CHAPTER 4: Feasibility of Proposed Standards

Section 213(a)(3) of the Clean Air Act presents statutory criteria that EPA must evaluate in determining standards for nonroad engines and vehicles. 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 proposed emission standards are technically achievable accounting for all the above factors.

4.1 CI Recreational Marine

The proposed emission standards CI recreational marine engines are summarized in the Executive Summary. We believe that manufacturers will be able to meet these standards using technology similar to that required for the commercial marine engine standards. This section discusses technology currently used on CI recreational marine engines and anticipated technology to meet the proposed standards. In addition, this section discusses the emission test procedures and not-to-exceed requirements.

4.1.1 Baseline Technology for CI Recreational Marine Engines

We developed estimates of the current mix of technology for CI recreational marine engines based on data from the 1999 Power Systems Research (PSR) database and from conversations with marine manufacturers. Based on this information, we estimate that 97 percent of new marine engines are turbocharged, and 80% of these turbocharged engines use aftercooling. The majority of these engines are four-strokes, but about 14% of new engines are two-strokes. Electronic controls have only recently been introduced into the marketplace; however, we anticipate that their use will increase as customers realize the performance benefits associated with electronic controls and as the natural migration of technology from on-highway to nonroad to marine occurs.

Table 4.1-1 presents data[1,2,3,4,5,6] from 25 recreational marine diesel engines based on the ISO E5 duty cycle. This data shows to what extent emissions need to be reduced from today's CI recreational marine engines to meet the proposed standards.[k] On average, we are requiring significant reductions in HC+NOx and PM. However, this data seems to show that the diesel engine designs will either have to be focused on NOx or PM due to the trade-off between calibrating to minimize these pollutants. The proposed CO standards will just act as a cap.

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[k] For most of the engines in Table 4.1-1, the proposed standards are of 7.2 g/kW-hr HC+NOx, 5 g/kW-hr CO, and 0.2 g/kW-hr PM

Table 4.1-1: Emissions Data from CI Recreational Marine Engines

Rated Power (kW)	*Control Management*	*Aftercooling*	*Emissions Data g/kW-hr*			
			HC	*NOx*	*CO*	*PM*
120	electronic	raw-water	0.09	5.8	0.9	–
132	mechanical	raw-water	0.07	4.2	0.2	–
142	mechanical	separate circuit	0.79	8.6	1.1	–
162	mechanical	raw-water	0.11	4.0	0.2	–
164	electronic	raw-water	0.28	5.1	1.6	–
170	mechanical	raw-water	0.36	8.1	0.6	0.20
186	mechanical	raw-water	0.30	10.2	1.2	0.12
209	mechanical	raw-water	0.42	10.8	2.3	0.22
230	electronic	raw-water	0.28	5.5	1.8	0.39
235	mechanical	raw-water	0.45	9.8	1.8	0.20
265	mechanical	jacket-water	0.58	10.8	1.4	–
276	mechanical	raw-water	0.60	10.7	1.9	0.24
287	electronic	raw-water	0.28	7.9	–	0.12
321	mechanical	raw-water	0.37	7.7	0.9	0.23
324	mechanical	jacket-water	0.30	7.9	2.9	0.95
336	electronic	jacket-water	0.18	11.0	0.5	0.10
336	electronic	jacket-water	0.09	11.9	–	0.16
447	electronic	raw-water	0.12	9.3	–	0.17
447	mechanical	jacket-water	0.60	12.0	1.5	0.18
474	electronic	raw-water	0.34	7.7	0.5	0.07
537	electronic	jacket-water	0.08	10.7	–	0.19
820	electronic	separate circuit	0.33	9.5	0.8	0.13
1040	electronic	jacket-water	0.09	9.3	–	0.21
1080	electronic	separate circuit	0.18	7.6	1.2	0.15
1340	electronic	separate circuit	0.27	7.2	0.9	0.15

4.1.2 Anticipated Technology for CI Recreational Marine Engines

Marine engines are generally derived from land-based nonroad, locomotive, and to some extent highway engines. In addition, recreational marine engines will be able to use technology developed for commercial marine engines. This allows recreational marine engines, which generally have lower sales volumes than other nonroad engines, to be produced more cost-effectively. Because the marine designs are derived from land-based engines, we believe that many of the emission-control technologies which are likely to be applied to nonroad engines to meet their Tier 2 and 3 emission standards will be applicable to marine engines. We also believe that the technologies listed below will be sufficient for meeting both the new emission standards and the Not to Exceed requirements discussed later in this chapter.

We anticipate that timing retard will likely be used in most CI recreational marine applications, especially at cruising speeds, to gain NOx reductions. The negative impacts of timing retard on HC, PM and fuel consumption can be offset with advanced fuel injection systems with higher fuel injection pressures, optimized nozzle geometry, and potentially through rate shaping. We do not expect marine engine manufacturers to convert from direct injection to indirect injection due to these standards.

Regardless of environmental regulations, we believe that recreational marine engine manufacturers would make more use of electronic engine management controls in the future to satisfy customer demands of increased power and fuel economy. Through the use of electronic controls, additional reductions in HC, CO, NOx, and PM can be achieved. Electronics may be used to optimize engine calibrations under a wider range of operation. Most of the significant research and development for the improved fuel injection and engine management systems should be accomplished for land-based nonroad diesel engines which are being designed to meet Tier 2 and Tier 3 standards. Common rail should prove to be a useful technology for meeting even lower emission levels in the future, especially for smaller engines. Thus, the challenge for this control program will be transferring land-based techniques to marine engines.

We project that all CI recreational marine engines will be turbocharged and most will be aftercooled to meet proposed emission standards. Aftercooling strategies will likely be mostly jacket-water charge air cooling, and in some cases, we believe that separate cooling circuits for the aftercooling will be used. We do not expect a significant increase in the use of raw-water charge air cooling for marine engines as a result of this proposed rule. We recognize that raw-water aftercooling systems are currently in use in many applications. Chapter 4 presents one possible scenario of how these technologies could be used on Category 1 marine diesel engines to meet the proposed standards.

By proposing standards that will not go into effect until 2006, we are providing engine manufacturers with substantial lead time for developing, testing, and implementing emission control technologies. This lead time and the coordination of standards with those for commercial marine engines allows for a comprehensive program to integrate the most effective emission control approaches into the manufacturers' overall design goals related to performance, durability, reliability, and fuel consumption.

4.1.3 Emission Measurement Procedures for CI Recreational Marine Engines

In any program we design to achieve emissions reductions from internal combustion engines, the test procedures we use to measure emissions are as important as the standards we put into place. These test procedure issues include duty cycle for certification, in-use verification testing, emission sampling methods, and test fuels.

4.1.3.1 Certification Duty Cycles

In choosing duty cycles for certification, we turned to the International Standards Organization (ISO).[7] For CI recreational marine engines, we based our standards on the ISO E5 duty cycle. This duty cycle is intended for "diesel engines for craft less than 24m length (propeller law)."

We are proposing to use the E5 duty cycle to measure emissions from diesel recreational marine engines. This cycle is similar to the E3 duty cycle which is used for commercial marine in that both cycles have four steady-state test points on an assumed cubic propeller curve. However, the E5 includes an extra mode at idle and has an average weighted power of 34% compared to the 69% for the E3. This duty cycle is presented in Table 4.1-2.

Table 4.1-2: ISO E5 Marine Duty Cycle

Mode	*% of Rated Speed*	*% of Power at Rated Speed*	*Weighting Factor*
1	100	100	0.08
2	91	75	0.13
3	80	50	0.17
4	63	25	0.32
5	idle	0	0.30

4.1.3.2 Emission Control of Typical In-Use Operation

We are 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 boat which do not necessarily lie on the test duty cycles. For instance, the test modes for the E5 duty cycle lie on average propeller curves. However, a propulsion marine engine may never be fitted with an "average propeller." In addition, a given engine on a boat may operate at higher torques than average if the boat is heavily loaded. We are also aware that, before a boat comes to plane, the engine operates closer to its full torque map than to the propeller curve.

We propose to apply the “not-to-exceed” (NTE) limit concept to recreational marine engines similar to commercial marine engines. This concept basically picks a zone of operation under which a marine engine must not exceed the standard by a fixed percentage and is discussed in more detail in the commercial marine FRM. Of course, the shape of the zone must be adjusted to reflect recreational engine use.

Under this proposal, we would have the authority to use test data from new or in-use engines to confirm emissions compliance. The engines tested would have to be within their regulatory useful lives.

4.1.3.2.1 Engine operation included for NTE

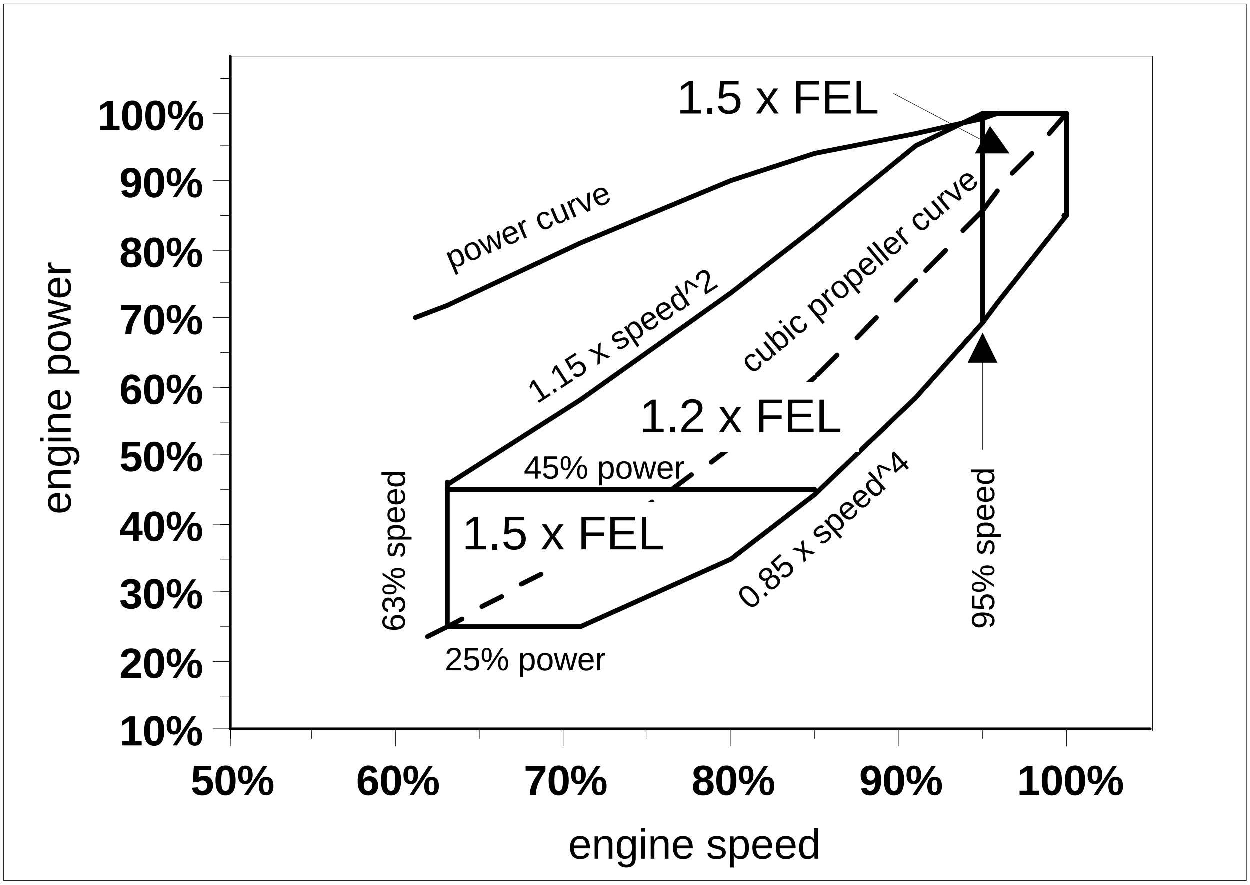
The shape of the NTE zones are based on our understanding of how recreational marine engines are used. Operation at low power is omitted from the NTE zone even though marine engines operate here in use. This omission is because, by definition, brake-specific emissions become very large at low power due to dividing by power values approaching zero.

We believe that the majority of marine engine operation is steady-state. This is why we are proposing that only steady-state operation be considered in the NTE requirements. Also, this is a technology forcing proposal and we would expect to see reductions even under transient operation. If we were to find that the effectiveness of this program is hurt due to high emissions under transient operation, we would revisit this issue in the future.

It should be noted that the emissions caps for operation in the NTE zone would be based on the weighted emissions over the E5 duty cycle. Because idle emissions are part of these weighted values but not included in the NTE zone, it is likely that emissions in the NTE zone will be less than the weighted average. This alone reduces the stringency of a “not-to-exceed” approach for recreational when compared to commercial marine engines.

For compression-ignition engines, the NTE zone is defined by the maximum power curve, actual propeller curves, and speed and load limits. The E5 duty cycle itself is based on a cubic power curve through the peak power point. For the NTE zone, we propose to define the upper boundary using a speed squared propeller curve passing through the 115% load point at rated speed and the lower boundary using on a speed to the fourth power curve passing through the 85% load point at rated speed. We believe these propeller curves represent the range of propeller curves seen in use.[8] To prevent imposing an unrealistic cap on a brake-specific basis, we are proposing to limit this region to power at or above 25% of rated power and speeds at or above 63% of rated speed. These limits are consistent with mode 4 of the E5 duty cycle. Figure 4.1-1 presents the proposed NTE zone for CI recreational marine engines.

Figure 4.1-1: Proposed NTE Zone for Recreational CI Marine Engines



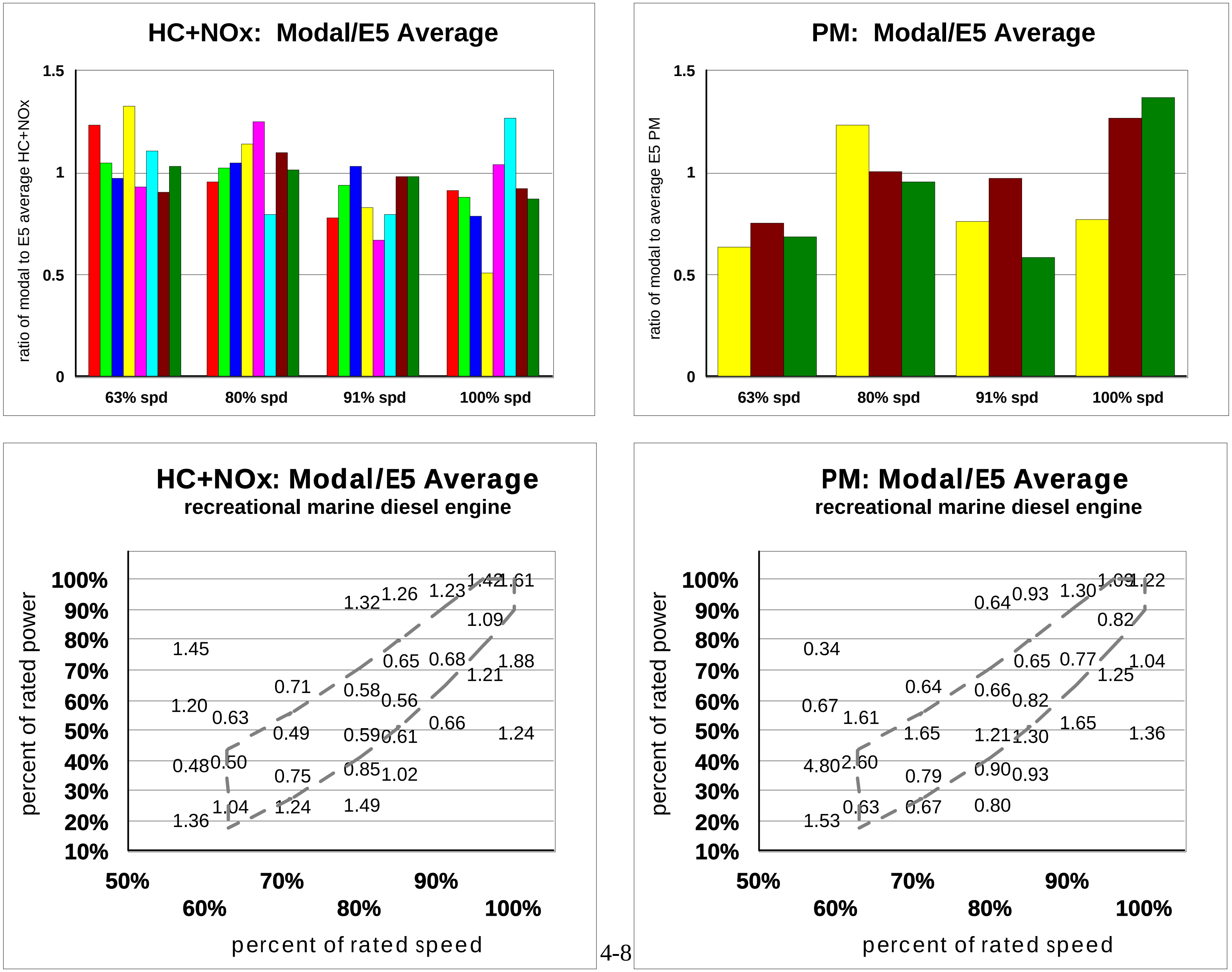
We understand that an engine tested onboard a boat in use may not be operating as the manufacturer intended. Specifically, the owner may not be using a propeller that is properly matched to the engine and boat. Or, the owner may have a boat that is overloaded and too heavy for the engine. The boundaries in Figure 4.1-1 are intended to contain typical operation of recreational diesel engines and exclude engines which are not used properly. Although the E5 uses a cubic power curve engines generally see some variation in use. These boundaries are consistent with operational data we collected.[9]

We are proposing emissions caps for the NTE zone 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 steady-state tests included in this rule.

Consistent with the commercial requirements, we propose that recreational CI marine engines must meet a cap of 1.5 times the certified level for HC+NOx, PM, and CO for the speed and power subzone below 45% of rated power and a cap of 1.2 times the certified levels at or above 45% of rated power. However, we are proposing an additional subzone, when compared to the commercial NTE zone, at speeds greater than 95% of rated. We are proposing a cap of 1.5 times the certified levels for this subzone. Our purpose for this additional subzone is to address the typical recreational design for higher rated power. This power is needed to ensure that the engine can bring the boat to plane.

We based the proposed caps both on emissions data collected on the assumed propeller curve and on data collected from a recreational marine diesel engine over a wide range of steady-state operation. All of this data is cited earlier in this chapter. The data in Figure 4.1-2 shows that, within the range of in-use testing points, HC+NOx and PM are generally well below the E5 weighted averages. This is likely due to the effects of emissions at idle. For all of these engines, modal CO results were well below the proposed standard. None of these engines are calibrated for emissions control.

Figure 4.1-2: Ratio of Modal Emissions to E5 Cycle Weighted Emissions for Marine Diesel Engines



4.1.3.2.2 Ambient conditions during testing

Variations in ambient conditions can affect emissions from a marine engine. Such conditions include air temperature, humidity, and (especially for diesels) water temperature. We are proposing to apply the commercial marine engine ranges for these variables. Within the ranges, no corrections can be made for emissions. Outside of the ranges, emissions can be corrected back to the nearest edge of the range. The proposed ambient variable ranges are:

intake air temperature	13-35°C (55-95°F)
intake air humidity	7.1-10.7 g water/kg dry air (50-75 grains/lb. dry air)
ambient water temperature	5-27°C (41-80°F)

The proposed air temperature and humidity ranges are consistent with those developed for NTE testing of highway heavy-duty diesel engines. The air temperature ranges were based on temperatures seen during ozone exceedences.[10] For NTE testing in which the air temperature or humidity is outside of the range, we propose that the emissions be corrected back to the air temperature or humidity range. These corrections would have to be consistent with the equations in Title 40 of the Code of Federal Regulations except that these equations correct to 25°C and 10.7 grams per kilogram of dry air while corrections associated with the NTE testing shall be to the nearest outside edge of the specified ranges. For instance, if the temperature were higher than 35°C, a temperature correction factor may be applied to the emissions results to determine what the emissions would be at 35°C.

For marine engines using aftercooling, we believe the charge air temperature is insensitive to ambient air temperature compared to the cooling effect of the aftercooler. SwRI tested this theory and found that when the ambient air temperature was increased from 21.9 to 32.2°C, the cooling water to the aftercooler of a diesel marine engine only had to be reduced by 0.5°C to maintain a constant charge air temperature.[11] According to the CFR correction factor, there is only a ±3% variation in NOx in the proposed NTE humidity range.

Some CI recreational marine engines, are naturally aspirated. Naturally aspirated engines should be more sensitive to intake air temperature because the temperature affects the density of the air into the engine. Therefore, high temperatures can limit the amount of air drawn into the cylinder. However, our understanding is that many engines operate in and draw air from small engine compartments. This suggests that most recreational engines are already designed to operate with high intake air temperatures.

Ambient water temperature also may affect emissions due to its impact on engine and charge air cooling. We believe that this effect is small for naturally aspirated engines. We based the proposed water temperature range on temperatures that marine engines experience in the U.S. in use. Although marine engines experience water temperatures near freezing, we don't believe that additional emission control will be gained by lowering the minimum water temperature below 5°C. At this time, we aren't aware of an established correction factor for ambient water temperature. For this reason, we propose that NTE zone testing must be within the specified ambient water temperature range.

We don't think that the range of ambient water temperatures discussed above will have a significant effect on the stringency of the NTE requirements, even for aftercooled engines. Following the normal engine test practice recommended by SAE[12] for aftercooled engines, the cooling water temperature would be set to 25±5°C. This upper portion of the NTE temperature range is within the range suggested by SAE for engine testing. For lower temperatures, manufacturers would be able to use a thermostat or other temperature regulating device to ensure that the charge air is not overcooled. In addition, the SAE practice presents data from four aftercooled diesel engines on the effects of cooling medium temperature on emissions. For every 5°C increase in temperature, HC decreases 1.8%, NOx increases 0.6%, and PM increases 0.1%.

We are aware that many marine engines are designed for operation in a given climate. For instance, recreational vessels operated in Seattle don't need to be designed for 27°C water temperatures. For situations such as this, we propose that manufacturers be allowed to petition for the appropriate temperature ranges associated with the NTE zone for a specific engine design. In addition, we understand there are times when emission control needs to be compromised for startability or safety. Manufacturers would not be responsible for the NTE requirements under start up conditions. In addition, we propose that manufacturers would be able to petition to be exempt from emission control under specified extreme conditions such as engine overheating where emissions may increase under the engine protection strategy.

4.1.3.3 Emissions Sampling

Aside from the duty cycle, the test procedures for marine engines are similar to those for land-based nonroad engines. However, there are a few other aspects of marine engine testing that need to be considered. Most recreational marine engines mix cooling water into the exhaust. This exhaust cooling is generally done to keep surface temperatures low for safety reasons and to tune the exhaust for performance and noise. Because the exhaust must be dry for dilute emission sampling, the cooling water must be routed away from the exhaust in a test engine.

Even though many marine engines exhaust their emissions directly into the water, we base our proposed test procedures and associated standards on the emissions levels in the "dry" exhaust. Relatively little is known about water scrubbing of emissions. We must therefore consider all pollutants out of the engine to be a risk to public health. Additionally, we are not aware of a repeatable laboratory test procedure for measuring "wet" emissions. This sort of testing is nearly impossible from a vessel in-use. Finally, a large share of the emissions from this category come from large engines which emit their exhaust directly to the atmosphere.

The established method for sampling emissions is through the use of full dilution sampling. However, for larger engines the exhaust flows become so large that conventional dilute testing requires a very large and costly dilution tunnel. One option for these engines is to use a partial dilute sampling method in which only a portion of the exhaust is sampled. It is important that the partial sample be representative of the total exhaust flow. The total flow of exhaust can be determined by measuring fuel flow and balancing the carbon atoms in and out of the engine. For guidance on shipboard testing, the MARPOL NOx Technical Code specifies analytical instruments, test procedures, and data reduction techniques for performing test-bed and in-use emission measurements.[13] Partial dilution sampling methods can provide accurate steady-state measurements and show great promise for measuring transient emissions in the near future. We intend to pursue development of this method and put it in place prior to the date that the standards in this final rule become enforceable.

Pulling a marine engine from a boat and bringing it to a laboratory for testing could be burdensome. For this reason, we propose to be able to perform in-use confirmatory testing onboard a boat. Our goal would be to perform the same sort of testing as proposed for the laboratory. However, engines tested in a boat are not likely to operate exactly on the assumed propeller curve. For this reason, we propose that emissions measured within the NTE zone must meet the subzone caps based on the certified level during onboard testing. To facilitate onboard testing, our proposal requires that manufacturers provide a location with a threaded tap where a sampling probe may be inserted. This location would have to be upstream of where the water and exhaust mix at a location where the exhaust gases could be expected to be the most homogeneous.

There are several portable sampling systems on the market that, if used carefully, can give fairly accurate results for onboard testing. Engine speed can be monitored directly, but load may have to be determined indirectly. For engines operating at a constant speed, it should be relatively easy to set the engine to the points specified in the duty cycles.

4.1.3.4 Test Fuel Specifications

We propose to apply the recently finalized test fuel specifications for commercial marine engines to recreational marine diesel engines. These fuel specifications are similar to land-based nonroad fuel with a change in the sulfur content upper limit from 0.4 to 0.8 weight-percent (wt%). We believe that this will simplify development and certification burdens for marine engines that are developed from land-based counterparts. This test fuel has a sulfur specification range of 0.03 to 0.80 wt%, which covers the range of sulfur levels observed for most in-use fuels. Manufacturers will be able to test using any fuel within this range for the purposes of certification. Thus, they will be able to harmonize their marine test fuel with U.S. highway (<0.05 wt%) and nonroad (0.03 to 0.40 wt%), and European testing (0.1 to 0.2 wt%).

The intent of these proposed test fuel specifications is to ensure that engine manufacturers design their engines for the full range of typical fuels used by Category 1 marine engines in use. Because the technological feasibility of the new emission standards is based on fuel with up to 0.4 wt% sulfur, any testing done using fuel with a sulfur content above 0.4 wt% would be done with an allowance to adjust the measured PM emissions to the level they would be if the fuel used were 0.4 wt% sulfur. The full range of test fuel specifications are presented in Table 4.1-3. Because testing conducted by us is limited to the test fuel specifications, it is important that the test fuel be representative of in-use fuels.

Table 4.1-3: Recreational Marine Diesel Test Fuel Specifications

Item	*Procedure (ASTM)*	*Value (Type 2-D)*
Cetane	D613-86	40-48
Initial Boiling Point, °C	D86-90	171-204
10% point, °C	D86-90	204-238
50% point, °C	D86-90	243-282
90% point, °C	D86-90	293-332
End Point, °C	D86-90	321-366
Gravity, API	D287-92	32-37
Total Sulfur, % mass	D129-21 or D2622-92	0.03-0.80
Aromatics, % volume	D1319-89 or D5186-91	10 minimum
Parafins, Napthenes, Olefins	D1319-89	remainder
Flashpoint, °C	D93-90	54 minimum
Viscosity @ 38 °C, centistokes	D445-88	2.0-3.2

4.1.4 Impacts on Noise, Energy, and Safety

The Clean Air Act requires EPA to consider potential impacts on noise, energy, and safety when establishing the feasibility of emission standards for CI recreational marine engines.

One important source of noise in diesel combustion is the sound associated with the combustion event itself. When a premixed charge of fuel and air ignites, the very rapid combustion leads to a sharp increase in pressure, which is easily heard and recognized as the characteristic sound of a diesel engine. The conditions that lead to high noise levels also cause high levels of NOx formation. Fuel injection changes and other NOx control strategies therefore typically reduce engine noise, sometimes dramatically.

The impact of the new emission standards on energy is measured by the effect on fuel consumption from complying engines. Many of the marine engine manufacturers are expected to retard engine timing which increases fuel consumption somewhat. Most of the technology changes anticipated in response to the new standards, however, have the potential to reduce fuel consumption as well as emissions. Redesigning combustion chambers, incorporating improved fuel injection systems, and introducing electronic controls provide the engine designer with powerful tools for improving fuel efficiency while simultaneously controlling emission formation. To the extent that manufacturers add aftercooling to non aftercooled engines and shift from jacket-water aftercooling to raw-water aftercooling, there will be a marked improvement in fuel-efficiency. Manufacturers of highway diesel engines have been able to steadily improve fuel efficiency even as new emission standards required significantly reduced emissions.

There are no apparent safety issues associated with the new emission standards. Marine engine manufacturers will likely use only proven technology that is currently used in other engines such as nonroad land-based diesel applications, locomotives, and diesel trucks.

4.2 Large Industrial SI Engines

This category of engines generally includes all nonrecreational land-based spark-ignition engines rated above 19 kW that are not installed in motor vehicles or stationary applications. In an earlier memorandum, we described the rationale for developing emission measurement procedures for transient and off-cycle engine operation.[14] Information from that memorandum is not repeated here, except to the extent that it supports decisions about the selecting the proposed numerical emission standards.

The proposed emission standards for Large SI engines are listed in the Executive Summary. The following paragraphs summarize the data and rationale supporting the proposed standards.

4.2.1 Proposed 2004 Standards

Engine manufacturers are currently developing technologies and calibrations to meet the 2004 standards that apply in California. We expect manufacturers to rely on electronically controlled, closed-loop fuel systems and three-way catalysts to meet those emission standards. As described below, emission data show that water-cooled engines can readily meet the California ARB standards (3 g/hp-hr NMHC+NOx; 37 g/hp-hr CO).

Our projected date for a final rule—September 2002—allows manufacturers just over one year to prepare engines for nationwide sales starting in 2004. Implementing new standards with such a short lead time is only possible because manufacturers have been aware of their need to comply with the California ARB standards. With no need to further modify engine designs, manufacturers should have time before 2004 to plan for increasing production volume for nationwide sale of engines that can meet the 2004 California ARB standards.

Adopting standards starting in 2004 allows us to align near-term requirements with those adopted by California ARB. This also provides early emission reductions and gives manufacturers the opportunity to amortize their costs over a broader sales volume before investing in the changes needed to address the long-term standards described below.

4.2.2 Proposed 2007 Standards

The proposed 2004 standards described above would be effective in reducing emissions from Large SI engines, but we believe these levels don’t fulfill our obligation to adopt standards achieving the “greatest degree of reduction achievable” from these engines in the long term. With additional time to optimize designs to better control emissions, manufacturers can optimize their designs to reduce emissions below the levels required by the proposed 2004 standards. We are also proposing new procedures for measuring emissions starting in 2007, which would require further efforts to more carefully design and calibrate emission-control systems to achieve in-use emission reductions. The following discussion explains why we believe the proposed 2007 emission standards are feasible.

The biggest uncertainty in adopting emission standards for Large SI engines has been the degree to which emission-control systems deteriorate with age. While three-way catalysts and closed-loop fueling systems have been in place in highway applications for almost 20 years, there is very little information showing how these systems hold up under nonroad use. To address this, we participated in an investigative effort with Southwest Research Institute (SwRI), California ARB, and South Coast Air Quality Management District, as described in the memorandum referenced above. The engines selected for testing had been retrofitted with emission-control systems in Spring 1997 after having already run for 5,000 and 12,000 hours. Both engines are in-line four-cylinder models operating on liquefied petroleum gas (LPG)—a 2-liter Mazda engine rated at 32 hp and a 3-liter GM engine rated at 45 hp. The retrofit consisted of a new, conventional three-way catalyst, electronic controls to work with the existing fuel system, and the associated sensors, wiring, and other hardware. The electronic controller allowed only a single adjustment for controlling air-fuel ratios across the range of speed-load combinations.

Laboratory testing consisted of measuring steady-state and transient emission levels, both before and after taking steps to optimize the system for low emissions. While the engines' emission-control systems originally focused on controlling CO emissions, the testing effort focused on simultaneously reducing HC, NOx, and CO emissions. This testing provides a good indication of the capability of these systems to control emissions over an engine's full useful life. The testing also shows the degree to which transient emissions are higher than steady-state emission levels for Large SI engine operation. Finally, the testing shows how emission levels vary for different engine operating modes. Emission testing included engine operation at a wide range of steady-state operating points and further engine operation over several different transient duty cycles. Much of the emissions variability at different speeds and loads can be attributed to the basic design of the controller, which has a single, global calibration setting. This data showing the variability of emissions is necessary to support the proposed field-testing emission standards, as described further below.

4.2.2.1. Steady-state testing results

Testing results from the aged engines at SwRI showed very good emission control capability over the full useful life. Test results with new hardware on the aged engines lead to the conclusion that the systems operated with relatively stable emission levels over the several thousand hours. As shown in Table 4.2-1, the emission levels measured by SwRI are consistent with results from a wide variety of measurements on other engines. The data listed in the table includes only LPG-fueled engines. See Section 4.2.2.6 a discussion of gasoline-fueled engines.

Table 4.2-1
Steady-State Emission Results from LPG-fueled Engines

Test engine	HC+NOx* g/hp-hr	CO g/hp-hr	Notes**
Mazda 2L[15]	0.51	3.25	4,000 hours, add-on retrofit
GM 3L	0.87	1.84	5,600 hours, add-on retrofit
Engine B	0.22	2.79	250 hours
GFI[16]	0.52 NMHC+NOx	2.23	5,000 hours
Toyota/ECS 2L[17]	1.14	0.78	zero-hour; ISO C1 duty cycle for nonroad diesel engines
GM/Impco 3L[18]	0.26	0.21	zero-hour

*Measurements are THC+NOx, unless otherwise noted.
**Emissions were measured on the ISO C2 duty cycle, unless otherwise noted.

This data set supports emission standards significantly more stringent than the proposed 2004 standards. However, considering the need to focus on transient emission measurements, we believe it is not appropriate to adopt more stringent emission standards based on the steady-state duty cycles. Stringent emission standards based on certain discrete modes of operation may unnecessarily constrain manufacturers from controlling emissions across the whole range of engine speeds and loads. We therefore intend to rely more heavily on the transient testing to determine the stringency of the emission-control program.

4.2.2.2 Transient testing results

The SwRI testing is currently the only source of information available for evaluating the transient emission levels from Large SI engines equipped with emission-control systems. Table 4.2-2 shows the results of this testing. The transient emission levels, though considerably lower than the 2004 standards, are higher than those measured on the steady-state duty cycles. A combination of factors contribute to this. First, engines are unlikely to maintain precise control of air-fuel ratios during rapid changes in speed or load, resulting in decreased catalyst-conversion efficiency. Also, the transient duty cycle includes operation at engine speeds and loads that have higher steady-state emission levels than the seven modes constituting the C2 duty cycle. Both of these factors would also cause uncontrolled emission levels to be higher, so the measured emission levels with the catalyst system still show a substantial reduction in emissions.

Table 4.2-2
Transient Test Results from SwRI Testing

Engine*	Duty Cycle	THC+NOx g/hp-hr	CO g/hp-hr
Mazda	Variable-speed, variable-load	1.1	9.9
	Constant-speed, variable-load	1.5	8.4
GM	Variable-speed, variable-load	1.2	7.0

*Based on the best calibration on the engine operating with an aged catalyst.

4.2.2.3 Off-cycle testing results

Engines operate in the field under both steady-state and transient operation. Although these emission levels are related to some degree, they are measured separately. This section therefore first considers steady-state operation.

Figures 4.2-1 through 4.2-6 show plots of emission levels from the test engines at several different steady-state operating modes. This includes the seven speed-load points in the ISO C2 duty cycle, with many additional test points spread across the engine map to show how emissions vary with engine operation. The plotted emission level shows the emissions at each normalized speed and normalized load point. The 100-percent load points at varying engine speeds form the engine’s lug curve, which appears as a straight line because of the normalizing step.

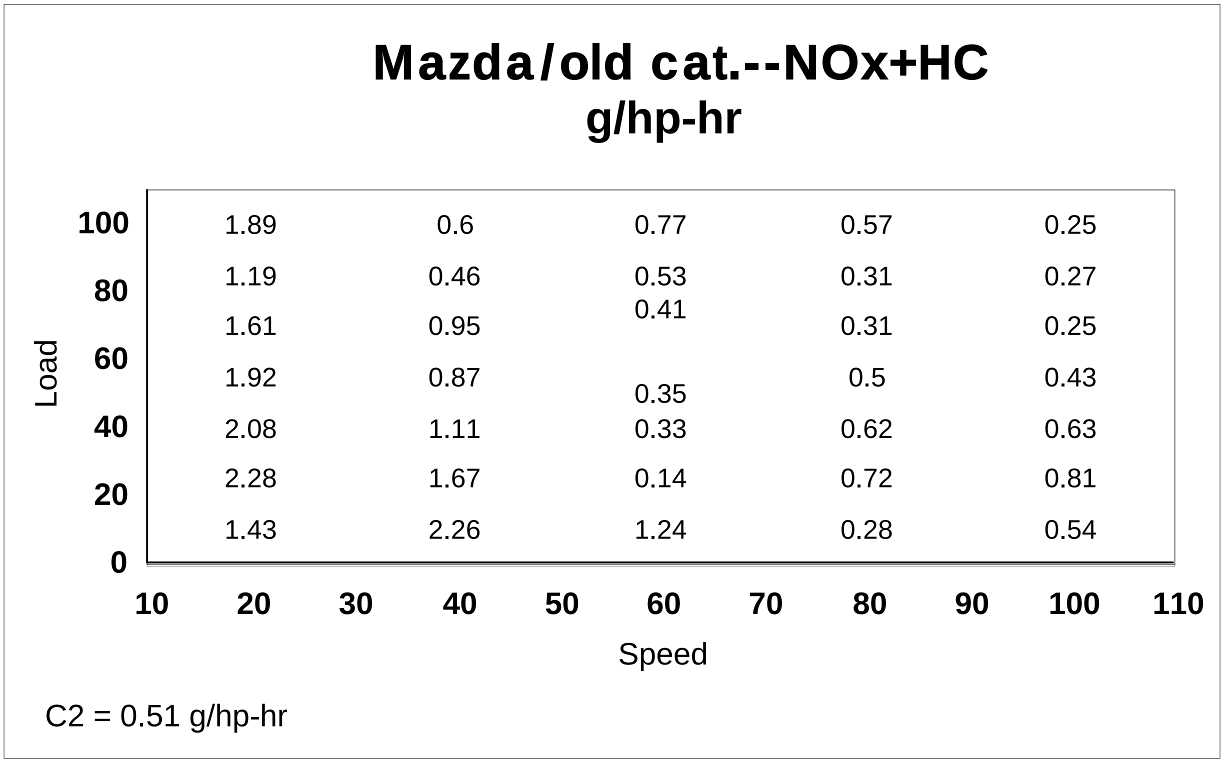
Figure 4.2-1 shows the THC+NOx emissions from the Mazda engine when tested with the aged catalyst. While several points are higher than the 0.51 g/hp-hr level measured on the C2 duty cycle, the highest levels observed from the Mazda engine are around 2.3 g/hp-hr. The highest emissions are generally found at low engine speeds. Emission testing on the Mazda engine with a new catalyst showed very similar results, so they are not shown here.

CO emissions from the same engine had a similar mix of very low emission points and several higher measurements. The CO levels along the engine’s lug curve (100 percent load) range 12 to 22 g/hp-hr, well above the other points, most of which are under 4 g/hp-hr. The corner of the map with high-speed and low-load operation also has a high level of 9 g/hp-hr. These high-emission modes point to the need to address control of air-fuel ratios at these extremes of engine operation.

If CO emissions at these points would be an inherent problem associated with these engines, we could take that into account in setting the standard. Figure 4.2-4 shows, however, that the GM engine with the same kind of aged emission-control system had emission levels at most of these points ranging from 0.7 to 4.7 g/hp-hr. The one remaining high point on the GM engine was 11.6 g/hp-hr at full load and low speed. A new high-emission point was 28 g/hp-hr at the lowest measured speed and load. Both of these points are much lower on the same engine with the new catalyst installed (see Figure 4.2-6). These data reinforce the conclusion that adequate development effort will enable manufacturers to achieve broad control of emissions across the engine map.

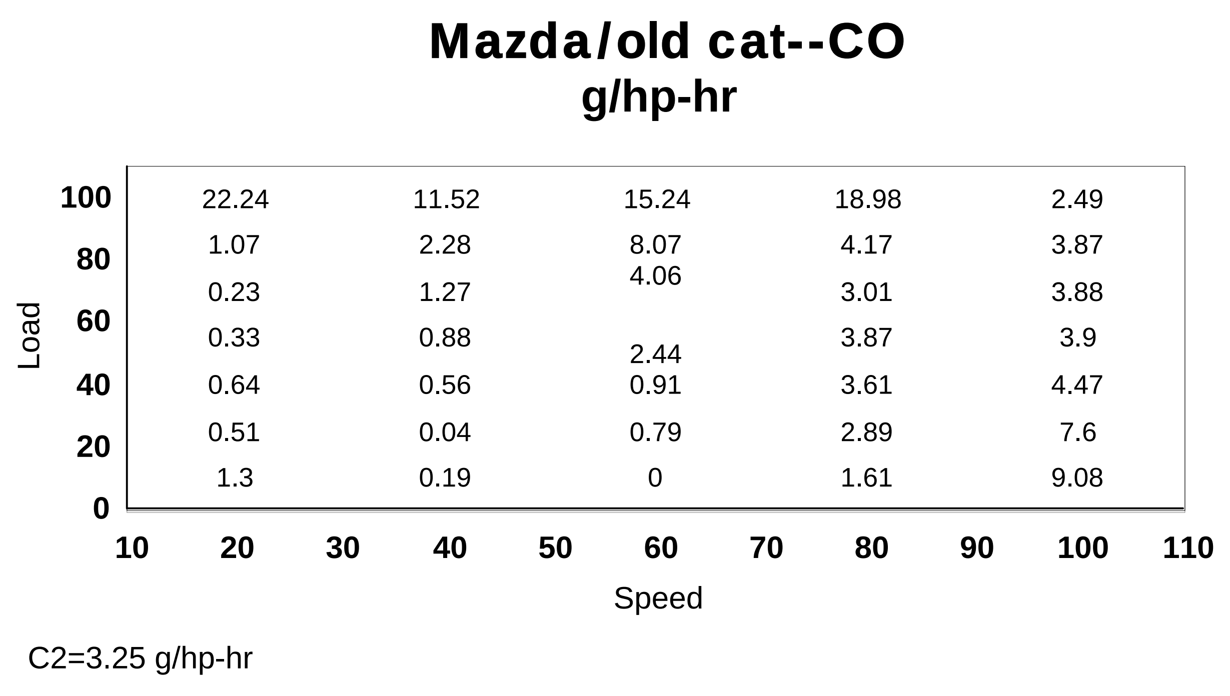
Figure 4.2-3 shows the THC+NOx emissions from the GM engine when tested with the aged catalyst. Emission trends across the engine map are similar to those from the Mazda engine, with somewhat higher low-speed emission levels between 2.3 and 4.4 g/hp-hr at various points. Operation on the new catalyst shows a significant shifting of high and low emission levels at low-speed operation, but the general observation is that the highest emission levels disappear, with 2.3 g/hp-hr being again the highest observed emission level over the engine map (see Figure 4.2-5).

Figure 4.2-1


Mazda/old cat.--NOx+HC
g/hp-hr

C2 = 0.51 g/hp-hr

Figure 4.2-2


Mazda/old cat--CO
g/hp-hr

C2=3.25 g/hp-hr

Figure 4.2-3

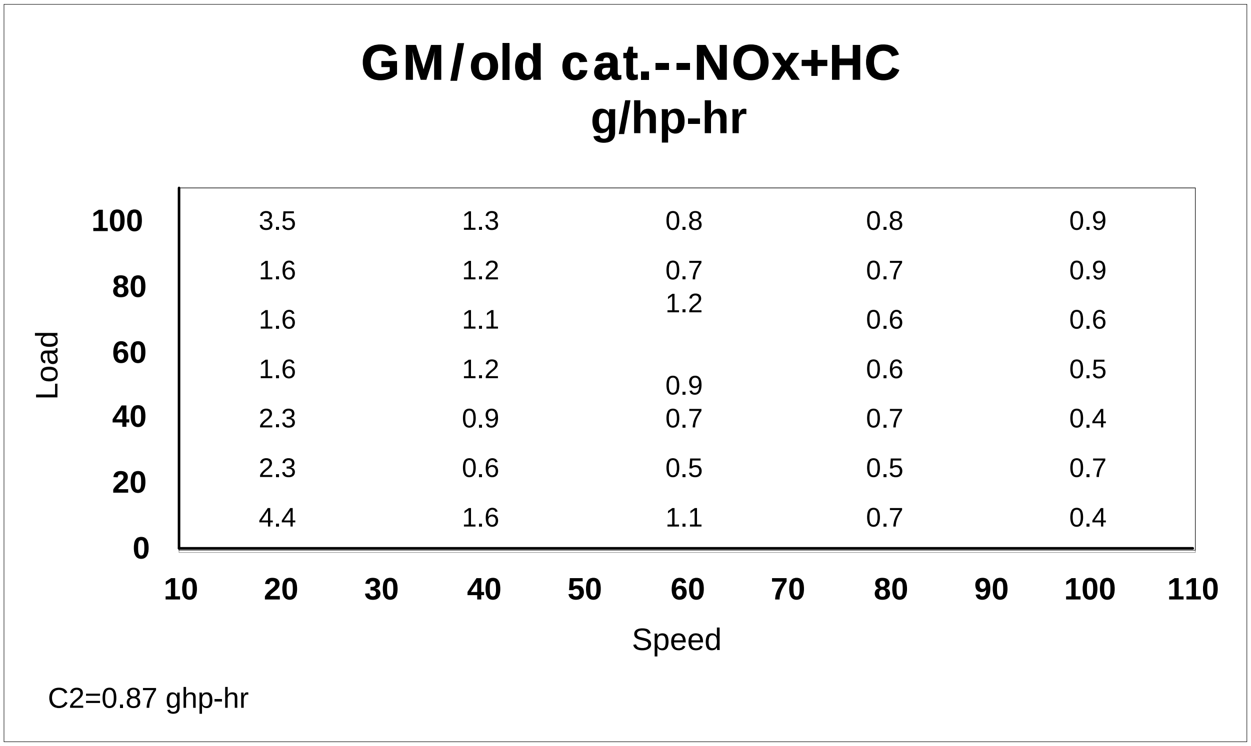


Figure 4.2-4

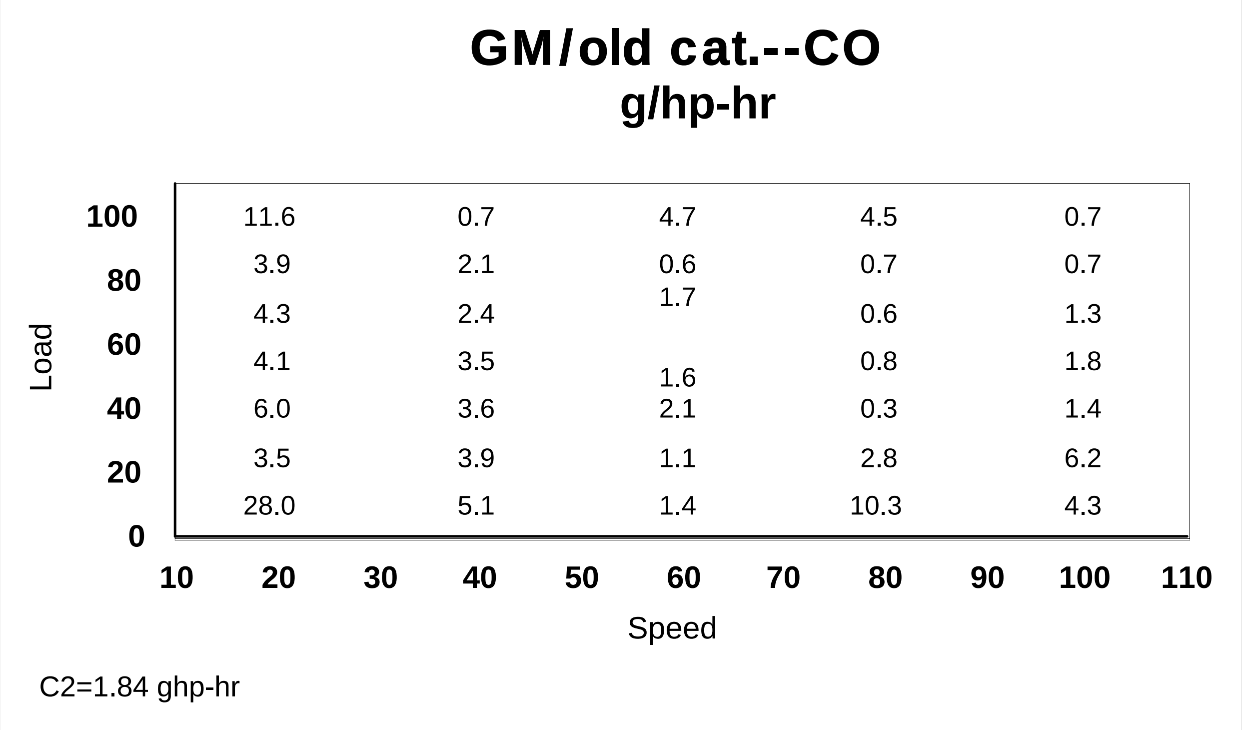
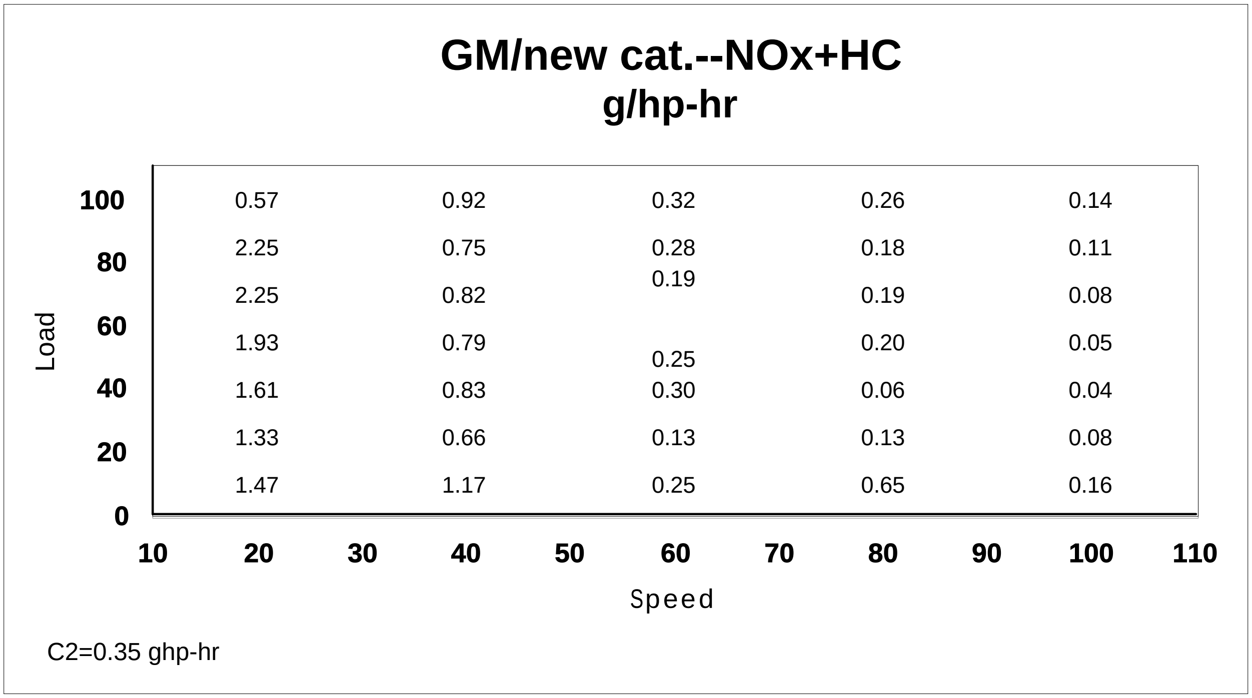
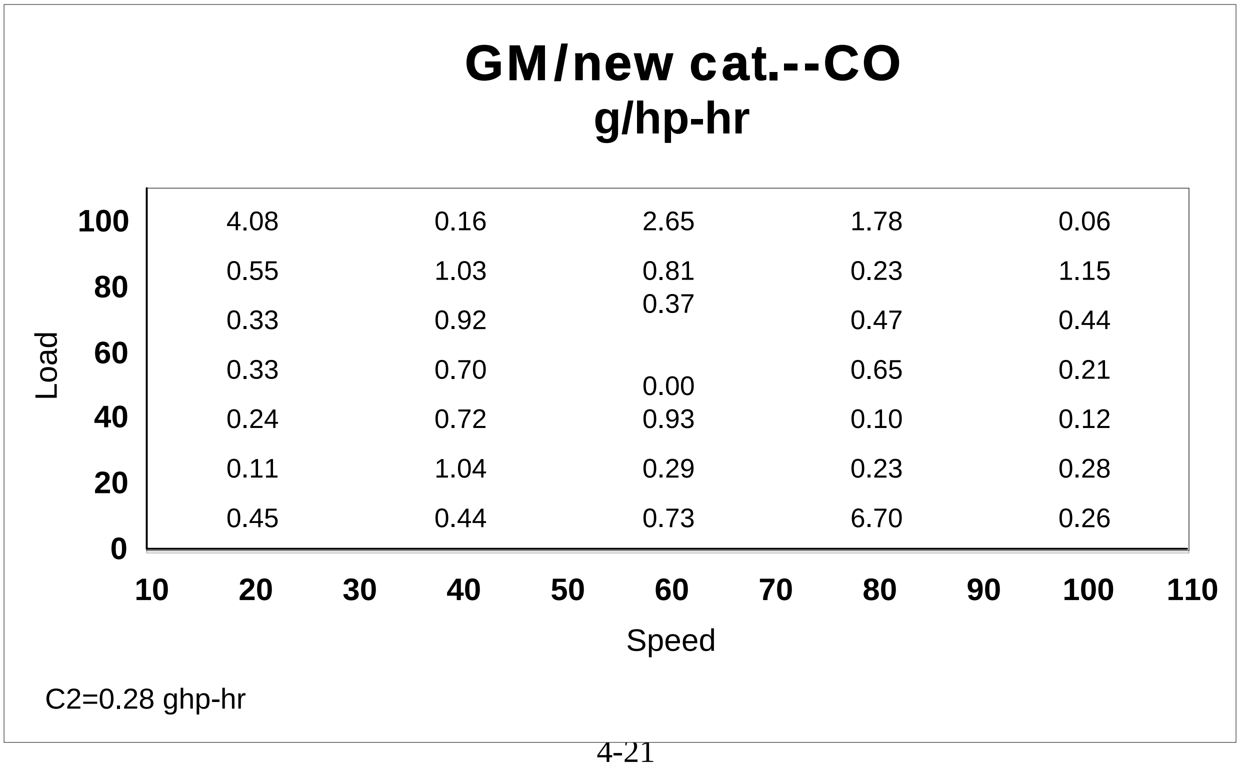


Figure 4.2-5



C2=0.35 ghp-hr

Figure 4.2-6



C2=0.28 ghp-hr

Field testing will typically also include transient emission measurement. We are proposing that a field-testing measurement may include any segment of normal operation with a two-minute minimum sampling period. This would not include engine starting, extended idling, or other cold-engine operation. Table 4.2-3 shows a wide variety of transient emission levels from the two test engines. While the engines were tested in the laboratory, the results show emissions would vary under normal operation when installed in nonroad equipment. These segments could be considered as valid field-testing measurements to show that an engine meets emission standards in the field when tested in nonroad equipment in which the engines are installed. Several segments included in the table were run with a hot start, which could significantly increase emission levels, depending on how long the engine runs in open loop after starting. This is especially important for CO emissions. Even with varied strategies for soaking and warming up engines, emission levels are generally between 1 and 2 g/hp-hr THC+NOx and between 4 and 13 g/hp-hr CO. Emission levels don't seem to vary dramatically between cycle segments, even where engine operation is significantly different.

Table 4.2-3
Transient Emission Measurements from SwRI Testing

Engine	Test Segment	THC+NOx g/hp-hr	CO, g/hp-hr	Notes
Mazda	"typical" forklift (5 min.)	2.0	5.7	hot start
	"high-transient" forklift (5 min.)	1.3	4.3	hot start
	highway certification test	1.2	4.6	hot start
	backhoe/loader cycle	1.3	9.1	20-minute soak before test
GM	"typical" forklift (5 min.)	1.3	9.5	hot start
	"high-transient" forklift (5 min.)	2.0	12.6	hot start
	highway certification test	1.0	4.4	3-minute warm-up; 2-minute soak
	backhoe/loader cycle	1.0	3.8	3-minute warm-up; 2-minute soak

4.2.2.4 Ambient conditions

While certification testing involves engine operation in a controlled environment, engines operate in conditions of widely varying temperature, pressure, and humidity. To take this into account, we are proposing to broaden the range of acceptable ambient conditions for field-testing measurements. We are proposing to limit field-testing emission measurements to ambient temperatures from 13° to 35° C (55° to 95° F), and to ambient pressures from 600 to 775 millimeters of mercury (which should cover almost all normal pressures from sea level to 7,000 feet above sea level). Tests would be considered valid regardless of humidity levels. This allows testing under a wider range of conditions in addition to helping ensure that engines are able to control emissions under the whole range of conditions under which they operate.

The SwRI test data published here are based on testing under laboratory conditions typical for the test location. Ambient temperatures ranged from 70 to 86° F. Barometric pressures were in a narrow range around 730 mm Hg. Humidity levels ranged from about 4 to 14 g of water per kg dry air, but all emission levels were corrected to a reference condition of 10.7 g/kg. Most testing occurred at humidity levels above 10.7, in which case actual NOx emission levels were up to 7 percent lower than reported by SwRI. In the driest conditions, measured NOx emission levels were up to 10 percent higher than reported. The proposed field-testing standards take into account the possibility of a humidity effect of increasing NOx emissions. We are not aware of any reasons that varying ambient temperatures or pressures would have an inherent effect on emission levels from spark-ignition engines.

4.2.2.5 Durability of Emission-Control Systems

SwRI tested engines that had already operated for the full proposed useful life period with functioning emission-control systems. Before being retrofitted with catalysts and electronic fuel systems, these engines had already operated for 5,000 and 12,000 hours, respectively. The tested systems therefore provide very helpful information to show the capability of the anticipated emission-control technologies to function over a lifetime of normal in-use operation.

The testing effort required selection, testing, and re-calibration of installed emission-control systems that were not designed specifically to meet emission standards. These systems were therefore not necessarily designed for simultaneously controlling NOx, HC, and CO emissions, for lasting 5,000 hours or longer, or for performing effectively under all conditions and all types of operation that may occur. The testing effort therefore included a variety of judgments, and adjustments to evaluate the emission-control capability of the installed hardware. This effort highlighted several lessons that should help manufacturers design and produce durable systems.

Selecting engines from the field provided the first insights into the functionality of these systems. Tailpipe ppm measurements showed that several engines had catalysts that were inactive (or nearly inactive). These units were found to have loose catalyst material inside the housing, which led to a significant loss of the working volume of the catalyst and exhaust flow bypassing the catalyst material. Dimensional measurements showed that this resulted from a straightforward production error of improperly assembling the catalyst inside the shell.[19] This is not an inherent problem with catalyst production and is easily addressed with automated or more careful manual production processes. The catalyst from the GM engine selected for testing had also lost some of its structural integrity. Almost 20 percent of the working volume of the catalyst had disappeared. This catalyst was properly re-assembled with its reduced volume for further testing. This experience underscores the need for effective quality-control procedures in assembling catalysts.

Substituting a new catalyst on the aged system allowed emission measurements that help us estimate how much the catalysts degraded over time. This assessment is rather approximate, since we have no information about the zero-hour emissions performance of that exact catalyst.

The new catalysts, which were produced about three years later under the same part numbers and nominal characteristics, generally performed in a way that was consistent with the aged catalysts. Not surprisingly, the catalyst with the reduced working volume showed a higher rate of deterioration than the intact catalyst. Both units, however, showed very stable control of NOx and HC emissions. CO deterioration rates were generally higher, but the degree of observed deterioration was very dependent on the particular duty cycle and calibration for a given set of emission measurements.

Measured emission levels from the aged catalysts shows what degree of conversion efficiency is possible for each pollutant after several thousand hours of operation. The emission data from the new catalysts suggest that manufacturers would probably need to target low enough zero-hour CO emission levels to account for significant deterioration. The data also show that catalyst size is an important factor in addressing full-life emission control. The nominal sizes of the catalysts on the test engines were between 50 and 55 percent of total engine displacement. The cost analysis in Chapter 5 is based on initial compliance with a catalyst sized at 60 percent of total engine displacement. We would expect manufacturers to reduce catalyst size as much as possible to reduce costs without risking the possibility of high in-use emissions.

Another important issue relates to degradation associated with fuel impurities, potential lack of maintenance, and wear of oxygen sensors. Fuel system components in LPG systems are prone to fuel deposits, primarily from condensation of heavy hydrocarbon constituents in the fuel. The vaporizer and mixer on the test engines showed a typical degree of fuel deposits from LPG operation. The vaporizer remained in the as-received condition for all emission measurements throughout the test program. Emission tests before and after cleaning the mixer give an indication of how much the deposits affect the ability of the closed-loop fueling system to keep the engine at stoichiometry. For the GM engine operating with the aged catalyst, the combined steps of cleaning the mixer and replacing the oxygen sensor improved overall catalyst efficiency on the C2 duty cycle from 55 to 61 percent for NOx. CO conversion efficiency improved only slightly. For the Mazda engine, the single step of cleaning the mixer slightly *decreased* average catalyst efficiency on the C2 duty cycle for NOx emissions; HC and CO conversion efficiency improved a small amount (see Table 4.2-4). Engines operating with new catalysts showed the same general patterns. These data show that closed-loop fueling systems can be relatively tolerant of problems related to fuel impurities.

Table 4.2-4
Average C2 Catalyst Conversion Efficiencies Before and After Maintenance

Engine	Pollutant	OLD CATALYST		NEW CATALYST	
		before maintenance	after maintenance	before maintenance	after maintenance
GM	NOx	54.7%	61.1%	45.6%	56.1%
	CO	96.3%	98.1%	99.3%	99.5%
	HC	93.8%	93.6%	93.6%	93.7%
Mazda	NOx	62.3%	61.5%	60.3%	60.1%
	CO	96.9%	98.9%	99.6%	99.6%
	HC	86.9%	93.2%	86.2%	94.3%

Manufacturers may nevertheless be concerned that some in-use operation can cause fuel deposits that exceed the fuel system's compensating ability to maintain correct air-fuel ratios. Two technologies are available to address this concern. First, the diagnostic system we are proposing would inform the operator if fuel-quality problems are severe enough to prevent the engine from operating at stoichiometry. A straightforward cleaning step would restore the fuel system to normal operation. Manufacturers may also be able to monitor mixer performance directly to detect problems with fuel deposits, rather than depending on air-fuel ratios as a secondary indicator. In any case, by informing the operator of the need for maintenance, the diagnostic system reduces the chance that the manufacturer will find high in-use emissions that result from fuel deposits.

The second technology to consider is designed to prevent fuel deposits from forming. A commercially available thermostat regulates fuel temperatures to avoid high-temperature and low-temperature effects.

Maintaining the integrity of the exhaust pipe is another basic but essential element of keeping control of air-fuel ratios. Any leaks in the exhaust pipe between the exhaust valves and the oxygen sensor would allow dilution air into the exhaust stream. The extra oxygen from the dilution air would cause the oxygen sensor to signal a need to run at a air-fuel ratio that is richer than optimal. If an exhaust leak occurs between the oxygen sensor and the catalyst, the engine will run at the right air-fuel ratio, but the extra oxygen would affect catalyst conversion efficiencies. As evidenced by the test engines, manufacturers can select materials with sufficient quality to prevent exhaust leaks over the useful life of the engine.

4.2.2.6 Gasoline-fueled engines

Most of the available emission data for Large SI engines is from LPG-fueled engines. Gasoline-fueled engines, while less common, represent an important element of the market. Emission-control technologies for automotive engines and heavy-duty highway engines have advanced to the point of reducing emissions well below the standards we are proposing for Large SI engines. The experience with these highway applications makes clear that gasoline-fueled engines can achieve very low emissions.

Part of the concern expressed by manufacturers has been that gasoline-fueled engines sometimes need to operate at rich air-fuel ratios for short periods to protect engines from overheating. This generally causes higher CO emissions, while NOx emissions either decrease or stay the same. Concern related to the feasibility of meeting emission standard with gasoline-fueled engines are therefore mostly focused on achievable CO emission levels. Most people understand that gasoline-fueled industrial engines have high CO emissions, so they generally don't operate in indoor applications or in other enclosed areas. Controlling NOx emissions from these engines therefore becomes relatively more important than controlling CO emissions.

To address this concern, we are proposing alternate emission standards that provide flexibility in balancing the tradeoff between controlling NOx and CO emissions. We believe this flexibility will allow manufacturers to achieve the greatest degree of emission reduction at the lowest cost for their particular engines. See Section 4.2.2.7.3 for a discussion of the alternate emission standards.

4.2.2.7 Proposed emission standards

4.2.2.7.1 Technology Basis

Three-way catalyst systems with electronic, closed-loop fuel systems have a great potential to reduce emissions from Large SI engines. We believe these technologies are capable of the greatest degree of emission reduction achievable from these engines in the projected time frame, considering the various statutory factors. This reflects a concern for the cost sensitivity of Large SI engines. In particular, we are not basing the proposed emission standards on the emission-control capability from any of the following technologies.

- Spark timing
- Combustion-chamber redesign
- Gaseous fuel injection
- Exhaust gas recirculation

Incorporating these technologies with new engines could further reduce emissions; however, Large SI engine manufacturers typically produce 10,000 to 15,000 units annually, which limits the resources available for an extensive development program. Considering the limited development budgets for improving these engines, we believe it is more important to make a robust design with basic emission-control hardware than to achieve very low emission levels with complex hardware at a small number of steady-state test modes. Even without these additional technologies, we anticipate that manufacturers will be able to reduce emissions by 90 percent or more from uncontrolled levels. Further optimizing an engine with a full set of emission-control hardware while meeting transient and field-testing emission standards is more of a cost burden than Large SI manufacturers can bear in the projected time frame.

Manufacturers producing new engines may find it best to use some of these supplemental technologies to achieve the desired level of emission control and performance at an acceptable cost.

4.2.2.7.2 Duty-cycle emission standards

The SwRI testing program was based on aged engines and involved no effort to fine-tune air-fuel ratios or emission levels across the engine map. We expect that manufacturers will be able to take steps to control emission levels more broadly across the range of engine speeds and loads, which will correspondingly reduce transient emission levels. The data presented above show that Large SI engines can meet the proposed 2007 emission standards for both steady-state and transient duty cycles.

We project that the proposed emission standards will reduce NOx, HC, and CO emissions by about 90 percent from uncontrolled levels. Further reductions may be possible with a very extensive development effort to adapt advanced highway engine technologies to nonroad applications. We have, for example, adopted emission standards for gasoline-fueled engines for highway trucks that will require manufacturers to reduce emissions by 80 or 90 percent beyond the levels we are proposing for Large SI engines. Due to the relatively low sales volumes of Large SI engines, we believe it is not appropriate to propose standards at these more stringent levels. With smaller R&D budgets, Large SI engine manufacturers will need to apply a focused effort to meet the standards we are proposing.

On the other hand, the proposed emission standards for Large SI engines are significantly more stringent than those we are proposing for recreational vehicles and those we have adopted for lawn & garden engines. We believe this is appropriate, for several reasons. First, the similarity to automotive engines makes it possible to use basic automotive technology that has already been adapted to industrial use. Second the cost of Large SI equipment is typically much higher than the recreational or other light-duty products, so there is more capability for manufacturers to pass along cost increases in the marketplace. Third, the proposed Large SI emission standards correspond with a substantial fuel savings, which offset the cost of regulation and provide a great value to the many commercial customers.

The SwRI testing program involved about eight weeks of development effort to characterize and modify two engines to for optimized emissions on the steady-state and transient duty cycles, and for all kinds of off-cycle operation. Both of the test engines had logged several thousand hours of operation using off-the-shelf technologies that have been available for nonroad engines for many years. Several hardware and software adjustments were made to maintain optimal air-fuel ratios for effective control of all pollutants under all operating modes. Some further development effort will be necessary to address the few isolated modes with high emission levels, as described below. Manufacturers may save development time by upgrading to the modestly more expensive controller with independent air-fuel control capability in different speed-load zones. We believe that the several years until 2007 allow enough lead time for manufacturers to carry out this development effort for all their engines.

We expect the SwRI testing program to provide extensive, basic information on optimizing the subject engines for low emissions, so manufacturers will need significantly less time and testing resources to modify additional engine models. For example, the SwRI testing shows how emissions change over varying speeds and loads; as a result, future testing can focus on far fewer test points to characterize a calibration. The test results also show how manufacturers will need to balance calibrations for controlling emissions of different pollutants across the range of engine speeds and loads.

Given the control technology, as described above, there is a need to select emission standards that balance the tradeoff between NOx and CO emissions. Both NOx and CO vary with changing air-fuel ratios, but in an inverse relationship. This is especially important considering the degree to which these engines are used on enclosed areas. Table 4.2-5 shows the range of measured emission values from the engines with optimized emission controls. These values are plotted in Figure 4.2-7, showing the NOx-CO tradeoff. The measured emission levels include a variety of duty cycles, but this doesn't seem to affect the observed trends. Also, Table 4.2-5 notes the length of time the engine was turned off before starting the transient duty cycle. All the data points shown are from measurements with the aged catalysts. Several measurements with the new catalyst showed that engines were able to achieve very low levels of both NOx and CO emissions.

Figures 4.2-8 and 4.2-9 show two attempts to apply a curve-fit to the data points. Using a log-log relationship as shown yielded an R-square value of 0.93, indicating a relatively good fit to the data. Similarly, the best curve-fit with the 1/CO relationship has an R-square value of 0.83. Table 4.2-6 shows a range of values relating CO and HC+NOx emission levels. This involves starting with a set of CO emission levels, then selecting the HC+NOx emission level corresponding with the higher of the two values predicted by the two curve-fitting equations. Finally, both CO and HC+NOx emission levels are increased by 10 percent to account for a compliance margin around the measured data points. This collection of points, shown in Figure 4.2-10, serve as a range of possible combinations of CO and HC+NOx emission standards.

Table 4.2-5
Range of Measured Emission Levels (g/hp-hr)

Engine*	HC	NOx	HC+NOx	CO	Cycle	soak, min.
GM	0.30	3.82	4.12	0.66	Backhoe-loader	4
GM	0.27	4.14	4.41	0.68	Backhoe-loader	2
GM	0.41	5.91	6.32	0.83	Backhoe-loader	20
GM	0.29	5.89	6.18	0.86	Large SI Composite	6
GM	0.27	4.42	4.69	0.87	Highway FTP	3
GM	0.28	5.33	5.61	0.89	Highway FTP	3
Mazda	0.34	0.88	1.22	4.61	Highway FTP	5
Mazda	0.58	0.15	0.73	6.66	Large SI Composite	5
Mazda	0.61	0.19	0.8	6.97	Large SI Composite	5
Mazda	0.66	0.14	0.8	7.5	Large SI Composite	5
Mazda	0.6	0.35	0.95	7.61	Large SI Composite	7
Mazda	0.51	0.7	1.21	7.76	Welder	4

*Both engines operated on LPG for all tests.

Figure 4.2-7

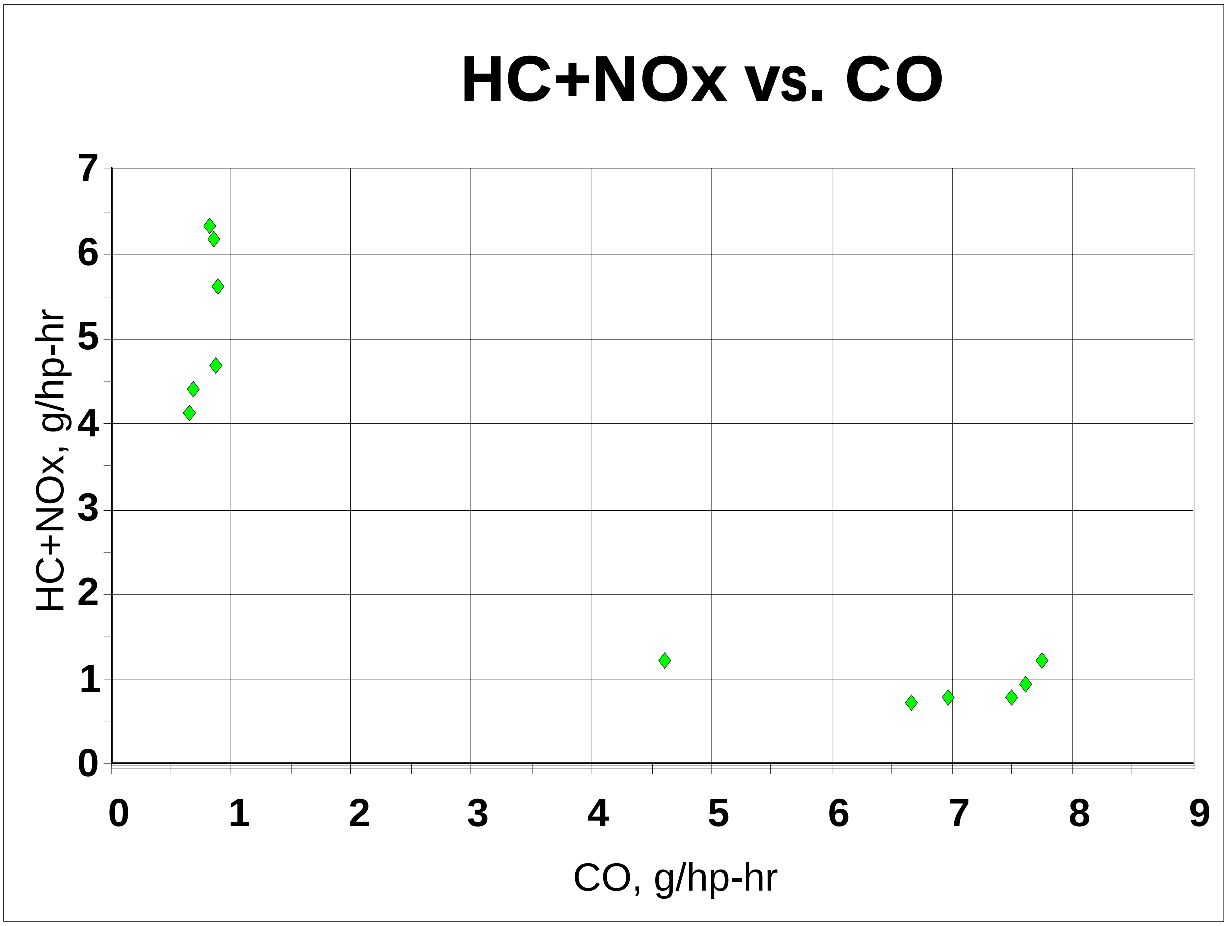


Figure 4.2-8

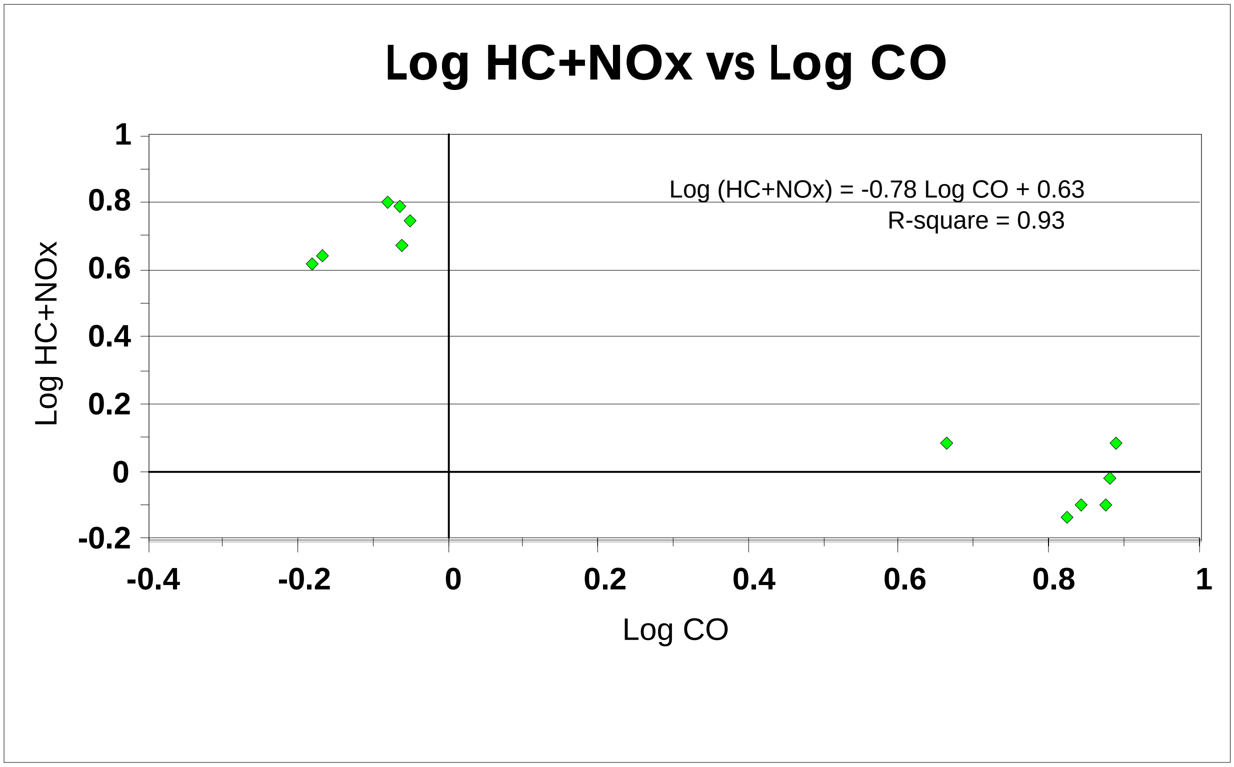


Figure 4.2-9

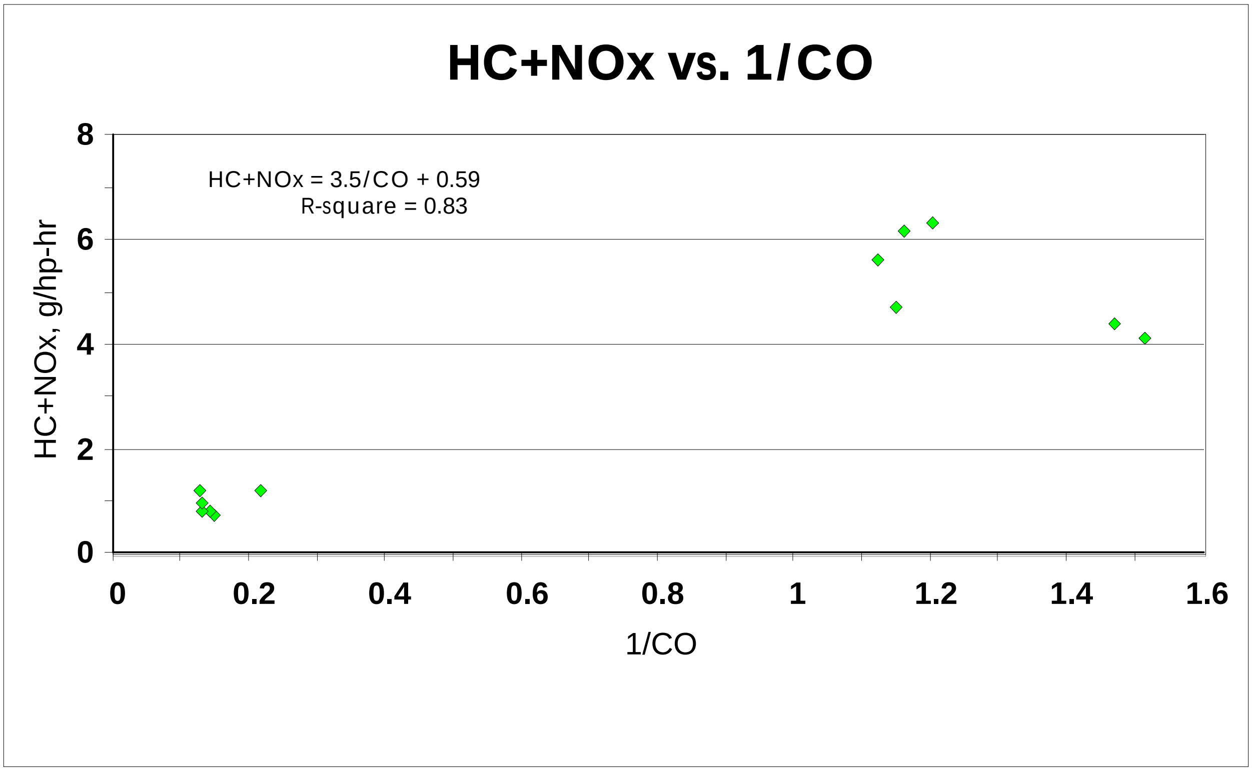


Table 4.2-6
Range of Feasible Emission Standards

CO Emission Level	Predicted HC+NOx Emission Level (Log basis)	Predicted HC+NOx Emission Level (1/CO basis)	Higher Predicted HC+NOx Emission Level	HC+NOx standard*	CO standard*
1.0	4.27	4.09	4.27	4.7	1.1
1.5	3.11	2.92	3.11	3.4	1.7
1.75	**2.76**	**2.59**	**2.76**	**3.0**	**1.9**
2.0	2.48	2.34	2.48	2.7	2.2
2.3	**2.27**	**2.15**	**2.27**	**2.5**	**2.5**
2.5	2.09	1.99	2.09	2.3	2.8
3.0	**1.81**	**1.76**	**1.81**	**2.0**	**3.3**
4.0	1.45	1.47	1.47	1.6	4.4
5.0	1.22	1.29	1.29	1.4	5.5
6.0	1.05	1.17	1.17	1.3	6.6
7.0	0.94	1.09	1.09	1.2	7.7
8.0	0.84	1.03	1.03	1.1	8.8
9.0	0.77	0.98	0.98	1.1	9.9
10.0	0.71	0.94	0.94	1.0	11.0

*Incorporates 10-percent compliance margin.

We generally set standards by focusing on attaining ambient air quality in broad outdoor areas. Any of the emission standards under consideration would provide large reductions to address this concern. More careful balancing of CO and HC+NOx emission standards would allow us to simultaneously address concerns for individual exposure to elevated levels of CO, NO, and NO_2.

Modeling a scenario of indoor engine operation allows us to evaluate the relative exposure of different pollutants under varying engine calibrations. Since the analysis relates primarily to the relative concentrations of the different pollutants, the conclusions drawn here are relatively insensitive to the simplifying assumptions in the calculations. Calculations are based on a forklift operating for eight hours at 20 hp (on average) in a 40' by 60' room with a 20' ceiling. With a dilution rate of one full air exchange per hour, the effective volume is 432,000 ft^3. This volume of air has a mass of about 14,000 kg (or 500,000 moles). Hydrocarbon emissions are estimated to be 20 percent of the total HC+NOx emissions rate, which is typical for Large SI engines. Similarly, the analysis estimates that 90 percent of NOx emissions are NO, with the remainder being NO_2. Plugging in several values from the candidate combinations of emission standards in Figure 4.2-10 results in a shifting balance of HC+NOx and CO emissions.

Table 4.2-7 shows the calculated resulting ambient ppm levels for three different scenarios and compares these values to the threshold limit value published by the American Conference of Governmental Industrial Hygienists. The scenario with emission standards of 3.0 g/hp-hr HC+NOx and 1.9 g/hp-hr CO shows equal relative protection from NO and CO exposures, with both values somewhat lower than the threshold limit values. The second scenario with emission standards of 2.5 g/hp-hr HC+NOx and 2.5 g/hp-hr CO shows the expected shift to lower ambient NO levels, with CO levels slightly over the threshold limit value. The third scenario with emission standards of 2.0 g/hp-hr HC+NOx and 3.3 g/hp-hr CO shows ambient NO levels decreasing to 14 ppm, with ambient CO up to 34 ppm. We are proposing emission standards of 2.5 g/hp-hr for both HC+NOx and for CO as the most appropriate balance in setting emission standards for these pollutants.

Figure 4.2-10

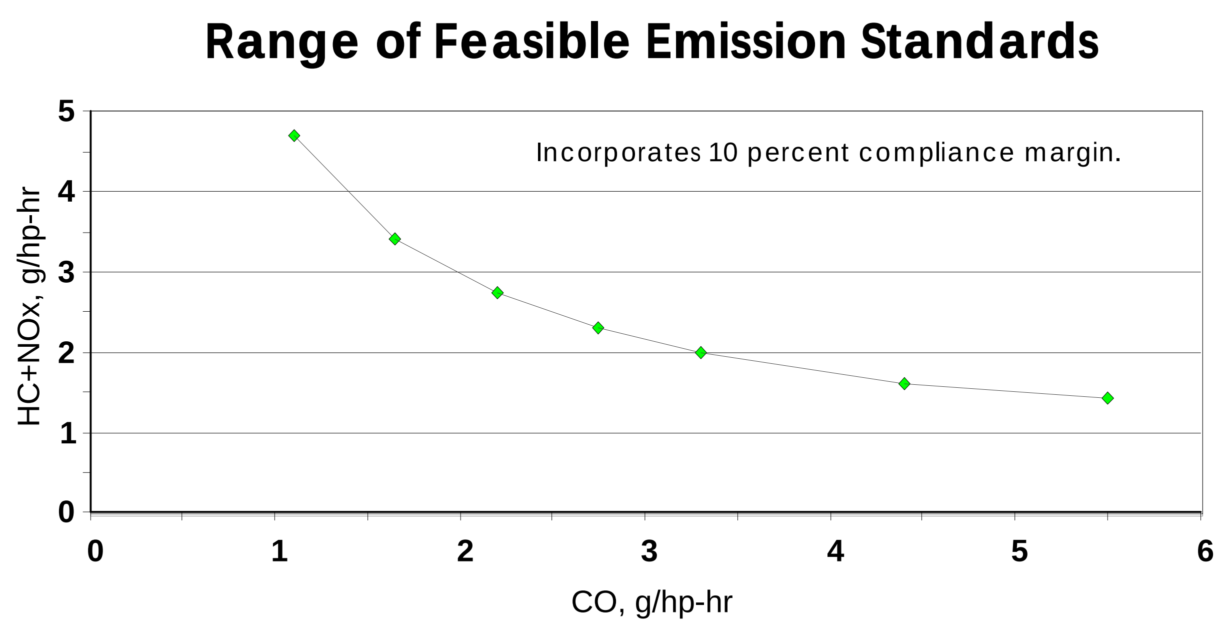


Table 4.2-7
Exposure Scenario for Indoor Operation*

Emission standards, g/hp-hr		Pollutant	Emission factor (g/hp-hr)	Emission rate, g	Emission rate, mol	Ambient ppm	Threshold Limit Value
HC+NOx	CO						
3.0	0.9	NO	2.2	311	10.4	**21**	25
		NO2	0.2	35	0.8	**1.5**	3
		CO	1.9	274	9.8	**20**	25
2.5	2.5	NO	1.8	259	8.6	**17**	25
		NO2	0.2	29	0.6	**1.3**	3
		CO	2.5	360	12.9	**26**	25
2.0	3.3	NO	1.4	207	6.9	**14**	25
		NO2	0.2	23	0.5	**1.0**	3
		CO	3.3	475	17	**34**	25

*Based on emission standards of 3.0 g/hp-hr for HC+NOx and 1.9 g/hp-hr for CO.

4.2.2.7.3 Alternate emission standards

As described in Section 4.2.2.7, we believe that gasoline-fueled engines are most likely to utilize the proposed alternate emission standards, which allow for more stringent NOx+HC emission standards with less stringent CO emission standards. As engines increase their CO emission levels, they are generally capable of achieving lower NOx emission levels. Preliminary data suggest that Large SI engines can meet a 1.0 g/hp-hr HC+NOx emission level when CO emission levels are allowed to increase up to 20 g/hp-hr.

Ongoing testing efforts at SwRI are focused on achieving effective emission control from a gasoline-fueled industrial engine. As we continue this testing, we intend to place emission testing results in the docket as soon as they become available.

4.2.2.7.4 Field-testing emission standards

We are proposing to allow manufacturers to do testing under the in-use testing program using field-testing procedures. This has the potential to substantially reduce the cost of testing. Setting an emission standard for testing engines in the field requires that we take into account all the variability inherent in testing outside the laboratory. As discussed further below, this includes varying engine operation, and a wider range of ambient conditions, and the potential for less accurate or less precise emission measurements and calculations. Also, while the proposed field-testing standards and procedures are designed for testing engines installed in equipment, engines can also be tested on a dynamometer to simulate what would happen in the field. In this case, extra precautionary steps would be necessary to ensure that the dynamometer testing could be characterized as “normal operation.” Also, the less stringent field-testing standards would apply to any simulated field-testing on a dynamometer to take emission-measurement variability into account, as described below.

The SwRI test engines also show that Large SI engines are capable of controlling emissions under the wide range of operation covered by the proposed field-testing provisions. A modest amount of additional development would be necessary to address isolated high-emission points uncovered by the testing, but the above discussion makes clear that it would be feasible to resolve these issues well before 2007. Field testing may also include operation at a wider range of ambient conditions than for certification testing. Selecting emission standards for field testing that correspond with the duty-cycle standards requires consideration of the following factors:

- The data presented above show that emissions vary for different modes of engine operation. Manufacturers will need to spend time addressing high-emission points to ensure that engines are not overly sensitive to operation at certain speeds or loads. The data suggest that spark-ignition engines can be calibrated to improve control at the points with the highest emission rates.
- Established correction factors allow for adjustment to account for varying ambient conditions. Allowing adjustment of up to 10 percent would adequately cover any potential increase in emissions resulting from extreme conditions.

- While emission measurements with field-testing equipment allow more flexibility in testing, they are not as precise or as accurate as in the laboratory; the proposed regulations define specifications to limit the error in emission measurements. For most mass-flow and gas analyzer hardware, these tolerance remain quite small. Measurements and calculations for torque values introduce a greater potential for error in determining brake-specific emission levels. The proposed tolerance for onboard torque readings allows for a 15-percent error in understating torque values, which would translate into a 15-percent error in overstating brake-specific emissions.

Taking all these factors into account, we believe it is appropriate to allow for a 40-percent increase in HC+NOx emissions relative to the SwRI measured values to account for the factors listed above. CO emissions are generally somewhat more sensitive to varying engine operation, so a 50-percent adjustment is appropriate for CO. We are therefore proposing field-testing emission standards of 3.5 g/hp-hr THC+NOx and 3.8 g/hp-hr CO.

These same numerical field-testing standards would apply to natural gas engines. Much like for certification, we are proposing to exclude methane measurements from natural gas engines. Since there are currently no portable devices to measure methane (and therefore nonmethane hydrocarbons), we are proposing that the 3.5 g/hp-hr field-testing standard apply only to NOx emissions for natural gas engines.

We would expect to apply the same adjustments to the alternate emission standards to select the appropriate field-testing standard for these engines. As a result, we are proposing alternate field-testing standards of 1.4 g/hp-hr HC+NOx and 31 g/hp-hr CO.

4.2.2.7.5 Evaporative emissions

Several manufacturers are currently producing products with pressurized fuel tanks to comply with Underwriters Laboratories specifications. Most fuel tanks in industrial applications are made of a thick-grade sheet metal or structural steel, so increasing fuel pressures within the anticipated limits poses no risk of bursting or collapsing tanks. For those few applications that use plastic fuel tanks or thinner sheet steel, straightforward technologies such as insulation or a volume-compensating bag would allow for adequate suppression of fuel vapors.

4.2.2.7.6 Conclusions

Manufacturers have been developing emission-control technologies to meet the proposed 2004 emission standards since October 1998, when California ARB adopted the same standards. We expect that manufacturers will add three-way catalysts to their engines and use electronic closed-loop fueling systems. These technologies have been available for industrial engines for many years.

As described above, technology development has shown that these technologies can be optimized to achieve the more stringent emission standards proposed for 2007 and later engines. The testing effort on aged engines with off-the-shelf hardware showed that engines can meet not only the proposed steady-state emission standards, but also the standards that would apply to testing with the proposed transient duty cycles. Similarly, testing over a wide range of engine operation has shown that engines with the these established emission-control technologies can meet the field-testing standards under any normal operation.

4.2.3 Impacts on Noise, Energy, and Safety

The Clean Air Act directs us to consider potential impacts on noise, energy, and safety when establishing the feasibility of emission standards for nonroad engines.

As automotive technology demonstrates, achieving low emissions from spark-ignition engines can correspond with greatly reduced noise levels. Electronically controlled fuel systems are able to improve management the combustion event, and catalysts can be incorporated into existing equipment designs without compromising the muffling capabilities in the exhaust.

Adopting new technologies for controlling fuel metering and air-fuel mixing will lead to substantial improvements in fuel consumption rates. We project fuel consumption improvements that will reduce total nationwide fuel consumption by about 300 million gallons annually once the program is fully phased in. While a small number of engines already have these technologies, it seems that the industrial engine marketplace has generally not valued fuel economy highly enough to create sufficient demand for these technologies.

We believe the technology discussed here would have no negative impacts on safety. Electronic fuel injection is almost universally used in cars and trucks in the United States with very reliable performance. In addition, we expect cases of CO poisoning from these engines to decrease as a result of the reduced emission levels.

4.3 Snowmobiles

The following paragraphs summarize the data and rationale supporting the proposed emission standards for snowmobiles, which are listed in the Executive Summary.

4.3.1 Baseline Technology and Emissions

Snowmobiles are equipped with relatively small high-performance two-stroke two and three cylinder engines that are either air- or liquid-cooled. The main emphasis of engine design is on performance, durability, and cost and, because these engines are currently unregulated, they have no emission controls. The fuel system used on these engines are almost exclusively carburetors, although a small number have electronic fuel injection. Two-stroke engines lubricate the piston and crankshaft by mixing oil with the air and fuel mixture. This is accomplished by most contemporary 2-stroke engines with a pump that sends two-cycle oil from a separate oil reserve to the carburetor where it is mixed with the air and fuel mixture. Some less expensive two-stroke engines require that the oil be mixed with the gasoline in the fuel tank. In fact, because performance and durability are such important qualities for snowmobile engines, they all operate with a “rich” air and fuel mixture. That is, they operate with excess fuel, which enhances performance and allows engine cooling which promotes longer lasting engine life. However, rich operation results in high levels of HC, CO, and PM emissions. Also, two-stroke engines tend to have high scavenging losses, where up to a third of the unburned air and fuel mixture goes out of the exhaust resulting in high levels of raw HC.

We developed average baseline emission rates for snowmobiles based on the results of emissions testing of 23 snowmobiles.[20] Current average snowmobile emissions rates are 397 g/kW-hr (296 g/hp-hr) CO and 149 g/kW-hr (111 g/hp-hr) HC.

4.3.2 Potentially Available Snowmobile Technologies

A variety of technologies are currently available or in stages of development to be available for use on 2-stroke snowmobiles. These include engine modifications, improvements to carburetion (improved fuel control and atomization, as well as improved production tolerances), enleanment strategies for both carbureted and fuel injected engines, pulse air, and semi-direct and direct fuel injection. In addition to these 2-stroke technologies, converting to 4-stroke engines may be feasible for some snowmobile types. Each of these is discussed in the following sections.

4.3.2.1 Engine Modifications

There are a variety of engine modifications that could reduce emissions from two-stroke engines. The modifications generally either increase trapping efficiency (i.e., reduce fuel short-circuiting) or improve combustion efficiency. Those modifications that increase trapping efficiency include optimizing the intake, scavenge and exhaust port shape and size, and port placement, as well as optimizing port exhaust tuning and bore/stroke ratios. Optimized combustion charge swirl, squish and tumble would serve to improve the combustion of the intake charge. These modifications have the potential to reduce emissions by up to 40 percent, depending on how well the unmodified engine is optimized for these things.

4.3.2.2 Carburetion Improvements

There are several things that can be done to improve carburetion in snowmobile engines. First, strategies to improve fuel atomization would promote more complete combustion of the fuel/air mixture. Additionally, production tolerances could be improved for more consistent fuel metering. Both of these things would allow for more accurate control of the air/fuel ratio. In conjunction with these improvements in carburetion, the air/fuel ration could be leaned out some. Snowmobile engines are currently calibrated with rich air/fuel ratios for durability reasons. Leaner calibrations would serve to reduce CO and HC emissions by up to 20 percent, depending on how lean the unmodified engine is prior to recalibration. Small improvements in fuel economy could also be expected with recalibration.

The calibration changes just discussed (as well as some of the engine modifications previously discussed) would also reduce snowmobile engine durability. There are many engine improvements that could be made to regain lost durability that occurs with leaner calibration. These include changes to the cylinder head, pistons, ports and pipes to reduce knock. In addition critical engine components could be made more robust to improve durability.

The same calibration changes to the air/fuel ratio just discussed for carbureted engines could also be employed, possibly with more accuracy, with the use of fuel injection. At least one major snowmobile manufacturer currently employs electronic fuel injection on several of its snowmobile models.

4.3.2.3 Pulse Air

Pulse air injection into the exhaust stream mixes oxygen with the high temperature HC and CO in the exhaust. The added oxygen allows the further combustion of these exhaust constituents between the combustion chamber and tailpipe exhaust. Pulse air can achieve 10 to 40 percent reductions in four-stroke applications, and we expect some modest reductions in two-stroke applications as well.

4.3.2.4 Direct and Semi-direct Fuel Injection

In addition to rich air/fuel ratios, one of the main reasons that emissions from two-stroke engines are high is scavenging losses, as described above. One way to reduce or eliminate such losses is to inject the fuel into the cylinder after the exhaust port has closed. This can be done by injecting the fuel into the cylinder through the transfer port (semi-direct injection) or directly into the cylinder (direct injection). Both of these approaches are currently being used successfully in two-stroke personal watercraft engines. Manufacturers have indicated to us that two-stroke engines equipped with direct fuel injection systems could reduce HC emissions by 70 to 75 percent and reduce CO emissions by 50 to 60 percent. Certification results for 1999 and 2000 model year outboard engines and PWC support the manufacturers projections, as shown in Table 4.3-1. This table shows the paired certification data from some PWC engines in both uncontrolled and direct injection configurations. The percent difference in FEL column refers to the HC + NOx FEL. This is a pretty good surrogate for HC since most of the HC + NOx level is made up of HC, as can be seen from the table.

Table 4.3-1
Certification Levels of Direct Injection vs. Uncontrolled Engines

Mfr	% difference in FEL	size (liter)	power (kw)	FEL (HC + NOx)	HC cert level	CO cert level	Technology
Kawasaki	50%	1.074	95.6	70.0	58.4	148.6	Direct injection, electronic control
		1.073	88.3	140.0	136.76	241.8	none
Arctic Cat	55%	1.104	84.31	75	69.09	148.56	Direct injection
		1.103	88	167	not reported	not reported	none
Bombardier	60%	0.9514	88.85	54.06	45.98	143.0	Direct injection, electronic control
		0.9513	89.5	136.8	136.20	361.30	none
Polaris	70%	1.16	85.26	46.0	37.46	100.4	Direct injection
		1.16	93.25	149.4	not reported	not reported	none

Substantial improvements in fuel economy could also be expected with these technologies. We believe these technologies hold promise for application to snowmobiles. Manufacturers must address a variety of technical design issues for adapting the technology to snowmobile operation, such as operating in colder ambient temperatures and at variable altitude. The several years of lead time give manufacturers time to incorporate these development efforts into their overall research plan as they apply these technologies to snowmobiles.

4.3.2.5 Four-stroke Engines

In addition to the two-stroke technologies just discussed, the use of four-stroke engines in snowmobiles is feasible. One manufacturer has already introduced a four-stroke snowmobile on a limited basis, with wider availability planned, and another is preparing for the introduction of a four-stroke model. Since four-stroke engines do not rely on scavenging of the exhaust gases with the incoming air/fuel mixture, they have inherently lower HC emissions compared to two-strokes (up to 90 percent lower). Somewhat lesser reductions in CO could also be expected. Four-stroke engines have a lower power to weight ratio than two-stroke engines. Thus, they are more likely to be used in snowmobile models where extreme power and acceleration are not the primary selling points. Such models include touring and sport trail sleds, as opposed to high performance sleds such as those used for aggressive trail, cross country, mountain and lake riding.

4.3.3 Test Procedure

We are proposing to largely adopt the snowmobile test procedure developed by Southwest Research Institute in cooperation with the International Snowmobile Manufacturers Association for all snowmobile emissions testing.[21] This test procedure consists of two main parts; the duty cycle that the snowmobile engine would operate over during testing and other testing protocols surrounding the measurement of emissions (sampling and analytical equipment, specification of test fuel, atmospheric conditions for testing, etc.). While the duty cycle we are proposing was developed specifically to reflect snowmobile operation, many of the testing protocols are well established in other EPA emissions programs and have been simply adapted where appropriate for snowmobiles.

The snowmobile duty cycle was developed by instrumenting several snowmobiles and operating them in the field in a variety of typical riding styles, including aggressive (trail), moderate (trail), double (trail with operator and one passenger), freestyle (off-trail), and lake driving. A statistical analysis of the collected data produced the five mode steady-state test cycle shown in Table 4.3-2.

Table 4.3-2
Proposed Snowmobile Engine Test Cycle

Mode	1	2	3	4	5
Normalized Speed	1	0.85	0.75	0.65	Idle
Normalized Torque	1	0.51	0.33	0.19	0
Relative Weighting (%)	12	27	25	31	5

We believe this duty cycle is representative of typical snowmobile operation, and is therefore appropriate for use in demonstrating compliance with the proposed snowmobile emission standards.

The other testing protocols we are proposing are largely derived from our regulations for marine outboard and personal watercraft engines.[22] The testing equipment and procedures from that regulation are largely appropriate for snowmobiles. However, unlike snowmobiles, outboard and personal watercraft engines tend to operate in fairly warm ambient temperatures. Thus, some provision needs to be made in the snowmobile test procedure to account for the colder ambient temperatures typical of snowmobile operation. Since snowmobile carburetors are jetted for specific ambient temperatures and pressures, we could take one of two general approaches. The first is to require testing at ambient temperatures typical of snowmobile operation, with appropriate jetting. A variation of this option is to simply require that the engine inlet air temperature be representative of typical snowmobile operation, without requiring that the entire test cell be at that temperature. The second is to allow testing at higher temperatures than typically experienced during snowmobile operation, with jetting appropriate to the warmer ambient temperatures.

We are proposing that snowmobile engine inlet air temperature be between -15°C and -5°C (5°F and 23°F), but that the ambient temperature in the test cell not be required to be refrigerated. We believe that this approach strikes an appropriate balance between the need to test at conditions that are representative of actual use, and the fact that simply cooling the inlet air would be significantly less costly than requiring a complete cold test cell.

4.3.4 Impacts on Noise, Energy, and Safety

The Clean Air Act directs us to consider potential impacts on noise, energy, and safety when establishing the feasibility of emission standards for nonroad engines.

As automotive technology demonstrates, achieving low emissions from spark-ignition engines can correspond with greatly reduced noise levels. Four-stroke engines can have considerably lower sound levels than two-stroke engines. Electronically controlled fuel systems are able to improve management of the combustion event which can help lower noise levels.

Adopting new technologies for controlling fuel metering and air-fuel mixing will lead to substantial improvements in fuel consumption rates for two-stroke engines as well as for four-stroke engines. Four-stroke engines have far less fuel consumption than two-stroke engines. Average mileage for a baseline two-stroke snowmobile is 12 miles per gallon (mpg). Average mileage for a four-stroke snowmobile is 18 mpg and up to 20 mpg for a two-stroke with direct injection. We project that these fuel consumption benefits will reduce total nationwide fuel consumption by more than 50 million gallons annually once the program is fully phased in.

We believe the technology discussed here would have no negative impacts on safety. Electronic fuel injection is almost universally used in cars, trucks and highway motorcycles in the United States with very reliable performance.

4.3.5 Conclusion

4.3.6.1 2006 Standards

We expect that the proposed 2006 model year snowmobile emission standards will largely be met through a combination of engine modifications and carburetion improvements. However, the other technologies discussed have the potential to reduce emissions beyond what could be expected from engine modifications and carburetion improvements. These other technologies also have potential benefits beyond emission reductions (e.g., improved fuel economy, reliability and performance, reduced noise). We expect that as snowmobile manufacturers develop and refine these other technologies they will find their way into the marketplace in certain applications where their non-emissions benefits would outweigh their cost.

4.3.6.2 2010 Standards

There are a number of different technology mixes which could be used to meet the proposed 50 percent average reductions in HC and CO. The Table 4.3-3 provided below presents the approach we used for purposes of further analysis. The average reduction level at the bottom of the table represents average reductions for a manufacturer’s entire fleet which already incorporates compliance margin consideration, since each engine family FEL will have a unique compliance margin. The percent reduction presented in the table are based on CO, since it is likely to be the pollutant most difficult to control. Larger HC reductions would be achieved with these technologies. Obviously, a manufacturer could change the technology mix based on cost and performance considerations. For example, the percent of direct injection two-stroke engine could be increased thus allowing fewer four-stroke or more modified two-stroke engines (e.g., calibration & engine modifications). We expect the manufacturers to select the most technically attractive and cost-effective approach which meet their perceived customer needs. Clearly there are options available to accomplish this goal.

Table 4.3-3
Potential Snowmobile Technology Mix for 2010

Technology	Percent Reduction	Percent Use to Meet Standard	Total Percent Reduction
Carburetor/EFI Recalibration + Engine Modifications + Pulse Air Injection	35%	50%	0.175
Direct Injection	70%	40%	0.280
Four-Stroke	50%	10%	0.050
Average Reduction			**0.505**

4.4 All-Terrain Vehicles

The following paragraphs summarize the data and rationale supporting the proposed emission standards for ATVs, which are listed in the Executive Summary.

4.4.1 Baseline Technology and Emissions

ATVs have been in existence for many years, but have only become popular over the last 25 years. Some of the earliest and most popular ATVs were three-wheeled off-highway motorcycles with large balloon tires. Due to safety concerns, the three-wheeled ATVs were phased-out in the mid-1980s and replaced by the current and more popular vehicle known as "quad runners" or simply "quads." Quads resemble the earlier three-wheeled ATVs except the single front wheel was replaced with two wheels that are controlled by a steering system. The ATV steering system uses motorcycle handlebars, but otherwise looks and operates like an automotive design. The operator sits on and rides the quad much like a motorcycle. The engines used in quads tend to be very similar to those used in off-highway motorcycles - relatively small single cylinder two- or four-stroke engines that are either air- or liquid-cooled. Recently, some manufacturers have introduced ATVs equipped with larger four-stroke two-cylinder V-twin engines. Quads are typically divided into two types: utility and sport. The utility quads are designed for recreational use but have the ability to perform many utility functions such as plowing snow, tilling gardens, and mowing lawns to name a few. They are typically heavier and equipped with relatively large four-stroke engines and automatic transmissions with reverse gear. Sport quads are smaller and designed primarily for recreational purposes. They are equipped with two- or four-stroke engines and manual transmissions.

There are two other types of ATVs, although they are not nearly as common as quad runners. Both types of vehicles are equipped with six wheels. The first type looks similar to a large golf cart, with a bed for hauling cargo much like a pick-up truck. These ATVs are typically manufactured by the same companies that make quad runners and use similar engines. The other type of six-wheeled ATV is an amphibious unit that can operate in water as well as on land. These ATVs are typically equipped with small spark-ignition gasoline-powered engines similar to those found in lawn and garden tractors, rather than the motorcycle engines used in quads, although some also use large SI engines as well.

Although ATVs are not currently regulated federally, they are regulated in California. The California ATV standards are based on the FTP cycle just like highway motorcycles, however, they allow manufacturers to optionally certify to a steady-state engine cycle (SAE J1088) and meet the California non-handheld small SI utility engine standards. Manufacturers have felt that these standards are unattainable with two-stroke engine technology. Therefore, all of the ATVs certified in California are equipped with four-stroke engines. California ultimately allowed manufacturers to sell uncertified engines as long as those ATVs and motorcycles equipped with these engines were operated exclusively on restricted public lands and at specified times of the year. This allowed manufacturers to continue to manufacture and sell two-stroke ATVs in California. Thus, the main emphasis of ATV engine design federally, and for two-stroke powered ATVs in California, is on performance, durability, and cost. Although some manufacturers offer some of their California models nationwide, most ATVs sold federally have no emission controls.

ATVs predominantly use four-stroke engines (e.g., 80 percent of all sales are four-stroke). The smaller percentage of two-stroke engines are found primarily in the small engine displacement "youth" models. Of the seven major ATV manufacturers, only two make two-stroke ATVs for adults. These models are either inexpensive entry models or high-performance sport models. The fuel system used on ATVs, whether two- or four-stroke, are almost exclusively carburetors, although at least one manufacturer has introduced a four-stroke ATV with electronic fuel injection. Although ATVs are mostly four-stroke equipped, they still can have relatively high levels of HC and extremely high levels of CO, because many of them operate with a "rich" air and fuel mixture, which enhances performance and allows engine cooling which promotes longer lasting engine life. This is also true for two-stroke equipped ATVs. Rich operation results in high levels of HC, CO, and PM emissions. In addition, two-stroke engines lubricate the piston and crankshaft by mixing oil with the air and fuel mixture. This is accomplished by most contemporary 2-stroke engines with a pump that sends two-cycle oil from a separate oil reserve to the carburetor where it is mixed with the air and fuel mixture. Some less expensive two-stroke engines require that the oil be mixed with the gasoline in the fuel tank. Because two-stroke engines tend to have high scavenging losses, where up to a third of the unburned air and fuel mixture goes out of the exhaust, lubricating oil particles are also released into the atmosphere, becoming HC particles or particulate matter (PM). The scavenging losses also result in high levels of raw HC. This is in contrast to four-stroke engines that use the crankcase as an oil sump and a pump to distribute oil throughout the engine, resulting in virtually no PM..

We tested five adult four-stroke and two youth two-stroke ATVs over the FTP. Tables 4.4-1 and 4.4-2 shows that the HC emissions for the four-stroke ATVs is significantly lower than for the two-stroke ATVs, whereas the NOx emissions from the two-strokes were considerably lower. Although the two-stroke ATVs tested were youth models, it can be argued that the emissions from these two models are lower than what could be expected from larger engines, since smaller displacement engines typically generate less emissions. The CO emissions were also lower for the two-stroke ATVs. The four-stroke ATVs that we tested that had high levels of CO happened to be 50-state certified vehicles, meaning they are California vehicles sold nationwide. Because there are California standards for HC+NOx, manufacturers have tended to calibrate the ATVs even richer then normal to meet the NOx standard. Since the CO standard in California is relatively high, these ATVs can run rich and still meet the CO standards.

Table 4.4-1
Four-Stroke ATV Emissions (g/km)

Make	Model	Model Year	Eng. Displ.	HC	CO	NOx
Kawasaki	Bayou	1989	280 cc	1.17	14.09	0.640
Honda	300EX	1997	298 cc	1.14	34.60	0.155
Polaris	Trail Boss	1998	324 cc	1.56	43.41	0.195
Yamaha	Banshee	1998	349 cc	0.98	19.44	0.190
Polaris	Sportsman	2001	499 cc	2.68	56.50	0.295
Average				1.51	33.61	0.295

Table 4.4-2
Two-Stroke ATV Emissions (g/km)

Make	Model	Model Year	Eng. Displ.	HC	CO	NOx
Suzuki	LT80	1998	79 cc	7.66	24.23	0.047
Polaris	Scrambler	2001	89 cc	38.12	25.08	0.057
Average				22.89	24.66	0.052

4.4.2 Potentially Available ATV Technologies

A variety of technologies are currently available or in stages of development to be available for use on two-stroke ATVs, such as engine modifications, improvements to carburetion (improved fuel control and atomization, as well as improved production tolerances), enleanment strategies for both carbureted and fuel injected engines, and semi-direct and direct fuel injection. However, it is our belief that manufacturers will choose to convert their two-stroke engines to four-stroke applications, because of the cost and complexity of the above mentioned technologies necessary to make a two-stroke engine meet our proposed standards. For our proposed phase 1 standards, we believe that a four-stroke engine with minor improvements to carburetion and enleanment strategies will be all that is required. For our proposed phase 2 standards, we believe the use of a four-stroke engine with improved carburetion or possible use of electronic fuel injection, enleanment strategies, possible engine modifications, secondary air and/or possibly the use of a oxidation catalyst will be necessary. Each of these is discussed in the following sections.

4.4.2.1 Engine Modifications

There are a variety of engine modifications that could reduce emissions from two-stroke and four-stroke engines. The modifications generally either increase trapping efficiency (i.e., reduce fuel short-circuiting) or improve combustion efficiency. Those modifications for two-stroke engines that increase trapping efficiency include optimizing the intake, scavenge and exhaust port shape and size, and port placement, as well as optimizing port exhaust tuning and bore/stroke ratios. Optimized combustion charge swirl, squish and tumble would serve to improve the combustion of the intake charge for both two- and four-stroke engines. These modifications for two-stroke engines have the potential to reduce emissions by up to 40 percent, depending on how well the unmodified engine is optimized for these things, but would be insufficient alone to meet our proposed phase 1 standards.

4.4.2.2 Carburetion Improvements

There are several things that can be done to improve carburetion in ATV engines. First, strategies to improve fuel atomization would promote more complete combustion of the fuel/air mixture. Additionally, production tolerances could be improved for more consistent fuel metering. Both of these things would allow for more accurate control of the air/fuel ratio. In conjunction with these improvements in carburetion, the air/fuel ratio could be leaned out some. ATV engines are currently calibrated with rich air/fuel ratios for durability and performance reasons. Leaner calibrations would serve to reduce CO and HC emissions by up to 20 percent, depending on how lean the unmodified engine is prior to recalibration. Small improvements in fuel economy could also be expected with recalibration.

The calibration changes just discussed (as well as some of the engine modifications previously discussed) would also reduce ATV engine durability. There are many engine improvements that could be made to regain lost durability that occurs with leaner calibration. These include changes to the cylinder head, pistons, pipes and ports for two-stroke and valves for four-stroke, to reduce knock. In addition critical engine components could be made more robust to improve durability.

The same calibration changes to the air/fuel ratio just discussed for carbureted engines could also be employed, possibly with more accuracy, with the use of fuel injection. At least one ATV manufacturer currently employs electronic fuel injection on one of its ATV models.

4.4.2.3 Direct and Semi-Direct Fuel Injection

In addition to rich air/fuel ratios, one of the main reasons that two-stroke engines have such high levels of HC emissions is scavenging losses, as described above. One way to reduce or eliminate such losses is to inject the fuel into the cylinder after the exhaust port has closed. This can be done by injecting the fuel into the cylinder through the transfer port (semi-direct injection) or directly into the cylinder (direct injection). Both of these approaches are currently being used successfully in two-stroke personal watercraft engines and some are showing upwards of 70 percent reductions in emissions. Direct injection is also being used by some motorcycle manufacturers (e.g., Aprilla) on small mopeds, scooters, and motorcycles to meet emission standards for two-strokes in Europe and Asia. Substantial improvements in fuel economy could also be expected with these technologies. However, there are some issues with ATV operation (larger displacement engines that experience more transient operation than watercraft and small mopeds) that make the application of the direct injection technologies somewhat more challenging for ATVs than for personal watercraft and small displacement scooters. The biggest obstacle for this technology is that the many of the two-stroke equipped ATVs are youth models which emphasize low price. Direct injection is relatively expensive and is currently not considered to be cost effective for these engines.

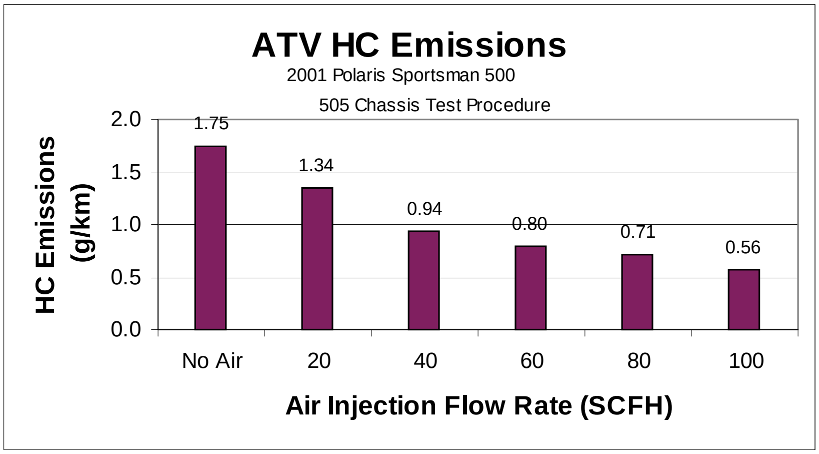
4.4.2.4 Four-Stroke Engines

Since 80 percent of all ATVs sold each year are four-stroke, there is no question about the feasibility of using four-stroke technology for ATVs. The ATV models that are currently equipped with two-stroke engines tend to be small-displacement youth models, entry-level adult ATVs and high-performance adult sport ATVs. While most youth ATVs are equipped with two-stroke engines, there are several manufactures who offer four-stroke models. Youth ATVs are regulated by the Consumer Product Safety Commission (CPSC). Although the regulations are voluntary, manufactures take them very seriously, and one of the their requirements is that youth ATV speeds be governed. For “Y6" ATVs (i.e., age 6 and up) the maximum speed is 15 miles per hour (mph) and for “Y12" ATVs (i.e., age 12 and up), the maximum speed is 30 mph. Some manufacturers have argued that because of these speed constraints, they need to use light-weight two-stroke engines, which have higher power-to-weight ratios than four-stroke engines, in order to have sufficient power to operate the ATV. As mentioned earlier, some manufacturers already use four-stroke engines in these applications without any problem. The power required to meet the maximum speed limits for these little ATVs is low enough that a four-stroke engine is more than adequate. The real issue appears to be cost. Manufacturers argue that youth ATVs are price sensitive and that minor increases in cost would be undesirable. Four-stroke engines are more expensive than similarly powered two-stroke engines. This appears to be the issue with entry-level adult ATVs as well. Those manufacturers that offer two-stroke entry-level ATVs, also offer similar entry-level machines with four-stroke engines. The argument is that consumers of their product like having the ability to choose between engine types.

Adult sport ATVs equipped with two-stroke engines were at one time considered the only ATVs that were capable of providing true high-performance. However, advancements in four-stroke engine technology for ATVs and off-highway motorcycles have now made it possible for larger displacement high-powered four-stroke engines to equal, and in some cases surpass, the performance of the high-powered two-stroke engines. Again, the argument for two-stroke engines appears to be a matter of choice for consumers. However, since only two manufacturers produce two-stroke adult ATVs, we believe that the relatively low sales volumes for these models will make it cost prohibitive to reduce two-stroke emissions to the levels necessary to meet our proposed phase I standards.

Conversion from two-stroke to four-stroke engine technology will also result in improvements to fuel consumption and engine durability. These benefits could be especially valuable to consumers who purchase utility ATVs.

4.4.2.5 Air Injection



Secondary pulse air injection involves the introduction of fresh air into the exhaust pipe immediately after the gases exit the engine. The extra air causes further combustion to occur as the gases pass through the exhaust pipe, thereby controlling more of the hydrocarbons that escape the combustion chamber. This type of system is relatively inexpensive and uncomplicated because it does not require an air pump; air is drawn into the exhaust through a one-way reed valve due to the pulses of negative pressure inside the exhaust pipe. Secondary pulse-air injection is one of the most effective non-catalytic, emissions control technologies; compared to engines without the system, reductions of 10-40% for HC are possible with pulse-air injection.

This technology is fairly common on highway motorcycles and is used on some off-highway motorcycle models in California to meet the California off-highway motorcycle and ATV emission standards. We believe that secondary air injection will not be necessary to meet our proposed phase 1 standards, but will be a viable technology for meeting our proposed phase 2 emission standards. Secondary air injection can also be used in conjunction with an oxidation catalyst to achieve even further reductions. We are planning to test several four-stroke ATVs with secondary air injection. Initial test results for a 2001 Polaris Sportsman 500 four-stroke ATV indicate that secondary air injection could result in up to a 70 percent reduction in HC emissions and a 50 percent reduction in CO emissions from baseline four-stroke ATV emission levels.

Figure 4.4-1

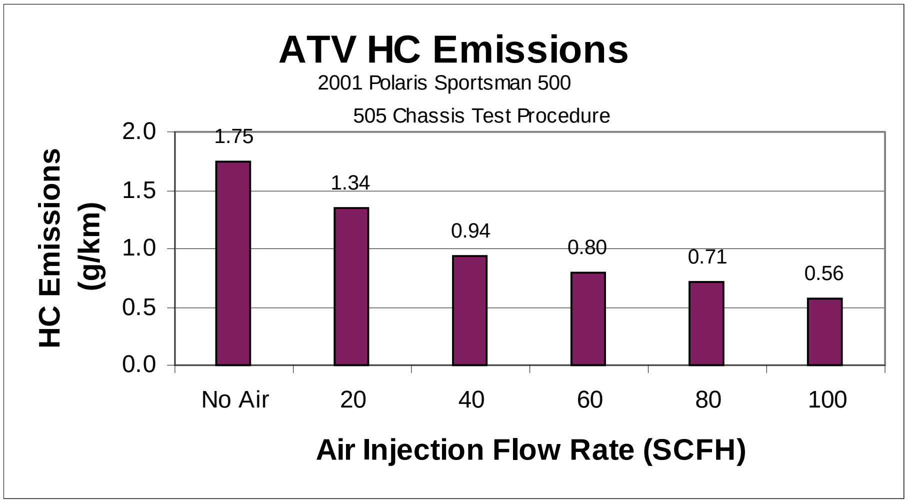
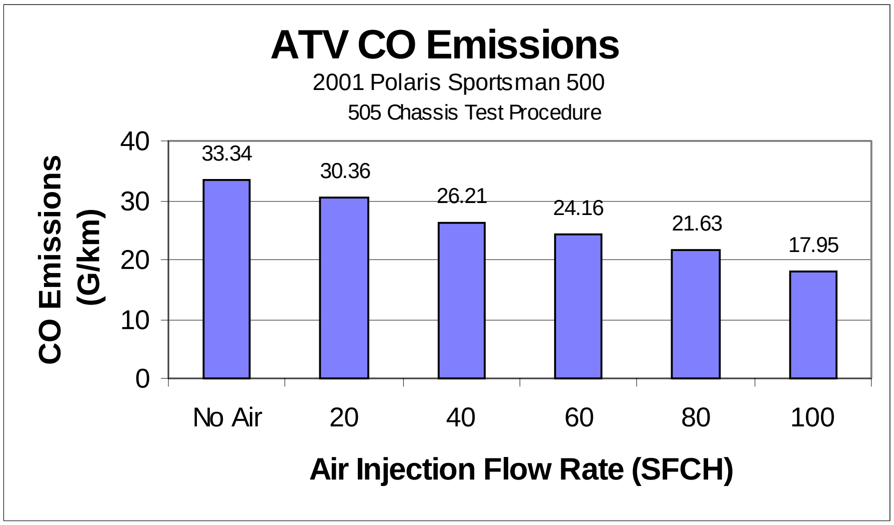


Figure 4.4-2



4.4.2.6 Catalyst Technology

Catalyst technology may be necessary for some ATV models to meet our proposed phase-2 emission standards. Depending on the model, the respective engine and it's unique characteristics and the manufacturers preference, manufacturers may choose to use a two-way or oxidation catalyst or a three-way catalyst. If NOx emissions are inherently low for a given engine, a manufacturer may decide to use an oxidation catalyst. If high NOx levels are a concern, the manufacturer may choose to use a three-way catalyst instead. Oxidation catalysts typically use platinum and/or palladium to oxidize HC and CO emissions. Because some ATV engines operate so rich, it may be necessary to also use secondary air injection in conjunction with an oxidation catalyst in order to provide adequate oxygen for oxidation to occur.

Three-way catalytic converters traditionally utilize rhodium and platinum/palladium as the catalytic material to control the emissions of all three major pollutants (HC, CO, and NOx). Although this type of catalyst is very effective at converting exhaust pollutants, rhodium, which is primarily used to reduce NOx to nitrogen and oxygen, tends to thermally deteriorate at temperatures significantly lower than platinum. Recent advances in palladium and tri-metal (i.e., palladium-platinum-rhodium) catalyst technology, however, have improved both the light-off performance and high temperature durability over previous catalysts. In addition, other refinements to catalyst technology, such as higher cell density substrates and adding a second layer of catalyst washcoat to the substrate (dual-layered washcoats), have further improved catalyst performance from just a few years ago.

Typical cell densities for conventional catalysts used in motorcycles are less than 300 cells per square inch (cpsi). To meet our proposed phase 2 standards, we expect manufacturers to use catalysts with cell densities of 100 to 200 cpsi. If catalyst volume is maintained at the same level (we assume volumes of up to 50% of engine displacement), using a higher density catalyst effectively increases the amount of surface area available for reacting with pollutants. Catalyst manufacturers have been able to increase cell density by using thinner walls between each cell without increasing thermal mass (and detrimentally affecting catalyst light-off) or sacrificing durability and performance.

We have tested a 2001 model year Polaris Sportsman 500 ATV. It is a large utility ATV equipped with a 500 cc four-stroke engine and is one of the largest ATV models currently offered in the market. We chose this model to demonstrate catalyst viability because it had the highest baseline emissions of any of the ATVs we tested, and it is a California certified vehicle that is sold nationwide. We tested the Polaris with three different catalysts. Two of the catalysts were three-way catalysts with metal substrates and cell densities of 200 cpsi. One of the catalyst's had a Pt/Rh washcoat, while the other used a Pd-only washcoat. The third catalyst was an oxidation catalyst with a ceramic substrate and a cell density of 400 cpsi. Table 4.4-3 shows that the use of either an oxidation or three-way catalyst can significantly reduce emissions from an ATV. This particular ATV had baseline HC and CO emissions that were 77% higher for HC and 68% higher for CO than the average of the baseline levels of all of the ATVs we tested (see above in Table 4.4-1). We measured air/fuel ratio during testing and found this vehicle to operate extremely rich. We plan to test the ATV with a leaner carburetor setting and with secondary air injection. We anticipate that either one or perhaps both of these strategies would result in even further emission reductions. We also measured exhaust backpressure and found that none of the catalysts tested resulted in a significant increase in backpressure, which could correspond to reduced engine performance.

Although the test results for the Polaris did not meet our proposed phase 2 standards, we are confident that the data illustrate that the use of a catalytic converter can achieve these levels, since the percent reductions from baseline levels with the catalysts were approximately 52% for HC and 38% for CO. These levels of reduction when applied to the average baseline emissions from our test fleet would result in emission levels at or below our proposed phase 2 standards.

Table 4.4-3
Polaris Sportsman 500 Emissions with Various Catalysts

Catalyst	HC	CO	NOx	HC+NOx
Baseline	2.68	56.50	0.30	2.98
TWC (Pd-only)	1.27	35.27	0.05	1.32
TWC (Pt/Rh)	1.29	32.60	0.04	1.33
Oxidation	1.38	28.87	0.02	1.40

Increased precious metal loading (up to a certain point) will reduce exhaust emissions because it increases the opportunities for pollutants to be converted to harmless constituents. The extent to which precious metal loading is increased will be dependent upon the precious metals used and other catalyst design parameters. We believe recent developments in palladium/rhodium catalysts are very promising since rhodium is very efficient at converting NOx, and catalyst suppliers have been investigating methods to increase the amount of rhodium in catalysts for improved NOx conversion.

Double layer technologies allow optimization of each individual precious metal used in the washcoat. This technology can provide reduction of undesired metal-metal or metal-base oxide interactions while allowing desirable interactions. Industry studies have shown that durability and pollutant conversion efficiencies are enhanced with double layer washcoats. These recent improvements in catalysts can help manufacturers meet the proposed phase 2 standards at reduced cost relative to older three-way catalysts.

New washcoat formulations are now thermally stable up to 1050 ^{o}C. This is a significant improvement from conventional washcoats, which are stable only up to about 900 ^{o}C. With the improvements in light-off capability, catalysts may not need to be placed as close to the engine as previously thought. However, if placement closer to the engine is required for better emission performance, improved catalysts based on the enhancements described above would be more capable of surviving the higher temperature environment without deteriorating. The improved resistance to thermal degradation will allow closer placement to the engines where feasible, thereby providing more heat to the catalyst and allowing them to become effective quickly.

It is well established that a warmed-up catalyst is very effective at converting exhaust pollutants. Recent tests on advanced catalyst systems in automobiles have shown that over 90% of emissions during the Federal Test Procedure (FTP) are now emitted during the first two minutes of testing after engine start up. Similarly, the highest emissions from a motorcycle occur shortly after start up. Although improvements in catalyst technology have helped reduce catalyst light-off times, there are several methods to provide additional heat to the catalyst. Retarding the ignition spark timing and computer-controlled, secondary air injection have been shown to increase the heat provided to the catalyst, thereby improving its cold-start effectiveness.

Improving insulation of the exhaust system is another method of furnishing heat to the catalyst. Similar to close-coupled catalysts, the principle behind insulating the exhaust system is to conserve the heat generated in the engine for aiding catalyst warm-up. Through the use of laminated thin-wall exhaust pipes, less heat will be lost in the exhaust system, enabling quicker catalyst light-off. As an added benefit, the use of insulated exhaust pipes will also reduce exhaust noise. Increasing numbers of manufacturers are expected to utilize air-gap exhaust manifolds (i.e., manifolds with metal inner and outer walls and an insulating layer of air sandwiched between them) for further heat conservation for highway motorcycles, although this may prove to be overkill for ATV applications.

4.4.3 Test Procedure

For ATVs, we propose that the current highway motorcycle test procedure be used for measuring emissions. The highway motorcycle test procedure is the same test procedure as used for light-duty vehicles (i.e., passenger cars and trucks) and is referred to as the Federal Test Procedure (FTP). The FTP for a particular class of engine or equipment is actually the aggregate of all of the emissions tests that the engine or equipment must meet to be certified. However, the term FTP has also been used traditionally to refer to the exhaust emission test based on the Urban Dynamometer Driving Schedule (UDDS), also referred to as the LA4 (Los Angeles Driving Cycle #4). The UDDS is a chassis dynamometer driving cycle that consists of numerous “hills” which represent a driving event. Each hill includes accelerations, steady-state operation, and decelerations. There is an idle between each hill. The FTP consists of a cold start UDDS, a 10 minute soak, and a hot start. The emissions from these three separate events are collected into three unique bags. Each bag represents one of the events. Bag 1 represents cold transient operation, bag 2 represents cold stabilized operation, and bag 3 represents hot transient operation.

Highway motorcycles are divided into three classes based on engine displacement, with class I (50 to 169 cc) being the smallest and class 3 (280 cc and over) being the largest. The highway motorcycle regulations allow class I motorcycles to be tested on a less severe UDDS cycle than the class II and III motorcycles. This is accomplished by reducing the acceleration and deceleration rates on some the more aggressive “hills.” We propose that this same class/cycle distinction be allowed for ATVs. In other words, ATVs with an engine displacement between 50 and 279 cc (class I and II) would be tested over the class I highway motorcycle FTP test cycle. ATVs with engine displacements greater than 280 cc would be tested over the class III highway motorcycle FTP test cycle. Some manufacturers have noted that they do not currently have chassis-based test facilities capable of testing ATVs. Manufacturers have noted that requiring chassis-based testing for ATVs would require them to invest in additional testing facilities which can handle ATVs, since ATVs do not fit on the same roller(s) as motorcycles used in chassis testing. Some manufacturers also have stated that low pressure tires on ATVs would not stand up to the rigors of a chassis dynamometer test. California provides manufacturers with the option of certifying ATVs using the engine-based, utility engine test procedure (SAE J1088), and most manufacturers use this option for certifying their ATVs. Manufacturers have facilities to chassis test motorcycles and therefore California does not provide an engine testing certification option for motorcycles.

We have tested numerous ATVs over the FTP and have found that several methods can be used to test ATVs on chassis dynamometers. The most practical method for testing an ATV on a motorcycle dynamometer is to disconnect one of the drive wheels and test with only one drive wheel in contact with the dynamometer. For chassis dynamometers set-up to test light-duty vehicles, wheel spacers or a wide axle can be utilized to make sure the drive wheels fit the width of the dynamometer. We have found that the low pressure tires have withstood dynamometer testing without any problems.

We acknowledge that a chassis dynamometer could be very costly to purchase and difficult to put in place in the short run, especially for some smaller manufacturers. Therefore, we are proposing that for the model years 2006 thru 2009, ATV manufacturers would be allowed the option to certify using the J1088 engine test cycle per the California off-highway motorcycle and ATV program. After 2009, this option would end and the FTP would be the required test cycle. If manufacturers can develop an alternate transient test cycle (engine or chassis) that shows correlation with the FTP or demonstrates representativeness of actual ATV operation greater than the FTP, then we would consider allowing the option of an alternative test cycle in place of the FTP.

4.4.4 Impacts on Noise, Energy, and Safety

The Clean Air Act directs us to consider potential impacts on noise, energy, and safety when establishing the feasibility of emission standards for nonroad engines.

As automotive technology demonstrates, achieving low emissions from spark-ignition engines can correspond with greatly reduced noise levels. Virtually all ATVs are equipped sound suppression systems or mufflers. The four-stroke engines used in ATVs are considerably more quiet than two-stroke engines. Electronically controlled fuel systems are able to improve management of the combustion event which can further help lower noise levels.

Adopting new technologies for controlling fuel metering and air-fuel mixing will lead to substantial improvements in fuel consumption rates for four-stroke engines. Four-stroke engines have far less fuel consumption than two-stroke engines. Average mileage for a baseline two-stroke ATV is 20-25 mpg, while the average four-stroke ATV gets 45-50 mpg.

We believe the technology discussed here would have no negative impacts on safety. Four-stroke engine technology has been utilized on ATVs for numerous years without any incident. Secondary air and catalysts have been utilized in highway motorcycles and lawn and garden equipment without any safety concerns.

4.4.5 Conclusion

We expect that the proposed phase 1 ATV emission standards will largely be met through the conversion of two-stroke engines to four-stroke engines with some minor carburetor calibration modifications and air-fuel ratio enleanment. Certification data from California's off-highway motorcycle and ATV program, as well as data from our own testing suggest that four-stroke engines with some minor fuel system calibration modifications will be capable of meeting our proposed emission standards. For our proposed phase 2 ATV emission standards, we expect manufacturers to use four-stroke engine technology with a possible combination of engine modifications, carburetion improvements, secondary air injection and/or catalyst aftertreatment. These technologies have been utilized in a number of different applications, such as highway motorcycles, personal watercraft, lawn and garden equipment, and small scooters. Preliminary testing performed by us and other research firms have also shown that these are viable technologies capable of meeting our proposed phase 2 standards. However, the other technologies discussed have the potential to reduce emissions beyond what could be expected from engine modifications and carburetion improvements. These other technologies also have potential benefits beyond emission reductions (e.g., improved fuel economy, reliability and performance, and reduced noise). We expect that as ATV manufacturers develop and refine these other technologies, they will find their way into the marketplace in certain applications where their non-emission benefits would outweigh their cost.

4.7 Off-Highway Motorcycles

The following paragraphs summarize the data and rationale supporting the proposed emission standards for off-highway motorcycles, which are listed in the Executive Summary.

4.7.1 Baseline Technology and Emissions

Off-highway motorcycles are similar in appearance to highway motorcycles (which are discussed in section 4.8.), but there are several important distinctions between the two types of machines. Off-highway motorcycles are not street-legal and are primarily operated on public and private lands over trails and open land. Off-highway motorcycles tend to be much smaller, lighter and more maneuverable than their larger highway counterparts. They are equipped with relatively small-displacement single- cylinder two- or four-stroke engines ranging from 50 to 650 cubic centimeters (cc). The exhaust systems for off-highway motorcycles are distinctively routed high on the frame to prevent damage from brush, rocks, and water. Off-highway motorcycles are designed to be operated over varying surfaces, such as dirt, sand, and mud, and are equipped with knobby tires which provide better traction in off-road conditions. Unlike highway motorcycles, off-highway motorcycles have fenders mounted far from the wheels and closer to the rider to keep dirt and mud from spraying the rider and clogging between the fender and tire. Off-highway motorcycles are also equipped with a more advanced suspension system than those for highway motorcycles. This allows the operator to ride over obstacles and make jumps safely.

Thirty percent of off-highway motorcycle sales are competition motorcycles. The vast majority of competition off-highway motorcycles are two-strokes. The CAA requires us to exempt from our regulations vehicles used for competition purposes. The off-highway motorcycles that remain once competition bikes are excluded are recreational trail bikes and small-displacement youth bikes. The majority of recreational trail bikes are equipped with four-stroke engines. Youth off-highway motorcycles are almost evenly divided between four-stroke and two-stroke engines.

The fuel system used on off-highway motorcycles, whether two- or four-stroke, are almost exclusively carburetors, although at least one manufacturer has introduced a four-stroke off-highway motorcycle with electronic fuel injection. Although many off-highway motorcycles are four-stroke equipped, they still can have relatively high levels of HC and extremely high levels of CO, because many of them operate with a “rich” air and fuel mixture, which enhances performance and allows engine cooling which promotes longer lasting engine life. This is also true for two-stroke equipped off-highway motorcycles. Rich operation results in high levels of HC, CO, and PM emissions. In addition, two-stroke engines lubricate the piston and crankshaft by mixing oil with the air and fuel mixture. This is accomplished by most contemporary two-stroke engines with a pump that sends two-cycle oil from a separate oil reserve to the carburetor where it is mixed with the air and fuel mixture. Some less expensive two-stroke engines require that the oil be mixed with the gasoline in the fuel tank. Because two-stroke engines tend to have high scavenging losses, where up to a third of the unburned air and fuel mixture goes out of the exhaust, lubricating oil particles are also released into the atmosphere, becoming HC particles or particulate matter (PM). The scavenging losses also result in high levels of raw HC. This is in contrast to four-stroke engines that use the crankcase as an oil sump and a pump to distribute oil throughout the engine, resulting in virtually no PM.

We tested six high-performance two-stroke motorcycles and four high-performance four-stroke motorcycles over the FTP. Tables 4.7-1 and 4.7-2 shows that the HC emissions for the four-stroke bikes is significantly lower than for the two-stroke bikes, whereas the NOx emissions from the two-strokes were considerably lower. The CO levels were also considerably lower for the four-stroke bikes.

Table 4.7-1
Four-Stroke Off-Highway Motorcycles Emissions (g/km)

Make	Model	Model Year	Eng. Displ.	HC	CO	NOx
Yamaha	WR250F	2001	249 cc	1.46	26.74	0.110
Yamah	WR400F	1999	398 cc	1.07	20.95	0.155
KTM	400EXC	2001	398 cc	1.17	28.61	0.050
Husaberg	FE501	2001	498 cc	1.30	25.81	0..163
Average				1.25	25.52	0.109

Table 4.7-2
Two-Stroke Off-Highway Motorcycles Emissions (g/km)

Make	Model	Model Year	Eng. Displ.	HC	CO	NOx
KTM	125SX	2001	124 cc	33.77	31.00	0.008
KTM	125SX	2001	124 cc	61.41	32.43	0.011
KTM	200EXC	2001	198 cc	53.09	39.89	0.025
KTM	250SX	2001	249 cc	62.89	49.29	0.011
KTM	250EXC	2001	249 cc	59.13	40.54	0.016
KTM	300EXC	2001	398 cc	47.39	45.29	0.012
Average				52.95	39.74	0.060

4.7.2 Potentially Available Off-Highway Motorcycle Technologies

A variety of technologies are currently available or in stages of development to be available for use on two-stroke off-highway motorcycles, such as engine modifications, improvements to carburetion (improved fuel control and atomization, as well as improved production tolerances), enleanment strategies for both carbureted and fuel injected engines, and semi-direct and direct fuel injection. However, it is our belief that manufacturers will choose to convert their two-stroke engines to four-stroke applications, because of the cost and complexity of the above mentioned technologies necessary to make a two-stroke engine meet our proposed standards. For our proposed standards, we believe that a four-stroke engine with minor improvements to carburetion and enleanment strategies will be all that is required. Each of these is discussed in the following sections.

4.7.2.1 Engine Modifications

There are a variety of engine modifications that could reduce emissions from two-stroke and four-stroke engines. The modifications generally either increase trapping efficiency (i.e., reduce fuel short-circuiting) or improve combustion efficiency. Those modifications for two-stroke engines that increase trapping efficiency include optimizing the intake, scavenge and exhaust port shape and size, and port placement, as well as optimizing port exhaust tuning and bore/stroke ratios. Optimized combustion charge swirl, squish and tumble would serve to improve the combustion of the intake charge for both two- and four-stroke engines. These modifications for two-stroke engines have the potential to reduce emissions by up to 40 percent, depending on how well the unmodified engine is optimized for these things, but would be insufficient alone to meet our proposed standards.

4.7.2.2 Carburetion Improvements

There are several things that can be done to improve carburetion in off-highway motorcycle engines. First, strategies to improve fuel atomization would promote more complete combustion of the fuel/air mixture. Additionally, production tolerances could be improved for more consistent fuel metering. Both of these things would allow for more accurate control of the air/fuel ratio. In conjunction with these improvements in carburetion, the air/fuel ratio could be leaned out some. Off-highway motorcycle engines are currently calibrated with rich air/fuel ratios for durability and performance reasons. Leaner calibrations would serve to reduce CO and HC emissions by up to 20 percent, depending on how lean the unmodified engine is prior to recalibration. Small improvements in fuel economy could also be expected with recalibration.

The calibration changes just discussed (as well as some of the engine modifications previously discussed) would also reduce off-highway motorcycle engine durability. There are many engine improvements that could be made to regain lost durability that occurs with leaner calibration. These include changes to the cylinder head, pistons, pipes and ports for two-stroke and valves for four-stroke, to reduce knock. In addition critical engine components could be made more robust to improve durability.

Carburetion improvements alone will not allow manufacturers to meet our proposed standards, especially for two-stroke engines. Carburetion improvements with four-stroke engines may be necessary.

The same calibration changes to the air/fuel ratio just discussed for carbureted engines could also be employed, possibly with more accuracy, with the use of fuel injection. At least one off-highway motorcycle manufacturer currently employs electronic fuel injection on one of its models.

4.7.2.3 Direct and Semi-Direct Fuel Injection

In addition to rich air/fuel ratios, one of the main reasons that two-stroke engines have such high levels of HC emissions is scavenging losses, as described above. One way to reduce or eliminate such losses is to inject the fuel into the cylinder after the exhaust port has closed. This can be done by injecting the fuel into the cylinder through the transfer port (semi-direct injection) or directly into the cylinder (direct injection). Both of these approaches are currently being used successfully in two-stroke personal watercraft engines and some are showing upwards of 70 percent reductions in emissions. Direct injection is also being used by some motorcycle manufacturers (e.g., Aprilla) on small mopeds, scooters, and motorcycles to meet emission standards for two-strokes in Europe and Asia. Substantial improvements in fuel economy could also be expected with these technologies. However, there are some issues with off-highway motorcycle operation (larger displacement engines that experience more transient operation than watercraft and small mopeds) that make the application of the direct injection technologies somewhat more challenging for motorcycles than for personal watercraft and small displacement scooters. The biggest obstacle for this technology is that the many of the two-stroke equipped off-highway motorcycles are youth models which emphasize low price. Direct injection is relatively expensive and is currently not considered to be cost effective for these engines.

4.7.2.4 Four-Stroke Engines

We expect that the conversion of off-highway motorcycle models utilizing two-stroke engines to four-stroke engines will be the main method of achieving our proposed off-highway motorcycle standards. As with ATVs, the question of feasibility for four-stroke engines in off-highway motorcycles is moot, since more than half of the existing off-highway models are already four-stroke and, in some cases, have been for a long time. Honda has used four-stroke engines in all of their off-highway motorcycles (except for their competition motocross bikes) for over thirty years. In fact, over the last 5 to 10 years, the trend has been to slowly replace two-stroke models with four-stroke engines. Although the California emission standards have had some impact on this, it has been minor. Four-stroke engines are more durable, reliable, quieter and get far better fuel economy than two-stroke engines. But probably the single most important factor in the spread of the four-stroke engine has been major advances in weight reduction and performance.

Four-stroke engines typically weigh more than two-stroke engines because they need a valve-train system, consisting of intake and exhaust valves, camshafts, valve springs, valve timing chains and other components, as well as storing lubricating oil in the crankcase. Since a four-stroke engine produces a power-stroke once every four revolutions of the crankshaft, compared to a two-stroke which produces one once every two revolutions, a four-stroke engine of equal displacement to a two-stroke engine produces less power, on the average of 30 percent less. So in the past, off-highway motorcycles that used four-stroke engines tended to use very heavy, large displacement engines, but yet had average power and performance. However, recent breakthroughs in technologies have allowed manufacturers to design off-highway motorcycles that use lighter and stronger materials for the engine and the motorcycle frame. The advanced four-stroke technologies, such as multiple valves, used in some of the high-performance four-stroke highway motorcycles, have found their way onto off-highway motorcycles, resulting in vastly improved performance. The newer four-stroke bikes also tend to have an engine power band or range that is milder of more forgiving than a typical two-stroke bike. Two-stroke bikes tend to run poorly at idle and during low load situations. They also typically generate low levels of torque at low to medium speeds, whereas four-stroke bikes traditionally generate a great deal of low-end and mid-range torque. This is important to off-highway motorcycle riders because it is common when riding off-highway motorcycles on trails or other surfaces to come across obstacles that require slower maneuverability. A two-stroke engine that idles poorly and has poor low-end torque can easily stall during these maneuvers, whereas a four-stroke bike excels under these conditions. Current sales figures, as well as articles in off-highway motorcycle trade magazines, indicate that four-stroke off-highway motorcycles are more popular than ever, and the public is buying them as fast as they can build them.

4.7.2.5 Air Injection

Secondary pulse air injection involves the introduction of fresh air into the exhaust pipe immediately after the gases exit the engine. The extra air causes further combustion to occur as the gases pass through the exhaust pipe, thereby controlling more of the hydrocarbons that escape the combustion chamber. This type of system is relatively inexpensive and uncomplicated because it does not require an air pump; air is drawn into the exhaust through a one-way reed valve due to the pulses of negative pressure inside the exhaust pipe. Secondary pulse-air injection is one of the most effective non-catalytic, emissions control technologies; compared to engines without the system, reductions of 10-40% for HC are possible with pulse-air injection.

This technology is fairly common on highway motorcycles and is used on some off-highway motorcycle models in California to meet the California off-highway motorcycle and ATV emission standards. We believe that secondary air injection should not be necessary to meet our proposed standards, however, some manufacturers may choose to use it on some four-stroke engine models.

4.7.3 Test Procedure

For off-highway motorcycles, we propose that the current highway motorcycle test procedure be used for measuring emissions. The highway motorcycle test procedure is the same test procedure as used for light-duty vehicles (i.e., passenger cars and trucks) and is referred to as the Federal Test Procedure (FTP). The FTP for a particular class of engine or equipment is actually the aggregate of all of the emissions tests that the engine or equipment must meet to be certified. However, the term FTP has also been used traditionally to refer to the exhaust emission test based on the Urban Dynamometer Driving Schedule (UDDS), also referred to as the LA4 (Los Angeles Driving Cycle #4). The UDDS is a chassis dynamometer driving cycle that consists of numerous “hills” which represent a driving event. Each hill includes accelerations, steady-state operation, and decelerations. There is an idle between each hill. The FTP consists of a cold start UDDS, a 10 minute soak, and a hot start. The emissions from these three separate events are collected into three unique bags. Each bag represents one of the events. Bag 1 represents cold transient operation, bag 2 represents cold stabilized operation, and bag 3 represents hot transient operation.

Highway motorcycles are divided into three classes based on engine displacement, with class I (50 to 169 cc) being the smallest and class 3 (280 cc and over) being the largest. The highway motorcycle regulations allow class I motorcycles to be tested on a less severe UDDS cycle than the class II and III motorcycles. This is accomplished by reducing the acceleration and deceleration rates on some the more aggressive “hills.” We propose that this same class/cycle distinction be allowed for off-highway motorcycles. In other words, off-highway motorcycles with an engine displacement between 50 and 279 cc (class I and II) would be tested over the class I highway motorcycle FTP test cycle. Off-highway motorcycles with engine displacements greater than 280 cc would be tested over the class III highway motorcycle FTP test cycle.

4.7.4 Impacts on Noise, Energy, and Safety

The Clean Air Act directs us to consider potential impacts on noise, energy, and safety when establishing the feasibility of emission standards for nonroad engines.

As automotive technology demonstrates, achieving low emissions from spark-ignition engines can correspond with greatly reduced noise levels. Virtually all recreational off-highway motorcycles are equipped with sound suppression systems or mufflers. The four-stroke engines used in off-highway motorcycles are considerably more quiet than the two-stroke engines used.

Adopting new technologies for controlling fuel metering and air-fuel mixing will lead to substantial improvements in fuel consumption rates for four-stroke engines. Four-stroke engines have far less fuel consumption than two-stroke engines. Average mileage for a baseline two-stroke off-highway motorcycle is 20-25 mpg, while the average four-stroke off-highway motorcycle gets 45-50 mpg.

We believe the technology discussed here would have no negative impacts on safety. Four-stroke engine technology has been utilized on off-highway motocycles for numerous years without any incident. Secondary air and catalysts have been utilized in highway motorcycles and lawn and garden equipment without any safety concerns.

4.7.5 Conclusion

We expect that the proposed off-highway motorcycle emission standards will largely be met through the conversion of two-stroke engines to four-stroke engines with some minor carburetor calibration modifications and air-fuel ratio enleanment. Four-stroke engines are common in many off-highway motorcycles and have been used for many years. Certification data from California's off-highway program, as well as data from our own testing suggest that four-stroke engines with some minor fuel system calibration modifications will be capable of meeting our proposed emission standards. We believe the current sales volumes of two-stroke off-highway motorcycles, combined with the cost to modify two-stroke engines for significant emission reductions, will discourage the use of two-stroke engine technology.

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