Chapter 4: Feasibility of 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 emission standards are technically achievable accounting for all the above factors.

It is important to note that the term "greatest degree of emission reduction achievable" applies with respect to in-use emissions from each production engine at the end of engine's useful life, rather than what is achievable under more ideal laboratory conditions. This means that the standards that are being established in this rulemaking must account for production variability and for deterioration in emission performance that will occur in use as the engines age and wear over the applicable useful life periods. We have considered these factors in determining the lowest emissions that will be feasible in the time frame required. Thus, in some cases, the emission standards are somewhat higher than the lowest emissions observed during laboratory testing. In general, we expect that manufacturers will design their engines and vehicles to be at 10- 20 percent below the applicable emission standard when produced to account for both production variability and deterioration. Chapter 6 includes more information about our expectations regarding compliance margins and deterioration rates.

4.1 CI Recreational Marine

The emission standards for 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 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 % of new marine engines are turbocharged, and 80% of these turbocharged engines use aftercooling. The majority of these engines are four-stroke, but about 14% of new engines are two-stroke. 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 engine applications 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 standards.[1] 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 CO standard will act more as a cap, but will require control to be established.

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[1] For most of the engines in Table 4.1-1, the 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-efficiently. 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 for the full useful life of these engines.

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, fuel consumption and power can be offset with improved fuel injection systems with higher fuel injection pressures, optimized nozzle geometry, and potentially through injection 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 will 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 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 rule. We recognize that raw-water aftercooling systems are currently in use in many applications. Chapter 5 presents one possible scenario of how these technologies could be used on CI recreational marine engines to meet the standards.

By adopting 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 specify the E5 duty cycle for measuring emissions from CI 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 small 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 are applying the "Not-to-Exceed" (NTE) limit concept to recreational marine engines in a way that is 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.[8] Of course, the shape of the zone must be adjusted to reflect recreational engine use.

Under this final rule, we have the authority to use test data from new or in-use engines to confirm emissions compliance throughout an engine's useful life.

4.1.3.2.1 Engine operation included for NTE

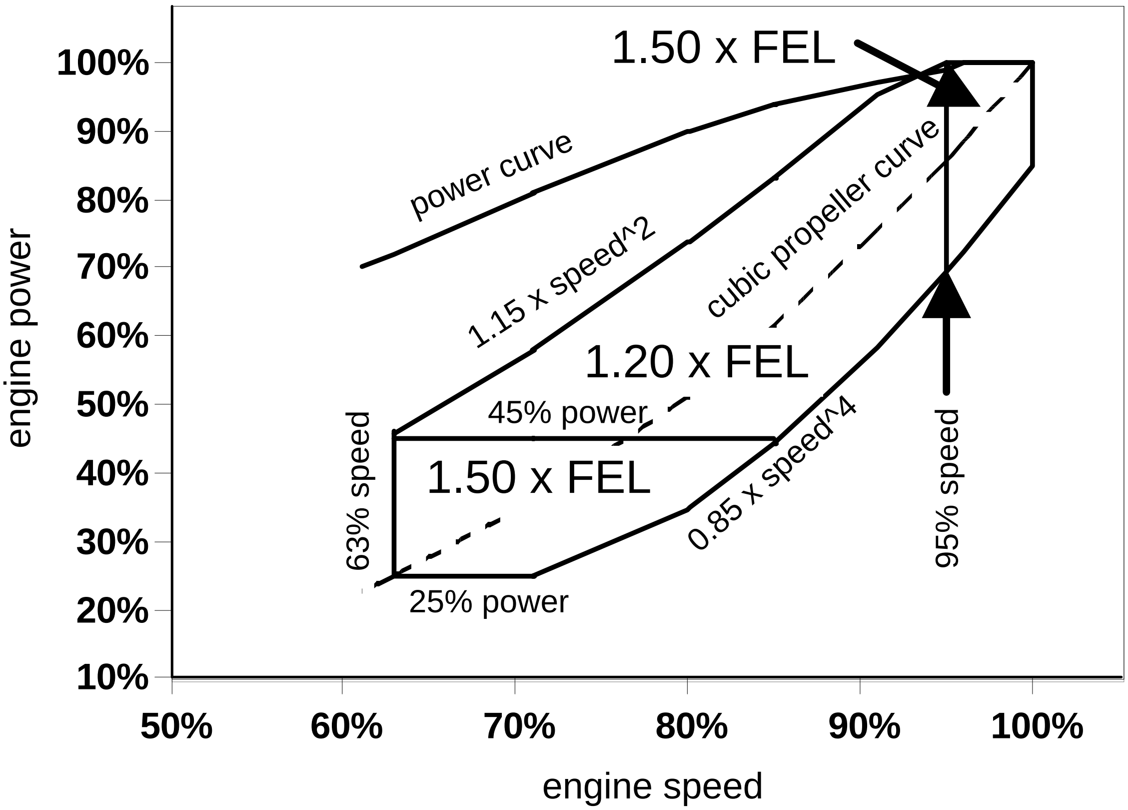
The shape of the NTE zones are based on our understanding of how recreational marine engines are used. Operation at low power is omitted from the NTE zone even though marine engines operate here in use. This omission is because, by definition, brake-specific emissions become very large at low power due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

We believe that the majority of marine engine operation is steady-state. We are therefore including only steady-state operation in the NTE requirements. Also, these are technology-forcing standards, so we expect engines to reduce emissions also under transient operation. If we find that the effectiveness of this program is compromised due to high emissions under transient operation, we will revisit this requirement in the future.

It should be noted that the emissions caps for operation in the NTE zone are 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 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.[9] To prevent imposing an unrealistic cap on a brake-specific basis, we are limiting 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 NTE zone for CI recreational marine engines.

Figure 4.1-1: 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 because the owner may not be using a propeller that is properly matched to the engine and boat. Also, 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.[10]

We are adopting emissions caps for the NTE zone that 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 1.00 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 require that CI recreational marine engines must meet a cap of 1.50 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 1.20 times the certified levels at or above 45% of rated power. However, we are including an additional subzone, when compared with the commercial NTE zone, at speeds greater than 95% of rated. We are adopting a cap of 1.50 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 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 Figures 4.1-2 through 4.1-4 show 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 below the standard. None of these engines are calibrated for emissions control.

Figure 4.1-2: Mode/E5 Average HC+NOx

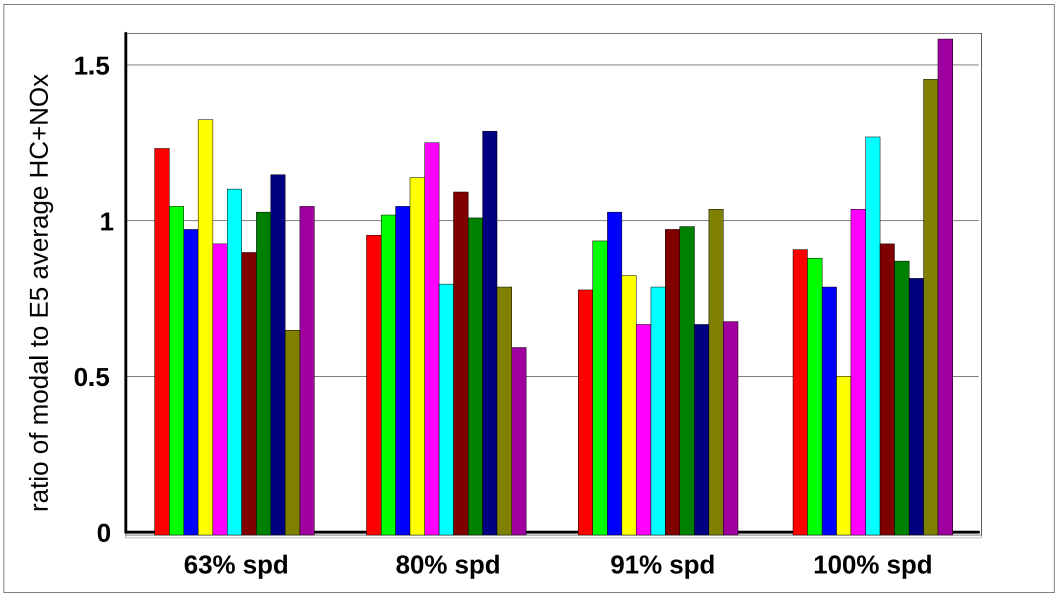


Figure 4.1-3: Mode/E5 Average PM

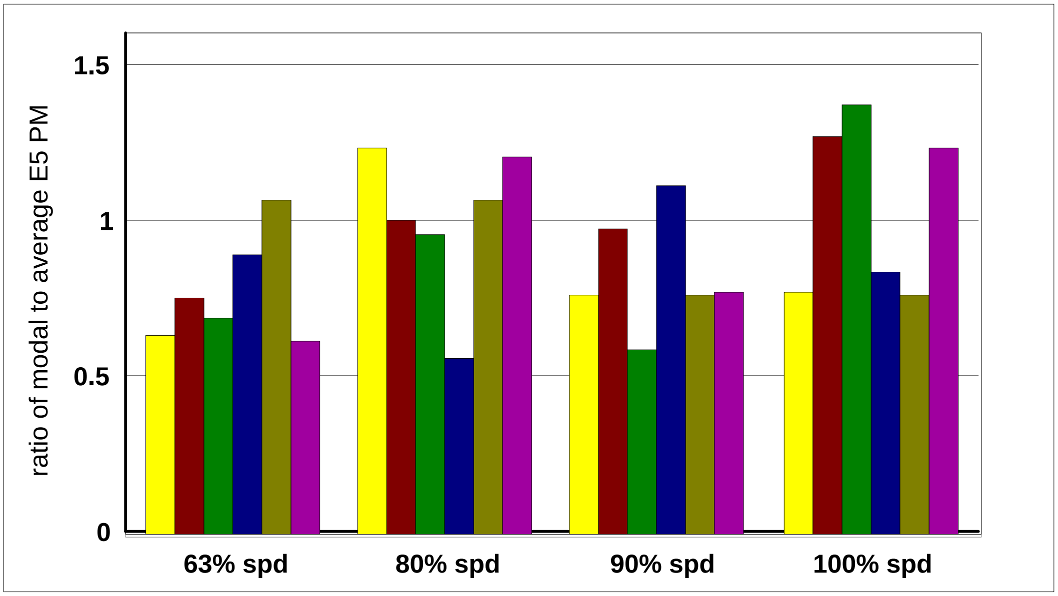
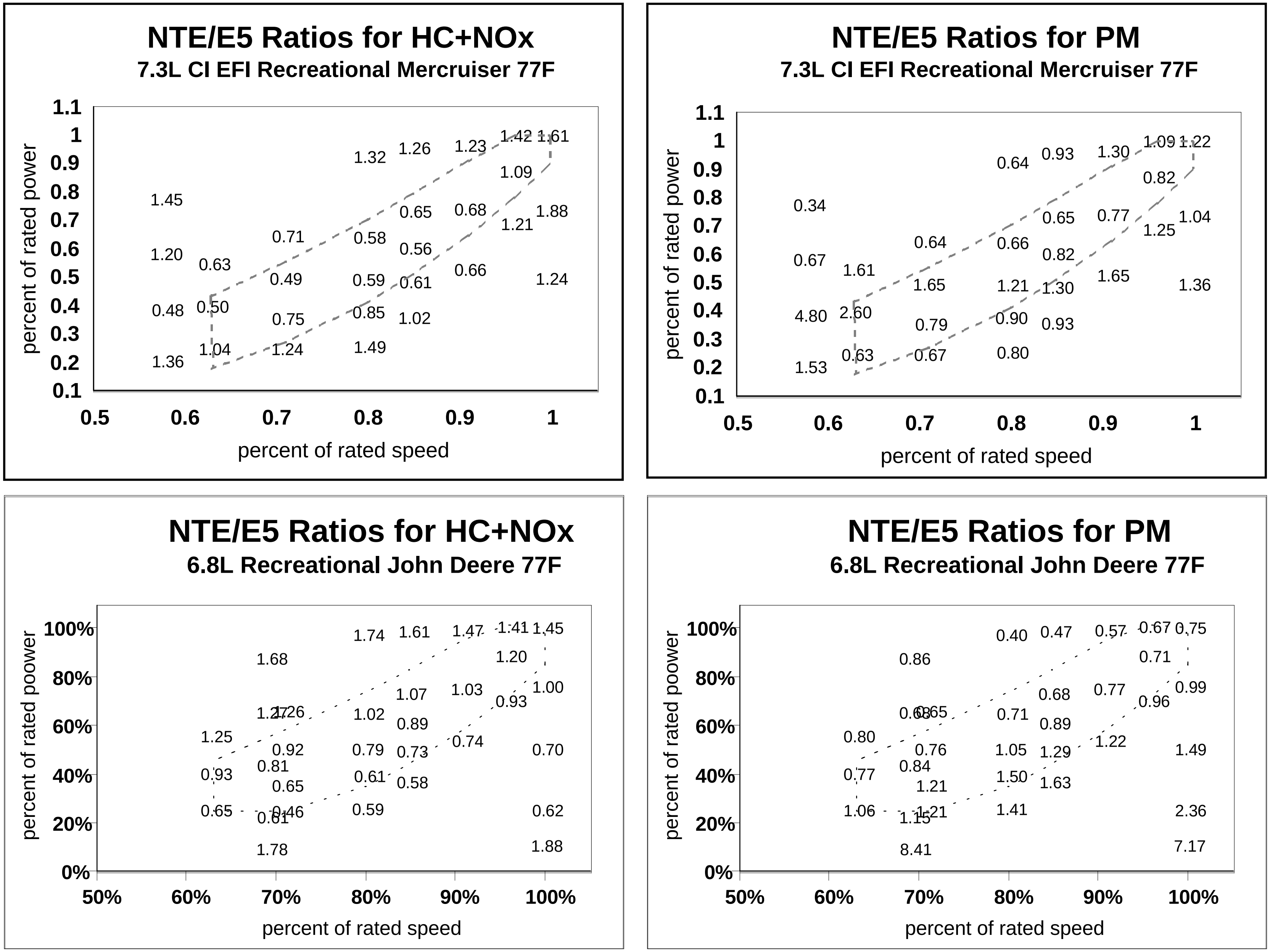


Figure 4.1-4: Ratio of Modal Emissions to E5 Cycle For Two Engines Tested Throughout NTE Zone



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 applying the same ranges for these variables that apply to commercial marine engine. 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 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 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 NAAQS exceedances.[11] For NTE testing in which the air temperature or humidity is outside of the range, emissions may be corrected back to the air temperature or humidity range. These corrections must be consistent with the equations in Title 40 of the Code of Federal Regulations (CFR), 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 essentially 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.[12] According to the CFR correction factor, there is only a ±3% variation in NOx in the NTE humidity range.

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. Our understanding is that many engines operate in and draw air from small engine compartments. This suggests that any naturally aspirated recreational engines used today are already designed to operate with high intake air temperatures. In any case, we do not believe that manufacturers will use naturally aspirated marine engines to meet the new standards.

Ambient water temperature also may affect emissions due to its impact on engine and charge air cooling. We based the 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, 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 for aftercooled engines, the cooling water temperature would be set to 25±5°C.[13] This upper portion of the NTE temperature range is within the range suggested by SAE for engine testing. For lower temperatures, manufacturers can 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, manufacturers may 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 may need to be compromised for startability or safety. Manufacturers are not responsible for the NTE requirements under start-up conditions. In addition, manufacturers may 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 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.[14] 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 may perform in-use confirmatory testing onboard a boat. Our goal would be to perform the same sort of testing as for the laboratory. However, engines tested in a boat are not likely to operate exactly on the assumed propeller curve. For this reason, emissions measured within the NTE zone must meet the subzone caps based on the certified level during onboard testing. To facilitate onboard testing, manufacturers must provide a location with a threaded tap where a sampling probe may be inserted. This location must 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 are applying 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 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 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 corresponding with a test using fuel with 0.4 wt% sulfur. We do not expect the sulfur content to have a large impact on PM emissions because only about 2 percent of the sulfur in the fuel is converted to direct sulfate PM.[15]

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)
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
Cetane	D613-86	40-48
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
Paraffins, 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 other 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 known 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.[16] Information from that memorandum is not repeated here, except to the extent that it supports decisions about the selecting the numerical emission standards.

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

4.2.1 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).

Manufacturers will have 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 as well as our proposal to implement those standards nationwide. 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 2007 Standards

The 2004 standards described above will reduce emissions from Large SI engines, but we believe these levels don't fulfill the requirement 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 2004 standards. We are also adopting new procedures for measuring emissions starting in 2007, which will 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 2007 emission standards are feasible.

The biggest uncertainty in adopting emission standards for Large SI engines was 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, we needed to collect 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.[17] 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 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 emission control 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 for 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[18]	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[19]	0.52 NMHC+NOx	2.23	5,000 hours
Toyota/ECS 2L[20]	1.14	0.78	zero-hour; ISO C1 duty cycle for nonroad diesel engines
GM/Impco 3L[21]	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 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 inappropriately 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 the only known source of information 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, these 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 also cause uncontrolled emission levels to be higher, so the measured emission levels with the catalyst system still show a substantial reduction in emissions. Additional emission data measured during transient operation is shown in Section 4.2.2.7 for selecting the numerical values for the standards.

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.

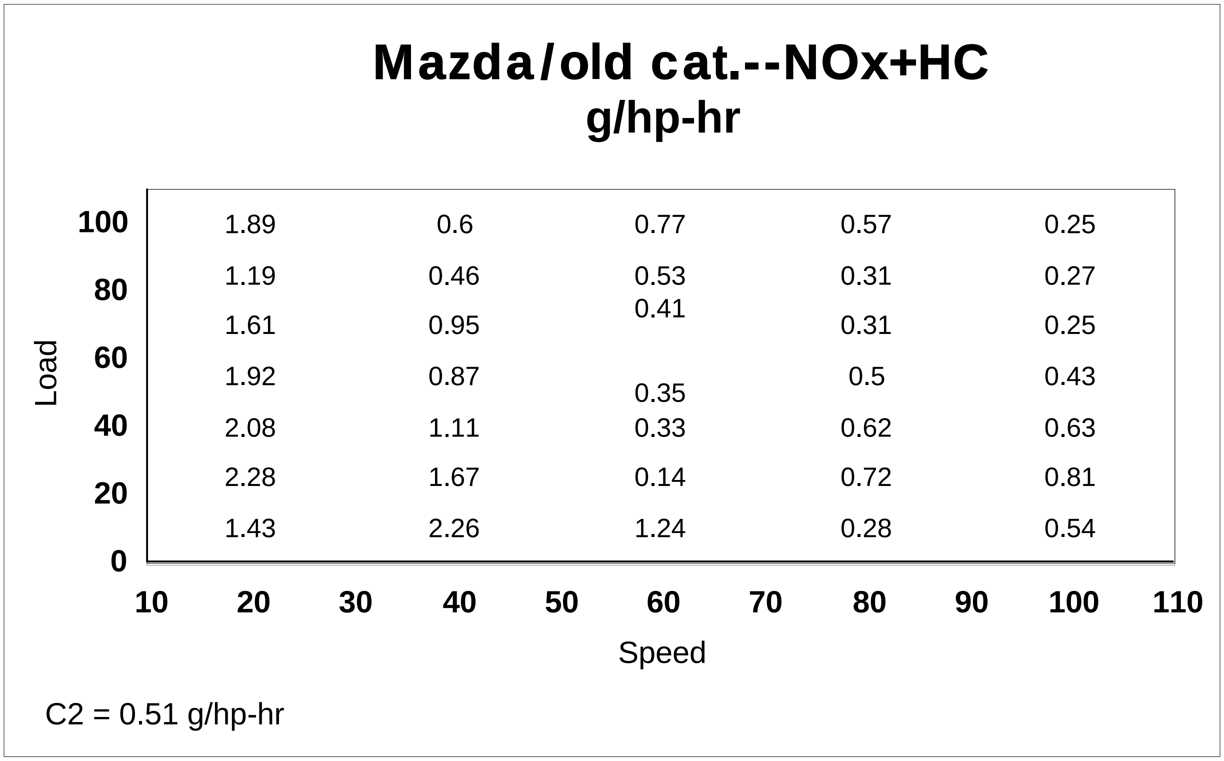
Figure 4.2-1 shows the THC+NOx emissions from the Mazda engine when tested with an aged catalyst. While several points are higher than the 0.51 g/hp-hr level measured on the C2 duty cycle, the highest levels observed from the Mazda engine are around 2.3 g/hp-hr. The highest emissions are generally found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

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 were 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.

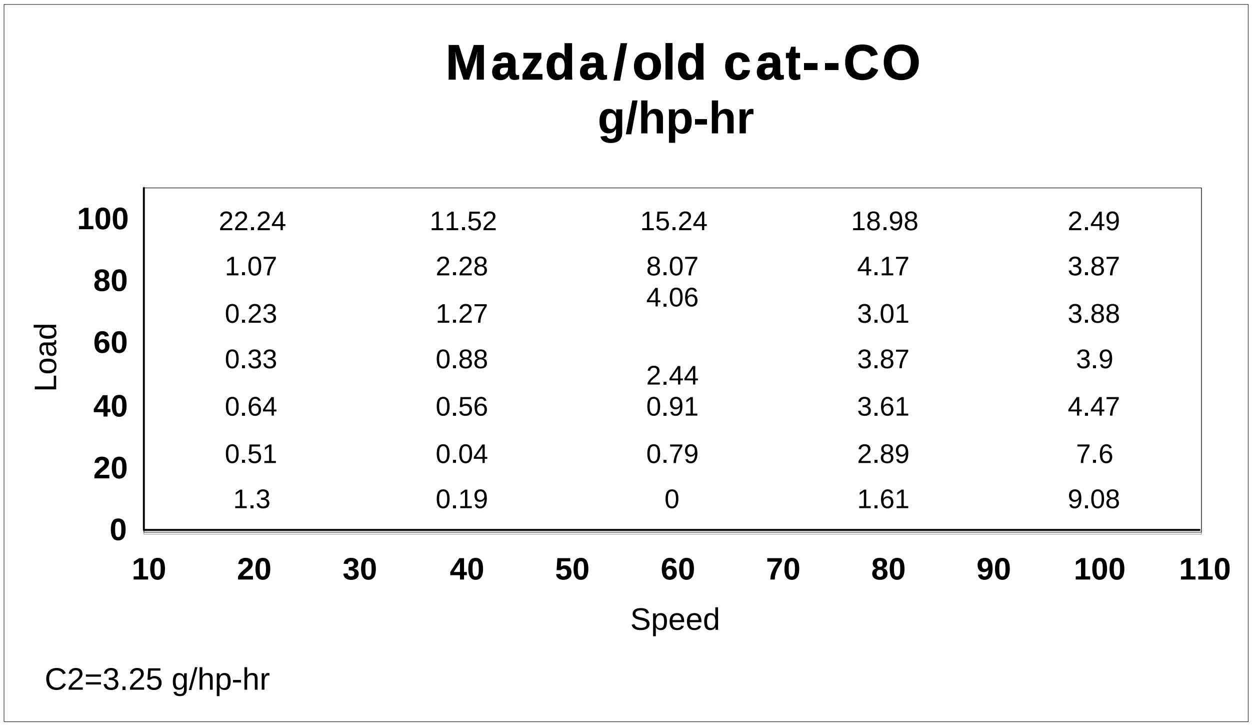
Figure 4.2-3 shows the THC+NOx emissions from the GM engine when tested with the aged catalyst. Emission trends across the engine map are similar to those from the Mazda engine, with somewhat higher low-speed emission levels between 2.3 and 4.4 g/hp-hr at various points. Operation on the new catalyst 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



C2 = 0.51 g/hp-hr

Figure 4.2-2



C2=3.25 g/hp-hr

Figure 4.2-3

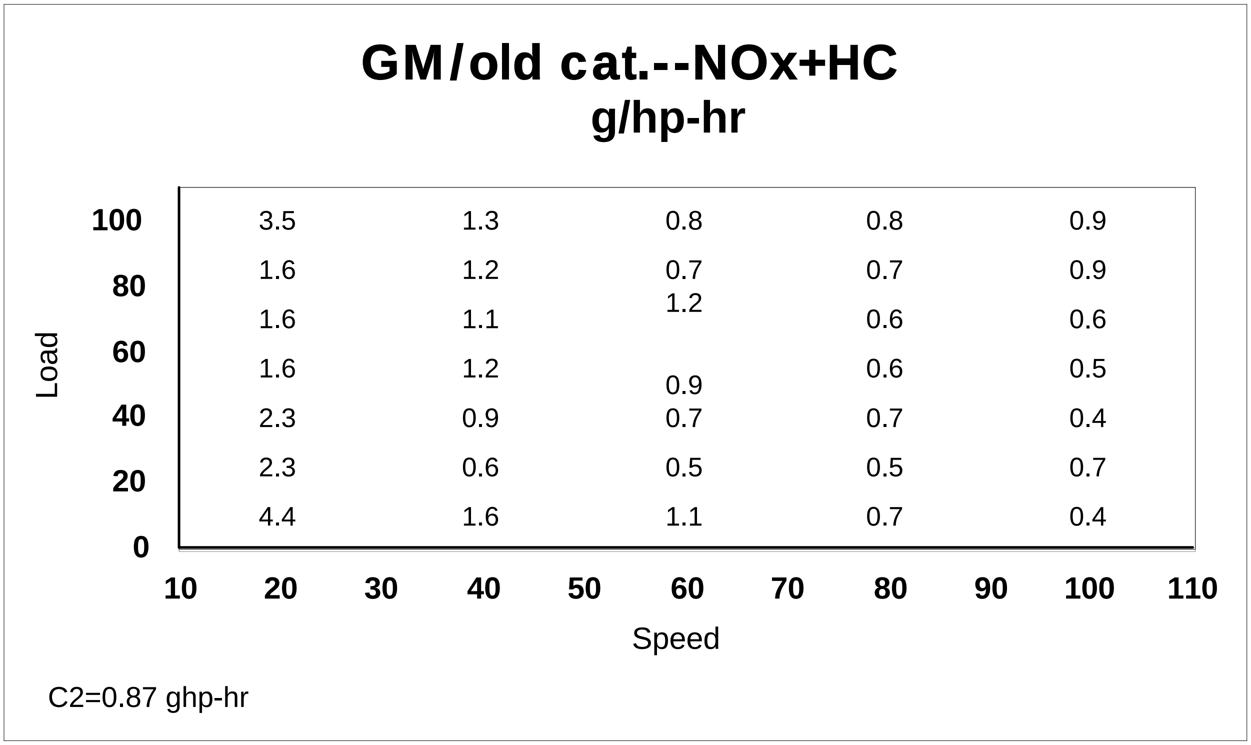


Figure 4.2-4

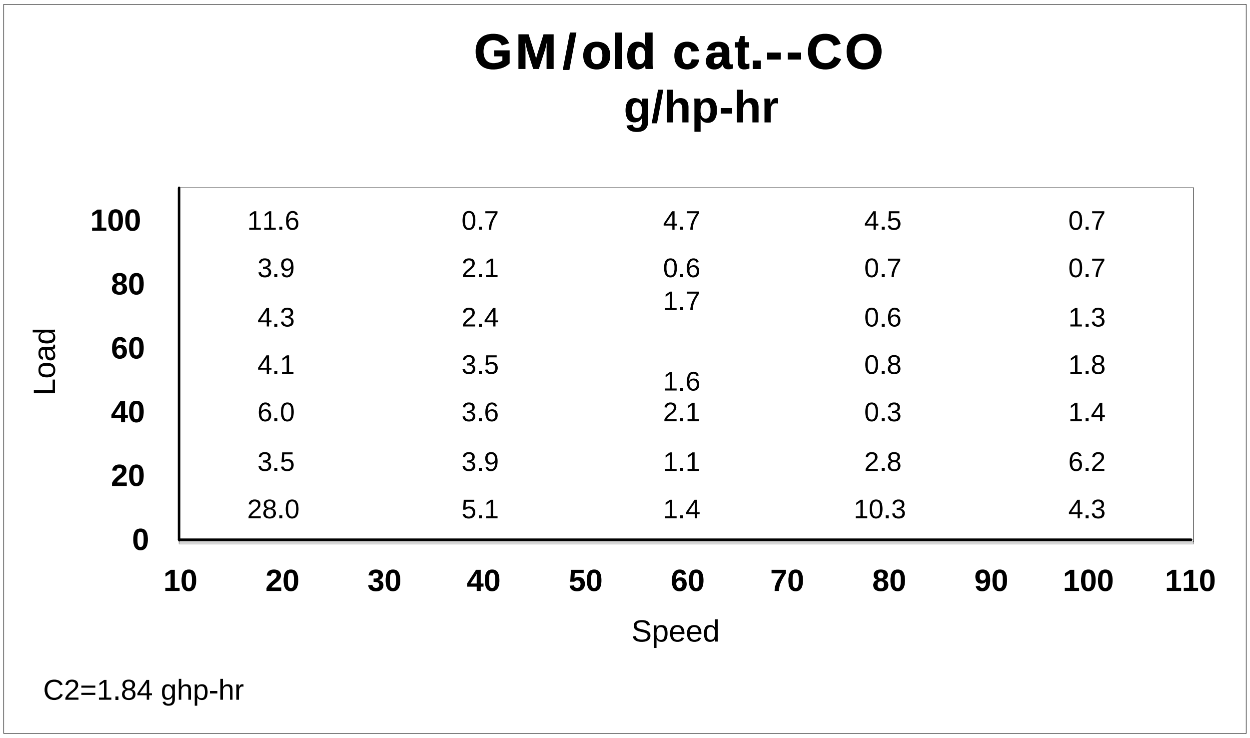
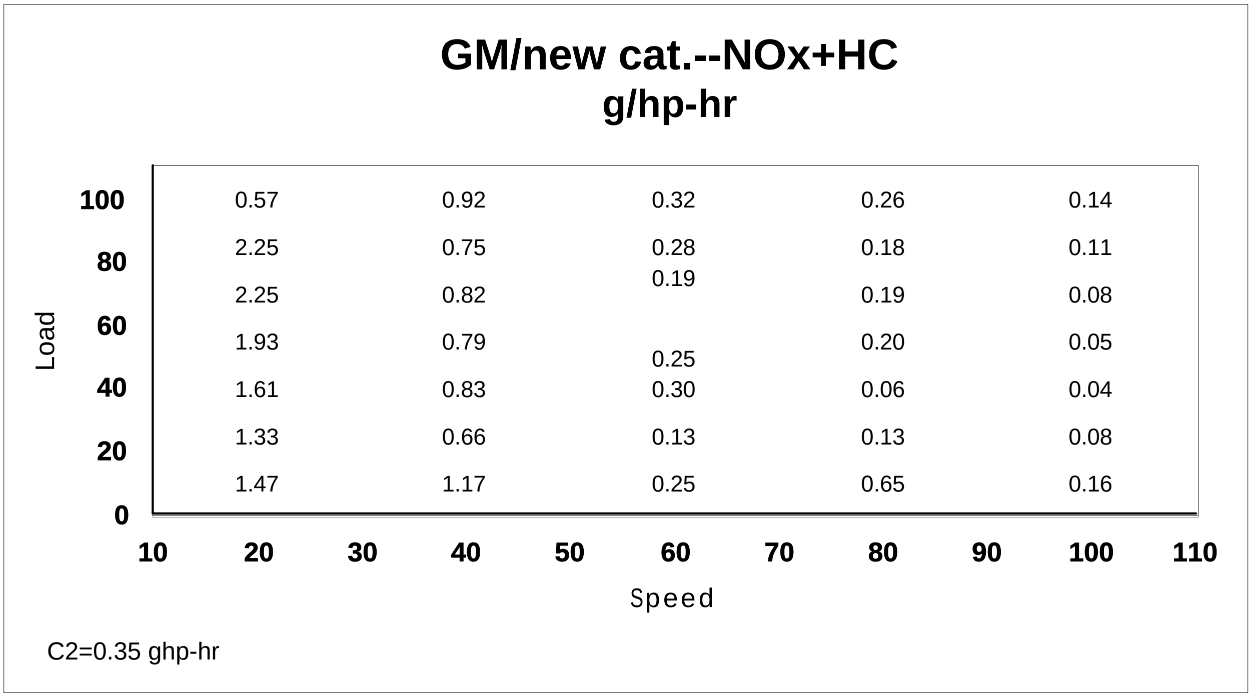
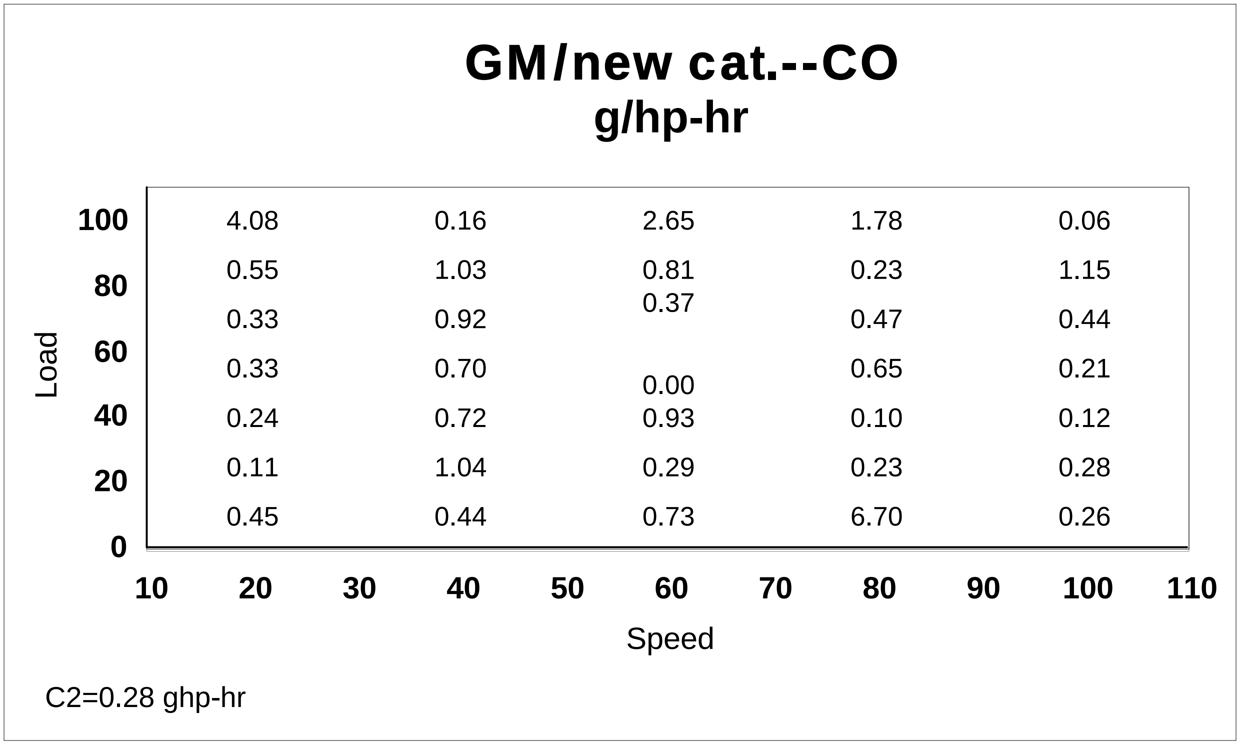


Figure 4.2-5



C2=0.35 ghp-hr

Figure 4.2-6



C2=0.28 ghp-hr

Field testing will typically also include transient emission measurement. Field-testing measurement may include any segment of normal operation with a two-minute minimum sampling period. This does 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 how emissions 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 broadening the range of acceptable ambient conditions for field-testing measurements. Field-testing emission measurements must occur with ambient temperatures between 13° and 35° C (55° and 95° F), and with ambient pressures between 600 and 775 millimeters of mercury (which should cover almost all normal pressures from sea level to 7,000 feet above sea level). Tests will 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 after correction.. In the driest conditions, measured NOx emission levels were up to 10 percent higher than reported. The 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 will have a significant 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 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.[22] 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 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 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 required diagnostic systems 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 any high-temperature or low-temperature effects. In addition, some industry participants have made the general observation that some engine models are more susceptible to fuel deposits than others, suggesting that there may be other engine-design parameters that may help prevent these problems.

Maintaining the integrity of the exhaust system 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 correct 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.

4.2.2.7 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. In particular, we are not basing the 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 about 90 percent 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 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

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 in enclosed areas.

Commenters representing states and environmental groups stressed the need to control HC+NOx emissions to address concerns for meeting ambient air quality standards for ozone. We are accordingly setting an HC+NOx emission standard of 2.0 g/hp-hr (2.7 g/kW-hr), which is somewhat more stringent than the proposed standard. We are adopting a slightly higher CO emission standard than proposed, which reflects the tradeoff between NOx and CO emissions. Further, we are adopting provisions that will encourage manufacturers to reduce HC+NOx even further by allowing higher CO levels where a manufacturer certifies to lower HC+NOx levels. Under this approach, customers desiring to protect workers or others in close proximity to the engines can choose engine models that offer the maximum control of CO emissions. Conversely, if individual exposure to CO emissions is less of a concern, manufacturers have a strong incentive to maximize control of HC+NOx emissions.

Table 4.2-5 shows the range of measured emission values from the engines tested with optimized emission controls. In general, the engines with higher CO values and lower HC+NOx values were calibrated with slightly richer air-fuel ratios, with all other engine parameters unchanged. 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.

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 shows an attempt 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. Table 4.2-6 and Figure 4.2-8 show the curve relating CO and HC+NOx emission levels using the mathematical relationship. This involves starting with a set of HC+NOx emission levels, then calculating the corresponding CO emission levels.[2] Finally, both CO and HC+NOx emission levels are increased by 10 percent to account for a compliance margin around the measured data points. These standards apply to all steady-state and transient duty-cycle testing for certification, production-line, and in-use testing.

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[2] While somewhat roundabout mathematically, solving for CO values from the logarithmic equation is most easily done by converting the curve-fit to an equation based on the natural log function. Using logarithm relationships yields the equivalent relationship (in metric units): $(HC+NOx) \times CO^{0.784} = 8.57$ or $CO = (8.57 \div (HC+NOx))^{1.276}$.

Figure 4.2-7

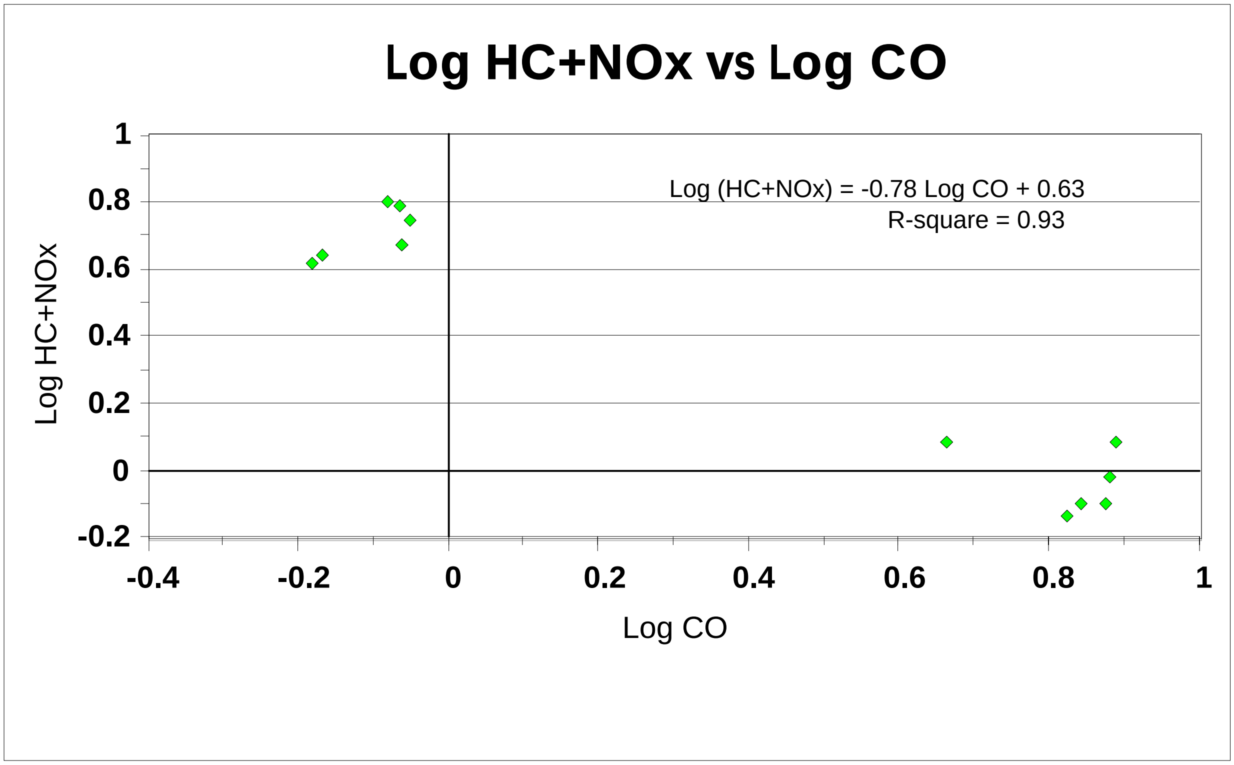
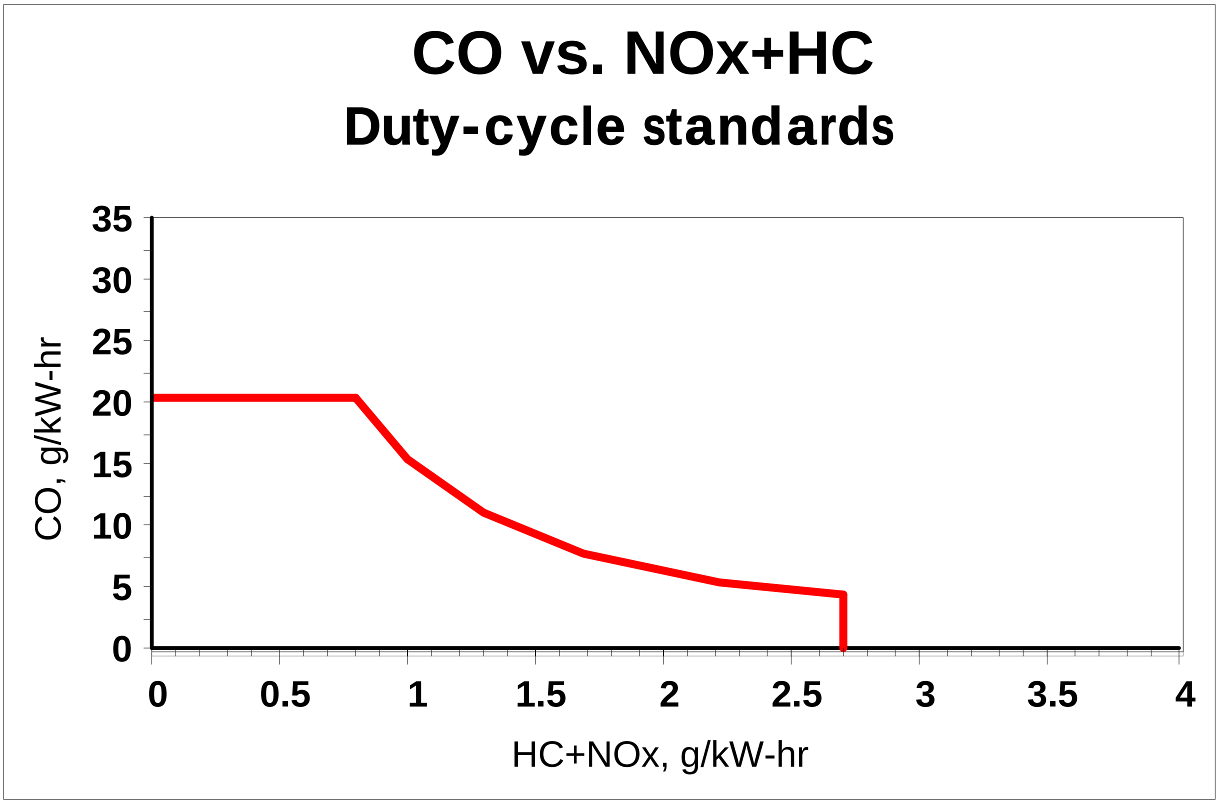


Table 4.2-6
Sample Standards Using the Optional Duty-cycle Standards(g/kW-hr)

HC+NOx	CO
2.70	4.4
2.20	5.6
1.70	7.9
1.30	11.1
1.00	15.5
0.80	20.6

Figure 4.2-8



We generally set standards by focusing on attaining ambient air quality in broad outdoor areas. The HC+NOx standard of 2.7 g/kW-hr is consistent with this focus and achieves significant reductions in ozone precursor emissions. Moreover, any of the emission levels shown in Table 4.2-6 provide large reductions in CO, NO, and NO_2 to address any concerns for individual exposures.

4.2.2.7.3 Engine protection

The table of standards above does not take into account the fact that some engines are unable to maintain sustained stoichiometric operation at high engine loads. Engines running rich at high load typically continue to have low HC+NOx emissions, but CO emissions increase substantially. However, operation over the transient duty cycle involves very little sustained high-load operation. Table 4.2-7 shows the total time during the 20-minute cycle with engine loads exceeding various thresholds. This alone shows that the standard for testing over the transient duty cycle needs little or no adjustment to account for rich operation under high-load conditions. Delaying rich operation would further ensure that emission-controls continue to function properly while still protecting against overheating. As a result, we don't believe that emission standards for the transient emission test should be adjusted to account for engine-protection strategies.

Table 4.2-7
Evaluation of High-Load Operation Over the Transient Duty Cycle

Torque threshold (percent of maximum at a given speed)	Total time over torque threshold (seconds)	Percent of 20-minute cycle	Average number of seconds during each minute
90%	16	1.3	0.8
85%	23	1.9	1.2
80%	41	3.4	2.0
75%	67	5.6	3.4

The steady-state duty cycles, however, have a fixed weighting to account for emission levels at high load operation. Also, delaying enrichment does not help with steady-state emissions, because emissions are measured only after engine operation and emission levels have stabilized. We are therefore setting a maximum CO level of 31 g/kW-hr during steady-state testing for engines needing protection strategies. This corresponds to the highest CO emission level we are allowing under field-testing standards, as noted in Table 1 and described further below. This less stringent standard would apply to all steady-state testing with the C2 or D2 duty cycles for certification, production-line, or in-use testing. The emission standards described in Table 1 would still apply to these engines when tested over the transient duty-cycle. We are also applying the field-testing standards equally to different engines, regardless of whether or not they are certifying to a less stringent CO emission standard for steady-state testing. This reflects our expectation that engines undergoing normal operation in the field will continue to meet emission standards.

Ford submitted test data with their gasoline engine showing that their emission levels comply with this less stringent CO standard for steady-state testing. For example, with a measured emission level of 23.9 g/kW-hr, they would have roughly a 20-percent compliance margin relative to a standard of 31 g/kW-hr. The proposed curve of candidate emission standards incorporated a 10-percent compliance margin, even though the measured emissions were from aged engines not designed to meet emission standards. Our emission modeling typically incorporates an assumed 20-percent compliance margin for spark-ignition engine emissions.

In addition, as described in the preamble to the final rule, we are adopting a combination of provisions to ensure that manufacturers will take steps to allow enrichment only under exceptional circumstances. This is necessary to ensure that engines in nonroad equipment don’t operate substantially under engine-protection regimes leading to compromised control of emissions.

4.2.2.7.4 Field-testing emission standards

Manufacturers may 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 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 field-testing provisions. A modest amount of additional development will be necessary to address isolated high-emission points uncovered by the testing. We believe that manufacturers will be able to reduce emissions as needed to meet the 2007 emission standards by spending time improving the precision of their engine calibrations, perhaps upgrading to more sophisticated control software to achieve this. 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 adequately covers 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 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 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.

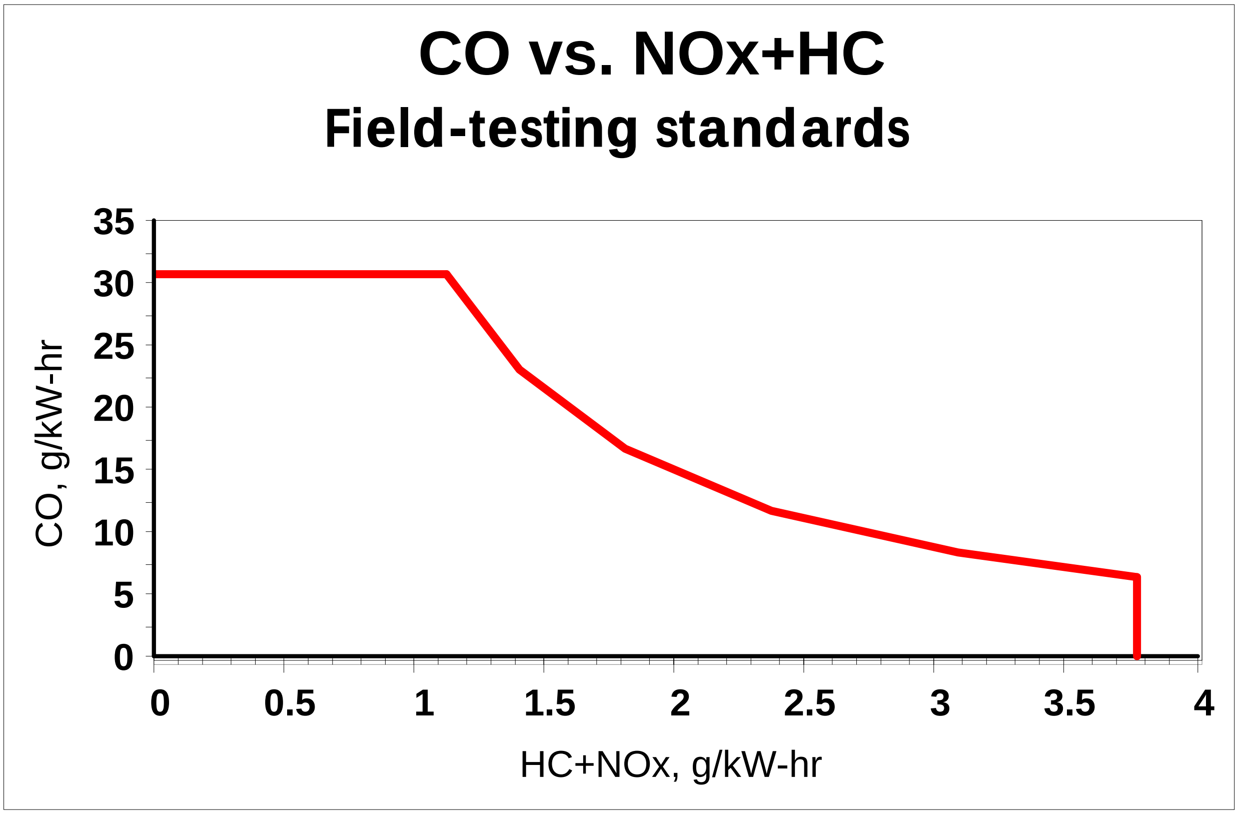
Taking all these factors into account, we believe it is appropriate to allow for a 40-percent increase in HC+NOx emissions relative to the SwRI measured values to account for the factors listed above. CO emissions are generally somewhat more sensitive to varying engine operation, so a 50-percent adjustment is appropriate for CO. The approach for field-testing standard follows the format described for duty-cycle testing. This results in an HC+NOx standard of 3.8 g/kW-hr (2.8 g/hp-hr), with scaled values for the CO standard, as shown in Table 4.2-8 and Figure 4.2-9.

These same numerical field-testing standards apply to natural gas engines. Much like for certification, we are excluding methane measurements from natural gas engines. Since there are currently no portable devices to measure methane (and therefore nonmethane hydrocarbons), the 3.8 g/kW-hr field-testing standard and the values in Table 4.2-8 apply only to NOx emissions for natural gas engines.

Table 4.2-8
Sample Standards Using the
Optional Field-testing Standards(g/kW-hr)

HC+NOx	CO
3.80	6.5
3.10	8.5
2.40	11.7
1.80	16.8
1.40	23.1
1.10	31.0

Figure 4.2-9



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-gauge 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, equipment manufacturers already use or could easily use blow-molded tanks that are also able to withstand substantial pressure buildup. If an exceptional application relies on a fuel tank that must keep internal pressures near ambient levels, a volume-compensating bag would allow for adequate suppression of fuel vapors with minimal pressure buildup.[3]

Testing with pressurized fuel tanks shows emission data related to sealing fuel tanks. The tests included several pressures ranging from 0.5 to 2.25 psi. The 2.25 psi valve was an off-the-shelf automotive fuel cap with a nominal 2 psi pressure relief valve and 0.5 psi vacuum relief valve. For the other pressure settings, we used another automotive cap modified to allow

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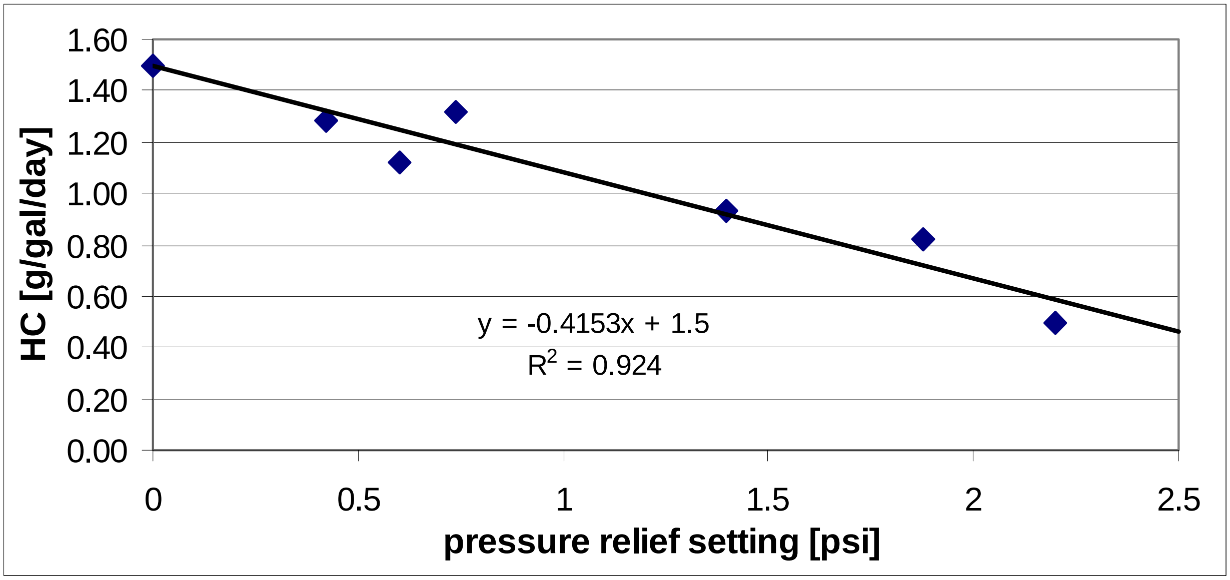
[3] "New Evaporative Control System for Gasoline Tanks," EPA Memorandum from Charles Moulis to Glenn Passavant, March 1, 2001, Docket A-2000-01, document II-B-16.

adjustments to the spring tension in the pressure relief valve. We performed these tests on an aluminum fuel tank to remove the variable of permeation. As shown in Figure 4.2-10, there was a fairly linear relationship between the pressure setting of the valve and the emissions measured over the proposed test procedure, which we would expect based on the theoretical relationships. At 3.5 psi, this relationship extropolates to a value of 0.2 g/gallon/day.

Figure 4.2-10: Effect of Pressure Cap on Diurnal Emissions



4.2.2.7.6 Conclusion

Manufacturers have been developing emission-control technologies to meet the 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.

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 control emission levels more broadly across the range of engine speeds and loads by improving control of air-fuel ratios at different operating modes. These improvements will reduce both steady-state and transient emission levels. The 2007 emission standards are based directly on the data presented above. The test results therefore show that these Large SI engines are capable of meeting the 2007 emission standards for both steady-state and transient duty cycles. Similarly, the data presented above show how off-cycle emissions vary for engines that have been designed for effective control of air-fuel ratios across the range of normal operation. Here too, the test engines generally had emission levels consistent with the 2007 field-testing standards, with certain limited exceptions as noted above.

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 earlier in this section. Manufacturers may save development time by upgrading to the modestly more expensive controller with independent air-fuel control capability in different speed-load zones. This would achieve the same result, but would potentially reduce the cost of meeting the standards by reducing engineering time. 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.

The emission standards for Large SI engines are significantly more stringent than those we are adopting for recreational vehicles and those we have already adopted for lawn and 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 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.

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 will 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 Snowmobile Engines

The following paragraphs summarize the data and rationale supporting the 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. 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.[23] 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, it is also feasible to convert from using 2-stroke engines to 4-stroke engines. 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 improve the combustion of the intake charge.

Various snowmobile manufacturers have told us that they believe these modifications have the potential to reduce emissions by up to 40 percent, depending on how well the unmodified engine is optimized for these changes[4].

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 promote more complete combustion of the fuel/air mixture. Additionally, production tolerances can be improved for more consistent fuel metering. Both of these allow for more accurate control of the air/fuel ratio. In conjunction with these improvements in carburetion, the air/fuel ratio can be leaned out somewhat. Snowmobile engines are currently calibrated with rich air/fuel ratios for durability reasons. Manufacturers have stated that based on their experience, leaner calibrations can reduce CO and HC emissions by up to 20 percent, depending on how lean the unmodified engine is prior to recalibration[5]. Small improvements in fuel economy can also be expected with recalibration.

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

The same calibration changes to the air/fuel ratio just discussed for carbureted engines can also be employed, possibly with more accuracy, with 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. Our testing of pulse air on four-stroke ATV engines indicated that reductions of 30-70% for HC and 30-80% for CO are possible. We believe similar reductions could be expected for engines used in snowmobile applications. We expect some modest reductions in two-stroke applications as well.

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[4] See “Memo to Docket on Technical Discussions with Recreational Vehicle Manufacturers,” from Linc Wehrly. Docket A-2000-01, IV-B-43.

[5] See “Memo to Docket on Technical Discussions with Recreational Vehicle Manufacturers,” from Linc Wehrly. Docket A-2000-01, IV-B-43.

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 (PWC) engines. Bombardier has developed a semi-direct injection engine for snowmobiles that will be available in several different models for the 2003 model year. 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 70 percent. Certification results for 2002 model year 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	67%	1.071	95.6	46.0	38.4	103.1	Direct injection, electronic control
		1.071	88.3	140.0	136.76	241.8	Carburetor
Polaris	72%	0.78	Not Reported	47.1	33.2	135.2	Direct injection
		0.70	Not Reported	165	158.8	217.0	Carburetor
Bombardier	73%	0.9514	88.9	36.8	24.5	100.1	Direct injection, electronic control
		0.9513	89.5	137.8	136.7	330.6	Carburetor
Polaris	65%	1.16	85.26	46.3	37.46	100.4	Direct injection
		1.16	93.25	134.0	130.8	359.3	Carburetor

Substantial improvements in fuel economy could also be expected with these technologies. We believe these technologies hold promise for application to snowmobiles. All four of the major snowmobile manufacturers have indicated that they consider direct fuel injection as a viable technology for controlling emissions and are currently either analyzing various direct injection systems or are in the process of developing their own system. 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.

Manufacturers have also stated that the direct injection systems used in many of their PWC cannot simply be placed into their snowmobiles because of inherent differences in snowmobile and PWC engines. Primarily the fact that PWC engines operate at considerably lower engine speeds than snowmobile engines. PWC engines typically operate at maximum engine speeds of 6,000 rpm, compared to engine speeds of almost double that for snowmobiles. This poses a problem because some of the current direct injection designs can't properly operate at such high engine speeds. While these are all legitimate concerns, we believe that this technology can be adapted without significant problems. Bombardier's use of direct fuel injection in several snowmobile models in the 2003 model year demonstrates that these issues have been resolved enough for Bombardier to be comfortable selling snowmobiles with such engines. However, direct fuel injection is a complex technology and there are several different types of approaches to designing these systems and not all manufacturers have the same access to the various systems. Therefore, it appears important to provide manufacturers with sufficient lead time to resolve all of the potential issues with direct injection so that it can be widely available for all snowmobile models, instead of a few niches models for a select manufacturer or two. That is why we believe it is appropriate to give manufacturers until 2012. This will give manufacturers sufficient time to incorporate these development efforts into their overall research plan and apply these technologies to a substantial percentage of their 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. Four-stroke engines have been used in numerous recreational vehicle applications for years. Four-stroke engines have also been used in limited numbers over the years in snowmobiles. In 1999, Arctic Cat released a four-stroke touring sled. Polaris followed two years later with their four-stroke touring sled in 2001. Table 4.3-2 provides emission results from a 2001 Arctic Cat four-stroke touring sled and a 2001 Polaris Frontier (four-stroke), both owned and tested by the National Park Service (NPS) at Southwest Research Institute. Table 4.3-3 presents certification data from four 2002 PWC's equipped with four-stroke engines. The engines in these PWC are higher output engines than the Arctic Cat and Polaris snowmobile four-stroke engines and have emission results very similar to that which a high-output four-stroke snowmobile engine could expect to emit.

Table 4.3-2
Four-Stroke Snowmobile Emissions

Manufacturer	Model	Engine Displacement	HC (g/kW-hr)	CO (g/kW-hr)	NOx (g/kW-hr)
Arctic Cat	4-Stroke Touring	660 cc	6.2	79.9	15.0
Polaris	Frontier	784 cc	3.2	79.1	7.0

Table 4.3-3
Four-Stroke PWC Certification Emission results

Manufacturer	Model	Engine Displacement	HC (g/kW-hr)	CO (g/kW-hr)	NOx (g/kW-hr)
Honda	Aqua Trax F-12	1,244 cc	11.2	266.0	3.8
Honda	Aqua Trax F-12X	1,244 cc	10.7	235.3	4.6
Bombardier	GTX 4-TEC	1,504 cc	9.6	161.7	5.0
Yamaha	FX140	998 cc	16.6	255.1	5.9

Much has changed in the time since we published our proposed standards. In October 2001, when we published our proposed standards for snowmobiles, there was only one manufacturer that had introduced a four-stroke snowmobile (the Polaris Frontier was released soon after). Today, all four of the major snowmobile manufacturers have developed a four-stroke engine for snowmobiles. In fact, the 2003 model year will see four-stroke engines in several models from all four manufacturers. The models will range from touring sleds to sport, mountain, and high-performance models. 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). Four-stroke engines can also have reductions in CO emissions, depending on the power output of the engines and the engine calibration. A smaller four-stroke engine calibrated to operate at or near stoichiometry could reduce CO emissions significantly. This is demonstrated above in Table 4.3-2, since both of these snowmobiles use four-stroke engines equipped with closed-loop control EFI systems which try to maintain the air and fuel mixture at or near stoichiometry. A larger four-stroke engine calibrated for maximum power could generate CO emission levels closer to a comparably powered two-stroke engine. Table 4.3-3 above, demonstrates this. Although the engines in this table are from PWCs, they are high-output four-stroke engines producing horsepower in excess of 100 hp, that are very similar to what could be expected to be used in a high-performance snowmobile. The CO emissions from the four PWC engines are considerably higher than the CO levels from the two lower powered four-stroke snowmobiles. Four-stroke engines have a lower power density compared to two-stroke engines. Two-stroke engines have a power stroke every other stroke compared to a power stroke every fourth stroke for a four-stroke engine. Thus, a comparably powered four-stroke engine requires almost a third more engine displacement, to equal the power of a two-stroke engine. The impact this has on snowmobile applications is that a four-stroke engine is already heavier than a two-stroke engine because of the valve-train system. In order to have comparable power output with a two-stroke, a four-stroke engine needs to have a larger displacement. This is achieved through an increase in the cylinder bore and/or stroke or by adding more cylinders, which all have the potential effect of adding even more weight. Thus, for a four-stroke to be competitive with a two-stroke engine, manufacturers need to find a way to reduce weight in the engine and elsewhere in the snowmobile. This could entail the use of lighter materials in the engine and chassis or reducing the size of the fuel tank to take advantage of the superior fuel efficiency of the four-stroke engine while maintaining the same cruising time/range.

Another way to increase the output from a four-stroke engine is to use a turbocharger or supercharger. Both of these devices act as air compressors, providing increased air density in the engines's combustion chambers, which allows more efficient burning of air and fuel and results in higher horsepower output. A turbocharger uses exhaust gases to compress air, while a supercharger is mechanically driven using a belt between the supercharger and typically the camshaft. Honda is currently selling a turbocharged version of their four-stroke personal watercraft. A turbocharger or supercharger could provide an increase in power without having to increase the engine displacement. Regardless of the strategy used, it is apparent that four-stroke engines will have a larger role in snowmobile applications than originally thought.

However, it is important to provide sufficient lead time for the development and implementation of some four-stroke engines in snowmobiles, similar to the concern with direct fuel injection. For example, in the case of the Yamaha four-stroke snowmobile, a considerable amount of effort and resources went into designing a new snowmobile from the ground up specifically to accommodate the size, weight and power characteristics of a four-stroke engine. A completely new chassis was designed which allowed the somewhat heavier engine to be placed lower and further back than is typical for two-stroke snowmobiles. This was necessary to maintain the kind of handling characteristics required of a high performance snowmobile. While a stock four-stroke engine can be placed into an existing snowmobile model and made to work acceptably, as can be seen in the Polaris and Arctic Cat four-stroke offerings, such designs are only practical for lower powered touring snowmobiles. Since the vast majority of the snowmobile market is in higher performance sleds, we believe that the conversion of all snowmobiles to four-strokes would require that many current snowmobile chassis be replaced with new models designed from the ground up. This could be a substantial undertaking for the snowmobile industry given the number of models it offers and niche markets it currently serves. That is why we believe the delay of our proposed Phase 2 standards by two years will give manufacturers time to incorporate these development efforts into their overall research plan as they apply these technologies to their snowmobiles.

4.3.3 Test and Measurement Issues

4.3.3.1 Test procedure

We are generally adopting the snowmobile test procedure developed by Southwest Research Institute in cooperation with the International Snowmobile Manufacturers Association for all snowmobile emissions testing.[24] This test procedure consists of two main parts; the duty cycle that the snowmobile engine operates over during testing and other testing protocols involving the measurement of emissions (sampling and analytical equipment, specification of test fuel, atmospheric conditions for testing, etc.). While the snowmobile duty cycle 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 4.3-4. The snowmobiles used to generate this data were not derived from members of the general public found openly operating in these riding styles, but were snowmobiles operated by contractor personnel in staged set-ups of these riding styles. This duty cycle was used to generate the baseline emissions levels for snowmobiles, and we believe it is the most appropriate cycle for demonstrating reductions in snowmobile emissions at this time.

Table 4.3-4
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

The other testing protocols are largely derived from our regulations for marine outboard and personal watercraft engines.[25] 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.

Manufacturers shared confidential emission data with us that indicated that there was no difference between testing snowmobiles with cold inlet air and testing at higher temperatures with carburetor jetting adjusted for the warmer temperature. We also did some limited testing which substantiates the manufacturer’s claim. Some manufacturers argued that even though there was no difference between the test methods, we should still require testing with cold inlet air because it would be more representative. Other manufacturers felt that the increased cost of cold inlet air testing made this approach undesirable. We decided that since there was ample evidence that two approaches would produce similar results with the technologies we expect to be used and that it did not make sense to require manufacturers to incur the cost of cold inlet air testing if it wouldn’t provide any additional benefit. Therefore, we are allowing manufacturers to test at warmer (i.e., typical test cell temperature 68°F-86°F) with carburetor jetting set to the appropriate temperature.

4.3.3.2 HC is a Good Proxy for Fine PM Emissions

We believe the best way to regulate fine PM emissions from current snowmobile engines is to set standards based on HC emissions. Unlike other recreational vehicles, the current fleet of snowmobiles consists almost exclusively of two-stroke engines. Two-stroke engines inject lubricating oil into the air intake system where it is combusted with the air and fuel mixture in the combustion chamber. This is done to provide lubrication to the piston and crankshaft, since the crankcase is used as part of the fuel delivery system and cannot be used as a sump for oil storage as in four-stroke engines. As a result, in addition to products of incomplete combustion, two-stroke engines also emit a mixture of uncombusted fuel and lubricant oil. HC-related emissions from snowmobiles increase PM concentrations in two ways. Snowmobile engines emit HCs directly as particles (e.g., droplets of lubricant oil). Snowmobile engines also emit HC gases, as well as raw unburned HCs from the fuel which either condense in cold temperatures to particles or react chemically to transform into particles as they move in the atmosphere. As discussed above, fine particles can cause a variety of adverse health and welfare effects, including visibility impairment.

We believe HC measurements will serve as a reasonable surrogate for fine PM measurement for snowmobiles for several reasons. First, emissions of PM and HC from these engines are related. Test data show that over 70 percent of the average volatile organic fraction of PM from a typical 2-stroke snowmobile engine is organic hydrocarbons, largely from lubricating oil components.[6] The HC measurements (which use a 191 Celsius/375.8 degree Fahrenheit heated FID) would capture the volatile component which in ambient temperatures would be particles (as droplets).

Second, many of the technologies that will be employed to reduce HC emissions are expected to reduce PM (e.g., 4-stroke engines, pulse air, and direct fuel injection techniques). The organic emissions are a mixture of fuel and oil, and reductions in the organic emissions will likely yield both HC and PM reductions. For example, the HC emission factor for a typical 2-stroke snowmobile is 111 g/hp-hr. The HC emission factor for a direct fuel injection engine is 21.8, and for a 4-stroke is 7.8 g/hp-hr, representing a 80 percent and 99 percent reduction, respectively. Similarly, the PM emission factor for a typical 2-stroke snowmobile is 2.7 g/hp-hr. The corresponding PM emission factor for a direct fuel injection engine is 0.57, and for a 4-

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[6] Memo to Docket, Mike Samulski. “Hydrocarbon Measurements as an Indicator for Particulate Matter Emissions in Snowmobiles,” September 6, 2002, Docket A-2000-01; Document IV-B.

Carroll, JN, JJ White, IA Khalek, NY Kado. Characterization of Snowmobile Particulate Emissions. Society of Automotive Engineers Technical Paper Series. Particle Size Distribution in the Exhaust of Diesel and Gasoline. SP-1552, 2000-01-2003. June 19-22, 2000.

stroke is 0.15 g/hp-hr, representing a 75 percent and 93 percent reduction, respectively. HC measurements would capture the reduction from both the gas and particle (at ambient temperature) phases.

Thus, manufacturers will generally reduce PM emissions as a result of reducing HC emissions, making separate PM standards less necessary. Moreover, PM standards would only cover the PM directly emitted at the tailpipe. It would not measure the gaseous or semi-volatile organic emissions which would condense or be converted into PM in the atmosphere. By contrast HC measurements would include the gaseous HC which could condense or be converted into PM in the atmosphere. Thus, the HC measurement would be a more comprehensive measurement. HC standards actually will reduce secondary PM emissions that would not necessarily be reduced by PM standards.

Finally, from an implementation point of view, PM is not routinely measured in snowmobiles, and there is no currently established protocol for measuring PM and substantial technical issues to overcome to create a new method. Establishing additional PM test procedures would entail additional costs for manufacturers. HC measurements are more routinely performed on these types of engines, and these measurements serve as a more reliable basis for setting a numeric standard. Thus, we believe that regulation of HC is the best way to reduce PM emissions from current snowmobile engines.

We included a NOx standard for snowmobiles as part of the long-term program. NOx emissions from current snowmobiles are very small, especially compared to HC. This standard will essentially cap NOx emissions from these engines to prevent backsliding in advanced technology engines. We are not promulgating standards that would require substantial reductions in NOx because we believe that non-aftertreatment based standards which force substantial NOx reductions could put upward pressure on HC emissions and would not necessarily lead to reductions in ambient PM. Given the overwhelming level of HC, CO and PM compared to NOx, and the secondary PM expected to result from high HC levels, it would be premature and possibly counterproductive to promulgate NOx standards that require significant NOx reductions from snowmobiles at this time. We have therefore decided to structure our long term HC+NOx standard for 2012 and later model year snowmobiles to require only a cap on NOx emissions from the advanced technology engines which will be the dominant technology in the new snowmobiles certified at that time.

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 will 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. While the manufacturers have expressed some concern about heavier weight and cold-starting for four stroke engines we believe these are not significant concerns. There are already four-stroke models in production today and obviously they are not being introduced into commerce with known safety concerns. A two-stroke snowmobile has a fuel tank of about 12 gallons. A four-stroke could have a fuel tank of 8 gallons and maintain the same driving time/range. This would lead to a weight reaction of 25 pounds to help offset concerns about increased weight of four-stroke snowmobiles. If cold starting of four strokes is an issue, it can be resolved with the assistance of an electronic starter or a dry sump oil system that stores oil in a separate tank rather than in the crankcase, thus eliminating the concern over high viscous oil adding excessive resistance to the starting process.

4.3.5 Conclusions

4.3.5.1 Phase 1 Standards

For the Phase 1 standards which start in the 2006 model year, we are allowing a phase-in schedule that requires 50 percent of a manufacturers snowmobile fleet to meet the standards in the 2006 model year and 100 percent to meet the standards in the 2007 model year. Snowmobile manufacturers will have three main emission control technologies for meeting these standards: modified two-stroke technologies (combination of engine modifications and fuel system improvements), direct fuel injection, and four-stroke engine technology. We expect that the Phase 1 emission standards will be met through a combination or mixture of these three emission control strategies. All three of these strategies have been proven to be feasible and are already available on some sleds today. Four-stroke engines and direct fuel injection technology have already been demonstrated to be capable of achieving emission reductions well in excess of our standards. Significant reductions are also achievable using modified two-stroke technologies.

For the 2006 model year, we expect manufacturers to rely most heavily on modifications to existing two-stroke engines with a small amount (e.g., 10 percent) of direct injection two-stroke engines and four-stroke engines (e.g., another 10 percent). In the context of an averaging program, the use of direct injection technology and four-stroke engines will not only be necessary to meet the standards, but may also allow some manufacturers to leave a small percentage of engines unchanged, most specifically, inexpensive entry-level sleds that manufacturers have argued are very cost sensitive. Such an approach may be necessary given the lead time and the fairly large number of engine models to be modified and certified. Table 4.3-5 provided below presents a potential technology mix scenario for the Phase 1 standards. The average reduction level at the bottom of the table represents average reductions for a manufacturer's entire fleet which already incorporates compliance margin and useful life consideration, since each engine family FEL will have a unique compliance margin. The percent reduction presented in the table is based on HC and CO. Obviously, a manufacturer could change the technology mix based on cost and performance considerations.

Table 4.3-5
Potential Snowmobile Technology Mix for Phase 1 Standards

Technology	Percent Usage	Percent Reduction HC	Percent Reduction CO	Fleet % Reduction HC	Fleet % Reduction CO
Minimal Control Engines*	20%	0%	0%	0%	0%
Carburetor/EFI Recalibration + Engine Modifications	60%	30%	30%	18%	18%
Direct Injection	10%	75%	70%	7.5%	7%
Four-Stroke	10%	90%	50%	9%	5%
Average Reduction				35%	30%

* Some minimal control may be required to account for deterioration and to ensure certification FELs are met in production.

4.3.5.2 Phase 2 Standards

We are also finalizing Phase 2 standards in the 2010 model year that will serve as transitional standards to our more stringent Phase 3 standards. As for the Phase 1 standards, we believe manufactures will rely on a mixture of technologies, with the focus on modified two-stroke technologies, perhaps including pulse air injection, direct fuel injection, and four-stroke engines. We expect that to meet the 2010 standards, manufacturers will employ more of the advanced technologies such as direct injection and four-stroke engines and less of the modified two-stroke technologies. We anticipate manufacturers will have numerous technology mix scenarios that they will consider. Table 4.3-6 provided below presents a potential technology mix scenario for the Phase 2 standards. Obviously, a manufacturer could change the technology mix based on cost and performance considerations. As for the Phase 1 standards, the use of advanced technologies such as direct injection and four-stroke engines, in the context of our averaging program, may allow some manufacturers to have a small percentage of engines with minimal change. As discussed above in sections 4.3.2.4 and 4.3.2.5, we believe the biggest task manufacturers will face in meeting our standards will be the converting of their large current fleet of snowmobiles equipped with unregulated two-stroke engines to snowmobiles equipped with advanced clean technologies, such as direct injection and four-stroke engines.

Table 4.3-6
Potential Snowmobile Technology Mix for 2010 Standards

Technology	Percent Usage	Percent Reduction HC	Percent Reduction CO	Fleet % Reduction HC	Fleet % Reduction CO
Minimal Control Engines*	20%	0%	0%	0%	0%
Carburetor/EFI Recalibration + Engine Modifications + Pulse Air Injection	30%	35%	35%	10.5%	10.5%
Direct Injection	35%	75%	70%	26%	24.5%
Four-Stroke	15%	90%	50%	13.5%	7.5%
Average Reduction				50%	43%

* Some minimal control may be required to account for deterioration and to ensure certification FELs are met in production.

4.3.5.3 Phase 3 Standards

We are finalizing Phase 3 standards in the 2012 model year that we believe will require a significant percentage of snowmobile models to be equipped with advanced technologies. As with our Phase 1 and Phase 2 standards, we believe manufactures will rely on a mixture of technologies, with the focus on direct fuel injection and four-stroke engines. While we expect that to meet the 2012 standards manufacturers will employ considerably more of the advanced technologies such as direct injection and four-stroke engines, they may still use a relatively small amount of the modified two-stroke technologies. To provide manufacturers with additional flexibility, we are allowing the Phase 3 standards to be met by using the following equation:

$$100 = \left(1 - \frac{(HC + NOx)_{STD} - 15}{150}\right) \times 100 + \left(1 - \frac{CO_{STD}}{400}\right) \times 100$$

Under this equation, the sum of reductions in HC+NOx and CO must equal or exceed 100 percent on a corporate average basis. Corporate average HC levels cannot exceed 75 g/kW-hr as in the Phase 2 requirement. We believe this will allow manufacturers to use a broader variety of technology mixes than our proposed Phase 2 standards. Tables 4.3-7 and 4.3-8 provided below present a couple of potential technology mix scenarios for the Phase 3 standards. For the Phase 3 standards, we are including a HC+NOx requirement. This was done because, as the tables below will show, the number of four-stroke snowmobiles is anticipated to significantly increase compared to the number used to meet our Phase 1 and Phase 2 standards. Four-stroke engines emit significantly higher levels of NOx emissions than two-stroke engines. In order to make sure that NOx emissions do not become a problem as a result of the increase in the number of four-stroke snowmobiles, we decided to establish a NOx standard as well. The NOx standard is set at a level that makes it more of a cap, 15 g/kW-hr. This level should be inherently achievable for the majority of four-stroke engines. However, should a manufacturer attempt to design a four-stroke snowmobile that operates with a very lean air and fuel mixture to get even further HC reductions, this standard will prevent backsliding. NOx emissions from two-stroke engines are inherently well below the 15 g/kW-hr level.

We do not believe that incorporating the 15 g/kW-hr NOx standard as part of the HC+NOx standard will provide any incentive to increase HC significantly. NOx emissions from four-stroke engines are sufficiently close to 15 g/kW-hr that there will be little ability to increase HC even marginally. For two-stroke engines, while the 15 g/kW-hr level for NOx is well above typical two-stroke NOx emissions, it is still well below two-stroke HC emissions and does not provide enough of a margin to avoid use of advanced technologies on most engines. At most, it may provide a slight compliance cushion for these engines.

Table 4.3-7
Potential Snowmobile Technology Mix for Phase 3 Standards

Technology	Percent Usage	Percent Reduction HC	Percent Reduction CO	Fleet % Reduction HC	Fleet % Reduction CO
Carburetor/EFI Recalibration + Engine Modifications + Pulse Air Injection	20-30%	23-35%	23-35%	7-11.5%	7-11.5%
Direct Injection	50%	75%	70%	37.5%	35%
Four-Stroke	20%	90%	50%	18%	10%
Average Reduction				63%	52%

Table 4.3-8
Potential Snowmobile Technology Mix for Phase 3 Standards

Technology	Percent Usage	Percent Reduction HC	Percent Reduction CO	Fleet % Reduction HC	Fleet % Reduction CO
Carburetor/EFI Recalibration + Engine Modifications + Pulse Air Injection	0-20%	0-35%	0-35%	0-7%	0-7%
Direct Injection	10%	75%	70%	7.5%	7%
Four-Stroke	70%	90%	50%	63%	35%
Average Reduction				71%	42%

Clearly the technologies necessary to meet our 2012 standards are feasible, and in many cases the technologies are already being used on various snowmobile applications. As these technologies have been shown to provide emission reductions at or beyond the reductions needed to meet the standards, the standards are clearly feasible given the appropriate lead time even when considering production variability and emissions deterioration. The challenge manufacturers will face will be deciding which technologies to use for different applications and how consumers will respond to those technologies. In our testing efforts we attempted to order one of the new 2003 Yamaha RX-1 high performance four-stroke snowmobiles, but were surprised to find out that local dealers said there would be a six month wait to get one due to the high demand. We verified with Yamaha that they indeed have commitments for virtually every one of the new RX-1 models they are making and it's not a limited run, but rather a full scale production build. Therefore, if the Yamaha case is any indication, we believe there are a number of viable technologies available to meet our 2010 standards and the public is not only going to accept them, but embrace them.

Tables 4.3-7 and 4.3-8 are meant to show some possible technology mix scenarios that manufacturers may choose to comply with the Phase 3 standards in 2012. Implicit in these tables is the possibility that, under the averaging program, there may still be some largely unmodified two-stroke engines sold under the Phase 3 program. There are several reasons why a manufacturer might choose to continue to sell a small number of baseline technology snowmobiles under the Phase 3 program. First, it may prove significantly more expensive to reduce the emissions of a particular engine family relative to a manufacturer's other product offerings, and the manufacturer may simply choose to apply additional technology to some of its other models rather than put the extra effort and expense into reducing emissions from every one of its models. Second, a particular engine family may not respond as well to technology changes as other engine families, and the manufacturer may choose to apply additional technology to some of its other offerings rather than spending the resources to overcome the technological hurdles associated with a particular engine family. This could be because the technologies may affect the performance of the particular snowmobile model, including increased weight and startability concerns, and thus need further refinement for implementation. Finally, a manufacturer may intend to discontinue a particular engine family in the near future and may choose to focus its efforts on its other product offerings rather than spend the resources to reduce emissions from an engine family that is scheduled to be discontinued.

While it is possible that there may be some baseline technology snowmobiles in the product mix under the Phase 3 program, we expect that sales of such snowmobiles will be minimal for the following reasons. First, as Tables 4.3-7 and 4.3-8 show, we expect that compliance with the Phase 3 standards will require that at least 70 percent of snowmobile production employ some form of advanced technology such as direct injection two-stroke technology, or four-stroke engines. There may be some uncertainty amongst manufacturers as to whether they will be able to sell enough snowmobiles with advanced technology to allow for including baseline technology snowmobiles in their product mix. Manufacturers will likely choose to apply some level of emissions control to every snowmobile they sell in order to assure compliance with the Phase 3 standards on average. Similarly, there is no assurance that the advanced technologies will reduce emissions as well as expected on all engine families in the time frame provided, and we expect that manufacturers will also choose to apply some level of technology to every snowmobile in order to provide a compliance margin in case some technologies or particular applications of technologies do not perform as expected.

4.4 All-Terrain Vehicles/Engines

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

4.4.1 Baseline Technology and Emissions

ATVs have been in popular use for over 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.

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, California allows 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 uncertified engines were operated exclusively on restricted public lands and at specified times of the year. This allowed manufacturers to continue to produce 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 reservoir 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 11 four-stroke and three two-stroke ATVs over the FTP. Tables 4.4-1 and 4.4-2 shows that the HC emission rate 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 than from the four-strokes. The CO emissions were also lower for the two-stroke ATVs. The four-stroke ATVs that we tested that had high levels of CO also 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 fuel system to run even richer than 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. Another observation that can be made from the test results is that of the 11 four-stroke models tested, the four ATVs with the lowest emissions were sport models. The other seven models were all utility models. The four sport models, the Yamaha Warrior and Raptor, the Honda 300EX, and Polaris Trail Boss had an average HC+NOx level of 1.35 g/km, below our 1.5 g/km standard, and an average CO level of 28.5 g/km, only slightly above our standard of 25 g/km. In fact, the Warrior and Raptor already meet our standards with considerable headroom. The average HC+NOx and CO emissions levels for the seven utility models were 2.20 g/km and 33.7 g/km, respectively. This may indicate that when testing over the highway motorcycle test procedure, utility ATVs may be at a disadvantage compared to the sport models because of their lower power-to-weight ratio and use of continuously variable transmissions. Even when tested over the less strenuous Class I highway motorcycle test cycle, the utility ATVs appeared to be operating at higher loads than the sport models. Although we didn't examine all of the ATVs, the Warrior operated at a slightly leaner air and fuel mixture than the Polaris Sportsman. This could be model or manufacturer specific, but if this is at all indicative of how sport and utility ATVs fuel systems are calibrated, the fact that utility ATVs already operate very rich could be exacerbated when operated over the FTP, resulting in the higher HC and CO levels that we observed.

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	Warrior	1998	349 cc	0.98	19.44	0.190
Polaris	Sportsman	2001	499 cc	2.68	56.50	0.295
Arctic Cat	375 Automatic	2001	375 cc	1.70	49.70	0.190
Yamaha	Big Bear	2001	400 cc	2.30	41.41	0.170
Honda	Rancher	2001	400 cc	1.74	33.98	0.150
Bombardier	4X4 AWD	2001	500 cc	1.62	20.70	0.740
Polaris	Sportsman	2001	499 cc	1.56	19.21	0.420
Yamaha	Raptor	2001	660 cc	0.97	16.56	0.210
Average				1.58	31.78	0.305

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
Polaris	Trailblazer	2000	250 cc	18.91	44.71	0.040
Average				21.56	31.34	0.048

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 standards. We believe that to meet our ATV standards, manufacturers will use four-stroke engines. Depending on the size, performance and calibration of the engine, they will also need to make improvements to the fuel system, consisting of improved carburetor tolerances and a leaner air and fuel mixture, and in some cases the use of pulse air injection.

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. Manufacturers have indicated that they believe 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 standards[7].

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. According to manufacturers, based on their experience, leaner calibrations could serve to reduce CO and HC emissions by up to 20 percent, depending on how lean the unmodified engine is prior to recalibration[8]. 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) could create concerns about ATV engine durability. There are many engine improvements that could be made to regain any 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 with improvements such as better metallurgy 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

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[7] See “Memo to Docket on Technical Discussions with Recreational Vehicle Manufacturers,” from Linc Wehrly. Docket A-2000-01, IV-B-43.

[8] See “Memo to Docket on Technical Discussions with Recreational Vehicle Manufacturers,” from Linc Wehrly. Docket A-2000-01, IV-B-43.

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. A new start-up company called Rev! Motorcycles plans to manufacturer high-performance recreational and competition off-highway motorcycles with direct fuel injection two-stroke engines in the next year or so (for more, see Section 4.7.2.3). They have not indicated whether they will manufacturer any ATVs. 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 may not be considered to be cost effective for these engines.

4.4.2.4 Four-Stroke Engines

Four-stroke engines produce significantly lower levels of HC emissions than two-stroke engines. This is primarily due to the fact that two-stroke engines experience high scavenging losses that allow up to a third of the unburned air and fuel mixture to escape into the atmosphere during the combustion process. Since four-stroke engines have a valve-train system and introduce the air and fuel mixture into the combustion chamber when the exhaust valve is closed or almost closed, there is very little scavenging of unburned fuel. Thus, four-stroke engines have superior HC control to conventional two-stroke engines. Four-stroke engines have comparable CO performance to two-stroke engines. CO emissions result from incomplete combustion due to an excess of fuel in the air and fuel mixture. Thus, CO emissions are a function of air and fuel mixture. Current unregulated four-stroke and two-stroke engines both operate with a rich air and fuel mixture, resulting in high levels of CO emissions. Therefore, four-stroke engines do not have inherently low CO emission levels. Four-stroke engines also generate higher NOx emission levels than two-stroke engines. This is because NOx emissions are a function of temperature. Higher combustion temperatures generate higher NOx emission levels. Four-stroke engines have more complete combustion than conventional two-stroke engines, which results in higher combustion temperatures and higher NOx emission levels. Thus, four-stroke engines are an excellent choice for significantly reducing HC emissions. However, to reduce CO emissions, a four-stroke engine may need some fuel system calibration changes, engine modifications, or the use of secondary air or a catalyst. To reduce NOx emissions from a four-stroke engine would require fuel system calibration changes, engine modifications, exhaust gas recirculation (EGR), or a catalyst.

Since 80 percent of all ATVs sold each year are four-stroke, there is no question about the feasibility of using four-stroke engine technology for ATVs. Conversion from two-stroke to four-stroke engine technology also results in improvements to fuel consumption and engine durability. These benefits could be especially valuable to consumers who purchase utility 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, manufacturers 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. By Consent Decree these are limited to 50 cc and 90 cc, respectively. Some manufacturers have argued that because of these 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. However, 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. In addition, manufacturers have expressed concern that these smaller engines have lower cylinder surface to volume area ratios than larger displacement engines, thus increasing the difficulty of in-cylinder control of HC emissions. That is one of the reasons that we 1) are allowing engines under 99 cc to stay in the relatively less stringent utility engine program and 2) that we permit averaging across the entire spectrum of ATV vehicles/engines if they certify to the FTP-based standards.

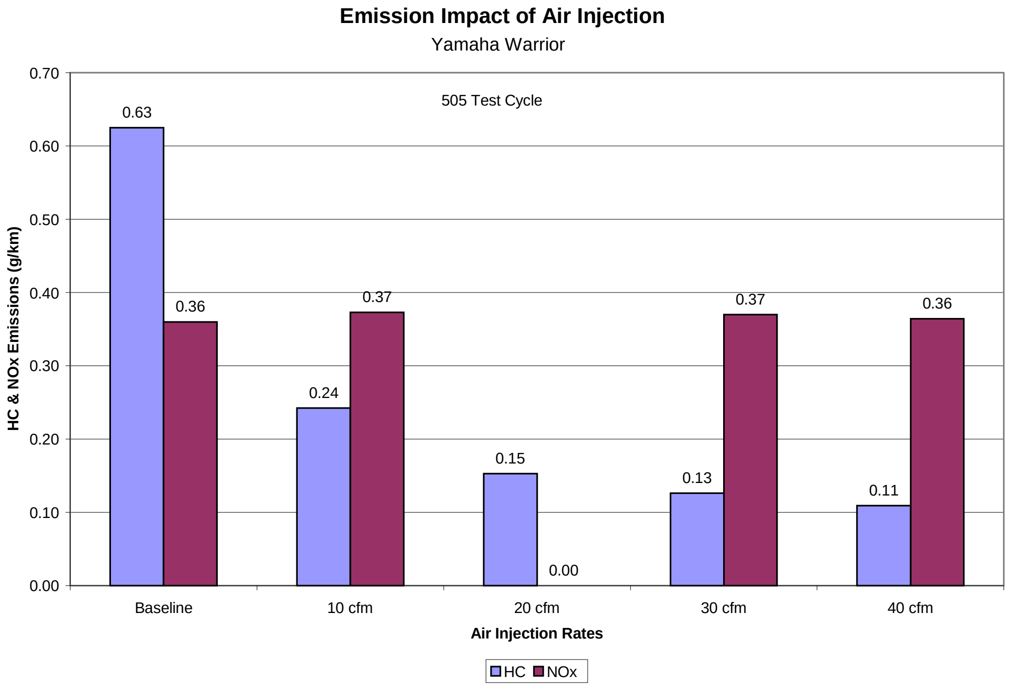
Adult sport ATVs equipped with two-stroke engines were at one time considered the only ATVs that were capable of providing true high-performance. However, advancements in four-stroke engine technology for ATVs and off-highway motorcycles have now made it possible for larger displacement high-powered 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 standards. Nonetheless, the credit exchange program (ABT) we are including for ATV s creates the possibility for manufacturers to retain some lower emission two-stroke ATVs and offset their higher emissions with reductions from 4-stroke models.

4.4.2.5 Air Injection

Secondary pulse air injection involves the introduction of fresh air into the exhaust pipe immediately after the exhaust gases exit the engine. The extra air causes further combustion to occur as the gases pass through the exhaust pipe, thereby oxidizing more of the HC and CO 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 30-70% for HC and 30-80% for CO 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 standards for all models, but will be a viable control technology for some machines. We tested three different four-stroke ATVs with secondary air. A 1998 Yamaha Warrior sport model, a 2001 Polaris Sportsman High Output (H.O.) utility model, and a 2001 Polaris Sportsman utility model. Initially we didn't have access to a pulse air system so we used shop air introduced into the exhaust manifold at various flow rates to simulate air injection. To save time and money, we performed our tests over the hot 505 section of the Class I Motorcycle cycle. This is a warmed-up version of the first bag or 505 seconds of the FTP test cycle. The initial tests with shop air indicated that air injected into the exhaust stream could reduce HC emissions from 5-percent to 60-percent depending on the vehicle and the amount of air injected. For example, the Warrior was very responsive to air injection. We tested at flow rates of 10, 20, 30, and 40 cubic feet per minute (cfm). HC emissions were reduced from 25-percent to 60-percent depending on the flow rate. Figure 4.4-1 illustrates these reductions. We also experimented with the air and fuel mixture and found that if we leaned the mixture slightly, the air injection had an even greater effect, reducing HC emissions by 83-percent from the uncontrolled baseline level with 40 cfm of air. Our next task was to determine how the various flow rates we tested compared to the capabilities of a pulse air system. A pulse air system uses a system of check valves which uses the normal pressure pulsations in the intake manifold to draw in air from outside and inject into the exhaust manifold. A reed valve is used in the exhaust manifold to prevent reverse airflow of exhaust gases through the system. A valve called the “air injection” valve reacts to high intake manifold vacuum and will cut-off the supply of air during engine decelerations, thereby preventing after burn in the exhaust system.

Figure 4.4-1



Since generic pulse air systems can't be simply purchased from the store or dealership, we had to modify an existing pulse air system to work on our test ATVs. We purchased a pulse air system for a 1995 BMW 100R. Because this is a multi-cylindered engine, we had to make some modifications to get it to work with a single-cylinder ATV engine. We were able to successfully install the pulse air system onto the Warrior and performed several hot 505 test runs to see how the pulse air system compared with the various flow rates of shop air. For our shop air tests, we injected a constant flow rate over the entire 505 seconds of the test. Because a pulse air system relies on drawing air into the exhaust system during negative pressure pulses in the cylinder, increasing the engine speed increases the magnitude of the positive pressure pulses resulting in increased back-pressure which can make a pulse air system ineffective. Our biggest concern was that a pulse air system might not have the same overall flow capacity as our shop air experiments since the pulse air system is only capable of drawing air into the exhaust manifold during lower speeds where increased exhaust back-pressure is decreased. Due to timing constraints, we only tested the Warrior with the pulse air system in conjunction with the enleaned carburetor setting. The carburetor was enleaned by raising the jet needle one clip notch. When we raised the clip two notches, the engine ran too lean and performance and driveability were affected. With pulse air and the slightly lean calibration, the Warrior had emissions comparable to the 20-30 cfm shop air results. Figure 4.4-2 shows the results between shop air and the pulse air results. When the Warrior was tested over the full FTP with pulse air and the slightly lean calibration, HC and CO emissions were reduced from baseline levels, while NOx increased. HC was reduced by 73-percent, CO was reduced by 83-percent and NOx was increased by 47-percent. The NOx emission increase is most likely due to the leaner air and fuel mixture. The HC+NOx level was reduced by 54-percent from the baseline level as shown in Table 4.4-3.

Figure 4.4-2

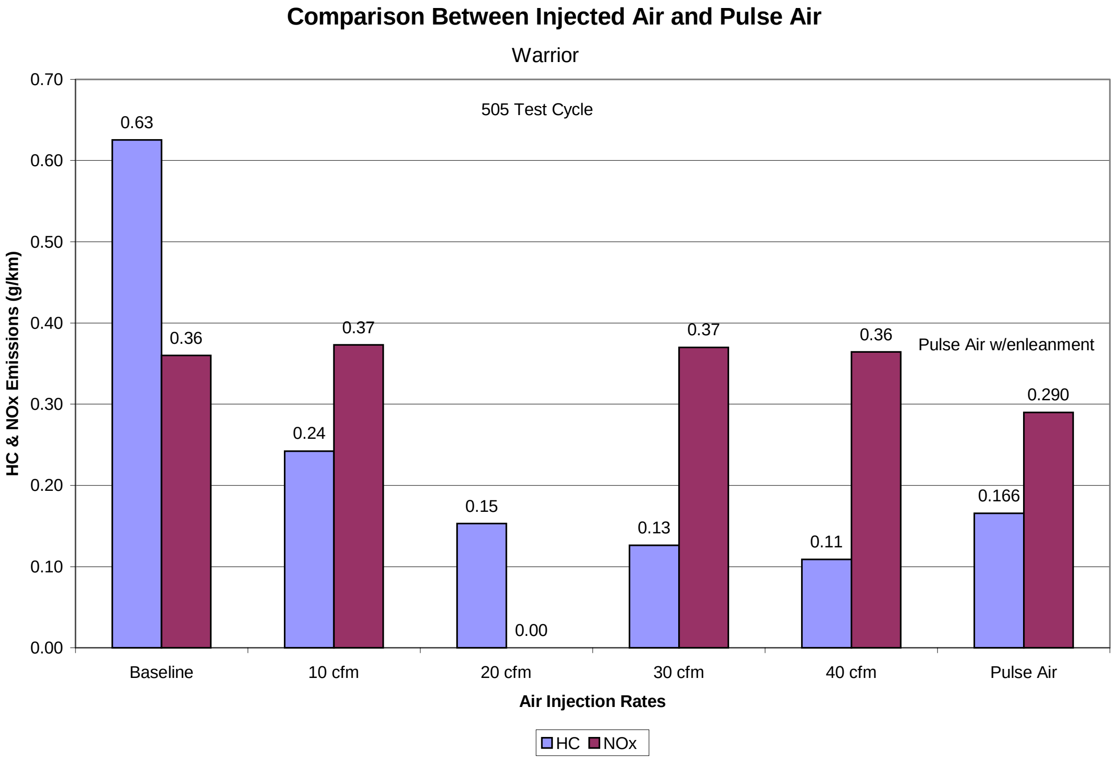


Table 4.4-3
Yamaha Warrior Emissions with and without Pulse Air Injection

Test Configuration	HC	CO	NOx	HC+NOx
Baseline	0.98	19.44	0.19	1.17
Pulse Air w/enleanment	0.26	3.33	0.28	0.54

The two Polaris Sportsman models proved to be more problematic than the Warrior. As discussed above, the utility ATVs all had higher baseline emissions levels than the sport models. The Polaris Sportsman High Output (H.O.) had the highest baseline emissions of any of the ATVs we tested. HC+NOx emissions were 3.0 g/km, almost 100-percent higher than our standard of 1.5 g/km, while CO was 56.5 g/km, 125-percent higher than the standard of 25 g/km. The regular Sportsman was cleaner than the H.O. model with a HC+NOx level of 1.98 g/km and a CO level of 19.2 g/km. As a result of these higher baseline emissions, the two Sportsman models were at a disadvantage compared to the relatively clean Warrior. When supplying shop air to the two Sportsman models we saw varied results. The higher emitting H.O. model responded to air injection. However, the emissions were still so high that we stopped any further testing and focused on catalyst use for this model. The regular Sportsman model was less receptive to air injection. In fact the same levels of flow that resulted in sharp reductions for the Warrior had only minimal effects for this vehicle. Further investigation indicated that the air and fuel mixture was too rich for the injected air to have any significant effect. We tried to lean-out the air and fuel mixture by raising the jet needle clip to the top of the needle, similar to what we did for the Warrior, but there was no response. We had to use a different, leaner main jet, in order to successfully lean-out the air and fuel mixture. With the air and fuel mixture leaner, we ran several tests with shop air and found that the Sportsman was more receptive to air injection, so we decided to install the BMW pulse air system that we modified for the Yamaha Warrior to the Sportsman. We ran a full FTP with the pulse air system and the leaner main jet installed and found that emissions were reduced considerably. HC and CO were reduced by 71-percent and 68-percent, respectively. NOx emissions increased by 45-percent. Limited time prevented us from further investigating ways to reduce the air and fuel mixture. However, as Table 4.4-4 shows, the Sportsman was able to meet the standard using this approach.

Table 4.4-4
Polaris Sportsman Emissions with and without Pulse Air Injection

Test Configuration	HC	CO	NOx	HC+NOx
Baseline	1.56	19.21	0.42	1.98
Pulse Air w/enleanment	0.49	6.12	0.60	1.09

4.4.2.6 Catalyst Technology

For our proposal, we proposed Phase 2 standards of 1.0 g/km HC+NOx. To achieve a standard of 1.0 g/km, manufacturers will actually have to design their emission control system to meet an emission level lower than the standard to account for deterioration and provide an acceptable certification emission margin. Manufactures typically aim for a certification emissions margin of 20 percent. Our NONROAD emission model uses a deterioration factor of 1.17 for four-stroke ATV engines. Taking these factors into consideration would result in a potential emission level design goal of approximately 0.7 g/km. To meet this level of HC+NOx control, we projected in our proposal that it might be necessary for some ATV models to use a catalyst. To establish the feasibility of using a catalyst on an ATV, we tested the Polaris Sportsman High Output (HO) ATV equipped with several different catalysts. The Sportsman is a large utility ATV equipped with a 500 cc (HO) four-stroke engine and is one of the larger ATV models currently offered in the market. We chose this model to demonstrate catalyst viability because, as mentioned above, 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 cells/in^2 . 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 cells/in^2. Table 4.4-5 shows that emissions were significantly reduced when the various catalysts were installed on the Sportsman. However, even though there was a significant reduction in emissions, the ATV was still unable to meet the proposed 1.0 g/km HC+NOx standard, let alone the design target of approximately 0.7 g/km.

Table 4.4-5
Polaris Sportsman 500 Emissions with Various Catalysts

Catalyst	HC	CO	NOx	HC+NOx
Baseline	2.68	56.5	0.3	2.98
TWC (Pd-only)	1.27	35.27	0.05	1.32
TWC (Pt/Rh)	1.29	32.6	0.04	1.33
Oxidation	1.38	28.87	0.02	1.4

The three catalysts that we used had volumes ranging from 400 to 500 cc. Most highway motorcycles typically use catalysts with a catalyst-to-engine volume ratio of one half. In other words, they typically use a catalyst that has a volume approximately half of the engine's displacement. For our catalyst cost estimation in the proposal, we argued that this would be a good assumption for ATVs as well. We estimated that for ATVs, the catalyst size necessary to meet our proposed HC+NOx standard of 1.0 g/km would be equal to half of the engine displacement. We projected an average catalyst volume of 200 cc. The catalysts that we tested were roughly double the size of catalysts we projected would be necessary to meet our standards. We chose to use these catalysts not because of their size, but because of their availability. All three catalysts are used in production highway motorcycle applications and were provided to us by catalyst manufacturers. The highway motorcycles that these catalyst are from have an engine displacement of approximately 900 cc. The implication of this is that even with catalysts twice as large as we projected would be necessary to meet our 1.0 g/km standard, the emission reductions for this ATV were still about 33-percent short of the standard.

Due to rulemaking schedule constraints, we had limited time to perform the testing and analyses that we felt were necessary to support the proposed standards. One of the consequences of this timing was that were unable to test the Sportsman with the various catalysts with pulse air injection and a leaner air and fuel mixture. It is quite possible, that had we been able to perform those tests we would have found that the emissions from the Sportsman could be brought down to levels below the proposed Phase 2 standards. However, with our limited success with air injection and enleaning of the air and fuel mixture with the two Sportsman models, it is also possible that these additional strategies would not have helped quickly. We are confident that the use of a catalyst has the potential to significantly reduce emissions for many ATV applications, but at this time we can not confidently claim they will work for all applications without further investigation.

4.4.3 Test Cycle/Procedure

For ATVs, we specify the current highway motorcycle test procedure 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 III (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" and by reducing the top speed from 56 miles per hour to 35 mile per hour. California requires ATVs to be tested over the Class I motorcycle cycle. Our testing has shown that some utility ATVs are at a disadvantage when tested over the Class II and III cycles because utility ATVs use continuously variable transmissions (CVT), similar to snowmobiles. These transmissions tend to be geared towards lower speed operation for ATVs with high torque generation at lower engine speeds. This is so they can perform a broad variety of utilitarian tasks, such as plowing snow, hauling loads, cutting grass and other high load activities. As a result, when operated over the Class II or III motorcycle test cycle, these vehicles operate under a much higher load than would be typically expected in real-world operating conditions. Operating under higher loads means the engine runs at a richer air and fuel mixture and generates higher levels of emissions. We received comments from manufacturers stating that if keep the FTP as the main ATV test cycle, that we should only require the Class I cycle, similar to California. As a result of these comments and our own experience testing various ATVs over the FTP, we have decided to require Class I motorcycle test cycle rather than using all three cycles depending on the engine displacement as proposed.

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 chassis dynamometer 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 off-highway 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 costly to purchase and difficult to put in place in the short run, especially for some smaller manufacturers. ATV manufacturers may therefore certify using the J1088 engine test cycle per the California off-highway motorcycle and ATV program for the model years 2006 through 2008. After 2008, this option expires and the FTP becomes 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, through rulemaking, we would consider allowing the option of an alternative test cycle in place of the FTP.

4.4.4 Small Displacement Engines

For small displacement ATVs of 70 cc or less, we proposed that they would have the permanent option to certify to the proposed FTP-based ATV standards or meet the Phase 1 Small SI emission standards for non-handheld Class 1 engines. These standards are 16.1 g/kW-hr HC+NOx and 610 g/kW-hr CO. Manufacturers argued that ATVs with engine displacements between 70 cc and 99 cc also should be allowed to certify to the Small SI standards, since the differences between a 70 cc and 99 cc engine is very small and the ATVs equipped with 99 cc engines face the same obstacles with the FTP test cycle as the 70 cc and below ATVs. They also argued that the Phase 1 Small SI standards are too stringent for these engines and recommended that EPA adopt the Phase 2 standards for Class 1B engines of 40 g/kW-hr for HC+NOx and 610 g/kW-hr for CO.

We recognize that the vast majority of engine families, including 4-stroke engines, below 100 cc are not certified to the California standards, which is an indication to us that the standards proposed may not be feasible for most engines in this size range given the lead time provided. However, manufacturers did not provide supporting data and we do not have data to confirm that the level recommended by the manufacturers would result in an appropriate level of control. We examined the 2002 model year certification data for non-handheld Small SI engines certified to the Phase 2 Class I-A and I-B engine standards (engines below 100 cc)and found that the five engine families certified to these standards had average emissions for HC+NOx of about 25 g/kW-hr (see Table 4.4-6). All of these engine families had CO emissions below 500 g/kW-hr and well below the 610 g/kW-hr level recommended by manufacturers.

Table 4.4-6
2002 Certification Data for Non-Handheld Small SI Phase 2 Class I-A and I-B Engines

Manufacturer	Engine Family	Displacement	HC+NOx (g/kW-hr)	CO (g/kW-hr)
Honda	2HNXS.0224AK	22.2	31.6	329.8
MTD Southwest	2MTDS.0264Y2	26.2	14.7	483.2
Honda	2HNXS.0314AK	31.1	41.0	391.4
Honda	2HNXS.0574AK	49.4	25.4	372.1
Honda	2HNXS.0991AK	98.5	13.4	445.3
Average			25.2	404.4

We believe these levels are more representative of the levels that can be achieved with the lead time provided through the use of 4-stroke engines than the standards recommended by the manufacturers. Since we are offering averaging with the HC+NOx standard, a standard based on the average of 25.0 g/kW-hr for the five engine families is appropriate for ATVs with an engine displacement under 99 cc. Since we are not offering an averaging program for CO emissions, it is apparent from the above data that a standard of 400 g/kW-hr would be very difficult for these smaller ATV engines to achieve. Therefore, based on the above data, we believe that a standard of 500 g/kW-hr can be achieved with engines under 99 cc. We believe these standards can be meet through the use of the various technologies described above.

4.4.5 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 30-50 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.

4.4.6 Conclusion

We expect that the ATV emission standards will largely be met through the conversion of two-stroke engines to four-stroke engines and with some minor carburetor calibration modifications and air-fuel ratio enleanment, combined with some use of pulse air injection for the four-stroke engines which now dominate this market. Our test data indicates that ATVs can have a wide variety of emissions performance. Some models are very clean and will require a relatively minor improvement to meet our standards. Other ATVs, especially larger heavier utility models, will require substantially more work. Our development testing indicates that control strategies such as carburetor enleanment and pulse air injection can significantly reduce emissions. In particular, these strategies are a path to allow most ATV models to meet a HC+NOx standard of 1.5 g/km with due consideration to useful life requirements and compliance margins most manufacturers adopt for various reasons. The other main control strategy that we examined was the use of catalysts. While it is well known that catalysts can significantly reduce exhaust emissions, the results that we had in our testing program fell short of complete success. For numerous reasons, including lack of time and hardware, we were unsuccessful at getting all of our test ATVs to meet our proposed HC+NOx standard of 1.0 g/km. We believe further investigation is warranted. However, due to scheduling concerns, we did not have the time to complete this investigation. As a result, we have decided to postpone the setting of phase 2 standards at this time. We plan to continue to investigate the emission reduction capabilities of ATVs and may establish a second phase of standards in the future.

We are confident that control strategies such as the use of a four-stroke engine with carburetor enleanment and pulse air injection can easily meet our HC+NOx emission standard of 1.5 g/km even with a 20-percent headroom to accommodate production variability and deterioration by the 2006 model year. That is why we are, for now, establishing a single set of standards for ATVs of 1.5 g/km HC+NOx and 25 g/km CO. These technologies have been utilized in a number of different applications, such as highway motorcycles, personal watercraft, lawn and garden equipment, and small scooters. These technologies also have potential benefits beyond emission reductions (e.g., improved fuel economy, reliability and performance, and reduced noise).

4.5 Off-Highway Motorcycles

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

4.5.1 Baseline Technology and Emissions

Off-highway motorcycles are similar in appearance to highway motorcycles, 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. This advanced suspension system tends to make off-highway motorcycles much taller than highway motorcycles, in some cases up to a foot taller.

Thirty percent of off-highway motorcycle sales are generally considered to be 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 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 reservoir 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 4.5-1 and 4.5-2 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 a bit lower. The CO levels were also considerably lower for the four-stroke bikes.

Table 4.5-1
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
Yamaha	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 4.5-2
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

4.5.2 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, in most cases, 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 standards. For our 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.

4.5.2.1 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. Manufacturers have indicated that 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 standards[9].

4.5.2.2 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. According to manufacturers, 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[10]. 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) could create concerns about off-highway motorcycle engine durability. There are many engine improvements that could be made to regain any 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 with improvements such as better metallurgy to improve durability.

Carburetion improvements alone will not allow manufacturers to meet our 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.

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[9] See “Memo to Docket on Technical Discussions with Recreational Vehicle Manufacturers,” from Linc Wehrly. Docket A-2000-01, IV-B-43.

[10] See “Memo to Docket on Technical Discussions with Recreational Vehicle Manufacturers,” from Linc Wehrly. Docket A-2000-01, IV-B-43.

4.5.2.3 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. As discussed above, a small start-up company called Rev! Motorcycles is planning in the near future to manufacture two-stroke high-performance recreational and competition off-highway motorcycles utilizing direct fuel injection. Rev! claims they will be able to meet our optional HC+NOx standard of 4.0 g/km. They have provided limited data based on computer simulation of what they expect their technology to achieve.[26]

Substantial improvements in fuel economy could also be expected with direct injection. 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. Rev! acknowledges that direct injection is expensive and their motorcycle will have a premium price, but they expressed confidence that the success of their system would attract customers and the cost of the system would eventually go down.

4.5.2.4 Four-Stroke Engines

Four-stroke engines produce significantly lower levels of HC emissions than two-stroke engines. This is primarily due to the fact that two-stroke engines experience high scavenging losses that allow up to a third of the unburned air and fuel mixture to escape into the atmosphere during the combustion process. Since four-stroke engines have a valve-train system and introduce the air and fuel mixture into the combustion chamber when the exhaust valve is closed or almost closed, there is very little scavenging of unburned fuel. Thus, four-stroke engines have superior HC control to conventional two-stroke engines. Four-stroke engines have comparable CO performance to two-stroke engines. CO emissions result from incomplete combustion due to an excess of fuel in the air and fuel mixture. Thus, CO emissions are a function of air and fuel mixture. Current unregulated four-stroke and two-stroke engines both operate with a rich air and fuel mixture, resulting in high levels of CO emissions. Therefore, four-stroke engines do not have inherently low CO emission levels. Four-stroke engines also generate higher NOx emission levels than two-stroke engines. This is because NOx emissions are a function of temperature. Higher combustion temperatures generate higher NOx emission levels. Four-stroke engines have more complete combustion than conventional two-stroke engines, which results in higher combustion temperatures and higher NOx emission levels. Thus, four-stroke engines are an excellent choice for significantly reducing HC emissions. However, to reduce CO emissions, a four-stroke engine may need some fuel system calibration changes, engine modifications, or the use of secondary air or a catalyst. To reduce Nox emissions from a four-stroke engine would require fuel system calibration changes, engine modifications, exhaust gas recirculation (EGR), or a catalyst.

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 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 trend, 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 slow speed 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.

4.5.2.5 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 standards, however, some manufacturers may choose to use it on some four-stroke engine models.

4.5.2.6 Catalyst Technology

We do not believe catalysts will be necessary to meet our standards of 2.0 g/km HC+NOx and 25.0 g/km CO. We did not pursue standards that would require catalyst technology for off-highway motorcycles because we do not believe that potential safety and durability issues with catalysts for off-highway motorcycle applications have been adequately addressed. As discussed above in Section 4.4.2.6, to meet our proposed Phase 2 ATV standard of 1.0 g/km HC+NOx would require a design goal of 0.6 to 0.7 g/km HC+NOx to account for certification compliance margin and emission system deterioration. Although we did not perform any testing of off-highway motorcycles with catalysts, the results from our ATV testing gave us additional concern over the viability of catalysts with off-highway motorcycles. For the Polaris Sportsman (HO), a large 500 cc utility ATV model, we were unable to successfully reduce HC+NOx emissions below 1.3 g/km using a production three-way catalyst from a federally certified 900 cc highway motorcycle. The catalysts were larger in volume, precious metal loading, and physical size than we had initially projected would be necessary for ATVs. The physical size of these catalysts were well beyond what would be considered acceptable for off-highway motorcycle applications. The highway motorcycle that the production catalysts were from weighs around 450 pounds. Typical four-stroke off-highway motorcycles weigh between 225 and 280 pounds. The exhaust system, and thus the catalyst, were routed low to the ground where the extra weight would be least noticeable. For a four-stroke off-highway motorcycle, the exhaust pipe is routed high on the frame to provide a better center of gravity and keep the exhaust pipe away from water, rocks, logs, and other items that could damage the pipe. Placing such a large catalyst in a four-stroke off-highway motorcycle would pose problems of extra weight and packaging, since it is difficult to find locations in the exhaust pipe to place a large catalyst so that it wouldn’t interfere with the rider.

We have concerns about the safety and durability of catalysts in off-highway motorcycle applications. As discussed above, off-highway motorcycles operate in very harsh conditions.

They experience extreme shock and jarring that can easily damage a catalyst. It is very common for off-highway motorcycles to come into contact with rocks, logs, stumps, and trees through the course of regular riding activities or accidentally in the form of a crash. The substrate of a catalyst can be very fragile, depending on the material used. We are unaware of any data on the durability of a catalyst under such harsh operating conditions. There currently are no off-highway motorcycle models equipped with a catalyst and we know of no studies performed on the long term durability of a catalyst in an off-highway motorcycle application.

Catalysts operate at very high temperatures which can be a concern for burning the rider or potentially starting a fire in the riding environment that they frequent, such as forests and grassy fields. While heat shields may possibly prevent the rider from burns, there is the problem of where to locate the catalyst so that the catalyst is not in the way of the rider adding concern over potential burns. Off-highway motorcycles are much taller than highway motorcycles. In fact, for some shorter riders they are unable to touch the ground with both feet when straddling their off-highway motorcycle. This can be an additional concern for potential catalyst burns and where to locate the catalyst. Because the motorcycle is so tall, the rider often has to lean to one side or another of the bike to keep their balance when the motorcycle is not moving. It is imperative that the catalyst not be located in a manner that would exacerbate the possibility of burning the rider or interfering with the riders balance when standing still on the motorcycle. There is also a question over the durability of heat shields in these harsh applications. Heat shields used for many highway vehicle applications are not designed for the extreme conditions that these vehicles operate in. Again, we are not aware of any data that demonstrates the effectiveness of catalyst heat shields for off-highway motorcycles.

4.5.3 Test Procedure

For off-highway motorcycles, we specify the current highway motorcycle test procedure for measuring emissions. The highway motorcycle test procedure is the same test procedure as that 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.

In the California program, highway motorcycles are divided into three classes based on engine displacement, with Class I (50 to 169 cc) being the smallest and Class III (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 are applying this same class/cycle distinction for off-highway motorcycles. In other words, off-highway motorcycles with an engine displacement between 50 and 279 cc (Class I and II) must 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.

4.5.4 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 motorcycles 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.

4.5.5 Conclusion

We expect that the 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 for some four-strokes. 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 presented below in Table 4.5-3, as well as data from our own testing (see Table 4.5-1 above) suggest that four-stroke engines with some minor fuel system calibration modifications will be capable of meeting our emission standards even when considering production variability and deterioration. 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.

Table 4.5-3
2001 Model Year California Off-highway Motorcycle Certification Data (g/km)

Manufacturer	Model*	Engine Disp.	HC	CO
Honda	XR650R	650 cc	1.0	11.7
Honda	XR400R	400 cc	0.5	6.2
Honda	XR200R	200 cc	0.7	6.8
Honda	XR100R	100 cc	0.8	4.9
Honda	XR80R	80 cc	0.6	6.3
Honda	XR70R	70 cc	0.8	8.2
Honda	XR50R	50 cc	1.0	8.6
Kawasaki	KLX300	300 cc	1.0	5.1
Yamaha	TT-R250	250 cc	0.7	10.9
Yamaha	TT-R225	225 cc	0.7	12.4
Yamaha	TT-R125	125 cc	0.8	5.1
Yamaha	TT-R90	90 cc	0.8	4.9

* All models are four-stroke

4.6 Permeation Control from Recreational Vehicles

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

4.6.1 Baseline Technology and Emissions

4.6.1.1 Fuel Tanks

Recreational vehicle fuel tanks are generally blow-molded or injection-molded using high density polyethylene (HDPE). Data on the permeation rates of fuel through the walls of polyethylene fuel tanks shows that recreational vehicle HDPE fuel tanks have very high permeation rates compared to those used in automotive applications. We tested four ATV fuel tanks in our lab for permeation. We also tested three portable marine fuel tanks and two portable gas cans which are of similar construction. This testing was performed at 29°C (85°F) with gasoline. Prior to testing, the fuel tanks had been stored with fuel in them for more than a month to stabilize the permeation rate. The permeation rates are presented in Table 4.6-1. The average for these ten fuel tanks is 1.32 grams per gallon per day.

Table 4.6-1: Permeation Rates for Plastic Fuel Tanks Tested by EPA at 29°C

Tank Capacity [gallons]	Permeation Loss [g/gal/day]	Tank Type
1.3	1.66	all terrain vehicle
1.3	2.90	all terrain vehicle
1.8	1.29	all terrain vehicle
2.1	2.28	all terrain vehicle
5.3	1.00	all terrain vehicle
6.0	0.61	portable marine
6.0	1.19	portable marine
6.0	0.78	portable marine
6.6	0.77	portable fuel container
6.6	0.75	portable fuel container

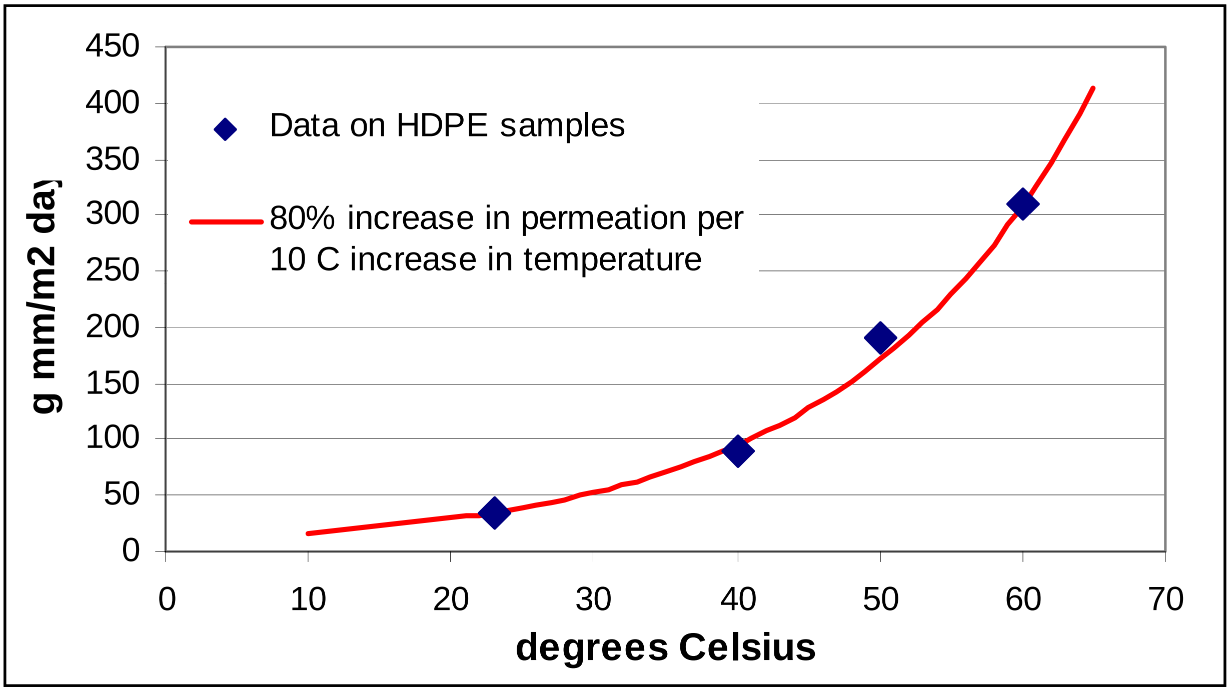
The California Air Resources Board (ARB) investigated permeation rates from portable fuel containers and lawn & garden equipment fuel tanks. Although this testing was not on recreational vehicle fuel tanks, the fuel tanks tested are of similar construction. The ARB data is compiled in several data reports on their web site and is included in our docket.[27,28,29,30,31] Table 4.6-2 presents a summary of this data which was collected using the ARB test procedures described in Section 4.6.3. Although the test temperature is cycled from 18 - 41°C rather than held at a constant temperature, the results would likely be similar if the data were collected at the average temperature of 29°C used in the EPA testing. The average for these 36 fuel tanks is 1.07 grams per gallon per day.

Table 4.6-2: Permeation Rates for Plastic Fuel Containers Tested by ARB Over a 18-41°C Diurnal

Tank Capacity [gallons]	Permeation Loss [g/gal/day]	Tank Type
1.0	1.63	portable fuel container
1.0	1.63	portable fuel container
1.0	1.51	portable fuel container
1.0	0.80	portable fuel container
1.0	0.75	portable fuel container
1.0	0.75	portable fuel container
1.3	0.50	portable fuel container
1.3	0.49	portable fuel container
1.3	0.51	portable fuel container
1.3	0.52	portable fuel container
1.3	0.51	portable fuel container
1.3	0.51	portable fuel container
1.3	1.51	portable fuel container
1.3	1.52	portable fuel container
1.4	1.27	lawn & garden
1.7	0.67	lawn & garden
2.1	1.88	portable fuel container
2.1	1.95	portable fuel container
2.1	1.91	portable fuel container
2.1	1.78	portable fuel container
2.5	1.46	portable fuel container
2.5	1.09	portable fuel container
3.9	0.77	lawn & garden
3.9	0.88	lawn & garden
5.0	0.89	portable fuel container
5.0	0.62	portable fuel container
5.0	0.99	portable fuel container
5.0	0.55	lawn & garden
5.0	0.77	lawn & garden
5.0	0.64	lawn & garden
5.0	1.39	portable fuel container
5.0	1.46	portable fuel container
5.0	1.41	portable fuel container
5.0	1.47	portable fuel container
6.6	1.09	portable fuel container
7.5	0.35	lawn & garden

It is well known that the rate of permeation is a function of temperature. For most materials, permeability increases by about a factor of 2 for every 10°C increase in temperature.[32] Based on data collected on HDPE samples at four temperatures,[33,34] we estimate that the permeation of gasoline through HDPE increases by about 80 percent for every 10°C increase in temperature. This relationship is presented in Figure 4.6-1, and the numeric data can be found in Section 4.6.2.3.

Figure 4.6-1: Effect of Temperature on HDPE Permeation



Based on the data from 46 fuel tanks in Tables 8.4-1 and 8.4-2, the average permeation rate at 29°C is 1.12 grams per gallon per day. However, the standard is based on units of grams per square meter per day at 28°C. Based on measurements of cut away fuel tanks of this size, we have found that the wall thickness ranges from 4 to 5 mm. Using an average wall thickness of 4.5 mm and a permeation rate for HDPE of 47 g mm/m^2/day at 28°C (Figure 4.6-1) we estimate that the baseline permeation rate is about 10.4 g/m^2/day. Data presented later in this chapter (see Section 4.2.8.3) shows that the permeation rate of fuel through HDPE is fairly insensitive to the amount of alcohol in the fuel.

4.6.1.2 Fuel Hoses

Fuel hoses produced for use in recreational vehicles are generally extruded nitrile rubber with a cover for abrasion resistance. These hoses are generally designed to meet the requirements under SAE J30[35] for an R7 classification. R7 hose has a maximum permeation rate of 550 g/m^2/day at 23°C on ASTM Fuel C (50% toluene, 50% iso-octane). On a fuel containing an alcohol blend, permeation would likely be higher from these fuel hoses. R7 hose is made primarily of nitrile rubber (NBR). Based on the data presented in Section 4.2.8.3, permeation through NBR is about 50 percent higher when tested on Fuel CE10 (10% ethanol) compared to testing on Fuel C.

4.6.2 Permeation Reduction Technologies

4.6.2.1 Fuel Tanks

As discussed in Chapter 3, there are several strategies that can be used to reduce permeation from plastic fuel tanks. This section presents data collected on five permeation control strategies: sulfonation, fluorination, non-continuous barrier platelets, coextruded continuous barrier, and alternative materials.

4.6.2.1.1 Sulfonation

We tested one sulfonated, 6 gallon, HDPE, portable marine fuel tank at 29°C (85°F) with gasoline. Prior to testing, the fuel tank had been stored with gasoline in it for more than 10 weeks to stabilize the permeation rate. We measured a permeation rate of 0.08 g/gallon/day which represents more than a 90 percent reduction from baseline.

The California Air Resources Board (ARB) collected test data on permeation rates from sulfonated portable fuel containers using California certification fuel.[36] The results show that sulfonation can be used to achieve significant reductions in permeation from plastic fuel containers. This data was collected using a diurnal cycle from 18-41°C which is roughly equivalent to steady-state permeation testing at 30°C. The average emission rate for the 32 sulfonated fuel tanks is 0.35 g/gal/day; however, there was a wide range in variation in the effectiveness of the sulfonation process for these fuel tanks. Some of the data outliers were actually higher than baseline emissions. This was likely due to leaks in the fuel tank which would result in large emission increases due to pressure built up with temperature variation over the diurnal cycle. Removing these five outliers, the average permeation rate is 0.17 g/gal/day with a minimum of 0.01 g/gal/day and a maximum of 0.64 g/gal/day.

Variation can occur in the effectiveness of this surface treatment if the sulfonation process is not properly matched to the plastic and additives used in the fuel tank material. For instance, if the sulfonater does not know what UV inhibitors or plasticizers are used, they cannot maximize the effectiveness of their process. In this test program, the sulfonater was not aware of the chemical make up of the fuel tanks. This is the likely reason for the variation in the data even when the obvious outliers are removed. In support of this theory, the permeation rates were consistently low for tanks provided by two of the four tank manufacturers. For these 11 fuel tanks, the average permeation rate was 0.07 which represents more than a 90 percent reduction from baseline. Earlier data collected by ARB showed consistently high emissions from sulfonated fuel tanks; however, ARB and the treatment manufacturers agree that this was due to inexperience with treating fuel tanks and that these issues have since been largely resolved.[37] For this reason we do not include the earlier data in this analysis. Table 4.6-3 includes all of the permeation data, including the outliers.

Table 4.6-3: Permeation Rates for Sulfonated Plastic Fuel Containers Tested by ARB Over a 18-41°C Diurnal

Tank Capacity [gallons]	Permeation Loss [g/gal/day]
1	0.05
1	0.05
1	0.05
1	0.06
1	0.06
1	0.06
1	0.08
1	0.12
1	0.14
1	1.23
1	1.47
1	1.87
2	0.02
2	0.02
2	0.48
2	0.54
2	1.21
2.5	0.03
2.5	0.08
2.5	0.32
2.5	0.38
2.5	0.42
2.5	0.52
2.5	0.64
2.5	0.80
5	0.01
5	0.04
5	0.05
5	0.06
5	0.11
5	0.13
5	0.15

ARB also investigated the effect of fuel slosh on the durability of sulfonated surfaces. Three sulfonated fuel tanks were tested for permeation before and after being rocked with fuel in them 1.2 million times.[38] The results of this testing show that an 85% reduction in permeation was achieved on average even after the slosh testing was performed. Table 4.6-4 presents these results which were recorded in units of g/m^2/day. The baseline level is an approximation based on testing of similar fuel tanks.

As with earlier tests performed by ARB, the sulfonater was not aware of the materials used in the fuel tanks sulfonated for the slosh testing. After the tests were performed, the sulfonater was able to get some information on the chemical make up of the fuel tanks and how it might affect the sulfonation process. For example, the UV inhibitor used in some of the fuel tanks is known as HALS. HALS also has the effect of reducing the effectiveness of the sulfonation process. Two other UV inhibitors, known as carbon black and adsorber UV, are also used in similar fuel tank applications. These UV inhibitors cost about the same as HALS, but have the benefit of not interfering with the sulfonation process. The sulfonater claimed that if HALS were not used in the fuel tanks, a 97% reduction in permeation would have been seen.[39] A list of resins and additives that are compatible with the sulfonation process is included in the docket.[40,41]

Table 4.6-4: Permeation Rates for Sulfonated Fuel Tanks with Slosh Testing by ARB Over a 18-41°C Diurnal

Technology Configuration	Units	Tank 1	Tank 2	Tank 3	Average
Approximate Baseline	$g/m^2/day$	10.4	10.4	10.4	10.4
Sulfonated	$g/m^2/day$ % reduction	0.73 93%	0.82 92%	1.78 83%	1.11 89%
Sulfonated & Sloshed	$g/m^2/day$ % reduction	1.04 90%	1.17 89%	2.49 76%	1.57 85%

An in-use durability testing program was also completed for sulfonated HDPE fuel tanks and bottles.[42] The fuel tank had a 25 gallon capacity and was removed from a station wagon that had been in use in southern California for five years (35,000 miles). The fuel tank was made of HDPE with carbon black used as an additive. After five years, the sulfonation level measured on the surface of the plastic fuel tank did not change. Tests before and after the aging both showed a 92 percent reduction in gasoline permeation due to the sulfonation barrier compared to the permeation rate of a new untreated tank. Testing was also done on 1 gallon bottles made of HDPE with 3% carbon black. These bottles were shown to retain over a 99 percent barrier after five years. This study also looked at other properties such as yield strength and mechanical fatigue and saw no significant deterioration.

One study looked at the effect of alcohol in the fuel on permeation rates from sulfonated fuel tanks.[43] In this study, the fuel tanks were tested with both gasoline and various methanol blends. No significant increase in permeation due to methanol in the fuel was observed.

4.6.2.1.2 Fluorination

We tested one fluorinated, 6 gallon, HDPE, portable marine fuel tank at 29°C (85°F) with gasoline. Prior to testing, the fuel tank had been stored with gasoline in it for about 20 weeks to stabilize the permeation rate. We measured a permeation rate of 0.05 g/gallon/day which represents more than a 95 percent reduction from baseline.

The California Air Resources Board (ARB) collected test data on permeation rates from fluorinated portable fuel containers using California certification fuel.[44,45] The results, presented in Table 4.6-5, show that fluorination can be used to achieve significant reductions in permeation from plastic fuel containers. This data was collected using a diurnal cycle from 18-41°C which is roughly equivalent to steady-state permeation testing at 30°C. Four different levels of fluorination treatment were tested. The average permeation rate for the 87 fluorinated fuel tanks is 0.21 g/gal/day which represents about a 75 percent reduction from baseline. However, for the highest level of fluorination, the average permeation rate was 0.04 g/gal/day which represents a 95 percent reduction from baseline. Earlier data collected by ARB showed consistently high emissions from fluorinated fuel tanks; however, ARB and the treatment manufacturers agree that this was due to inexperience with treating fuel tanks and that these issues have since been largely resolved.[46] For this reason we do not include the earlier data in this analysis.

Table 4.6-5: Permeation Rates for Fluorinated Plastic Fuel Containers Tested by ARB Over a 18-41°C Diurnal

Barrier Treatment*	Tank Capacity [gallons]	Permeation Loss [g/gal/day]
Level 3 (average = 0.27 g/gal/day)	1	0.04
	1	0.06
	1	0.25
	2	0.12
	2	0.15
	2	0.17
	2	0.09
	2	0.15
	2	0.12
	2	0.18
	2	0.17
	2	0.14
	2	0.18
	2	0.34
	2	0.41
	2	0.41
	2	0.36
	2	0.41
	2	0.23
	2	0.29
	2	0.31
	2	0.24
	2	0.32
	2	0.16
	2	0.19
	2	0.20
	2	0.11
	2	0.20
	5	0.06
	5	0.06
	5	0.07
	5	0.09
	5	0.10
	5	0.11
	5	0.15
	5	0.23
	5	0.31
	5	0.33
	5	0.24
	5	0.33
	5	0.33

	5	0.51
	5	0.47
	5	0.41
	5	0.45
	5	0.45
	5	0.35
	5	0.37
	5	0.28
	5	0.26
	5	0.35
	5	0.35
	5	0.37
	5	0.28
	5	0.35
	5	0.41
	5	0.47
	5	0.43
	5	0.39
	5	0.47
	5	0.55
Level 4 (average =0.09 g/gal/day)	1	0.05
	1	0.05
	1	0.06
	5	0.11
	5	0.11
	5	0.15
Level 5 (average =0.07 g/gal/day)	1	0.03
	1	0.04
	1	0.05
	1	0.05
	1	0.07
	1	0.08
	1	0.11
	1	0.11
	1	0.12
	2.5	0.04
	2.5	0.04
	2.5	0.05
	2.5	0.07
	2.5	0.07
	5	0.05
	5	0.10
	5	0.11
SPAL (average =0.04 g/gal/day)	5	0.04
	5	0.04
	5	0.04

*designations used in ARB report; shown in order of increasing treatment

All of the data on fluorinated fuel tanks presented above were based on fuel tanks fluorinated by the same company. Available data from another company that fluorinates fuel tanks shows a 98 percent reduction in gasoline permeation through a HDPE fuel tank due to fluorination.[47]

ARB investigated the effect of fuel slosh on the durability of fluorinated surfaces. Three fluorinated fuel tanks were tested for permeation before and after being rocked with fuel in them 1.2 million times.[48] The results of this testing show that an 80% reduction in permeation was achieved on average even after the slosh testing was performed. However, this data also shows that an 89 percent reduction is feasible. Table 4.6-6 presents these results which were recorded in units of g/m^2/day. The baseline level is an approximation based on testing of similar fuel tanks.

Table 4.6-6: Permeation Rates for Fluorinated Fuel Tanks with Slosh Testing by ARB Over a 18-41°C Diurnal

Technology Configuration	Units	Tank 1	Tank 2	Tank 3	Average
Approximate Baseline	g/m^2/day	10.4	10.4	10.4	10.4
Fluorinated	g/m^2/day	1.17	1.58	0.47	1.07
	% reduction	89%	85%	96%	90%
Fluorinated & Sloshed	g/m^2/day	2.38	2.86	1.13	2.12
	% reduction	77%	73%	89%	80%

One study looked at the effect of alcohol in the fuel on permeation rates from fluorinated fuel tanks.[49] In this study, the fuel tanks were tested with both gasoline and various methanol blends. No significant increase in permeation due to methanol in the fuel was observed.

4.6.2.1.3 Barrier Platelets

We tested four portable gas cans molded with low permeation non-continuous barrier platelets 29°C (85°F) with gasoline. Prior to testing, the fuel tanks had been stored with gasoline in it for more than 10 weeks to stabilize the permeation rate. Table 4.6-7 presents the emission results which represent an average of nearly an 85 percent reduction from baseline.

Table 4.6-7: Permeation Rates for Plastic Fuel Containers with Barrier Platelets Tested by EPA at 29°C

Percent Selar®*	Tank Capacity [gallons]	Permeation Loss [g/gal/day]
4%	5	0.34
4%	5.3	0.10
4%	6.6	0.14
4%	6.6	0.13

*trade name for barrier platelet technology used in test program

The California Air Resources Board (ARB) collected test data on permeation rates from portable fuel containers molded with low permeation non-continuous barrier platelets using California certification fuel. The results show that this technology can be used to achieve significant reductions in permeation from plastic fuel containers. This data was collected using a diurnal cycle from 18-41°C which is roughly equivalent to steady-state permeation testing at 30°C. Five different percentages of the barrier material were tested. The average permeation rate for the 67 fuel tanks is 0.24 g/gal/day; however, there was a wide range in variation in the effectiveness of the barrier platelets for these fuel tanks. Some of the data outliers were actually higher than baseline emissions. This was likely due to leaks in the fuel tank which would result in large emission increases due to pressure built up with temperature variation over the diurnal cycle. Removing these six outliers, the average permeation rate is 0.15 g/gal/day with a minimum of 0.04 g/gal/day and a maximum of 0.47 g/gal/day. This represents more than an 85 percent reduction from the average baseline. Table 4.6-8 includes all of the ARB test data, including the outliers.

Table 4.6-8: Permeation Rates for Plastic Fuel Containers with Barrier Platelets Tested by ARB Over a 18-41°C Diurnal

Percent Selar®*	Tank Capacity [gallons]	Permeation Loss [g/gal/day]
4%	5.00	0.08
	5.00	0.09
(average =0.12 g/gal/day)	5.00	0.13
	5.00	0.16
	5.00	0.17
	6.00	0.08
	6.00	0.10
6%	2.00	0.06
	2.00	0.07
(average =0.16 g/gal/day)	2.00	0.10
	2.00	0.10
	2.00	0.11
	2.00	0.11
	2.00	0.28
	2.00	0.44
	2.00	0.45
	2.00	0.47
	5.00	0.07
	5.00	0.07
	5.00	0.07
	5.00	0.08
	5.00	0.12
	5.00	0.17
	6.00	0.06
	6.00	0.07

8%	1.00	0.14
	1.00	0.17
(average =0.32 g/gal/day)	1.00	0.21
	1.00	0.21
	1.00	0.21
	1.00	0.65
	1.00	0.85
	1.00	0.98
	1.00	1.66
	2.00	0.04
	2.00	0.05
	2.00	0.07
	2.00	0.09
	2.00	0.12
	2.00	0.16
	2.00	0.44
	5.00	0.08
	5.00	0.10
	6.00	0.05
	6.00	0.06
10%	1.00	0.15
	1.00	0.19
(average =0.28 g/gal/day)	1.00	0.19
	1.00	0.21
	1.00	0.23
	1.00	0.26
	1.00	0.79
	1.00	0.83
	1.00	0.88
	2.00	0.06
	2.00	0.06
	2.00	0.07
	2.00	0.08
	2.00	0.13
	2.00	0.14
	2.00	0.23
12%	1.00	0.13
	1.00	0.14
(average =0.21 g/gal/day)	1.00	0.20
	1.00	0.21
	1.00	0.23
	1.00	0.35

*trade name for barrier platelet technology used in test program

The fuel containers tested by ARB used a technology known as Selar® which uses nylon as the barrier resin. Dupont, who manufacturers Selar®, has recently developed a new resin (Selar RB®) that uses ethylene vinyl alcohol (EVOH) as the barrier resin. EVOH has much lower permeation than nylon, especially with alcohol fuel blends (see Section 4.6.2.3). Table 4.6-9 presents permeation rates for HDPE and three Selar RB® blends when tested at 60°C on xylene.[50] Xylene is a component of gasoline and gives a rough indication of the permeation rates on gasoline. This report also shows a reduction of 99% on naptha and 98% on toluene for 8%

Selar RB®.

Table 4.6-9: Xylene Permeation Results for Selar RB® at 60°C

Composition	Permeation, g mm/m^2/day	% Reduction
100% HDPE	285	–
10% RB 215/HDPE	0.4	99.9%
10% RB 300/HDPE	3.5	98.8%
15% RB 421/HDPE	0.8	99.7%

4.6.2.1.4 Coextruded barrier

One study looks at the permeation rates, using ARB test procedures, through multi-layer fuel tanks.[51] The fuel tanks in this study were 6 layer coextruded plastic tanks with EVOH as the barrier layer (3% of wall thickness). The outer layers were HDPE and two adhesive layers were needed to bond the EVOH to the polyethylene. The sixth layer was made of recycled polyethylene. The two test fuels were a 10 percent ethanol blend (CE10) and a 15 percent methanol blend (CM15). See Table 4.6-10.

Table 4.6-10: Permeation Results for a Coextruded Fuel Tank Over a 18-41°C Diurnal

Composition	Permeation, g/day	% Reduction
100% HDPE (approximate)	6 - 8	–
3% EVOH, 10% ethanol (CE10)	0.2	97%
3% EVOH, 15% methanol (CM15)	0.3	96%

4.6.2.1.5 Alternative Materials

Permeation can also be reduced from fuel tanks by constructing them out of a lower permeation material than HDPE. For instance, an that would reduce permeation is the use of metal fuel tanks because gasoline does not permeate through metal. In addition, there are grades of plastics other than HDPE that could be molded into fuel tanks. One material that has been considered by manufacturers is nylon; however, although nylon has excellent permeation resistance on gasoline, it has poor chemical resistance to alcohol-blended fuels. As shown in Table 4.6-14, nylon would result in about a 98 percent reduction in permeation compared to HDPE for gasoline. However, for a 10 percent ethanol blend, this reduction would only be about 40-60 percent depending on the grade of nylon. For a 15 percent methanol blend, the permeation would actually be several times higher through nylon than HDPE.

Other materials, which have excellent permeation even with alcohol-blended fuels are acetal copolymers and thermoplastic polyesters. These polymers can be used to form fuel tanks in the blow-molding, rotational-molding, and injection-molding processes. An example of an acetal copolymer is known as Celcon® which has excellent chemical resistance to fuel and has been shown to be durable based on exposure to automotive fuels for 5000 hours at high temperatures.[52] As shown in Table 4.6-14, Celcon® would result in more than a 99 percent reduction in permeation compared to HDPE for gasoline. On a 10 percent ethanol blend, the use of Celcon® would result in more than a 95 percent reduction in permeation. Two thermoplastic polyesters, known as Celanex® and Vandar®, are being considered for fuel tank construction and are being evaluated for permeation resistance by the manufacturer.

4.6.2.2 Fuel Hoses

Thermoplastic fuel lines for automotive applications are generally built to SAE J2260 specifications.[53] Category 1 fuel lines under this specification have permeation rates of less than 25 g/m^2/day at 60°C on CM15 fuel. One thermoplastic used in automotive fuel line construction is polyvinylidene fluoride (PVDF). Based on the data presented in Section 4.6.2.3, a PDVF fuel line with a typical wall thickness (1 mm) would have a permeation rate of 0.2 g/m^2/day at 23°C on CM15 fuel. However, recreational vehicle manufacturers have commented that this fuel line would not be flexible enough to use in their applications because they require flexible rubber hose to fit tight radii and to resist vibration. In addition, using plastic fuel line rather than rubber hose would require the additional cost of changing hose fittings on the vehicles.

Manufacturers recommended using R9 fuel hose as a low permeation requirement. This hose is designated under SAE recommended practice J30[54] for fuel injection systems and has a maximum permeation rate of 15 g/m^2/day on ASTM Fuel C. On a fuel containing an alcohol blend, permeation would likely be much higher from these fuel hoses. SAE J30 specifically notes that “exposure of this hose to gasoline or diesel fuel which contain high levels, greater than 5% by volume, of oxygenates, i.e., ethanol, methanol, or MTBE, may result in significantly higher permeation rates than realized with ASTM Fuel C.” R9 hose is made with a thin low permeation barrier sandwiched between layers of rubber. A typical barrier material used in this construction is FKM. Based on the data presented in Section 4.2.8.3 for FKM, the permeation rate is 3-5 times higher on Fuel CE10 than Fuel C. Therefore, a typical R9 hose meeting 15 g/m^2/day at 23°C on Fuel C may actually permeate at a level of 40-50 g/m^2/day on fuel with a 10 percent ethanol blend.

SAE J30 also designates R11 and R12 hose which are intended for use as low permeation fuel feed and return hose. R11 has thee classes known as A, B, and C. Of these, R11-A has the lowest permeation specification which is a maximum of 25 g/m^2/day at 40°C on CM15 fuel. Because permeation rates are generally higher on CM15 than CE10 and because they are 2-4 times higher at 40°C than at 23°C, hose designed for this specification would likely meet our permeation requirement. R12 hose has a permeation requirement of 100 g/m^2/day at 60°C on CM15 fuel. This is roughly equivalent in stringency as the R11-A permeation requirement.

There are lower permeation fuel hoses available today that are manufactured for automotive applications. These hoses are generally used either as vapor hoses or as short sections of fuel line to provide flexibility and absorb vibration. One example of such a hose[55] is labeled by General Motors as “construction 6" which is a multilayer hose with an inner layer of THV sandwiched in inner and outer layers of a rubber known as ECO.[11] A hose of this

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[11] THV = tetrafluoroethylene hexafluoropropylene, ECO = epichlorohydrin/ethylene oxide

construction would have less than 8 g/m^2/day at 40°C when tested on CE10. In look and flexibility, this hose is not significantly different than the SAE J30 R7 hose generally used in recreational vehicle applications.

Permeation data on several low permeation hose designs were provided to EPA by an automotive fuel hose manufacturer.[56] This hose, which is as flexible as R9 hose, was designed for automotive applications and is available today. Table 4.6-11 presents permeation data on three hose designs that use THV 800 as the barrier layer. The difference in the three designs is the material used on the inner layer of the hose. This material does not significantly affect permeation emissions through the hose but can affect leakage at the plug during testing (or connector in use) and fuel that passes out of the end of the hose which is known as wicking. The permeation testing was performed using the ARB 18-41°C diurnal cycle using a fuel with a 10 percent ethanol blend (E10).

Table 4.6-11: Hose Permeation Rates with THV 800 Barrier over ARB Cycle (g/m^2/day)

Hose Name	Inner Layer	Permeation	Wicking	Leaking	Total
CADBAR 9610	THV	0.16	0.00	0.02	0.18
CADBAR 9710	NBR	0.17	0.29	0.01	0.47
CADBAR 9510	FKM	0.16	0.01	0.00	0.18

The data presented above shows that there is hose available that can easily meet the hose permeation standard on E10 fuel. Although hose using THV 800 is available, it is produced for automobiles that will need to meet the tighter evaporative emission requirements in the upcoming Tier 2 standards. Hose produced in mass quantities today uses THV 500. This hose is less expensive and could be used to meet the recreational vehicle permeation requirements. Table 4.6-12 presents information comparing hose using THV 500 with the hose described above using THV 800 as a barrier layer.[57] In addition, this data shows that permeation rates more than double when tested on CE10 versus Fuel C. One recreational vehicle manufacturer has expressed concern to EPA that this hose may be too stiff to stay on the fuel line and fuel tank connectors without clamps as does their current fuel line. If a manufacturer opts to use this or a similar line, this problem will need to be resolved either through further testing, a change to the connector geometry, the use of an adhesive, or the use of one of any of several of different types of clamps.

Table 4.6-12: Comparison of Hose Permeation Rates with THV 500 and 800 (g/m^2/day)*

Hose Inner Diameter, mm	THV 500		THV 800	
	Fuel C	Fuel CE10	Fuel C	Fuel CE10
6	0.5	1.4	0.2	0.5
8	0.5	1.4	0.3	0.5
10	0.5	1.5	0.2	0.5

* Calculated using data from Thwing Albert materials testing (may overstate permeation)

We contracted with an independent testing laboratory to test a section of R9 hose and a section of automotive vent line hose for permeation.[58] These hoses had a six mm inner diameter. The test lab used the SAE J30 test procedures for R9 hose with both Fuel C and Fuel CE10. We purchased the R9 hose (which was labeled as such) from a local auto parts store. According to this testing, the R9 hose is well below the SAE specification of 15 g/m^2/day. In fact, it meets this limit on Fuel CE10 as well. The automotive vent line showed similar results. This data is presented in Table 4.6-13.

Table 4.6-13: Test Results on Commercially Available Hose Samples (g/m^2/day)

Hose Sample	Fuel C	Fuel CE10
R9	10.1	12.1
Automotive vent line	10.9	9.0

4.6.2.3 Material Properties

This section presents data on permeation rates for a wide range of materials that can be used in fuel tanks and hoses. The data also includes effects of temperature and fuel type on permeation. Because the data was collected from several sources, there is not complete data on each of the materials tested in terms of temperature and test fuel. Table 4.6-14 gives an overview of the fuel systems materials included in the data set. Tables 4.6-15 through 4.6-18 present permeation rates using Fuel C, a 10% ethanol blend (CE10), and a 15% methanol blend (CE15) for the test temperatures of 23, 40, 50, and 60°C.

Table 4.6-14: Fuel System Materials

Material Name	Composition
HDPE	high-density polyethylene
Nylon 12	thermoplastic
EVOH	ethylene vinyl alcohol, thermoplastic
Polyacetal	thermoplastic
PBT	polybutylene terephthalate, thermoplastic
PVDF	polyvinylidene fluoride, fluorothermoplastic
NBR	nitrile rubber
HNBR	hydrogenated nitrile rubber
FVMQ	flourosilicone
FKM	fluoroelastomer
FEB	fluorothermoplastic
PFA	fluorothermoplastic
Carilon	aliphatic poly-ketone thermoplastic
HDPE	high density polyethylene
LDPE	low density polyethylene
Celcon	acetal copolymer
THV	tetra-fluoro-ethylene, hexa-fluoro-propylene, vinyledene fluoride
E14659	fluoropolymer film
E14944	fluoropolymer film
ETFE	ethylene-tetrafluoro-ethylene, fluoroplastic
GFLT	fluoroelastomer
FEP	fluorothermoplastic
PTFE	polytetrafluoroethylene, fluoroplastic
FPA	copolymer of tetrafluoroethylene and perfluoroalkoxy monomer

Table 4.6-15: Fuel System Material Permeation Rates at 23°C by Fuel Type [59,60,61,62,63]

Material Name	Fuel C g-mm/m^2/day	Fuel CE10 g-mm/m^2/day	CM15 g-mm/m^2/day
HDPE	35	–	35
Nylon 12, rigid	0.2	–	64
EVOH	–	–	10
Polyacetal	–	–	3.1
PBT	–	–	0.4
PVDF	–	–	0.2
NBR (33% ACN)	669	1028	1188
HNBR (44%ACN)	230	553	828
FVMQ	455	584	635
FKM Viton A200 (66%F)	0.80	7.5	36
FKM Viton B70 (66%F)	0.80	6.7	32
FKM Viton GLT (65%F)	2.60	14	60
FKM Viton B200 (68%F)	0.70	4.1	12
FKM Viton GF (70%F)	0.70	1.1	3.0
FKM Viton GFLT (67%F)	1.80	6.5	14
FKM - 2120	8	–	44
FKM - 5830	1.1	–	8
Teflon FEB 1000L	0.03	0.03	0.03
Teflon PFA 1000LP	0.18	0.03	0.13
Tefzel ETFE 1000LZ	0.03	0.05	0.20
Nylon 12 (GM grade)	6.0	24	83
Nitrile	130	635	1150
FKM	–	16	–
FE 5620Q (65.9% fluorine)	–	7	–
FE 5840Q (70.2% fluorine)	–	4	–
PTFE	0.05	–	0.08*
ETFE	0.02	–	0.04*
PFA	0.01	–	0.05*
THV 500	0.03	–	0.3

* tested on CM20.

Table 4.6-16: Fuel System Material Permeation Rates at 40°C by Fuel Type [64,65]

Material Name	Fuel C g-mm/m^2/day	Fuel CE10 g-mm/m^2/day	CM15 g-mm/m^2/day
Carilon	0.06	1.5	13
EVOH - F101	<0.0001	0.013	3.5
EVOH - XEP380	<0.0001	–	5.3
HDPE	90	69	71
LDPE	420	350	330
Nylon 12 (L2101F)	2.0	28	250
Nylon 12 (L2140)	1.8	44	–
Celcon	0.38	2.7	–
Dyneon E14659	0.25	–	2.1
Dyneon E14944	0.14	–	1.7
ETFE Aflon COP	0.24	0.67	1.8
m-ETFE	0.27	–	1.6
ETFE Aflon LM730 AP	0.41	0.79	2.6
FKM-70 16286	11	35	–
GFLT 19797	13	38	–
Nitrile	–	1540	3500
FKM	–	86	120
FE 5620Q (65.9% fluorine)	–	40	180
FE 5840Q (70.2% fluorine)	–	12	45
THV-310 X	–	–	5.0
THV-500	0.31	–	3.0
THV-610 X	–	–	2.1

Table 4.6-17: Fuel System Material Permeation Rates at 50°C by Fuel Type [66]

Material Name	Fuel C g-mm/m^2/day	Fuel CE10 g-mm/m^2/day	CM15 g-mm/m^2/day
Carilon	0.2	3.6	–
HDPE	190	150	–
Nylon 12 (L2140)	4.9	83	–
Celcon	0.76	5.8	–
ETFE Afcon COP	–	1.7	–
FKM-70 16286	25	79	–
GFLT 19797	28	77	–

Table 4.6-18: Fuel System Material Permeation Rates at 60°C by Fuel Type [67,68,69,70]

Material Name	Fuel C $g\text{-}mm/m^2/day$	Fuel CE10 $g\text{-}mm/m^2/day$	CM15 $g\text{-}mm/m^2/day$
Carilon	0.55	7.5	–
HDPE	310	230	–
Nylon 12 (L2140)	9.5	140	–
Celcon	1.7	11	–
ETFE Afcon COP	–	3.8	–
FKM-70 16286	56	170	–
GFLT 19797	60	130	–
polyeurethane (bladder)	285	460	–
THV-200	–	54	–
THV-310 X	–	–	38
THV-510 ESD	6.1	18	35
THV-500	–	11	20
THV-500 G	4.1	10	22
THV-610 X	2.4	5.4	9.0
ETFE 6235 G	1.1	3.0	6.5
THV-800	1.0	2.9	6.0
FEP	0.2	0.4	1.1

4.6.3 Test Procedures

4.6.3.1 Fuel Tanks

Essentially, two options may be used to test fuel tanks for certification. The first option is to perform all of the durability tests on a fuel tank and then test the permeation rate. The second option is to test a fuel tank that has been preconditioned and adjust the results using a deterioration factor. The deterioration factor would need to be based on testing of that tank or a similar tank unless you can use good engineering judgment to apply the results of previous durability testing with a different fuel system. Figure 4.6-2 provides flow charts for these two options.

4.6.3.1.1 Option 1: full test procedure

Under the first option, the fuel tank is tested both before and after a series of durability tests. We estimate that this test procedure would take about 49 weeks to complete. Prior to the first test, the fuel tank must be preconditioned to ensure that the hydrocarbon permeation rate has stabilized. Under this step, the fuel tank must be filled with a 10 percent ethanol blend (E10), sealed, and soaked for 20 weeks at a temperature of 28 °C ± 5 °C. Once the permeation rate has stabilized, the fuel tank is drained and refilled with E10, sealed, and tested for a baseline permeation rate. The baseline permeation rate from the fuel tank is determined by measuring the weight difference the fuel tank before and after soaking at a temperature of 28 °C ± 2 °C over a period of at least 2 weeks.

To determine a permeation emission deterioration factor, we are specifying three durability tests: slosh testing, pressure-vacuum cycling, and ultra-violet (UV) light exposure.

The purpose of these deterioration tests is to help ensure that the technology is durable and the measured emissions are representative of in-use permeation rates. For slosh testing, the fuel tank is filled to 40 percent capacity with E10 fuel and rocked for 1 million cycles. The pressure-vacuum testing contains 10,000 cycles from -0.5 to 2.0 psi. The slosh testing is designed to assess treatment durability as discussed above. These tests are designed to assess surface microcracking concerns. These two durability tests are based on a draft recommended SAE practice.[71] The third durability test is intended to assess potential impacts of UV sunlight (0.2 µm - 0.4 µm) on the durability of the surface treatment. In this test, the tank must be exposed to a UV light of at least 0.40 W-hr/m^2 /min on the tank surface for 15 hours per day for 30 days. Alternatively, it can be exposed to direct natural sunlight for an equivalent period of time in exposure hours.

The order of the durability tests is optional. However, we require that the fuel tank be soaked to ensure that the permeation rate is stabilized just prior to the final permeation test. If the slosh test is run last, the length of the slosh test may be considered as part of this soak period. Where possible, the deterioration tests may be run concurrently. For example, the fuel tank could be exposed to UV light during the slosh test. In addition, if a durability test can clearly be shown to not be appropriate for a given product, manufacturers may petition to have this test waived. For example, a fuel tank that is only used in vehicles where an outer shell prevents the tank from being exposed to sunlight may not benefit from UV testing.

After the durability testing, once the permeation rate has stabilized, the fuel tank is drained and refilled with E10, sealed, and tested for a final permeation rate. The final permeation rate from the fuel tank is determined using the same measurement method as for the baseline permeation rate. The final permeation rate would be used for the emission rate from this fuel tank. The difference between the baseline and final permeation rates would be used to determine a deterioration factor for use on subsequent testing of similar fuel tanks.

4.6.3.1.2 Option 2: base test with DF

Under the second option, the fuel tank is tested for baseline permeation only, then a deterioration factor (DF) is applied. We estimate that this test procedure would take about 22 weeks to complete. As with Option 1 baseline testing, the fuel tank must be preconditioned to ensure that the hydrocarbon permeation rate has stabilized. Under this step, the fuel tank must be filled with a 10 percent ethanol blend (E10), sealed, and soaked for 20 weeks at a temperature of 28 °C ± 5 °C. Once the permeation rate has stabilized, the fuel tank is drained and refilled with E10, sealed, and tested for a baseline permeation rate. The baseline permeation rate from the fuel tank is determined by measuring the weight difference the fuel tank before and after soaking at a temperature of 28 °C ± 2 °C over a period of at least 2 weeks.

The final permeation rate is then determined by applying a DF to the baseline permeation rate. The DF, in units of g/m^2/day, is added to the baseline permeation rate. This DF must be determined with testing on a fuel tank in the same emission family.

4.6.3.2 Fuel Hoses

The permeation rate from fuel hoses would be measured at a temperature of 23 °C ± 2 °C over a period of at least 2 weeks. A longer period may be necessary for an accurate measurement for hose with low permeation rates. Permeation would be measured through the weight loss technique described in SAE J30.[72] The hose must be preconditioned with a fuel soak to ensure that the permeation rate has stabilized. Based on times to achieve equilibrium for permeation measurement described in SAE J2260[73] for automotive fuel lines, and adjusting for temperature and test fuel type, we estimate a minimum soak time of 4 weeks. The fuel used for this testing would be a blend of 90 percent gasoline and ten percent ethanol. This fuel is consistent with the test fuel used for on-highway evaporative emission testing.

4.6.4 Conclusion

We believe that manufacturers will be able to meet the fuel tank permeation requirements through several design strategies that include sulfonation, fluorination, barrier platelets, and coextruded barriers. Our cost analysis, presented in Chapter 5, indicates that sulfonation would likely be the most attractive technology. However, conversations with manufacturers have revealed interest in each of these low permeation strategies. We believe the data presented above supports a final standard which requires about an 85% reduction in permeation, compared baseline HDPE fuel tanks, throughout the useful life of the recreational vehicle.

As discussed above, fuel hose is available today that meets the permeation requirements for recreational vehicles. Low permeation hose was generally developed for automotive applications; however, we believe that this fuel hose can be used in recreational vehicle applications. Even assuming that new hose clamps would be required, our analyses in Chapters 5 and 6 show that the low permeation hose would be inexpensive yet effective.

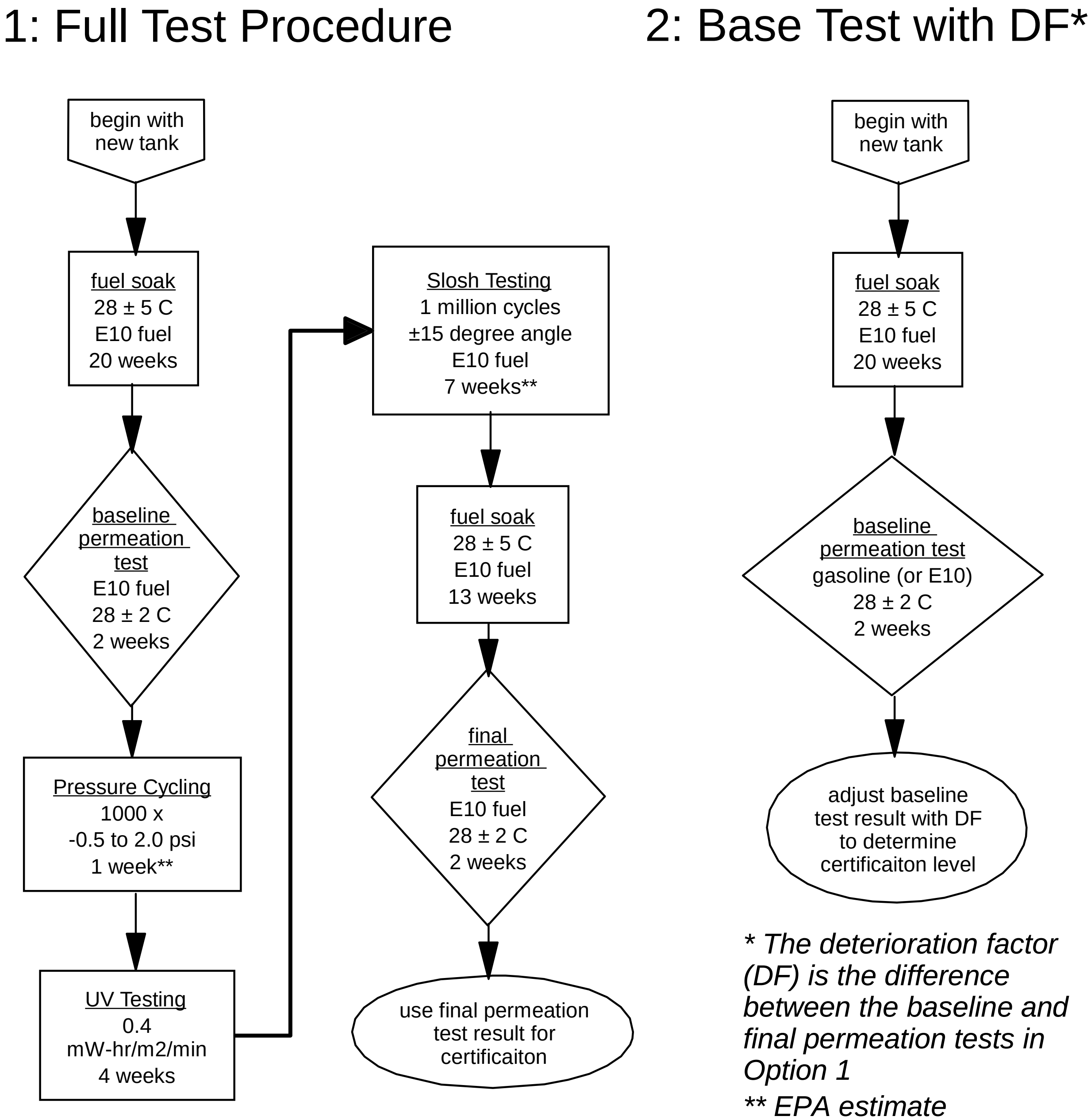
4.6.5 Impacts on Noise, Energy, and Safety

The Clean Air Act requires EPA to consider potential impacts on noise, energy, and safety when establishing the feasibility of new permeation standards for recreational vehicles. In this case, we would not expect evaporative emission controls to have any impact on noise from a vehicle because noise from the fuel system is insignificant.

We anticipate that permeation emission standards will have a positive impact on energy. By capturing or preventing the loss of fuel through permeation, we estimate that the average lifetime fuel savings will be 11.8 gallons for snowmobiles, 5.4 gallons for off-highway motorcycles and 6.5 gallons for all-terrain vehicles. This translates to a fuel savings of about 12 million gallons in 2030 when most recreational vehicles used in the U.S. are expected to have permeation emission control.

We believe that permeation emission standards will have no negative impacts on safety, and may even have some benefits due to the reduction of fuel vapor around a recreational vehicle.

Figure 4.6-2: Flow Chart of Fuel Tank Permeation Certification Test Options



** The deterioration factor (DF) is the difference between the baseline and final permeation tests in Option 1*

*** EPA estimate*

Appendix to Chapter 4: Emission Index For Recreational Vehicle Hangtags

Section1051.135(g) specifies that recreational vehicles should have consumer labels that show the emission characteristics of the vehicle using a normalized zero to ten index. The index is called a nonroad emission rating (NER). This appendix describes the derivation of those indices. The primary indices were derived based on four general principles:

The index should be simple for the consumer to use.

A vehicle with the highest emissions allowed or expected under the regulations should have a value of ten.

A vehicle with emissions equal to the average standard should be in the middle of the range. (For categories with two phases, a vehicle with emissions equal to the average Phase 2 standard under should be approximately five.)

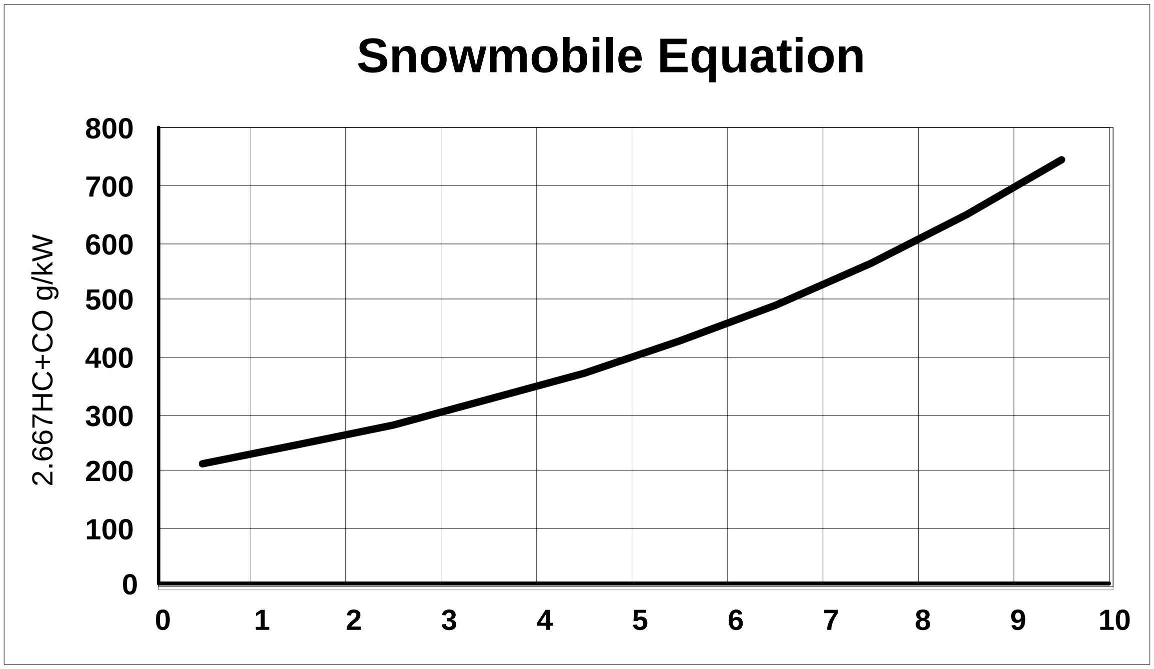
Each index should allow for vehicles that are significantly cleaner than the average. The indices should also work without adjustment if we were to establish more stringent standards in the future.

As described below, we applied these principles separately to each of the categories, considering the baseline emissions, FEL caps, average standards, and current and future technology options. In general, since the recreational vehicle programs are designed to allow different technology options, we believe that a logarithmic scale in generally appropriate. However, in some cases, a linear scale is more appropriate for all or part of the index. In some cases, it may be possible to have emissions high enough to calculate the NER as eleven or higher. In those cases, the regulations specify that the vehicle should be labeled as a ten.

4A.1 Snowmobiles

The index for snowmobiles uses a single log-linear curve to convert HC and CO emissions into normalized values between zero and ten. HC and CO emissions are weighted based on baseline values so that a 50 percent reduction in HC emissions is equivalent to a 50 percent reduction in CO emissions. (The ratio of baseline CO emissions to baseline HC emissions is 400:150, or 2.667.) The following equation gives a value of ten for vehicles with HC emissions of 150 g/kW-hr and CO emissions 400 g/kW-hr; and a value of five for vehicles with HC emissions of 75 g/kW-hr and CO emissions 200 g/kW-hr:

$$NER = 16.61 \times \log(2.667 HC + CO) - 38.22$$



4A.2 Off-highway Motorcycles

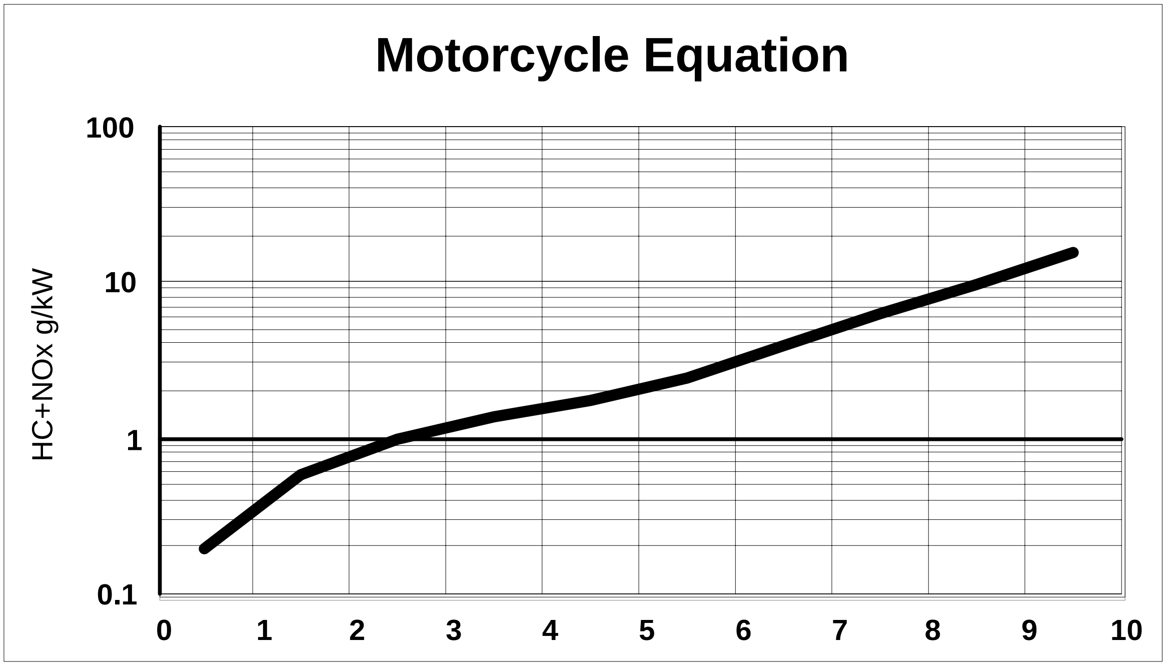
The index for off-highway motorcycles uses a combination of a linear curve and a log-linear curve to convert HC+NOx emissions into normalized values between zero and ten. The following linear equation, which applies for vehicles with below average emissions gives a value of five for vehicles with HC+NOx emissions of 2.0 g/km:

$$NER = 2.500(HC + NOx)$$

The following log-linear equation, which applies for vehicles with above average emissions gives a value of ten for vehicles with HC+NOx emissions of 20 g/km; and a value of five for vehicles with HC+NOx emissions of 2.0 g/km:

$$NER = 5.000 \times \log(HC + NOx) + 3.495$$

It was necessary to use a linear equation for the lower part of the curve to allow for more gradations just below the average, and fewer for very low levels. For example, using the log equation, it would have been necessary to have emission below 1.0 g/km to get an emission rating that would round to three, while with the linear equation, it would only be necessary to have emissions below 1.4 g/km to get an emission rating that would round to three.



4A.3 ATVs (g/km)

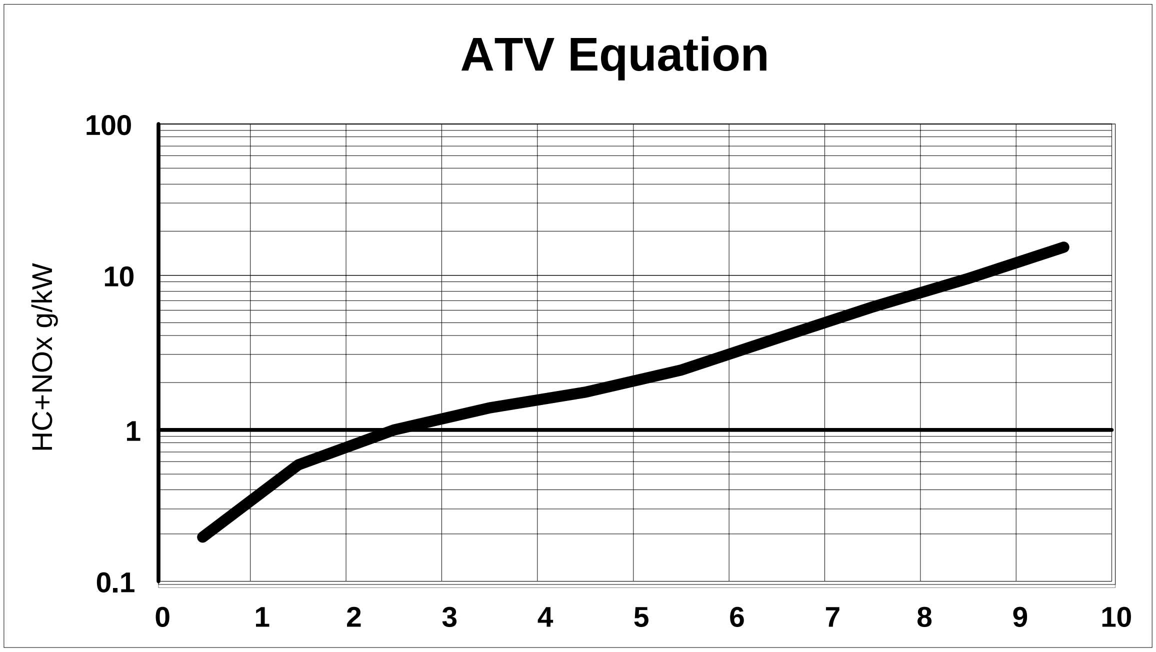
The primary index for ATVs uses a combination of a linear curve and a log-linear curve to convert HC+NOx emissions into normalized values between zero and ten. The following linear equation, which applies for vehicles with below average emissions gives a value of five for vehicles with HC+NOx emissions of 1.5 g/km:

$$NER = 3.333(HC + NOx)$$

The following log-linear equation, which applies for vehicles with above average emissions gives a value of ten for vehicles with HC+NOx emissions of 20 g/km; and a value of five for vehicles with HC+NOx emissions of 1.5 g/km:

$$NER = 4.444 \times \log(HC + NOx) + 4.217$$

It was necessary to use a linear equation for the lower part of the curve to allow for more gradations just below the average, and fewer for very low levels. For example, using the log equation, it would have been necessary to have emission below 0.7 g/km to get an emission rating that would round to three, while with the linear equation, it would only be necessary to have emissions below 1.1 g/km to get an emission rating that would round to three.
where HC +NOx is the cycle-weighted emission rates for hydrocarbons plus oxides of nitrogen in g/km.



4A.4 ATVs (g/kW)

There are two cases in which we allow ATVs to certify to g/kW emission standards based on engine testing: ATVs less than 100 cc, and ATVs built before 2009. We developed separate equations for these cases, based on the same general principles as for other ATVs. In developing these equations, we considered FEL caps, average standards, test cycle issues, and the available technology options. The following linear equation, applies for ATV with engine smaller than 100cc:

$$NER = 0.250(HC + NOx) + 0.250$$

The following log-linear equation, applies for larger ATVs certified under the interim engine testing option:

$$NER = 9.898 \times \log(HC + NOx) - 4.898$$

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