Duty Cycle Effects On Small Engine Emissions

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ABSTRACT

The paper presents emissions data obtained from seven lawn mower engines that were tested using three duty cycles: a six mode steady-state test, a quasi-steady-state test, and a transient test. A comparison of emissions from the three duty cycles is made for non-methane organic gases, carbon monoxide, nitrogen oxides, detailed hydrocarbons (percent of total organic emissions that are paraffin, olefin, aromatic, or acetylene), and toxic compounds (benzene, 1,3-butadiene, formaldehyde, and acetaldehyde). Differences in ozone potential are also determined and reported for each duty cycle. The study includes both regulated and unregulated (not certified to any emission standard) test engines that have a wide range of emission rates. Results indicate that regulated emission rate differences due to duty cycle are fairly small (less than ten percent on the average). For over half of the regulated emissions data, there is no significant difference in emission rates between data obtained using the steady-state and the transient duty cycle. Emission comparisons are even better between the quasi-steady-state and steady-state data. Ozone potential and toxic emissions are ten to twenty percent higher with the transient test cycle and organic composition appears unaffected by duty cycle selection.

INTRODUCTION

Emissions from small non-handheld engines are normally determined using a six-mode, steady-state test procedure. The contribution of these engines to the emissions inventory has been determined using results based on tests with this steady-state duty cycle. The engine is operated in each mode until engine temperature has stabilized, then exhaust samples are taken for analysis. The basic procedure, known as the SAE J1088, was developed and refined over time by the Society of Automotive Engineers.[1] Test procedures similar to the J1088 were adopted by the California Air Resources Board and the U.S. Environmental Protection Agency for use in certifying new nonroad spark-ignition engines at or below 19 kW.

Historically, steady-state tests for small engines have been appropriate because they are simpler and less expensive to perform than transient tests. The loads experienced by the engine during the test represent those experienced in actual operation and emissions occurring during modes where the engine normally resides are weighted more heavily than those that are used less.

Criticism of steady-state tests centers on their inability to simulate real-world conditions as well as transient tests do. Experience with motor vehicle engines has shown that emissions and fuel consumption results from steady-state tests are considerably lower than transient test results. Important emissions occurring during the transients may not be captured by the test. For engines that operate in steady-state applications, the test is a non-problem, but for many small engine applications, transient operation cannot be avoided.

Lawn mower engines, the most popular small engine application, operate through a series of transients where engine torque varies as a function of grass condition and type of lawn mower. A transient duty cycle for lawn mowers known as the Grass Cutting Duty Cycle (GCDC) was developed by recording real-time measurements of engine torque while mowing different lawns.[2] This duty cycle takes into account differences in load due to the type of mower (e.g., mulcher versus side discharge), and differences due to the condition of the grass being cut (e.g., short/tall, wet/dry).

Use of a transient test to certify small engines may not be justified at this time due to the costs and complexities of the test. But there are emission inventory concerns about the use of steady-state data that should be addressed. Errors in the inventory result if these tests fail to produce real-world emission results. It may be necessary to use transient test data for inventory purposes, or apply correction factors, if possible, to the steady-state data. On the other hand, if emissions are not significantly impacted by duty cycle, resources can be directed elsewhere.

Results from two previous studies comparing regulated (HC, CO, and NO_x) and carbon dioxide (CO_2) emission rates from steady-state, quasi-steady-state, and transient duty cycles have been published.[2,3] One study reported few differences while the other reported significant ones. No known attempt has been made to compare speciated hydrocarbon (HC) emissions data from different duty cycles. In fact, there is a lack of published speciated HC data for small engines. The Southwest Research Institute has conducted a number of small engine emissions' characterization studies that speciate hydrocarbons using a quasi-steady-state duty cycle recently named the C6M (Composite Six-Mode) duty cycle.[4,5,6] But no attempt has been made to compare speciated data from one duty cycle with that of another.

It is important to know if transient operation influences the organic composition of emissions. Organic composition of the exhaust gas determines both the photochemical reactivity and the toxicity of the emissions. Emission studies of on-road sources have recognized the importance of the transient cycle and have used it exclusively in tests which measure toxic and reactive emission rates. Tests that provide small engine emissions data for human exposure models must adequately simulate real-world emissions since exposure to these sources most often occurs in situations where transient operation is the norm (e.g., during lawn and garden work).

This study investigates the effect of duty cycle on regulated and unregulated (including speciated HCs) emissions. Emissions from steady-state, quasi-steady-state, and transient duty cycles are examined. Results are obtained in testing six four-stroke and one two-stroke lawn mower engines using the 1990 baseline gasoline.

EXPERIMENTAL METHOD

Test Equipment

The test cell has an eddy-current dynamometer that can absorb up to 12 kW. The dynamometer's low moment of inertia (1.55×10^{-3} kg-m^2) enables better simulation of small engine transient loads when operating at rapidly changing speeds. An engine-dynamometer controller consists of two separate units: a dynamometer controller that varies excitation current to the dynamometer to maintain either speed or torque, and a throttle controller that controls the engine's throttle to maintain desired torque, speed, or throttle position. The engine-dynamometer controller is interfaced to a computer that commands second-by-second speed, torque, or throttle position called for by the duty cycle. During these tests, engine torque is controlled by the dynamometer torque control and engine speed is controlled by the throttle controller.

During the test, engine torque, speed, and power, and various pressures and temperatures at the constant volume sampler (CVS) are needed in order to calculate emission rates. These are brought into a computer in real-time and downloaded to a spreadsheet after the test. Real-time regulated emissions (hydrocarbons (HC), CO, and nitrogen oxides (NO_x) are brought into a separate computer and also downloaded to the spreadsheet following the test. The spreadsheet contains a record of second-by-second data enabling the calculation of real-time or modal emission rates.

Engine exhaust is directed to a constant volume sampler (CVS) via a bell-mouthed opening positioned near the engine's exhaust outlet (see Figure 1). Dilution air from the engine room forms an envelope around the exhaust and diluted exhaust is drawn into the CVS at a rate of about 600 SCFM. Heated sample lines are used to draw samples from the CVS for aldehyde, real-time, and bag analyses. The bags are first analyzed for regulated emissions, then a sample is drawn off for HC speciation.

The test facility shares much of its sampling and analytical equipment with a chassis dynamometer emissions laboratory. Personnel assigned to the test cell are highly skilled in the characterization of emissions from gasoline and diesel engines.

Test Procedure

Exhaust gas emissions are generated by operating the engines over three different duty cycles: the federal small engine certification cycle (6-Mode), the C6M cycle, and the GCDC. The GCDC was developed by an EPA regulation negotiation test procedure task group and the C6M was developed by Southwest Research Institute (SwRI).[2,7] The C6M is a modification of the certification test for small (less than 19 kilowatts), non-handheld, engines that basically combines the sample taken during the six separate steady-state modes into one large sample. It is a quasi-steady-state duty cycle since emissions are collected during the transients that occur when shifting from mode-to-mode. The GCDC is a transient test with constantly varying loads being applied to the engine while the engine's speed is held steady using a throttle controller or the engine's governor.

The 6-Mode Test - The 6-Mode test is conducted by taking exhaust gas samples while the engine is operating at six different steady-state load points. Five of the load points are defined as 100, 75, 50, 25, and 10 percent of rated torque at 85 percent of rated speed; the sixth point is at idle load. The sample is taken for a 600 second period after all engine and sampling system readings have stabilized.

The C6M Test Cycle - The engine is run through six modes (same modes as in 6-Mode test) while emissions are sampled continuously. The time spent in each mode is proportional to the weight given the mode in the certification procedure. For example, if the weight of a mode is twice that of a second mode in the certification test, the length of time spent in that mode is twice that of the second mode. Instead of having twelve (six sample and six background) bags to analyze following the test, the C6M has only two (a sample and a background) bags. This greatly reduces the cost and simplifies the analysis component. During the C6M test, engine speed is maintained at 85 percent of rated speed except at idle when it decreases to the lowest speed inside a smooth operating regime. Equivalency between the C6M and the certification test has not established due to resource restraints, but Southwest Research concluded that the C6M produces results which are useful to a research program. Table 1 specifies the test parameters of the C6M.

The GCDC - The GCDC is derived in part from mulching *and* side discharge data when cutting grass under the following conditions: short dry, short wet, long dry, and long wet. These eight conditions plus one that simulates the bagging of long dry grass are all represented in the GCDC. The entire test extends for 1000 seconds and Figure 2 shows a trace of the torque versus time with one of the engines being operated using the GCDC. During the test, engine speed is maintained at 85 percent of rated speed using a throttle controller.

Table 2 shows the average or weighted engine speed, torque, and power for each test engine with all three duty cycles. The 6-Mode and C6M test values are obtained using the modal weighting factors given in the federal regulation.[8] The GCDC values are the average of the six replicate samples for each duty cycle. It is noted that the average and weighted power measured for the GCDC was consistently less than that for the other two test procedures. Had this study been designed from the standpoint of certification concerns rather than inventory concerns, the loads for the 6-Mode test would have been forced equal to those for the GCDC. This can be done by simply changing the weighting factors assigned to the 6-Mode to values that take into account the frequency distribution of loads in the GCDC.

The test matrix that was used is shown in Table 3. Six replicate C6M and GCDC tests and three replicate 6-Mode tests were performed with each engine.

Gaseous Emissions Measurement

Exhaust emission rates were determined for HC, CO and NO_x using standard sampling, analytical, and calculation procedures.[8] They were also determined using a real-time sampling and analysis procedure that enabled integrated results over that test period to be compared to bag sample results for quality control (QC) purposes. The NMOG emissions were determined by taking the sum of the individual non-methane HC emissions following analysis with a gas chromatography- flame ionization detector (GC/FID), then adding in the oxygenate and aldehyde emissions.

Dilute exhaust samples were collected in 60-L Tedlar bags for hydrocarbon speciation. The GC speciation methodologies are essentially the same as those used in the Auto/Oil Air Quality Improvement Research Program.[9] A background sample was taken during the test. Integrated GC-FID peak measurements were compared to the HC measurements obtained using the standard FID procedure for QC purposes.

Aldehydes were sampled through a heated sample line (110°C) and collected on dinitrophenylhydrazine (DNPH) -coated silica gel cartridges. Two cartridges were drawn during each test: one from the exhaust gas and one from the background. The aldehyde samples, trapped on the cartridge as individual DNPH aldehyde derivatives, were then analyzed by high-performance liquid chromatography.[9]

Emissions' Reactivity

Ozone-forming potential of the exhaust volatile organic compounds (VOC) is based upon the incremental reactivity approach developed by Carter and Atkinson.[10] Application of this concept has led to the development of the Maximum Incremental Reactivity (MIR) method, that expresses the reactivity of exhaust NMOG and CO from the test engine.[11] The method assigns a specific reactivity level to each of the organic species and to CO, and calculates a reactivity-weighted emission (RWE) rate for each specie by multiplying the specie's specific reactivity times its emission rate. The RWE rate for an exhaust sample is obtained by summing all of the individual RWE rates for each specie present. The RWE rate, expressed in units of grams ozone per kilowatt-hour, is a useful measure of the ozone potential of the CO and organic emissions in urban atmospheres where the VOC-to-NO_x ratios are relatively low (approximately 6). The specific reactivity of the organic emissions can easily be obtained by dividing the organic RWE rate by its emission rate.

Test Engines and Fuel

Six four-stroke engines were used in this study. The two having OHV configurations were regulated engines (#0034 & #2122) designed to comply with the Phase 1 emission standard for small non-handheld engines. One two-stroke engine (#4468) was tested to investigate its sensitivity to duty cycle. Approximately ten percent of the in-use lawn mowers are those powered by 2-stroke engines.[12] Three of the engines were tested with their governors in-place and four with them removed (#1001, #1035, #0034, & #4468). A more complete description of the engines is given in Table 4.

The test fuel used in this study was a 1990 Baseline Gasoline designated "RFA." A detailed description of the fuel is given in Table 5.

RESULTS AND DISCUSSION

The regulated and unregulated emission summaries are given in Table 6 for the seven engines tested. Average emission rates and percent differences relative to 6-Mode emission rates are given in each table. In Table 6, the percent difference was obtained by averaging the percent differences for each of the seven engines. The engine-by-engine emission rates, standard deviations, and percent differences compared to the 6-Mode test data are given in tables in the appendix. The emission rate values accompanied by standard deviations in Table A-1 represent the average of six runs for all C6M and GCDC data, and the average of three runs for the 6-Mode emission rates.

The average emission rates for the seven engines are strongly affected by emissions from the one 2-stroke engine that was tested. The 2-stroke engine's organic emission rates were about twenty times higher than the average 4-stroke emission rate. This resulted in elevated 2-stroke emissions of ozone precursors and toxic compounds. The average MIR ozone potential for the 4-stroke engines is 88 g O_3/kW-h compared to 1387 g O_3/kW-h for the 2-stroke engine. For toxic emission rates the comparison is 1.2 g/kW-h for the 4-stroke engines versus 12.4 g/kW-h for the 2-stroke engine.

Results given in Table 6 illustrate that emission rates for the C6M and GCDC tests compare fairly well with those from the 6-Mode test. The 6-Mode steady-state test is viewed as the reference method since it has been used extensively to determine emission rates from small engines and is the current EPA certification method. The regulated emissions data from each of the test engines lends itself to statistical analysis because replicate testing was performed with all of the duty cycles. The C6M and GCDC duty cycles were each run six times and the 6-Mode test was run three times for regulated emission analyses. The C6M emission rates were not significantly (95 percent confidence level) different from the 6-Mode rates for over 70 percent of the regulated emissions data. Comparison between emission rates for the transient test (GCDC) and the 6-Mode test is not as good, but there were still no significant differences for over 55 percent of the data.

Only one sample was taken for speciated organic emissions data (detailed hydrocarbons and aldehydes) collected using the 6-Mode test; therefore, no attempt is made to compare these data statistically with the mean emission rates from the GCDC and C6M tests. Generally, GCDC regulated and unregulated emission rates, with the exception of NO_x, are higher than those of the 6-Mode and C6M tests. This happens primarily because the loads with the GCDC (see Table 2) are less than those with the other two duty cycles. As engine loads decrease, emission rates, expressed in units of g/kW-h, usually increase. Emission rates from the GCDC and the 6-Mode test agree better when the weighting factors used in the 6-Mode test are changed to account for the load frequency distributions. For example, using such weighting factors causes the HCs for the 6-Mode test to be *greater* than those for the GCDC by an average of 5.8 percent. From Table 6, the HCs are *less* with the 6-Mode test an average 10.2 percent using the standard weighting factors. This study is concerned with duty cycle emission rate differences from an emissions inventory standpoint; therefore, the comparisons using the modified 6-Mode test are interesting but less relevant to the discussion.

The overall summaries of Table 6 show that unregulated emission rates and organic composition also appear roughly the same for each of the three duty cycles. Some percentages (differences relative to the 6-Mode test) may seem high but these are often the result of small differences between small numbers. In many cases the standard deviations for the mean values reported are greater than the differences due to duty cycle. The magnitude of the emission rate differences of this study tend to agree with those reported in an earlier study. In that study, a current technology lawn mower engine was tested using both steady-state (California test) and transient (GCDC) test procedures.[2] Replicate tests were run with each procedure and the differences in the corresponding mean emission rates are within 25 percent for each pollutant.

Another study that examined duty cycle effects for 19 two- and four-stroke engines came up with much larger differences than those reported here.[3] Hydrocarbon and CO emission rates were twice as high in the transient test compared to the steady-state test for two lawn mower engines. Emissions from other engines demonstrated similar increases in HC and CO emission rates as the duty cycle became more transient in nature. Replicate tests were not conducted and the engines tested were new with overhead valve configurations. Engines #0034 and #2122 of this study have overhead valve configurations but did not display such dramatic increases in HC and CO during transient testing.

CONCLUSIONS

The data support the notion that emission rates from small engines have not been seriously underestimated due to the use of a steady-state test procedure. However, the study's results are based on a limited test matrix due to resource constraints. Conclusions regarding emissions and duty cycle effects may not be representative of the entire lawn mower fleet. A better understanding of the overall problem will evolve as these results are pooled with those of similar studies.

The study is primarily interested in determining if emissions with transient testing are significantly different from those with a steady-state testing. Emissions are characterized from seven lawn mower engines using three duty cycles. With each engine, six replicate tests for emissions were run using both the transient GCDC and the quasi-steady-state C6M. Three replicate tests for regulated emissions and one for unregulated emissions were run with the 6-Mode steady-state test. Emissions obtained using the two non-steady-state duty cycles are not dramatically different from the 6-Mode results. Results with the C6M are closer to those of the 6-Mode test. A comparison of results from the seven engines leads to the following conclusions regarding emissions from the quasi-steady-state (C6M) test relative to those from the 6-Mode test:

- Hydrocarbon, CO, and NO_x emission rates are not significantly different for over 70 percent of the comparisons.
- Overall, the HC and NO_x emission rates are four and two percent lower, respectively, and the CO emission rates are five percent higher.
- Individual toxic emission rates range from zero to seven percent higher.
- The organic composition in terms of HC family fractions and their contribution to the ozone potential is about the same.

The following conclusions are made regarding GCDC emission rates relative to those from the 6-Mode test:

- Hydrocarbon, CO, and NO_x emission rates are not significantly different for over 50 percent of the comparisons.
- Overall, HC and CO emission rates are 10 and 9 percent higher, respectively, and the NO_x emission rates are two percent lower.
- Individual toxic emission rates range from 3 to 19 percent higher.
- The organic composition in terms of HC family fractions and their contribution to the ozone potential are about the same.

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DISCLAIMER

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APPENDIX

Table A-1a. Emission rates, compositions, and ozone potentials (standard deviations in parentheses) for the seven engines and three duty cycles examined in the study.

	Engine 1001			Engine 1035			Engine 2615		
	6Mode	C6M	GCDC	6Mode	C6M	GCDC	6Mode	C6M	GCDC
Regulated Emissions (g/kW-h)									
HC	29.2 (1.6)	31.3 (1.9)	31.1 (1.2)	13.8 (0.9)	13.9 (0.6)	15.7 (1.1)	14.2 (1.2)	15.5 (0.5)	16.4 (0.5)
CO	443 (27.3)	420 (64)	431 (19)	286 (38)	281 (32)	276 (43)	523 (44)	622 (19)	599 (19)
NOx	3.7 (0.9)	3.7 (0.4)	3.3 (0.6)	4.3 (0.7)	4.6 (0.8)	3.6 (0.6)	1.9 (0.6)	1.7 (0.3)	2.1 (0.1)
CO_2	1280 (78)	1273 (69)	1573 (34)	1208 (51)	1227 (57)	1456 (79)	1006 (77)	1006 (44)	1186 (45)
NMOG	26.7	27.7 (2.8)	29.6 (1.2)	12.6	12.7 (0.6)	14.6 (0.7)	12.0	14.3 (0.7)	15.3 (1.0)
Toxic Emissions (g/kW-h)									
1,3 Butadiene	0.26	0.37 (0.07)	0.40 (0.08)	0.19	0.21 (0.03)	0.24 (0.03)	0.10	0.10 (0.02)	0.11 (0.01)
Benzene	1.18	1.25 (0.07)	1.32 (0.05)	0.65	0.64 (0.03)	0.75 (0.05)	0.71	0.87 (0.05)	0.90 (0.05)
Formaldehyde	0.36	0.41 (0.06)	0.37 (0.02)	0.20	0.17 (0.02)	0.20 (0.01)	0.14	0.16 (0.01)	0.15 (0.01)
Acetaldehyde	0.08	0.10 (0.01)	0.09 (0.00)	0.04	0.03 (0)	0.04 (0)	0.02	0.03 (0)	0.03 (0)
Reactivity									
MIR (g O_3/kW-h)	140	150 (12)	156 (70)	75	75 (3)	82 (5)	77	91 (3)	95 (5)
Specific Reactivity (g O_3/g NMOG)	4.33	4.60 (0.16)	4.50 (0.09)	4.71	4.67 (0.12)	4.62 (0.06)	4.07	4.04 (0.11)	4.08 (0.09)
MIR Fractions									
Paraffin	6%	5% (1%)	6% (0)	4%	4% (0)	4% (0)	4%	4% (0)	4% (0)
Olefin	36%	41% (5%)	41% (1%)	44%	44% (2%)	45% (2%)	30%	28% (1%)	30% (1%)
Aromatic	35%	34% (5%)	34% (1%)	26%	27% (1%)	28% (1%)	25%	27% (2%)	28% (3%)
Acetylene	1%	2% (0)	2% (0)	2%	2% (0)	2% (0)	2%	2% (0)	2% (0)
Aldehyde	3%	3% (0)	3% (0)	3%	3% (0)	3% (0)	2%	2% (0)	2% (0)
CO	18%	15% (1%)	15% (2%)	21%	20% (2%)	19% (2%)	37%	37% (2%)	34% (2%)
HC Family Fractions									
Paraffin	32%	27% (2%)	30% (1%)	26%	25% (1%)	25% (0)	32%	32% (1%)	31% (1%)
Olefin	25%	28% (3%)	28% (1%)	32%	32% (1%)	31% (1%)	24%	22% (0)	23% (1%)
Aromatic	35%	35% (5%)	34% (1%)	30%	31% (1%)	31% (1%)	31%	32% (2%)	32% (2%)
Acetylene	8%	10% (1%)	9% (0)	11%	12% (1%)	12% (0)	13%	14% (2%)	14% (2%)

Table A-1b.

	Engine 0954			Engine 0034			Engine 2122			Engine 4468		
	6Mode	C6M	GCDC	6Mode	C6M	GCDC	6Mode	C6M	GCDC	6Mode	C6M	GCDC
Regulated Emissions (g/kW-h)												
HC	24.7 (5.2)	20.6 (3.2)	23.5 (3.0)	12.5 (3.3)	10.5 (0.1)	13.3 (1.2)	8.4 (0.5)	8.3 (0.5)	9.9 (1.0)	339 (44)	304 (9)	367 (16)
CO	487 (29)	506 (13)	510 (17)	360 (32)	405 (28)	467 (21)	381 (12)	389 (19)	414 (7)	952 (57)	912 (14)	1042 (24)
NOx	3.6 (0.3)	3.4 (0.6)	3.0 (0.4)	7.5 (1.0)	8.0 (0.5)	6.8 (0.4)	4.5 (0.3)	4.0 (0.3)	4.2 (0.4)	0.43 (0.34)	0.42 (0.30)	0.52 (0.60)
CO_2	1456 (216)	1381 (51)	1556 (96)	1178 (104)	1236 (26)	1491 (32)	1302 (23)	1302 (44)	1523 (32)	1283 (38)	1305 (83)	1471 (60)
NMOG	23.2	21.7 (2.6)	25.0 (2.3)	11.6	12.2 (0.8)	14.6 (1.0)	9.7	7.5 (0.7)	8.9 (0.9)	370	320 (19)	379 (32)
Toxic Emissions (g/kW-h)												
1,3 Butadiene	0.15	0.11 (0.07)	0.13 (0.10)	0.14	0.17 (0.03)	0.20 (0.03)	0.09	0.08 (0.02)	0.09 (0.01)	1.12	0.99 (0.05)	1.15 (0.36)
Benzene	1.06	1.12 (0.11)	1.28 (0.14)	0.61	0.66 (0.08)	0.84 (0.06)	0.65	0.58 (0.05)	0.70 (0.04)	9.26	8.11 (0.5)	9.47 (1.44)
Formaldehyde	0.19	0.20 (0.03)	0.22 (0.01)	0.22	0.23 (0.05)	0.26 (0.01)	0.14	0.13 (0.01)	0.15 (0.08)	1.51	1.15 (0.08)	1.24 (0.05)
Acetaldehyde	0.04	0.04 (0.01)	0.04 (0.00)	0.04	0.05 (0)	0.05 (0)	0.03	0.03 (0)	0.03 (0.02)	0.42	0.38 (0.07)	0.45 (0.02)
Reactivity												
MIR (g O_3/kW-h)	112	105 (6)	118 (7)	66	72 (5)	85 (5)	58	51 (3)	57 (2)	1387	1206 (100)	1473 (130)
Sp. React. (g O_3/g NMOG)	3.71	3.60 (0.26)	3.61 (0.11)	4.03	4.14 (0.12)	4.10 (0.06)	3.91	3.95 (0.11)	3.90 (0.18)	3.61	3.61 (0.14)	3.74 (0.18)
MIR Fractions												
Paraffin	10%	10% (2%)	10% (1%)	6%	5% (0)	5% (0)	6%	4% (0)	4% (1%)	15%	15% (1%)	15% (1%)
Olefin	33%	31% (3%)	32% (3%)	33%	35% (1%)	34% (1%)	27%	26% (1%)	27% (1%)	29%	28% (2%)	28% (2%)
Aromatic	30%	29% (5%)	31% (3%)	26%	25% (2%)	26% (2%)	28%	24% (2%)	24% (3%)	50%	50% (4%)	51% (3%)
Acetylene	2%	2% (0)	2% (0)	2%	2% (0)	2% (0)	2%	2% (0)	2% (0%)	1%	1% (0%)	1% (0%)
Aldehyde	2%	2% (0)	2% (0)	3%	3% (0)	3% (0)	2%	3% (0)	3% (1%)	1%	1% (0%)	1% (0%)
CO	23%	26% (1%)	23% (2%)	29%	30% (1%)	30% (2%)	35%	41% (2%)	39% (2%)	4%	4% (0.3%)	4% (0.3%)
HC Family Fractions												
Paraffin	42%	42% (5%)	42% (2%)	36%	32% (1%)	25% (0)	34%	30% (1%)	30% (4%)	46%	47% (2%)	46% (1%)
Olefin	21%	20% (2%)	20% (2%)	24%	25% (1%)	31% (1%)	21%	22% (0)	23% (1%)	15%	15% (1%)	15% (1%)
Aromatic	29%	28% (4%)	29% (3%)	30%	31% (3%)	31% (1%)	35%	35% (2%)	34% (3%)	34%	34% (2%)	35% (2%)
Acetylene	8%	9% (1%)	9% (1%)	10%	12% (1%)	12% (0)	11%	13% (2%)	13% (1%)	4%	4% (0%)	4% (0.6%)

Table A-2. Emission rate, composition, and ozone potential comparisons of C6M and GCDC results to the 6-Mode results for each of the seven engines examined.

Engine #	1001		1035		2615		0954		0034		2122		4468	
	C6M	GCDC	C6M	GCDC	C6M	GCDC	C6M	GCDC	C6M	GCDC	C6M	GCDC	C6M	GCDC
Regulated Emissions (percent different from 6-Mode test)														
HC	+9.1	+6.5	+0.8	+13.8	+9.5	+15.5	-16.6	-4.9	-16.0	+9.0	-1.2	+17.9	-10	8.3
CO	+0.2	-2.7	-1.5	-3.2	+18.8	+14.4	+3.7	+4.5	+12.5	+29.8	+2.2	+8.6	-4.2	9.5
NOx	+10.1	-1.1	+6.4	-15.6	-13.9	+10.4	-7.1	-17.5	+6.6	-9.3	-10.9	-5.5	-2.3	21
CO_2	-2.2	+22.8	+1.6	+20.5	-0.1	+17.8	-5.2	+6.9	+4.9	+26.6	-0.1	+16.8	1.7	15
NMOG	+5.2	+10.7	+1.0	+15.6	+19.5	+28.0	-6.1	+8.0	+4.5	+25.3	-22.3	-8.1	-13	2.4
Toxic Emissions (percent different from 6-Mode test)														
1,3 Butadiene	+44.3	+53.9	+0.8	+21.3	+1.4	+18.0	-18.6	-6.4	+21.4	+46.4	-15.2	-3.2	-11	2.7
Benzene	+6.0	+12.1	+0.5	+14.6	+21.4	+25.8	+5.7	+20.7	+8.2	+37.7	-11.9	+6.0	-12	2.3
Formaldehyde	+14.6	+2.0	+2.2	+1.7	+16.1	+13.5	-2.0	+10.0	+1.7	+14.2	-9.5	0	-24	-18
Acetaldehyde	+20.6	+6.3	+1.4	+11.3	+23.7	+32.0	-5.0	0	+15.0	+25.0	0	0	-9.5	4.8
Reactivity (percent different from 6-Mode test)														
MIR	+6.8	+11.0	-0.5	+9.9	+18.6	+23.3	-6.6	+4.8	+8.7	+23.9	-13.1	-2.5	-13	6.2
Sp. Reactivity	+6.1	+3.7	-0.9	-1.9	-0.8	+0.3	-3.2	-2.7	+2.5	+14.3	+1.0	-0.2	0	3.6
MIR Fractions (percent different from 6-Mode test)														
Paraffin	-20.0	-5.0	-12.5	-3.7	+10.0	+7.5	-2.0	-1.0	-16.6	-35.8	-31.6	-26.8	0	0
Olefin	+14.4	+14.7	+0.6	+2.7	-5.5	0	-5.7	-3.3	+5.4	+36.9	-4.4	+3.2	-3.4	-3.4
Aromatic	-3.2	-4.3	+4.2	+6.5	+6.3	+11.1	-3.0	+3.0	-5.0	+6.5	-13.5	-13.5	0	2
Acetylene	+75.0	+70.0	+7.5	+20.0	+2.5	-3.5	-1.5	-10.0	-10.0	+20.0	-15.0	-16.0	0	0
HC Family Fractions (percent different from 6-Mode test)														
Paraffin	-15.6	-6.9	-4.4	-3.6	+1.2	-3.5	+0.5	-0.7	-12.2	-11.7	-12.0	-11.4	2.2	0
Olefin	+13.7	+11.4	-1.8	-2.8	-9.4	-5.7	-5.2	-5.2	+7.9	+3.3	+4.7	+7.6	0	0
Aromatic	0	-2.9	+2.5	+3.1	+2.5	+4.0	-3.1	-0.3	-0.6	+3.6	+0.5	-2.5	0	3
Acetylene	+19.8	+5.1	+8.7	+8.8	+8.9	+10.5	+18.7	+17.5	+19.0	+21.0	+16.3	+18.1	0	0

Table 1. C6M duty cycle description.

COMPOSITE SIX MODE TEST CYCLE						
Mode Points	1	2	3	4	5	6
Speed	Intermediate (85% of Rated Speed)					Idle
Load Percent	100	75	50	25	10	0
Time in Mode (sec.)	108	240	348	360	84	60

Table 2. Average or weighted torque, speed, and load for each engine/duty cycle condition.

Engine #	1001	1035	2615	2122	0034	0954	4468
6-Mode							
Torque (n-m)	2.41	3.60	3.61	3.09	2.75	2.57	1.94
RPM	3047	3047	3047	2950	3056	3045	3042
Power (kW)	0.77	1.04	1.03	0.94	0.88	0.81	0.61
C6M							
Torque (n-m)	2.25	3.23	3.23	3.10	2.71	2.60	1.96
RPM	2996	3013	3090	2938	3029	3051	3055
Power (kW)	0.72	1.03	1.04	0.95	0.87	0.83	0.63
GCDC							
Torque (n-m)	1.85	2.62	2.65	2.53	2.20	2.13	1.59
RPM	3051	3059	3047	2977	3056	3052	3058
Power (kW)	0.59	0.82	0.84	0.78	0.70	0.67	0.50

Table 3. Test matrix with number of replicate measurements for each duty cycle.

	Day 1	Day 2	Day 3	Day 4	Day 5
Regulated Emissions	6-Mode	3 C6M 3 GCDC	3 GCDC 3 C6M	6-Mode	6-Mode
Speciated HCs & aldehydes	Modes 1 & 2 of 6-Mode	same as above	same as above	Modes 3 & 4 of 6-Mode	Modes 5 & 6 of 6-Mode

Table 4. Engine descriptions.

Engine Mfr. and Number	Model #	Age & Time In-Use (years)	Type Engine	Displace-Ment (cc)	Rated Power @ rpm	Max. Test Torque @ rpm	Valve Type
Briggs & Stratton (#2615)	12G702	1 yr. 60 hrs.	4-stroke	190	5.0 hp@3600	5.0 ft-lb@3060	Valve in head, L-head
Briggs & Stratton (#1035)	124702	4 yr. In use 1 year	4-stroke	190	5.0 hp@3600	5.0 ft-lb@3060	Valve in head, L-head
Briggs & Stratton (#1001)	92902	10 yr. In use 2 years	4-stroke	148	3.5 hp@3600	3.5ft-lb@3060	Valve in head, L-head
Briggs & Stratton (#0954)	10A902	New (10 hours)	4-stroke	160	4.0 hp@3600	4.0 ft-lb@3060	Valve-in-head L-head
Honda (#0034)	GXV140	New (15 hours)	4-stroke	135	4.4 hp@3600	4.2 ft-lb@3060	Overhead-valve
Kawasaki (#2122)	FC150V	New (10 hours)	4-stroke	153	5.5 hp@3600	4.8 ft-lb@2790	Overhead-valve
Lawn-Boy (#4468)	10227	New (8 hours)	2-stroke	127	2.8 hp@3060	3.0 ft-lb@3060	Reed valves

Table 5. Fuel description.

Fuel Type	RFA
Specific Gravity	0.7469
Sulfur, wt %	0.0315
Benzene, ppmC%	2.11
Aromatics, vol. % **Olefins, vol. %** **Paraffin, vol. %** **MTBE, vol. %**	31.8 11.5 56.7 0.1
Research Octane No. **Motor Octane No.** **Octane Index**	92.2 83.8 88.1
Carbon, wt %	13.3
Hydrogen, wt %	86.7
Reid vapor pressure, psi	8.65
Distillation, C° IBP **10%** **50%** **90%** **EP**	35 51 102 165 216

Table 6. Average emission rates, compositions, and ozone potentials from the seven engines tested, and comparison of C6M and GCDC emissions to 6-Mode test (each percentage given is the average of the percent differences obtained with each of the seven engines).

	6Mode	C6M	GCDC	C6M	GCDC
Primary Emissions	g/kW-h			Ave. of differences	
HC	63	57	68	-3.5%	10.2%
CO	490	505	534	4.6%	8.7%
NOx	3.7	3.7	3.4	-1.6%	-2.5%
CO2	1245	1247	1465	0.1%	18.0%
NMOG	66	59	69	-1.6%	11.7%
Toxic Emissions	g/kW-h				
1,3 Butadiene	0.29	0.29	0.33	3.2%	18.9%
Benzene	2.02	1.89	2.18	2.6%	17.0%
Formaldehyde	0.39	0.35	0.37	-0.1%	3.4%
Acetaldehyde	0.10	0.09	0.10	6.6%	11.7%
Reactivity					
MIR (g O3/kW-h)	273	250	295	0.1%	10.9%
Specific Reactivity (g O3/g NMOG)	4.05	4.09	4.08	0.7%	2.4%
MIR Fractions					
Paraffin	7%	7%	7%	-10.4%	-9.3%
Olefin	33%	33%	34%	0.2%	7.3%
Aromatic	31%	31%	32%	-2.0%	1.6%
Acetylene	2%	2%	2%	8.4%	11.5%
Aldehyde	2%	2%	2%	7%	8%
CO	24%	25%	23%	2%	-3%
HC Family Fractions					
Paraffin	35%	34%	33%	-5.8%	-5.4%
Olefin	23%	23%	24%	1.4%	1.2%
Aromatic	32%	32%	32%	0.3%	1.1%
Acetylene	9%	11%	10%	13.1%	11.6%

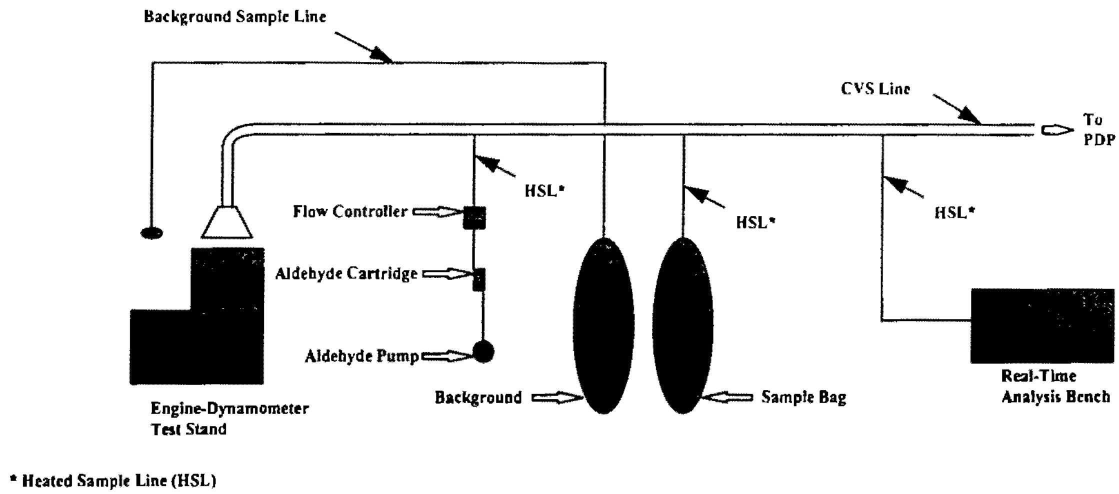

Figure 1. Schematic of small engine gas sampling system.

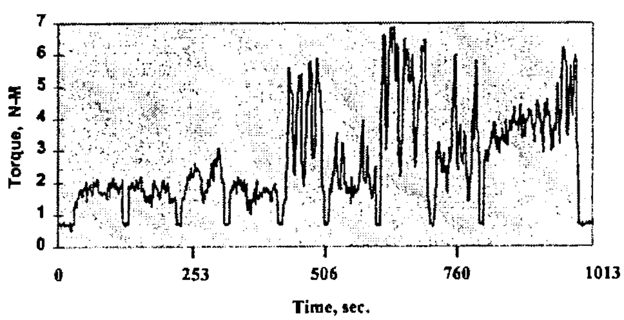

Figure 2. Torque-time trace for GCDC test.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

The paper presents emissions data obtained from seven lawn mower engines that were tested using three duty cycles: a six mode steady-state test, a quasi-steady-state test, and a transient test. A comparison of emissions from the three duty cycles is made for non-methane organic gases, carbon monoxide, nitrogen oxides, detailed hydrocarbons (percent of total organic emissions that are paraffin, olefin, aromatic, or acetylene), and toxic compounds (benzene, 1,3-butadiene, formaldehyde, and acetaldehyde). Differences in ozone potential are also determined and reported for each duty cycle. The study includes both regulated and unregulated (not certified to any emission standard) test engines that have a wide range of emission rates. Results indicate that regulated emission rate differences due to duty cycle are fairly small (less than ten percent on the average). For over half of the regulated emissions data, there is no significant difference in emission rates between data obtained using the steady-state and the transient duty cycle. Emission comparisons are even better between the quasi-steady-state and steady-state data. Ozone potential and toxic emissions are ten to twenty percent higher with the transient test cycle and organic composition appears unaffected by duty cycle selection.

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