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OFFICE OF
AIR AND RADIATION

MEMORANDUM

SUBJECT: Emission Data and Procedures for Large SI Engines

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TO: Docket A-2000-01

In an Advance Notice of Proposed Rulemaking from the Environmental Protection Agency, we announce our intent to develop a program to regulate emission levels from nonroad spark-ignition engines rated over 19 kW ("Large SI engines"). This category of engines generally includes all nonrecreational land-based engines that are not installed in motor vehicles or stationary applications. This memorandum reviews available technical information relevant to setting emission standards for these engines. The memorandum first considers various ways to define test procedures for measuring emissions, then presents emission data that will shed light on appropriate emission standards.

I. Emission Testing to Support the Development of Emission Standards

In 1998, California ARB conducted testing with Southwest Research Institute (SwRI) to determine the feasibility of achieving low emission levels with a three-way catalyst system that could be installed in nonroad equipment. They were successful in showing that an engine with a new emission-control system was capable of operating effectively, both to control emissions and to provide satisfactory performance in the equipment.[1] These data are summarized in Section III below.

In 2000 SwRI did further testing on Large SI engines with funding and/or consultation from the California ARB, the South Coast Air Quality Management District, and EPA. This effort focused on three principal remaining areas. First, we obtained transient duty cycle information by monitoring several engine, equipment, and ambient variables from normal forklift operation. Second, we removed these two engines from the forklifts and operated them in the laboratory. Since these engines had each accumulated several thousand hours of operation with a functioning catalyst system, this showed us how emission-control systems perform over extended normal operation in an industrial application. Third, emission testing on a full range of steady-state test points and several transient duty cycles, with optimized engine calibrations as appropriate, provided a good indication of the level of emission-control possible from the installed technologies.

The selected engines had been retrofitted with the 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 was the more basic type that allows only a single adjustment for controlling air-fuel ratios across the range of speed-load combinations.

Testing occurred in laboratory conditions typical for the test location. Ambient temperatures ranged from 70 to 86° F. Barometric pressures were in a narrow range around 730 mm Hg. Humidity levels ranged from about 4 to 14 g of water per kg dry air, but all emission levels were corrected to a reference condition of 10.7 g/kg. Most testing occurred at humidity levels above 10.7, in which case actual NOx emission levels were up to 7 percent lower than reported by SwRI. In the driest conditions, measured NOx emission levels were up to 10 percent higher than reported.

The SwRI report include a further description of these forklifts, the facility where they were operating, and the results of the laboratory testing.[2] These data are summarized in Section III below.

II. Emission Measurement

Before considering the appropriate emission standard for these emission-control technologies, it is important to consider the procedures for measuring emissions.

Defining emission standards based on steady-state duty cycles is a common approach. The Large SI emission standards set by California ARB, for example, are based on the ISO C2 and D2 duty cycles. The following sections describe a rationale for supplementing these steady-state duty cycles with additional ways to measure emission-control effectiveness.

A. Why measure emissions during transient operation?

An engine designed for low emissions from a small number of discrete test points may not effectively control emissions in use. We have measured engine operation in forklifts and found that, except for extended engine idling, there is very little steady-state operation over the course of normal operation. Similar measurements in a wide range of diesel equipment have also shown that steady-state operation in the field is quite rare for those engines. Engines that power arc welders are governed to operate at a constant speed, but even in this application, engine load varies significantly.

SwRI testing has shown a wide variation in transient emission levels from an engine with a consistent steady-state calibration that gives low emission levels on the C2 duty cycle. Table 1 shows a variety of measured transient emission levels corresponding with a single steady-state calibration. Transient HC+NOx levels were up to 20 times higher than steady-state levels on the same engine.[a] Transient CO levels were sometimes lower than steady-state levels, but were in some cases higher by a factor of five. This shows that the steady-state test results are a poor predictor of emissions during transient operation.

Table 1

Mazda Engine Emission Levels for Various Settings (g/hp-hr)

Test Engine	C2 Emission Levels		Transient Emission Levels	
	THC+NOx	CO	THC+NOx	CO
Mazda	0.51	3.25	10.1	0.07
			3.3	17.1

Some of the difference between steady-state and transient emission levels results from the fact that the transient operation traverses a wide range of steady-state test points, many of which may have emission levels significantly higher than those included in the seven modes of the C2 duty cycle. Optimizing the engine for its best control of transient emissions generally resulted from adjusting the control of air-fuel ratios to keep the engine at stoichiometry at idle and other low-speed operating points.

Requiring manufacturers to measure emissions on a prescribed transient duty cycle would be an effective way of ensuring that engines are able to control emissions in real-world operation. The design engineer can investigate control strategies to address high emission levels from transient operation, primarily by focusing on careful control of air-fuel ratios at idle and low-speed operation.

B. What are off-cycle emissions?

As described earlier, a steady-state duty cycle with a discrete number of test points fails to capture a wide range of in-use operation. A transient duty cycle helps address these concerns by exercising the engine as it goes

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[a] Throughout this memorandum, measured hydrocarbon emissions are either nonmethane hydrocarbon (NMHC) or total hydrocarbon (THC), which includes methane emissions.

through many different speeds and loads of real operation. However, a transient duty cycle based on measured operation from a few pieces of equipment still fails to include many kinds of operation from other engines. Similar equipment operating in a different facility may undergo significantly different operation in the field. Also, different types of equipment performing widely varying tasks will likely have engine operation that is unique to the application.

No single, defined duty cycle can include the whole range of engine operation. Not-to-exceed testing acknowledges this by setting a standard for any normal operation, taking into account the natural variation in emissions from varying engine operation at different speeds and loads. Similarly, engines in the field are not restricted to operating in controlled laboratory conditions. Any time engines are designed only to control emissions under a narrow range of operation or ambient conditions, there is a significant risk that the anticipated emission reductions will not materialize.

Emission measurements from the SwRI testing highlight this concern. Figure 3 shows that an engine can have very low NOx emission levels at some points, with a 10-fold increase at other points under the engine map. This variation is not the result of an intent to "beat" the cycle with a design that operates at low levels only for a certification test. Rather, this reflects the normal variation for a first-iteration effort to calibrate the engine for low emissions.

Figure 4 provides an example of a problematic calibration. This engine has very high CO levels at all the full-load points, indicating the likely need for a software adjustment to better control air-fuel ratios at those points. A transient duty cycle may include very little engine operation at these high-emission points, and would therefore not require manufacturers to optimize emission levels there. If this engine is installed in an application where it operates more often on the engine's lug curve, it will have much higher emissions than would be predicted by the steady-state or transient duty cycles.

Figure 3: Truck 29, Steady-State NO_x Emissions Results over Normalized Speed and Load

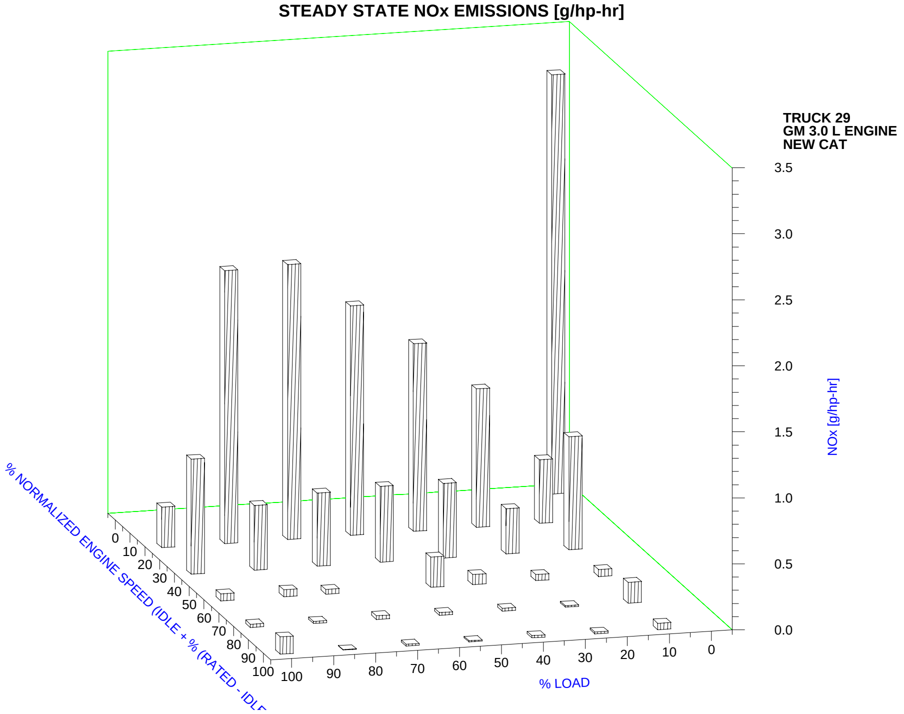
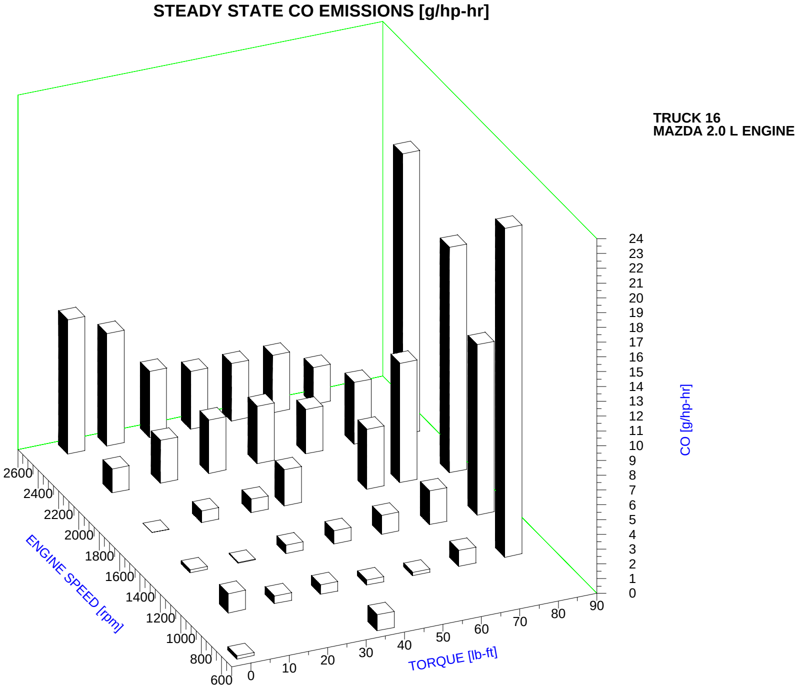


Figure 4: Truck 16, Steady-State CO Emissions Results



One of the SwRI test engines was found to be unable to provide enough fuel flow at one engine operating mode. The air-fuel ratio at this point was so high that there was no NOx reduction occurring in the catalyst. A simple adjustment to enable increased fuel flow allowed the engine to operate at stoichiometry, which brought the NOx conversion efficiency up to about 80 percent at that mode.

Adopting a not-to-exceed standard would require the design engineer to control an engine's emissions under the whole range of normal in-use operation. An additional important advantage of not-to-exceed testing relates to the ability to test engines in the field. If testing were limited to discrete steady-state or transient duty cycles, it would not be possible to conduct a valid emission test without a laboratory dynamometer. The next section addresses this in further detail.

C. Why do we want to measure emissions in the field?

Measuring an engine's emissions as it undergoes normal operation in the field, powering a specific piece of equipment on any given day, is the best way of verifying that an engine is achieving the intended level of emission control during real operation. The alternative to field testing is to remove engines and ship them to a laboratory for dynamometer testing. The high cost of this effort limits the amount of in-use testing we can reasonably conduct or expect manufacturers to conduct.

The tools for field measurement have advanced to the point that we are able to consider new equipment and procedures to do a valid emission test without removing the engine. The equipment in which the engine is installed serves as the dynamometer. The portable devices for measuring emissions in the field cost significantly less than full-size laboratory equipment.

Engineers can design an engine's onboard computer to monitor speed and load at all times. Identifying and recording speed is straightforward. For torque values, the manufacturer would need to monitor a surrogate value such as intake manifold pressure or throttle position, then rely on a look-up table programmed into the onboard computer to convert these torque indicators into foot-pounds or other equivalent torque units. Manufacturers may also choose to program the torque-conversion tables into a remote scan tool.

Such a method would allow manufacturers to test the required number of in-use engines at a much lower cost than in a laboratory. EPA or manufacturers could also do additional testing to better understand the in-use performance of engine designs certified to meet emission standards.

To use field-testing equipment and procedures as a tool to confirm that engines comply with emission standards, we would want to adopt test procedures, including calibration and measurement procedures, definitions, and other specifications. This would help ensure sufficient accuracy to rely on the measurement as a valid indication of an engine's emission level.

Designing an engine to monitor and report its instantaneous speeds and loads also has an additional benefit. Manufacturers could easily monitor engines to develop cycles of normal operation for individual applications. This could be used to verify that engine designs are able to control emissions in various applications, thereby reducing the risk of noncompliance from field measurements. This duty-cycle information could also be used for product-development purposes to ensure that engines will perform well in specific applications.

D. Why would we keep steady-state test procedures?

As described above, a steady-state duty cycle provides limited assurance that in-use engines will adequately control emissions over their useful life. However, we would likely propose including steady-state operation as part of the test program for four reasons.

First, measuring emissions on the available steady-state duty cycles addresses intermediate-speed operation that is not covered well by the transient segment. Currently available data for developing the transient duty cycle do not include engines used in vehicles like sweepers, aerial lifts and airport service vehicles that have more intermediate-speed operation. Thus, inclusion of the C2 test points adds to the overall representativeness of the duty cycle.

Second, using the C2 and D2 duty cycles would allow for better harmonization of our standards with those of California ARB. Worldwide harmonization is also at issue, since European and Japanese regulators have long relied on the steady-state ISO duty cycles to define emission standards.

Third, identifying emission levels on the C2 or D2 duty cycles provides a useful benchmark for later testing. For example, the goal of production-line testing is primarily to evaluate the effect of production variability on emissions performance. Routinely testing production-line engines under transient operation should therefore not be necessary. Simpler tests with the steady-state testing modes should be sufficient to quantify the effect of production variability. If steady-state testing reveals a problem, however, it may be best to do transient emission measurements before presuming noncompliance.

Fourth, the C2 and D2 duty cycles have been widely used as duty cycles for evaluating emission performance. Measuring emissions on these steady-state cycles provides consistency with emission requirements adopted by California ARB. This also helps for emission modeling purposes, where historical data is all based on steady-state emission levels.

E. How did EPA develop transient duty-cycle segments?

The primary goal in defining a transient duty cycle is to include a wide range of real engine operation. A well-designed duty cycle would provide assurance that engines used in a wide variety of applications are able to control emissions effectively. As a result, a good transient duty cycle would include a variety of challenging, real in-use operation to minimize the risk of surprisingly high emissions from not-to-exceed testing.

Our approach in constructing a transient duty cycle was to include measured engine operation from various sources. Forklifts are the dominant application, so it is clearly important to include operation from that application. Besides forklifts, Large SI equipment applications fall into two broad categories. First, other variable-speed applications usually have an operator who "drives" the equipment (sweepers, ice surfacing machines, etc.). We expect most of these other variable-speed applications to include a subset of the kinds of operation measured on the forklifts and therefore believe that the forklift operation may adequately cover these applications. This group of non-forklift engines is also relatively small, accounting for less than 10 percent of Large SI engines. Second, the remaining engines are used in a wide range of portable (or transportable) applications that experience much less variation in engine speeds than motive equipment. Examples include generators, welders, pumps, compressors, saws, and chippers. These applications are typically governed to operate within a narrow band of engine speeds.

We developed most of the data for a Large SI transient duty cycle in a contracted effort with Southwest Research Institute (SwRI), with assistance and consultation from California ARB and the South Coast Air Quality Management District. To do this, we selected a pair of forklifts operating at an apple-processing facility. The report describing this effort includes a further description of these forklifts and the facility where they were operating.[3] After a statistical characterization of the approximately 10 hours of measured engine operation, we selected one five-minute segment that had the most typical operation from each forklift.[4] Additional five-minute segments from each lift truck captured the most highly transient activity.

Using the two "typical" segments provides 10 minutes of test operation. Selecting the first half of each of the high-transient segments from each forklift adds another 5 minutes. This allows us to incorporate the real operation from the high-transient segment without overemphasizing it in the total measurement.

To include the operation of engines in portable applications, we borrowed a 5-minute segment of typical operation measured from a diesel welder. SwRI developed this under an earlier work assignment. The welder, governed to operate at rated speed, had engine loads generally varying between 10 and 50 percent. This aligns well with the modal distribution of the ISO D2 cycle. Also, we would expect diesel and spark-ignition engines operating an arc welder to have very similar engine operation. People using the welder would not likely change their welding methods for the different engine types. Welder manufacturers may size engines somewhat differently based on the type of engine, but the observed engine loads for the diesel welder appear to fall within the expected range for spark-ignition engines.

Combining the forklift and welder segments into a single 20-minute cycle results in a procedure that we believe will cause manufacturers to design emission-control systems that are effective at reducing emissions from a very wide range of engine applications. Adding in elements from other applications may improve the statistical representativeness of the duty cycle, but will not likely yield a significant degree of additional emission control.

The 20-minute transient duty cycle described above should not generally apply to engines that rarely or never operate that way. We are therefore considering a different transient duty cycle for all engines designed to operate only at constant speed. This alternate transient cycle is a 20-minute set of measured engine operation from the diesel welder. Half of this is from measured typical operation and half is from a high-transient segment. We expect to propose this same constant-speed transient cycle for nonroad diesel engines in a later rulemaking.

The warm-up sequence preceding the transient duty-cycle segment for emissions measurement is also important. The warm-up begins with a cold-start. This means that the engine should be very near room temperature before the test cycle begins. Once the engine is started, it would be operated over the first 3 minutes of the specified transient duty cycle without emission measurement. The purpose of the warm-up segment is to bring the engine up to normal operating temperature in a standardized way. The 3-minute warm-up period allows enough time for engine-out emissions to stabilize, for catalyst light-off to occur, and for the engine to start closed-loop operation. This serves as a defined and achievable target for the design engineer to limit cold-start emissions to a relatively short period. SwRI testing has shown that a wide variety of Large SI engines have stabilized engine-out emissions after 3 minutes of operation or less.[5]

F. How would field testing work?

The goal of field testing is to characterize the emission levels resulting from normal operation. With established equipment and procedures for measuring emissions, the field test can consist of direct measurement of exhaust concentrations without removing the engine. As with any in-use emission testing, all properly maintained engines would be expected to meet the emission standards.

We are considering constraints on several operating variables to ensure that emission sampling occurs during normal engine operation, and that measured emissions include no spurious data. We request comment on the following parameters:

- Average power should be above some threshold to avoid very high brake-specific emission levels (as a result of dividing by near-zero power). As much as possible, such a threshold should include normal operation without reaching unusually high brake-specific emission levels.
- The emission sampling period should not include a continuous idling period so long that catalyst temperatures cool enough to significantly decrease conversion rates. Longer idling periods could cool the catalyst below light-off temperatures, resulting in unrepresentatively high emission levels. Since idle operation is included in the steady-state test, it isn't necessary to include this in not-to-exceed testing.
- The emission sampling period should start after the engine has reached stable operating temperatures

and should not include engine starting. Cold-start effects are addressed at certification and need not be included in not-to-exceed measurements.

- We are considering a maximum frequency of acceleration events. A maximum number of accelerations per minute (or a comparable limit) should be based on the upper end of real-world operation from high-transient activity. More severe transient activity could pose an unrealistic challenge to consistently provide the right quantity of air to the cylinders.
- The sampling period should be longer than some minimum interval. We are considering a minimum sampling time between 30 and 120 seconds.
- Severe-duty engines are unable to operate for extended periods at wide-open-throttle without overheating. We are therefore considering a limit on this operation for severe-duty engines. For example, we could restrict operation to be above 90 percent of maximum engine power less than 10 percent of the emission sampling period. We also request comment on the need to apply this type of provision to water-cooled gasoline engines.

In addition, field testing should include emission measurement under a wide range of ambient conditions representative of conditions engines experience in the field. Based on similar programs with other engine categories, we are considering a range of ambient temperatures and pressures to reflecting normal variations in the conditions in which engines operate.

During the emission sampling period, manufacturers would operate the engine on a representative commercial fuel or on a fuel that meets the specifications for certification testing. We would allow the engine to operate on any commercially available fuel for service accumulation.

G. What about not-to-exceed testing in the laboratory?

The provisions described above for field testing would apply to not-to-exceed testing in the laboratory. Any steady-state operation consistent with the above criteria would be a possible test point. To measure transient not-to-exceed operation, the engine would need to operate over a sequence of speeds and loads that could be characterized as normal operation. This could come from any segments of measured engine operation, consistent with the listed criteria. Some examples of valid engine operation would include:

- A subset of the transient duty cycle for certification.
- Other segments of the lift truck operation measured by SwRI.
- New measurements of engine speeds and loads from another Large SI application.

We would not base emission measurements on engine operation in a given application if the manufacturer didn’t sell engines into that application. Conversely, if engines from an engine family power equipment in several different applications, any in-use engine tested on a dynamometer should comply with emission standards based on operation from any other type of equipment in which the engines are installed.

III. Selecting Emission Standards

The Clean Air Act requires that standards achieve the greatest degree of emission reduction achievable through the application of technology that will be available, giving appropriate consideration to cost and other factors. This section describes how we will consider applying this to Large SI engines.

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). The rest of this memorandum addresses the potential to meet more stringent emission standards with new test procedures.

The California ARB emission standards described above would be effective in reducing emissions from Large SI engines, but we believe these levels don’t fulfill our obligation to adopt standards achieving the “greatest degree of reduction achievable” from these engines.

The biggest uncertainty in adopting emission standards for Large SI engines has been the degree to which emission-control systems deteriorate with age. While three-way catalysts and closed-loop fueling systems have been in place in highway applications for almost 20 years, there is very little information showing how these systems hold up under nonroad use. To address this, we participated in an investigative effort with SwRI, the California ARB, and the South Coast Air Quality Management District, as described in Section I above.

Laboratory testing consisted of measuring steady-state and transient emission levels, both before and after taking steps to optimize the system for low 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. 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.

A. Steady-state testing results

Testing results from the aged engines at SwRI showed very good emission control capability over the full useful life. Test results with new hardware on the aged engines lead to the conclusion that the systems operated with relatively stable emission levels over the several thousand hours. As shown in Table 2, the emission levels measured by SwRI are consistent with results from a wide variety of measurements on other engines. This data set supports emission standards significantly more stringent than those presently established in California.

Table 2

Steady-State Emission Results from Various Engines

Test engine	Fuel	HC+NOx* g/hp-hr	CO g/hp-hr	Notes**
Mazda 2L[6]	LPG	0.51	3.25	4,000 hours
GM 3L[7]	LPG	0.87	1.84	5,600 hours
Engine B[8]	LPG	0.22	2.79	250 hours
Engine E[9]	gasoline	0.28	42.2	250 hours; air-cooled; ISO D2 duty cycle
GFI[10]	LPG	0.52 NMHC+NOx	2.23	5,000 hours
Toyota/ECS 2L[11]	LPG	1.14	0.78	zero-hour; ISO C1 duty cycle
GM/Impco 3L[12]	LPG	0.26	0.21	zero-hour

*Measurements are THC+NOx, unless noted otherwise

**Emissions were measured on the ISO C2 duty cycle, unless noted otherwise.

B. Transient testing results

The SwRI testing is currently the only source of information available for evaluating the transient emission levels from Large SI engines equipped with emission-control systems. Table 3 shows the results of this testing. The transient emission levels are higher than those measured on the steady-state duty cycles. This probably results primarily from the fact that 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.

Table 3

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.

C. Not-to-exceed testing results

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

Figures 5 through 10 show plots of emission levels from the test engines at several different steady-state operating modes. The plotted emission levels show 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.

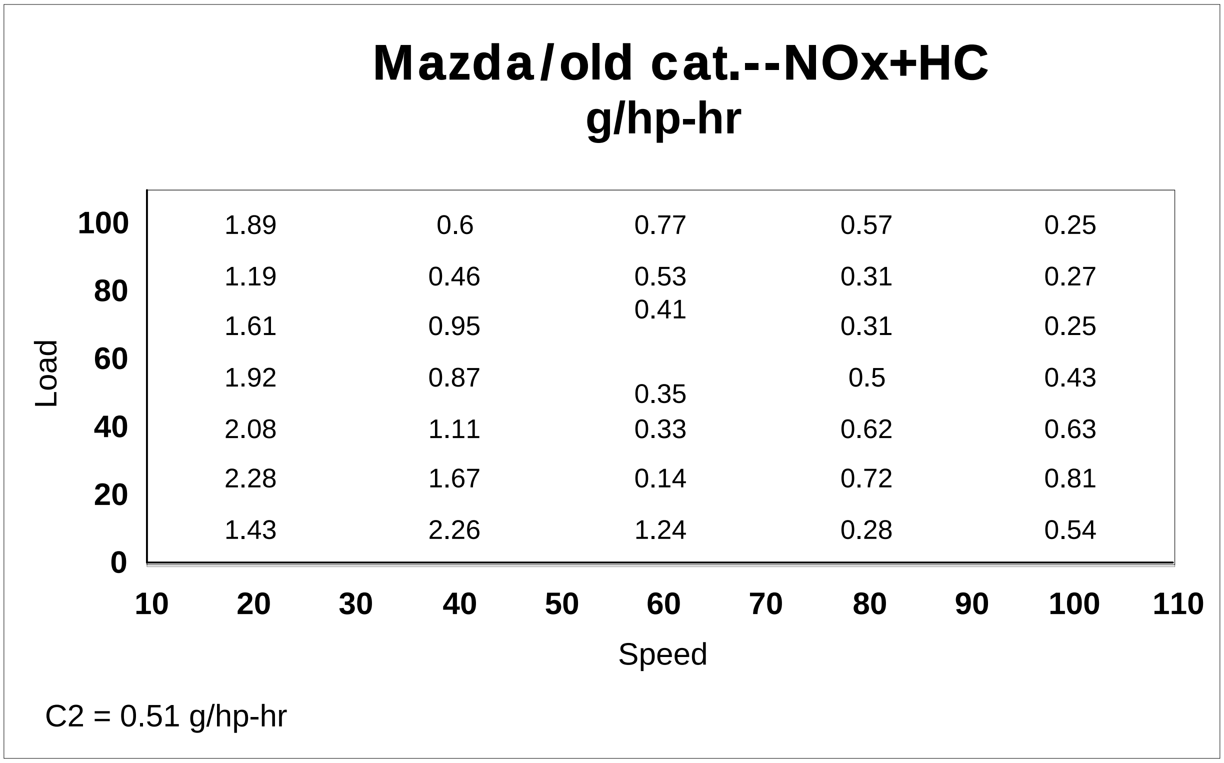
Figure 5 shows the THC+NOx emissions from the Mazda engine when tested with the aged catalyst. While several points are higher than the 0.51 g/hp-hr level measured on the C2 duty cycle, the highest levels observed from the Mazda engine are around 2.3 g/hp-hr. The highest emissions are generally found at low engine speeds.

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 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 are an inherent problem associated with these engines, we could take that into account in proposing the standard. Figure 8 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 10). These data reinforce the conclusion that adequate development effort will enable manufacturers to achieve broad control of emissions across the engine map.

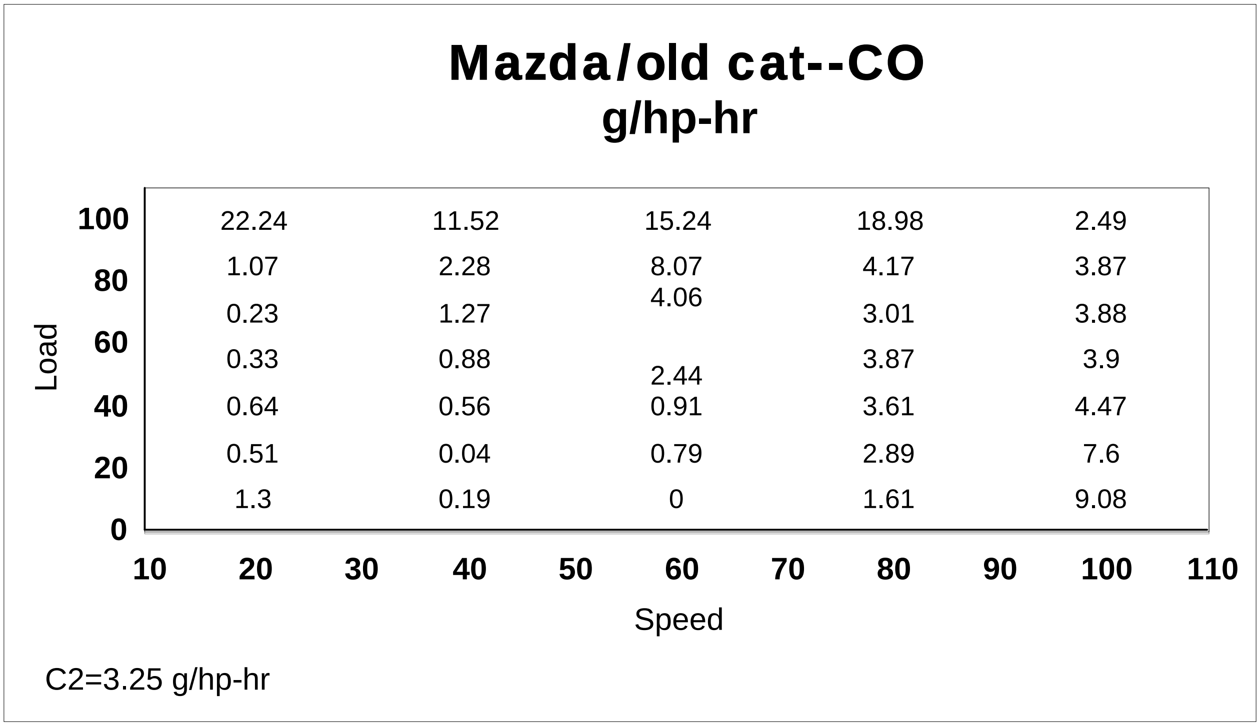
Figure 7 shows the THC+NOx emissions from the GM engine when tested with the aged catalyst. Emission trends across the engine map are similar to those from the GM engine, with somewhat higher low-speed emission levels between 2.3 and 4.4 g/hp-hr at various points. Operation on the new catalyst shows 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 9).

Figure 5



C2 = 0.51 g/hp-hr

Figure 6



C2=3.25 g/hp-hr

Figure 7

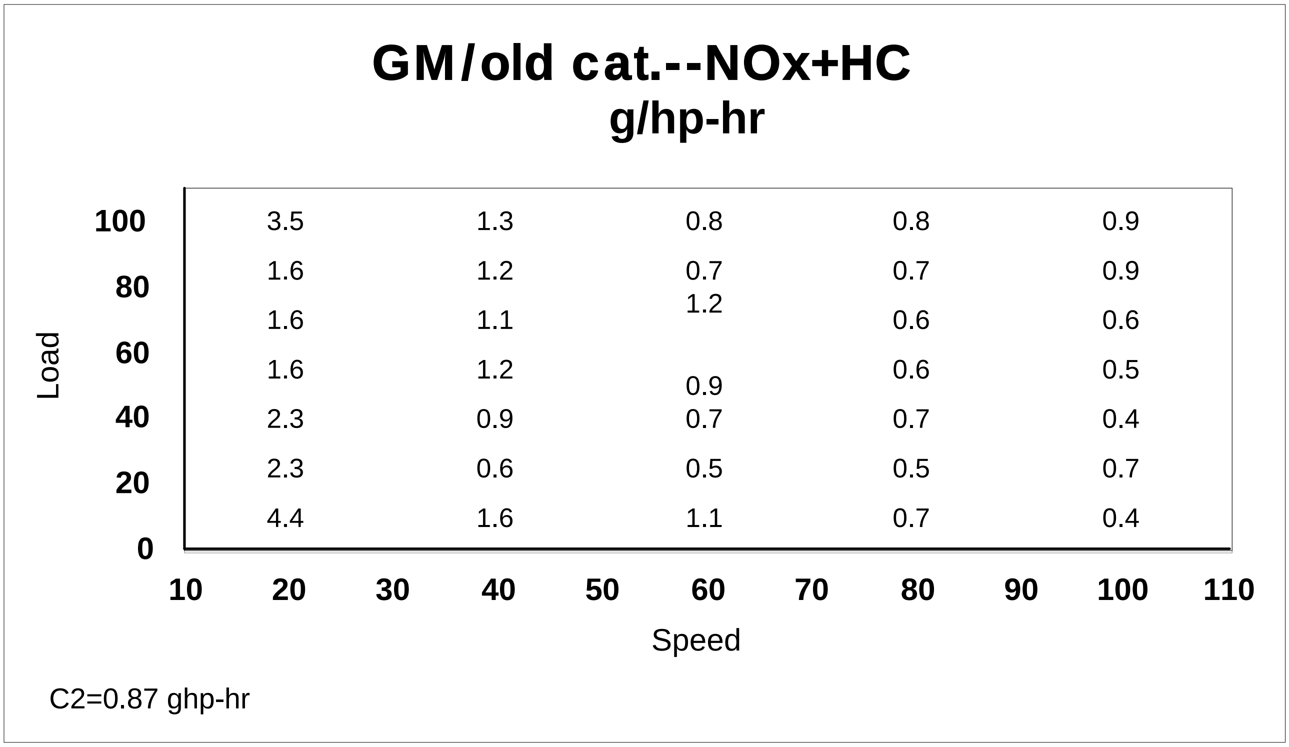


Figure 8

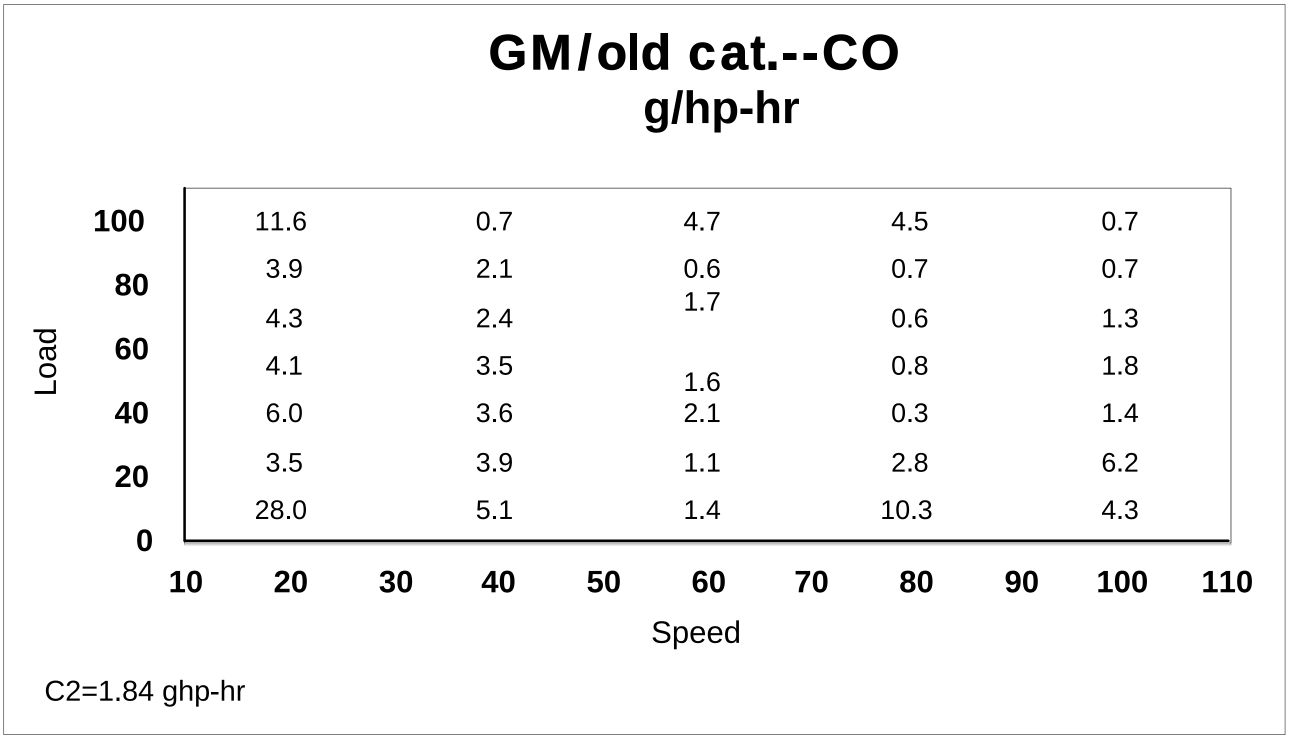


Figure 9

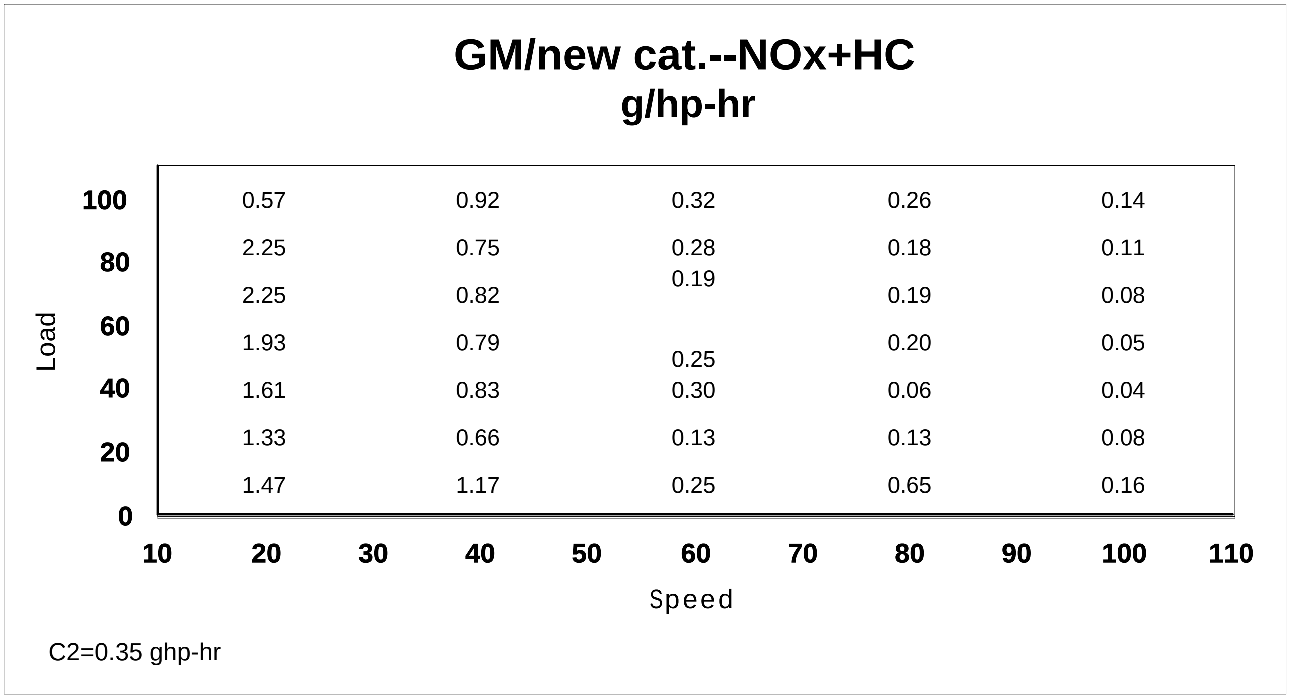
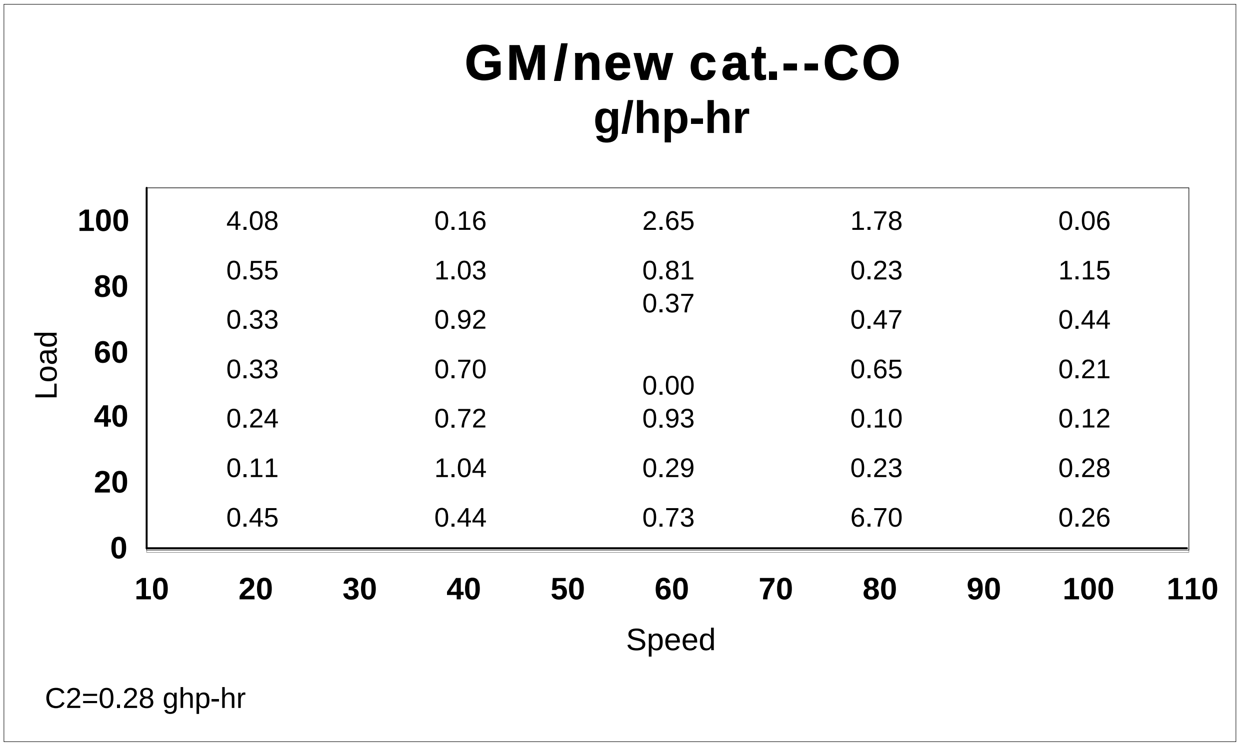


Figure 10



Not-to-exceed testing is designed to also include transient emission measurement. As described above, this might include any segment of normal operation above some minimum sampling period. We would not intend for this to include engine starting, extended idling, or other cold-engine operation. Table 4 shows a wide variety of transient emission levels from the two test engines. These could be considered as not-to-exceed measurements to evaluate whether an engine is meeting emission standards. Several segments included in the table include emission measurement after starting an engine that had soaked for up to 20 minutes in the lab. This can significantly increase emission levels, depending on how long the engine runs in open loop after starting. This seems to be 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

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

D. Durability of Emission-Control Systems

SwRI tested engines that had already operated for several thousand hours 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. This very likely resulted from a straightforward production error of improperly assembling the catalyst inside the shell.[13] This is not an inherent problem with catalyst production and is easily addressed with automated or more careful manual production processes. The catalyst from the GM engine selected for testing had also lost some of its structural integrity. Almost 20 percent of the working volume of the catalyst had disappeared. This catalyst was properly re-assembled with its reduced volume for further testing. This experience underscores the need for effective quality-control procedures in assembling catalysts.

Substituting a new catalyst on the aged system allowed emission measurements that help us estimate how much the catalysts degraded over time. This assessment is rather approximate, since we have no information about the zero-hour emissions performance of that exact catalyst. The new catalysts, which were produced about three years later under the same part numbers and nominal characteristics, generally performed in a way that was consistent with the aged catalysts. Not surprisingly, the catalyst with the reduced working volume showed a higher rate of deterioration than the intact catalyst. Both units, however, showed very stable control of NOx and HC emissions. CO deterioration rates were generally higher, but the degree of observed deterioration was very dependent on the particular duty cycle and calibration for a given set of emission measurements.

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

Another important issue relates to degradation associated with fuel impurities, potential lack of maintenance, and wear of oxygen sensors. Fuel system components in LPG systems are prone to fuel deposits, primarily from condensation of heavy hydrocarbon constituents in the fuel. The vaporizer and mixer on the test engines showed a typical degree of fuel deposits from LPG operation. The vaporizer remained in the as-received condition for all emission measurements throughout the test program. Emission tests before and after cleaning the mixer give an indication of how much the deposits affect the ability of the closed-loop fueling system to keep the engine at stoichiometry. For the GM engine, the combined steps of cleaning the mixer and replacing the oxygen sensor improved overall catalyst efficiency on the C2 duty cycle from 50 to 62 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 both NOx and CO emissions (see Table 5). These data show that closed-loop fueling systems can be relatively tolerant of problems related to fuel impurities.

Table 5

Average C2 Catalyst Conversion Efficiencies Before and After Maintenance

Engine	Pollutant	before maintenance	after maintenance
GM	NOx	50.4 %	61.7 %
	CO	95.5 %	96.0 %
Mazda	NOx	62.9 %	60.0 %
	CO	99.4 %	99.0 %

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

The second technology to consider is designed to prevent fuel deposits from forming. A commercially available device regulates fuel temperatures by heating the vaporizer with varying engine coolant flow. Keeping the fuel temperature above a given temperature reduces the likelihood that the heavy hydrocarbons will condense out downstream in the vaporizer or other fuel system components.

Manufacturers have also raised the question of whether oxygen sensors are durable enough to provide reliable performance for most of the engine's useful life. Oxygen sensors for highway engines have undergone significant improvements in reliability and durability to provide better long-term control of emissions. We request comment on how nonroad engines may cause oxygen sensors to be more susceptible to premature aging than oxygen sensors in highway vehicles.

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

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