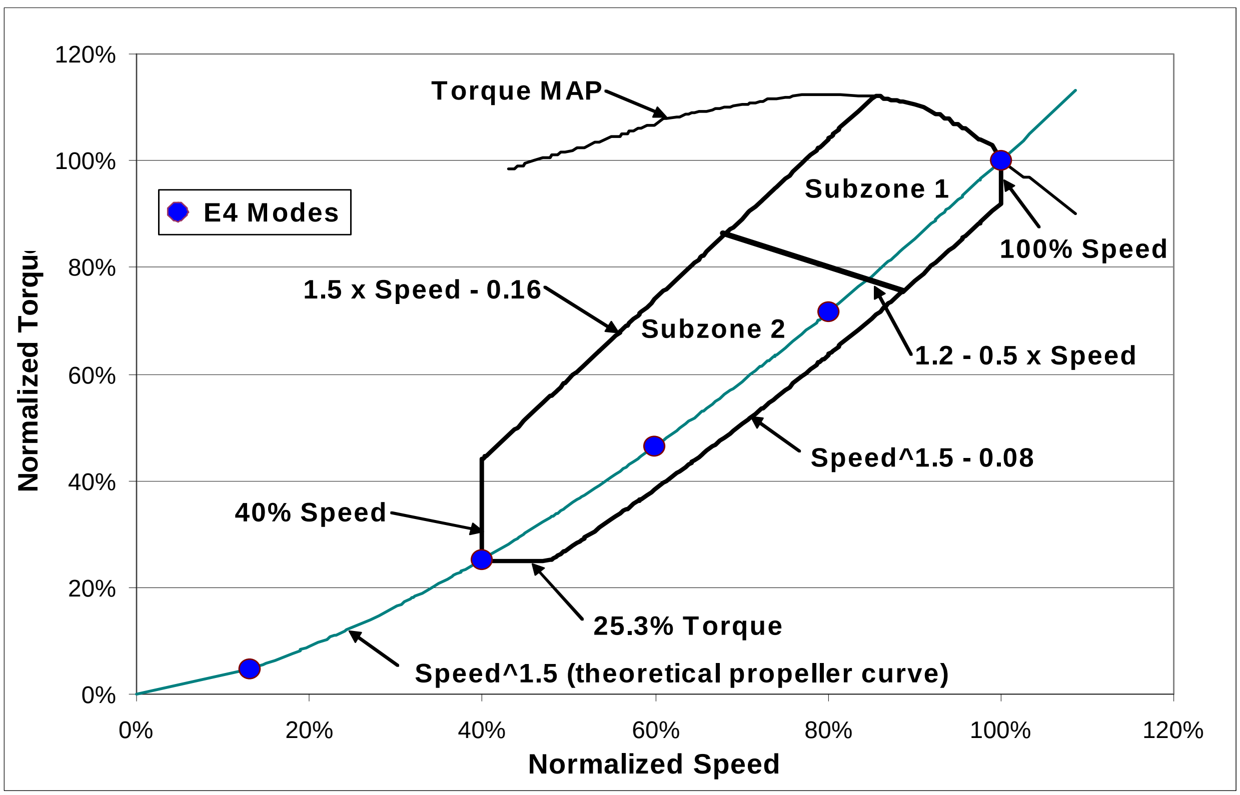
Figure 4.7-15 presents the NTE zone and high power subzone for catalyst-equipped marine engines. The shape of the high power subzone is based on the General Motors engine protection data. The emission limits are based on data discussed above on SD/I engines, with catalysts, operating in open-loop versus closed-loop engine control.

For catalyst-equipped engines, the largest contribution of emissions over the 5-mode duty cycle comes from open-loop operation at Mode 1. In addition, the idle point (Mode 5) is weighted

40 percent in the 5-mode duty cycle, but not included in the NTE zone. For this reason, brake-specific emissions throughout most of the NTE zone are less than the weighted average from the steady-state testing. For most of the NTE zone, we are therefore requiring a limit equal to the duty-cycle standard (i.e., NTE multiplier = 1.0).

Emission data on catalyst-equipped engines also show higher emissions near full-power operation. As discussed above, this is due to the need for richer fuel-air ratios under high-power operation to protect the engines from overheating. We are therefore establishing higher NTE limits for subzone 1 based on emissions performance during open-loop operation. Specifically, we are establishing an HC+NOx limit of 1.5 times the duty-cycle standard. Some HC+NOx control is expected in subzone 1 because a three-way catalyst will effectively reduce NOx emissions under rich conditions. However, for subzone 1, we are not setting a CO limit. Under rich conditions, a three-way catalyst is not at all effective for oxidizing HC or CO emissions. In addition, the cycle weighted emission level for CO is primarily driven by Mode 1.

Figure 4.7-15: Catalyst-Equipped Engine NTE Zone and Subzones



4.7.2.4 Ambient Conditions

Ambient air conditions, including temperature and humidity, may have a significant effect on emissions from marine engines in-use. To ensure real world emissions control, the NTE zone testing should include a wide range of ambient air conditions representative of real world conditions. Because these engines are used in similar environments as marine diesel engines, we are applying the same ambient ranges to the Marine SI NTE requirements as already exist for marine diesel engine NTE requirements.

We believe that the appropriate ranges should be 13-30°C (55-86°F) for air temperature and 7.1-10.7 grams water per kilogram dry air (50-75 grains/pound of dry air) for air humidity. The air temperature ranges are based on temperatures seen during ozone exceedences, except that the upper end of the temperature range has been adjusted to account for the cooling effect of a body of water on the air above it.[90] We are also aware, however, that marine engines sometimes draw their intake air from an engine compartment or engine room such that intake air temperatures are substantially higher than ambient air temperatures. In this case, we would retain 35°C as the end of the NTE temperature range for engines that do not draw their intake air directly from the outdoor ambient.

For NTE testing in which the air temperature or humidity is outside the specified range, we require that the emissions must be corrected back to the specified air temperature or humidity range. These corrections would be consistent with the equations in 40 CFR Part 91, Subpart E except that these equations correct to 25°C and 10.7 grams per kilogram of dry air while the NTE corrections would be to the nearest outside edge of the specified ranges. For instance, if the outdoor air temperature were higher than 30°C for an engine that drew fresh outdoor air into the intake, a temperature correction factor could be applied to the emissions results to determine what emissions would be at 30°C.

Ambient water temperature also may affect emissions due to it's impact on engine cooling. For this reason, we are requiring that the NTE testing include a range of ambient water temperatures from 5 to 27°C (41 to 80°F). The water temperature range is based on temperatures that marine engines experience in the U.S. in-use. At this time, we are not aware of an established correction for ambient water temperature, therefore the NTE zone testing would have to be withing the specified ambient water temperature range.

4.8 Impacts on Safety, Noise, and Energy

Section 213 of the Clean Air Act directs us to consider the potential impacts on safety, noise, and energy when establishing the feasibility of emission standards for nonroad engines. Furthermore, section 205 of Public Law 109-54 requires us to assess potential safety issues, including the risk of fire and burn to consumers in use, associated with the emission standards for nonroad spark-ignition engines under 50 horsepower. As further detailed in the following sections, we expect that the exhaust emission standards will either have no adverse affect on safety, noise, and energy or will improve certain aspects of these important characteristics.

4.8.1 Safety

We conducted a comprehensive, multi-year safety study of nonroad SI engines that focused on the following areas where we are finalizing new exhaust standards.[91] These areas are:

- New catalyst-based HC+NOx exhaust emission standards for Class I and II nonhandheld (NHH) engines; and

- New HC+NOx exhaust emission standards for outboard and personal watercraft (OB/PWC) engines and vessels, and a new CO exhaust emission standard for NHH engines used in marine auxiliary applications.

Each of these four areas is discussed in greater detail in the next sections.

4.8.1.1 Exhaust Emission Standards for Small Spark-Ignition Engines

The technology approaches that we assessed for achieving the Small SI engine standards included exhaust catalyst aftertreatment and improvements to engine and fuel system designs. In addition to our own testing and development effort, we also met with engine and equipment manufacturers to better understand their designs and technology and to determine the state of technological progress beyond EPA's Phase 2 standards.

The scope of our safety study included Class I and Class II engine systems that are used in residential walk-behind and ride-on lawn mower applications, respectively. Residential lawn mower equipment was chosen for the following reasons.

- Lawn mowers and the closely-related category of lawn tractors overwhelmingly represent the largest categories of equipment using Class I and Class II engines. We estimate that over 47 million walk-behind mowers and ride-on lawn and turf equipment are in-use in the US today.
- These equipment types represent the majority of sales for Small SI engines.
- Consumer Product Safety Commission (CPSC) data indicates that more thermal burn injuries associated with lawn mowers occur than with other NHH equipment; lawn mowers therefore represent the largest thermal burn risk for these classes of engines.
- General findings regarding advanced emission control technologies for residential lawn and garden equipment carry over to commercial lawn and turf care equipment as well as to other NHH equipment using Class I and Class II engines. Lawn mower design and use characteristics pose unique safety implications not encountered by other NHH equipment using these engines (i.e. a mower deck collects debris during operation whereas a pressure washer collects no debris). Thus, other NHH equipment may employ similar advanced emission control technologies for meeting the standards without a corresponding concern regarding the safety issues analyzed in this study.

We conducted the technical study of the incremental risk on several fronts. First, working with the CPSC, we evaluated their reports and databases and other outside sources to identify those in-use situations which create fire and burn risk for consumers. The outside sources included meetings, workshops, and discussions with engine and equipment manufacturers. The following scenarios were identified for evaluation:

- Thermal burns due to inadvertent contact with hot surface on engine or equipment;
- Fires from grass and leaf debris on the engine or equipment;

- Fires due to fuel leaks on hot surfaces;
- Fires related to spilled fuel or refueling vapor;
- Equipment or structure fire when equipment is left unattended after being used;
- Engine malfunction resulting in an ignitable mixture of unburned fuel and air in the muffler (engine misfire); and
- Fire due to operation with richer than designed air-fuel ratio in the engine or catalyst.

These scenarios cover a comprehensive variety of in-use conditions or circumstances which potentially could lead to an increase in burns or fires. They may occur presently or not at all, but were included in our study because of the potential impact on safety if they were to occur. The focus of the analysis was, therefore, on the incremental impact on the likelihood and severity of the adverse condition in addition to the potential causes as it related to the use of more advanced emissions control technology.

Second, we conducted extensive laboratory and field testing of both current technology (Phase 2) and prototype catalyst-equipped advanced-technology engines and equipment (Phase 3) to assess the emission control performance and thermal characteristics of the engines and equipment. This testing included a comparison of exhaust system, engine, and equipment surface temperatures using thermal imaging equipment.

Third, we contracted with Southwest Research Institute (SwRI) to conduct design and process Failure Mode and Effects Analyses (FMEA).[92] The SwRI FMEA focused on comparing current Phase 2 and Phase 3 compliant engines and equipment to evaluate incremental changes in risk probability as a way of evaluating the incremental risk of upgrading Phase 2 engines to meet Phase 3 emission standards. This is an engineering analysis tool to help engineers and other professional staff on the FMEA team to identify and manage risk. In a FMEA, potential failure modes, causes of failure, and failure effects are identified and a resulting risk probability is calculated from these results. This risk probability is used by the FMEA team to rank problems for potential action to reduce or eliminate the causal factors. Identifying these causal factors is important because they are the elements that a manufacturer can consider reducing the adverse effects that might result from a particular failure mode.

Our technical work and subsequent analysis of all of the data and information strongly indicate that effective catalyst-based standards can be implemented without an incremental increase in the risk of fire or burn to the consumer either during or after using the equipment. Similarly, we did not find any increase in the risk of fire during storage near typical combustible materials. In many cases, the designs used for catalyst-based technology can lead to an incremental decrease in such risk.

More specifically, our work included taking temperature measurements and infrared thermal images of both OEM mufflers and prototype catalyst/mufflers on six Class 1 engines and three Class 2 engines as part of the safety study. We integrated the emission reduction catalyst into the muffler. In doing so, we generally designed heat management features into the catalyst/muffler and cooling system. These heat management design elements, all of which were not used on every prototype, included: 1) positioning the catalyst within the cooling air flow of the engine fan or redirecting some cooling air over the catalyst area with a steel shroud; 2) redirecting exhaust flow through multiple chambers or baffles within the catalyst/muffler; 3) larger catalyst/muffler volumes than the original equipment muffler; and 4) minimizing CO oxidation at moderate to high load conditions to maintain exhaust system surface temperatures comparable to those of the OEM systems. The measurements and images were taken during various engine operating conditions and as the engines cooled down after being shut off.. This latter event, termed “hot soak,” is an important consideration since it is often when the operator is in close proximity to the engine either performing maintenance or refueling the equipment.

Figures 4.8-1 and 4.8-2 are an example of the measurements and images taken to compare Class 1 engine original equipment (OEM) mufflers to the same engines equipped with prototype catalyst/mufflers. The first figure depicts surface temperatures from engine number 244 while operated on a laboratory dynamometer over three modes of EPA’s A-cycle steady-state test cycle. The second figure shows surface temperatures for the same engine at different times during hot soak. The prototype catalyst/muffler system shown in these figures uses one of the most effective heat management designs in the safety study. As shown, the catalyst system in this example has much lower surface temperatures during both engine operation and hot soak.

Similar information was collected in the laboratory for Class 2 engines used in lawn tractors. However, those tests were conducted on the “raw” engines without the chassis, which is an integral part of the overall engine cooling system for most residential Class 2 applications. Because of this, we believe it is more appropriate to compare the thermal measurements from field testing of the integrated unit.

The test results for engine 251 are fairly typical of the Class 2 lawn tractor test results. During engine operation, the OEM muffler configuration had exposed surface temperatures of approximately 200 ˚C as viewed from both sides of the tractor when cutting moderate to heavy grass and peak temperatures as high as 300 to 365 ˚C. The lawn tractor equipped with engine 253, which is from the same engine family as number 251, was fitted with a prototype catalyst/muffler exhibited exposed surface temperatures of approximately 115 to 130 ˚C and peaks of 160 to 190 ˚C. The lower temperatures for the prototype catalyst system is in part due to the more effective cooling of the catalyst/mufflers due to the re-routing of cooling air through the chassis and other heat management design elements.

The hot soak results for the above engines and two other related Class 2 lawn mowers are shown in Figure 4.8-3. The two-minute nominal refueling point after engine shut-down following 30 minutes of grass-cutting operation is shown for reference. In these tests, both of the engines with prototype catalyst/mufflers had lower peak surface temperatures than the OEM muffler configurations.

Figure 4.8-1: Surface Temperature Infrared Thermal Images of Exhaust System Components for Class 1 Engine 244 with a Catalyst/Muffler (left) and an OEM Muffler (right) at Various Operating Modes.

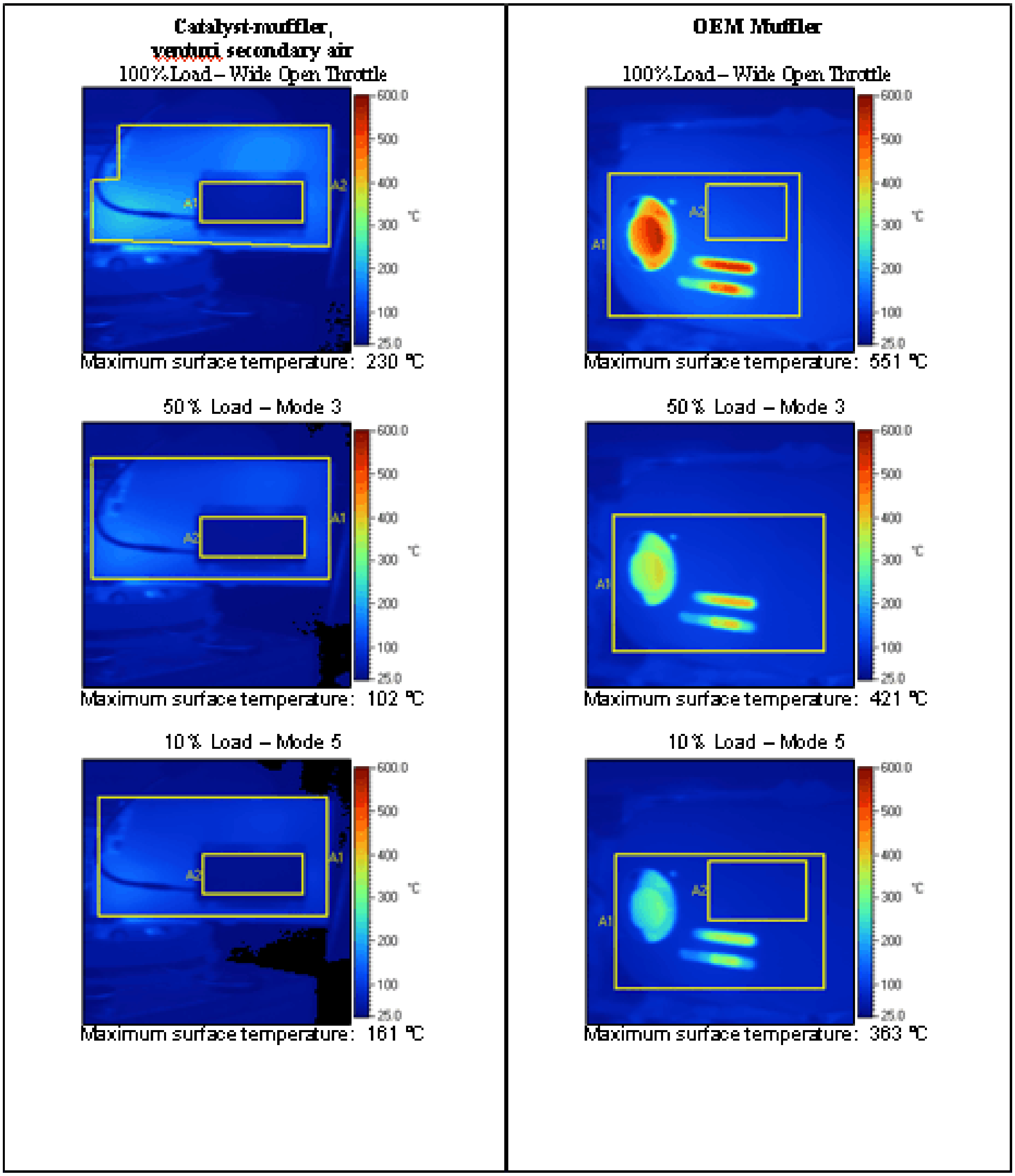


Figure 4.8-2: Hot Soak Surface Temperature Infrared Thermal Images of Exhaust System Components for Class 1 Engine 244 After Sustained Wide Open Throttle and 100 Percent Load.

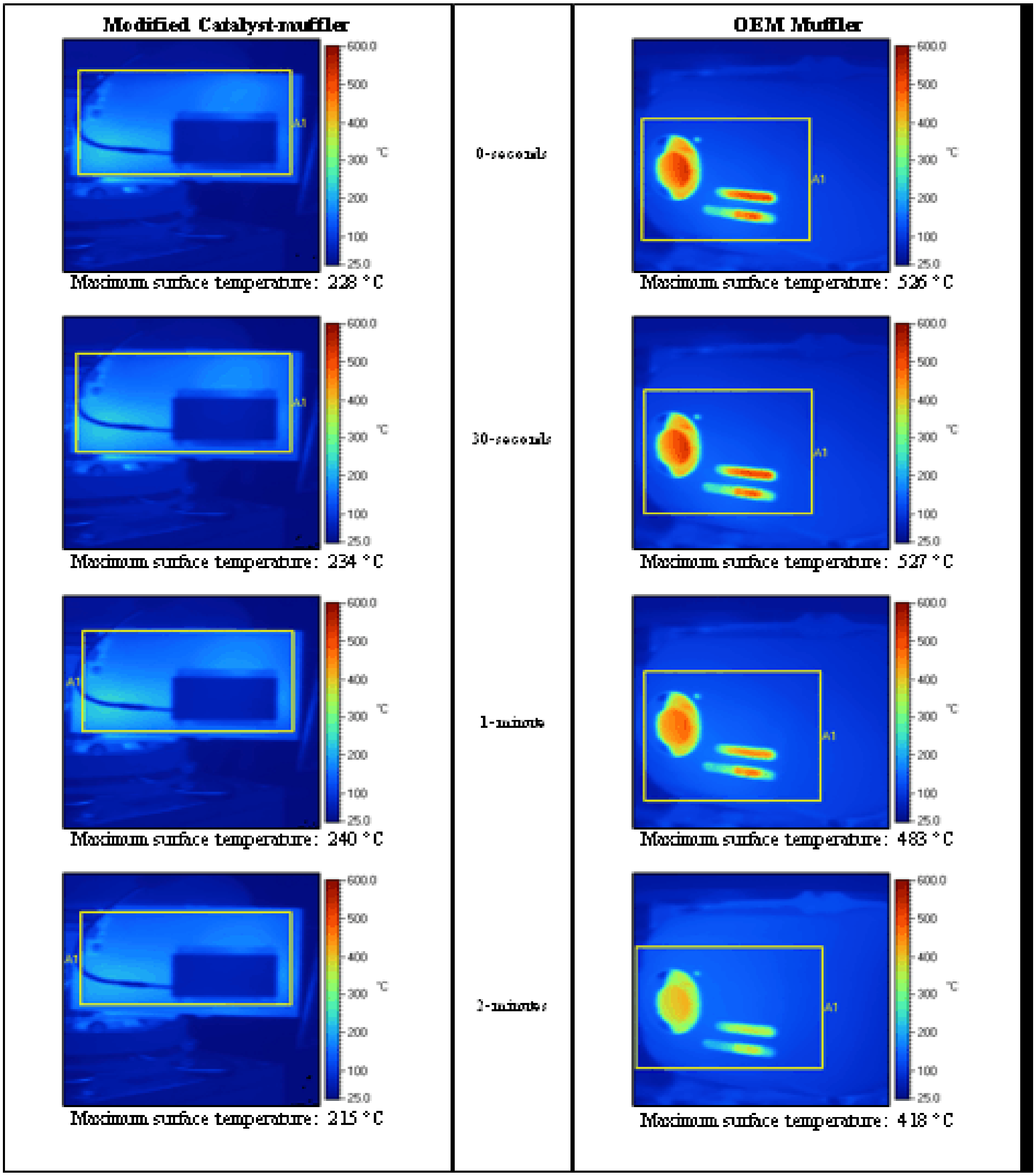
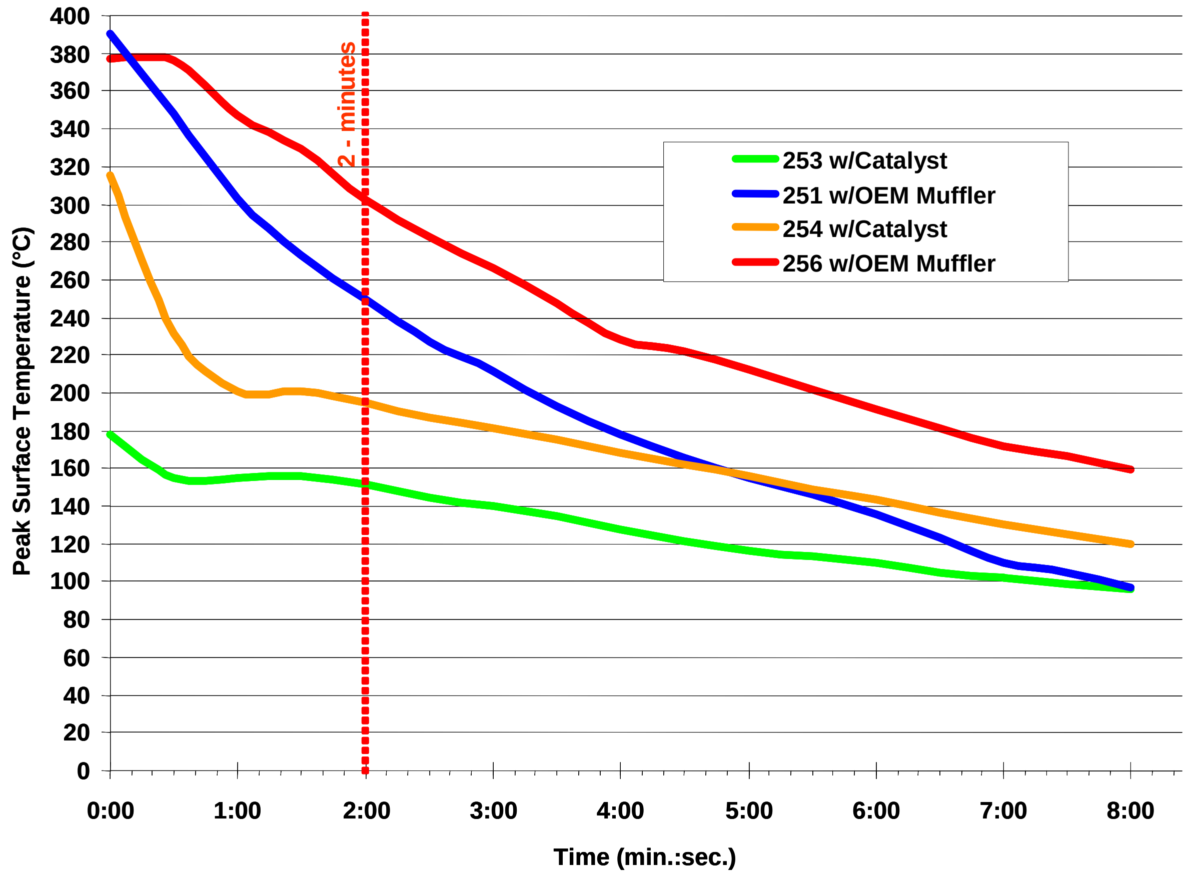


Figure 4.8-3: Hot Soak Peak Surface Temperatures Infrared Thermal Images for Class 2 Lawn Tractors Following After Approximately 30-Minutes of Grass Cutting.



4.8.1.2 Exhaust Emission Standards for Marine SI Engines

Our analysis of exhaust emission standards for Marine SI engines found that the U.S. Coast Guard has comprehensive safety standards that apply to engines and fuel systems used in these vessels. Additionally, organizations such as the Society of Automotive Engineers, Underwriters Laboratories, and the American Boat and Yacht Council (ABYC) also have safety standards that apply in this area. We also found that the four-stroke and two-stroke direct injection engine technologies likely to be used to meet the exhaust emission standards contemplated for Marine SI engines are in widespread use in the vessel fleet today. These more sophisticated engine technologies are replacing the traditional two-stroke carbureted engines. The four-stroke and two-stroke direct injection engines meet applicable Coast Guard and ABYC safety standards and future products will do so as well. The emission standards must be complementary to existing safety standards and our analysis indicates that this will be the case. There are no known safety issues with the advanced technologies compared with two-stroke carbureted engines. The newer-technology engines arguably provide safety benefits due to improved engine reliability in-use. Based on the applicability of Coast Guard and ABYC safety standards and the good in-use experience with advanced-technology engines in the current vessel fleet, we believe new emission standards would not create an incremental increase in the risk of fire or burn to the consumer.

4.8.2 Noise

As automotive technology demonstrates, achieving low emissions from spark-ignition engines can correspond with greatly reduced noise levels. Direct-injection two-stroke and four-stroke OB/PWC have been reported to be much quieter than traditional carbureted two-stroke engines. Catalysts in the exhaust act as mufflers which can reduce noise. Additionally, adding a properly designed catalyst to the existing muffler found on all Small SI engines can offer the opportunity to incrementally reduce noise.

4.8.3 Energy

Adopting new technologies for controlling fuel metering and air-fuel mixing, particularly the conversion of some carbureted engines to advanced fuel injection technologies, will lead to improvements in fuel consumption. This is especially true for OB/PWC engines where we expect the standards to result in the replacement of old-technology two stroke engines with more fuel efficient technologies such as two-stroke direct injection or four-stroke engines. Carbureted crankcase-scavenged two-stroke engines are inefficient in that 25 percent or more of the fuel entering the engine may leave the engine unburned. We estimate a fuel savings of about 61 million gallons of gasoline from marine engines in 2030, when most boats would be using engines complying with the standard.

The conversion of some carbureted Small SI engines to fuel injection technologies is also expected to improve fuel economy. We estimate approximately 7 percent of the Class II engines will be converted to fuel injection and that this will result in a fuel savings of about 10 percent for each converted engine. This translates to a fuel savings of about 22 million gallons of gasoline in 2030 when all of the Class II engines used in the U.S. will comply with the Phase 3 standards. By contrast, the use of catalyst-based control systems on Small SI engines is not expected to change their fuel consumption characteristics. These estimates are discussed in more detail in Chapter 6.

APPENDIX 4A: Normalized Modal Emissions for a 7.4 L MPI SD/I

Figure 4A-1: HC+NOx Ratios for 7.4L MPI Engine, Baseline

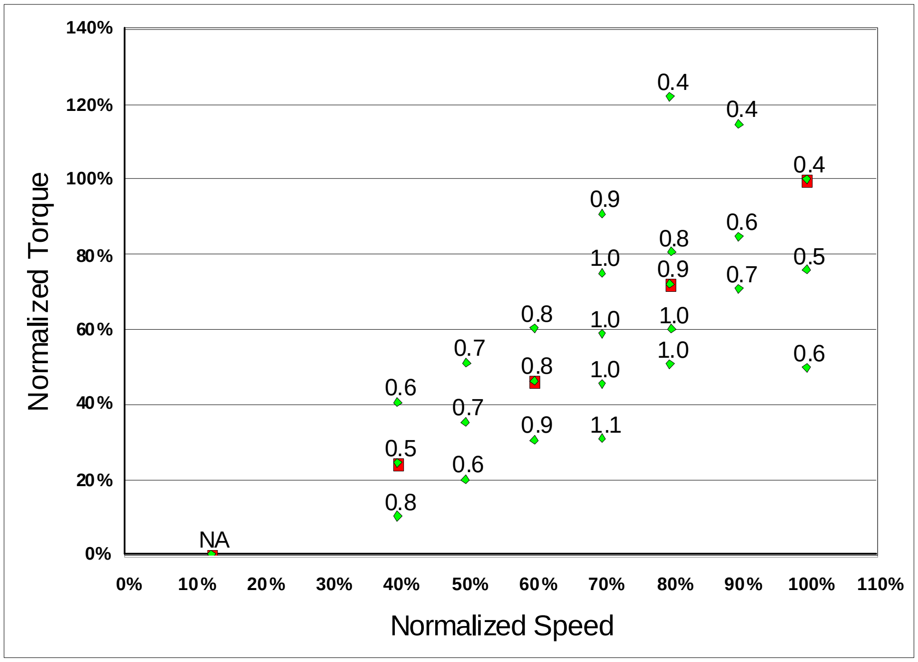


Figure 4A-2: CO Ratios for 7.4L MPI Engine, Baseline

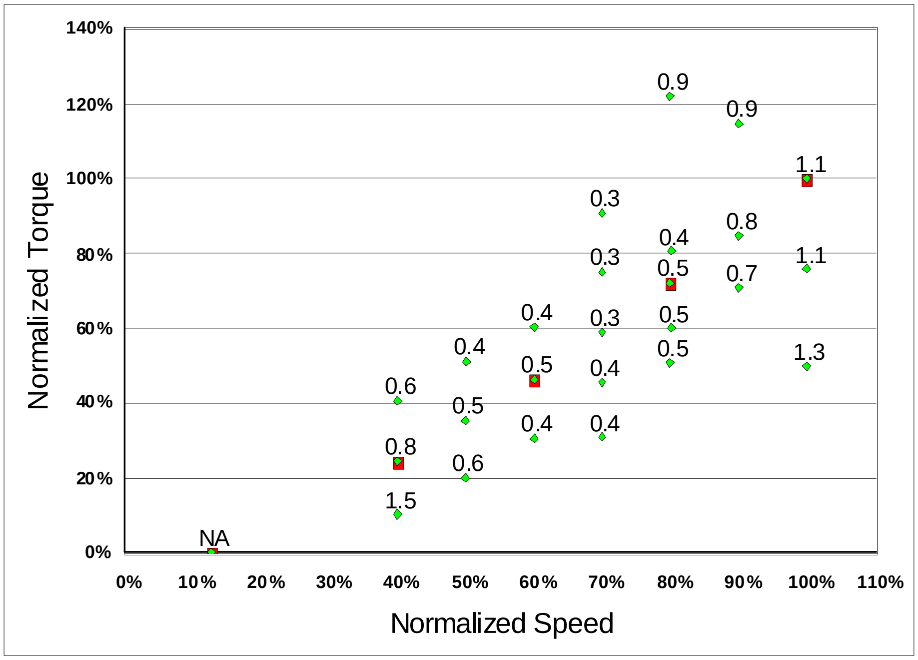


Figure 4A-3: HC+NOx Ratios for 7.4L MPI Engine, Riser Catalysts

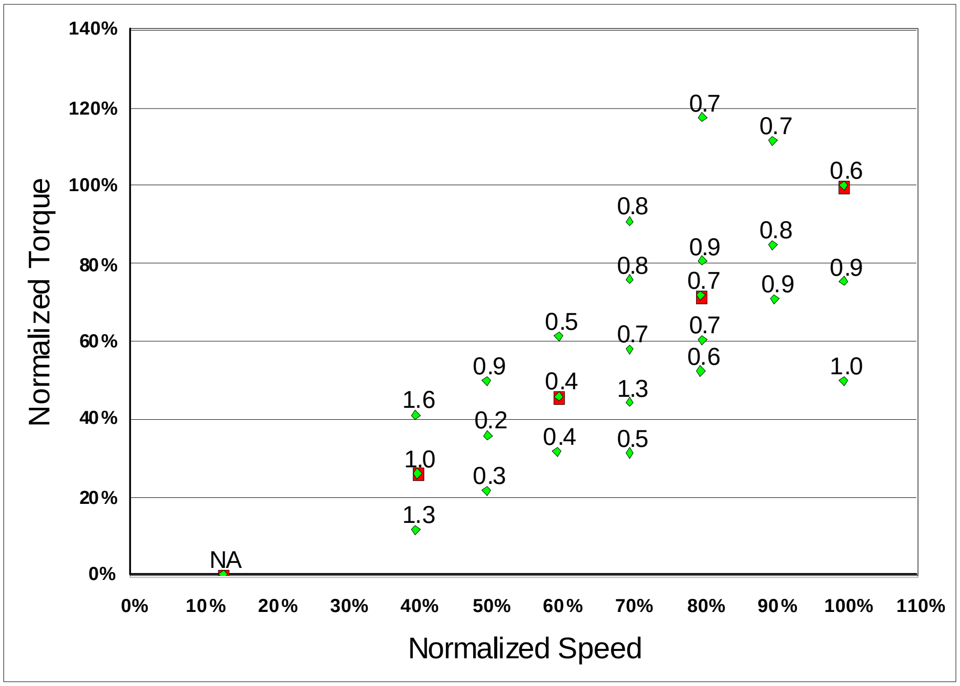


Figure 4A-4: CO Ratios for 7.4L MPI Engine, Riser Catalysts

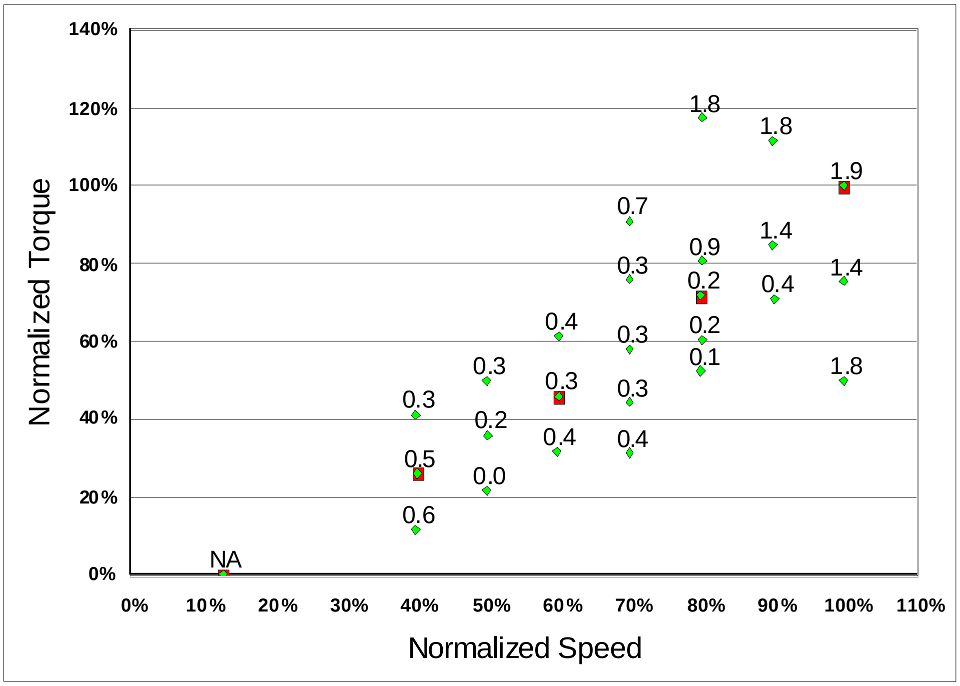


Figure 4A-5: HC+NOx Ratios for 7.4L MPI Engine, Elbow Catalysts

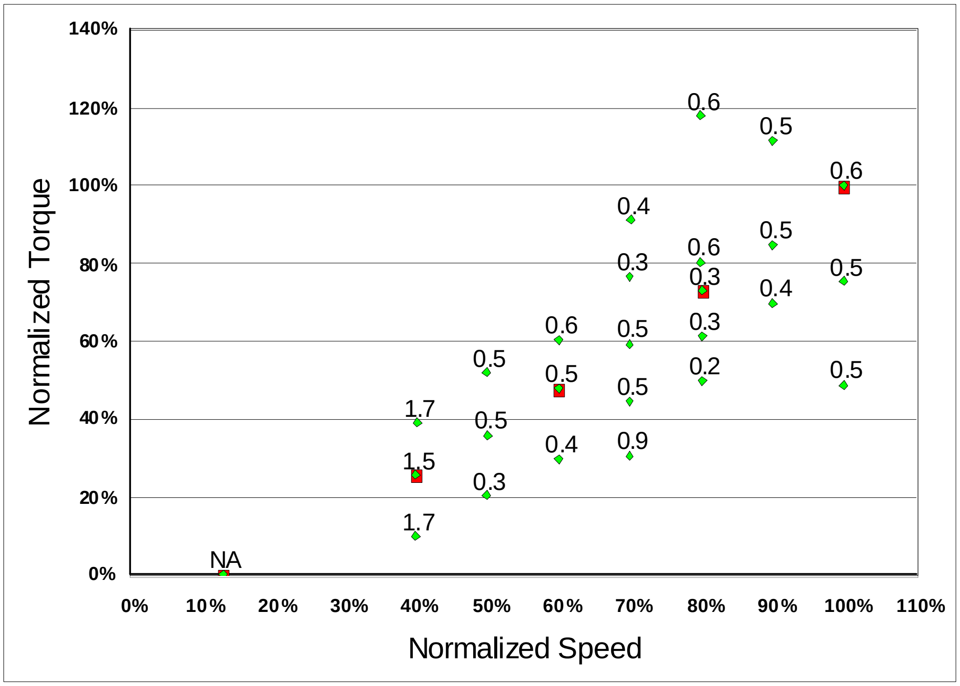


Figure 4A-6: CO Ratios for 7.4L MPI Engine, Elbow Catalysts

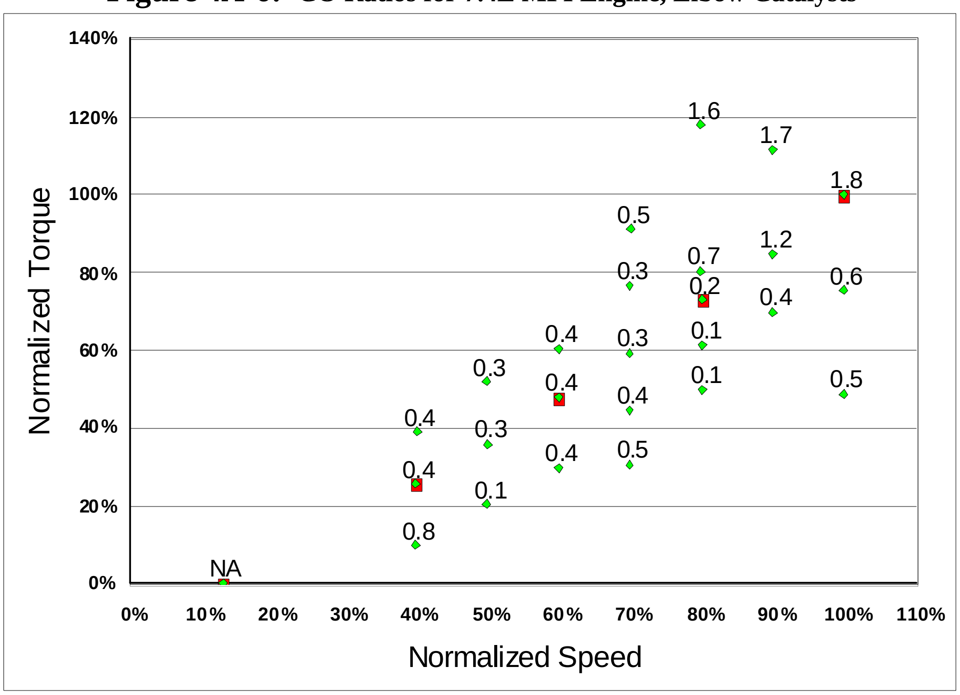


Figure 4A-7: **HC+NOx Ratios for 7.4L MPI Engine, External Catalysts**

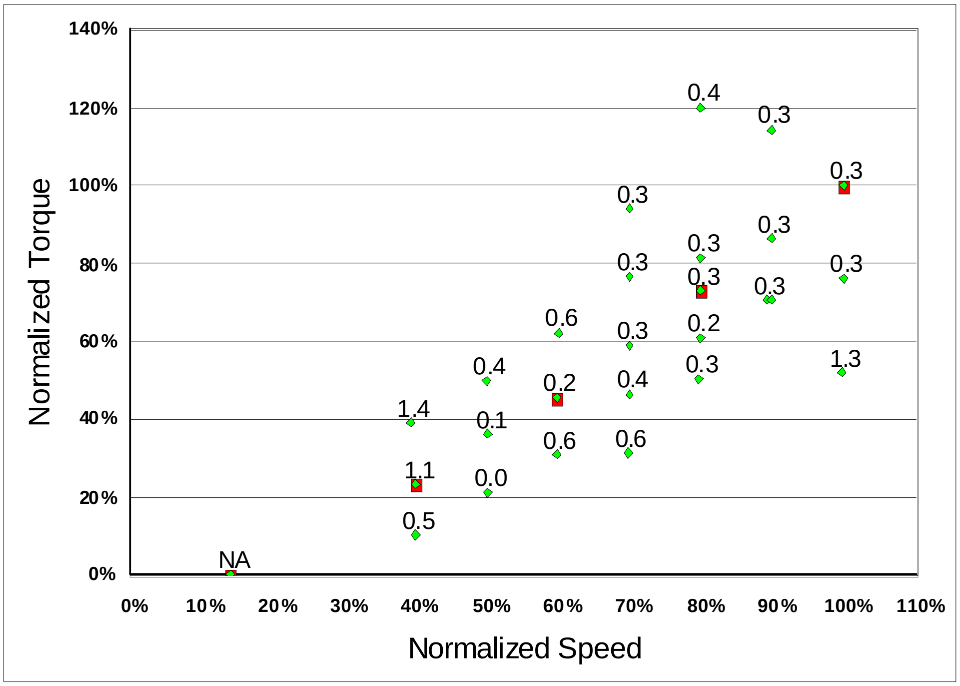
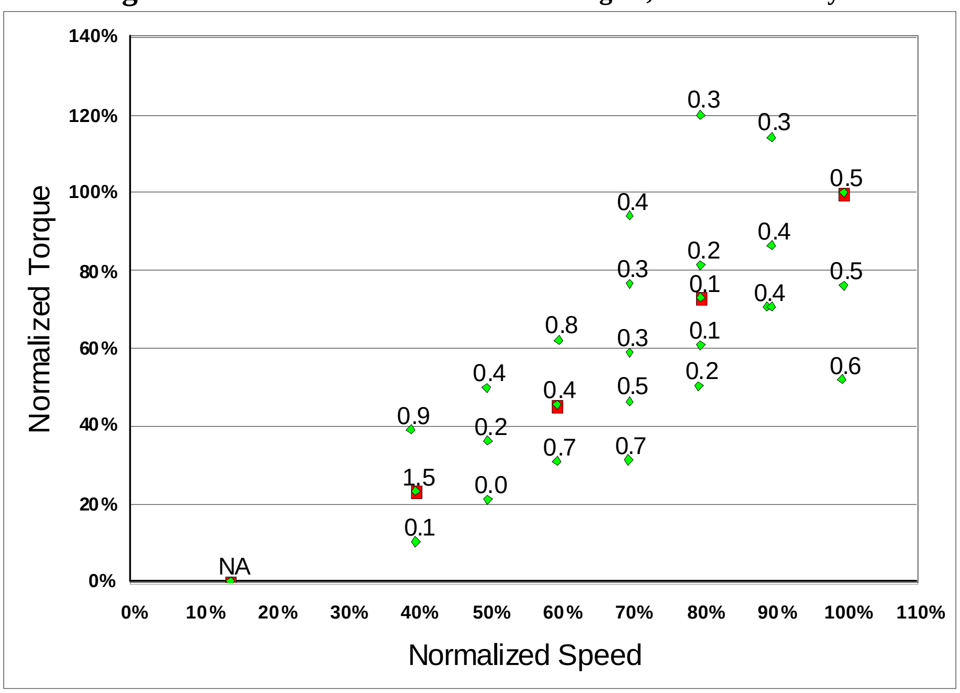


Figure 4A-8: **CO Ratios for 7.4L MPI Engine, External Catalysts**



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