United States Environmental Protection Agency
Air and Radiation
EPA420-P-02-012
June 2002
NR-003a

Exhaust Emission Effects of Fuel Sulfur and Oxygen on Gasoline Nonroad Engines

EPA420-P-02-012
June 2002

Exhaust Emission Effects of Sulfur and Oxygen on Gasoline Nonroad Engines

NR-003a

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

Exhaust Emission Effects of Fuel Sulfur and Oxygen on Gasoline Nonroad Engines

Report No. NR-003a

revised June 19, 2002

Assessment and Standards Division
U.S. EPA Office of Transportation and Air Quality

Purpose

The purpose of this memo is to document the effects of changing gasoline specifications on exhaust emissions from nonroad gasoline-fueled engines that are incorporated in EPA's draft NONROAD2002 emissions inventory model.

There have been a number of gasoline specifications that have changed or have been considered for change in the past few years. The most prominent of these changes has been summer volatility restrictions, wintertime oxygenated fuel requirements, and reformulated gasoline requirements which incorporate year-round oxygenate requirements and summertime emission requirements. For reasons described below, the effect of these fuel changes on nonroad gasoline engines' exhaust emissions of carbon monoxide (CO), nitrogen oxides (NOx), and volatile organic compounds (VOC) is ascribed mainly to the oxygen content. Any expected changes to the fuel sulfur is expected to reduce SOx emissions only.

Introduction

Nonroad gasoline engines differ from automotive engines in several important respects. Few, if any, nonroad gasoline engines have feedback control systems that monitor and correct the air to fuel ratio for combustion. No significant numbers of nonroad engines currently in use are known to have either oxidation or three-way catalysts or exhaust gas recirculation systems (EGR). The compression ratio for these engines is generally significantly less than in automotive engines; furthermore, very few nonroad gasoline engines have overhead valves as is common in automotive applications. Because of these design differences, the effects of fuel changes on emissions from nonroad gasoline engines are quite different from the effects of fuel changes on emissions from automotive gasoline engines.

The effects of fuel changes in this study are restricted to the fuel sulfur effects on sulfur oxide (SOx) emissions and the fuel oxygen perturbation of the air to fuel ratio. Other fuel changes (like reducing the aromatics, olefins, or heavy-end distillation products) in reformulated gasoline are considered in this study to have no effect on emissions. The paucity of data on these engines precludes the type of analysis done for the reformulated gasoline rulemaking [1], and the substantial design differences between nonroad and automotive engines precludes the use of automotive emissions data to estimate the effect of fuel changes on nonroad exhaust emissions.

For instance, the model does not include volatility effects on nonroad exhaust emissions because purge systems for evaporative emissions do not exist on nonroad engines, thereby eliminating the primary mechanism by which volatility is believed to affect emissions.

Impact of Fuel Sulfur on SOx Emissions

The sulfur effect is determined simply by taking the fraction of sulfur in the fuel multiplied by the consumption of fuel in the engine, on the presumption that the amount of fuel sulfur trapped in engine deposits is negligible and that fuel sulfur does not affect emissions of other pollutants.

Sulfur dioxide (SO_2) emission factors are expressed in terms of the amount of sulfur in the fuel. A mass balance approach is used and it is assumed that 97% of the sulfur in the fuel is converted to SO_2. The remaining sulfur is assumed to be emitted as sulfate particulates and SO_3 (which quickly converts to sulfuric acid mist in the presence of water vapor in the atmosphere). It is assumed that sulfate compounds are captured in the process of particulate testing and are included in the particulate emission factor.

Research on automotive engines indicates that sulfur affects exhaust VOC, NOx, and CO emissions by reducing catalyst efficiency, but current nonroad engines are not catalyst-equipped and few nonroad engines are expected to use this technology in the near future. When or if catalysts are more widely used for nonroad engines, the effect of sulfur on these other pollutants will be estimated for the fraction of the fleet using catalysts.

A default gasoline sulfur value for NONROAD of 339 ppm was chosen.[2] This level is identical to the default gasoline sulfur level used in MOBILE5a, and is based on the average 1990 gasoline sulfur level.

Impact of Fuel Oxygen on Exhaust Emissions

The effect of oxygen has been estimated in the past for nonroad engines from data on older technology highway automotive testing. [3] At that time only one study by Hare and White addressed this issue directly. [4] The Hare and White study investigates fuels at 2.7 and 3.5 weight percent oxygen for only two engines: a new two-stroke and a new four-stroke engine.

Since that time, two other studies have been completed using in-use nonroad engines tested on oxygenated fuel blends. The engines tested in these two studies were primarily 5 horsepower or less four-stroke engines, which were tested on a base gasoline and on oxygenated gasolines with 2.0-2.3 weight percent oxygen. The bulk of the data from these studies were taken from 13 lawnmower engines [5, 6] that were tested on a nonoxygenated base gasoline and a gasoline with nominally 2 weight percent oxygen. The original data are shown in Table 1. These studies determined the effects of oxygen at one oxygen level, nominally 2 weight percent oxygen, and ignored data collected at other oxygen levels. The test cycle used for these engines was a six-mode test also known as the J1088 developed by Hare and White [4] and used for certification by EPA.

Table 1 Emission Rates (g/kW-hr) for Base and Oxygenated Fuels using a Six-Mode Test and Four-Stroke Gasoline Engines [5, 6]

Engine	**Power**	**HC (Base)**	**HC (2% Oxygen)**	**NOx (Base)**	**NOx (2% Oxygen)**	**CO (Base)**	**CO (2% Oxygen)**
Briggs & Stratton #2615	5.0	9.14	9.73	1.72	1.88	568	508
Briggs & Stratton #1035	5.0	12.53	10.12	4.06	5.54	313	216
Briggs & Stratton #1023	3.0	50.36	43.40	1.26	2.67	836	615
Tecumseh #1079	3.5	21.97	19.24	5.31	6.53	399	324
Briggs & Stratton #9609	3.5	82.92	71.26	0.57	0.74	924	644
Briggs & Stratton #1001	3.5	35.74	32.11	3.37	4.94	487	396
Briggs & Stratton #XTE	5.0	9.14	7.01	4.38	5.93	351	258
Kawasaki #0032	5.5	6.81	5.71	3.44	4.89	339	262
Briggs & Stratton #1106	3.5	54.25	52.81	0.74	0.69	975	938
Briggs & Stratton #1036	5.0	31.66	26.66	1.24	1.42	699	662
Briggs & Stratton (new)	3.5	46.40	46.70	2.30	2.30	763	751
Briggs & Stratton (used)	3.5	71.00	65.00	1.16	1.31	1079	997
Kohler	14.0	5.77	5.41	3.00	3.20	339	323

Hare and White and Lindhjem and Charmley tested engines at two different oxygen contents with results indicating that more oxygen in the fuel will lead to greater changes in hydrocarbons (HC), nitrogen oxides (NOx), and carbon monoxide (CO) as shown in Table 2.

Qualitatively, it is seen that increases in fuel oxygen reduce HC and CO emissions with increasing NOx emissions. The effect of fuel oxygen is considered to be proportional to oxygen content because there is insufficient data to assume an alternative function form.

Table 2: Proportional Effect of Oxygen on Emissions

Engine	**Fuel**	**HC (g/kW-hr)**	**NOx (g/kW-hr)**	**CO (g/kW-hr)**
SwRI Tecumseh	Base	24.2	1.7	480
	2.7 % Oxygen	22.1	1.6	447
	3.5 % Oxygen	20.4	1.7	433
EPA Briggs& Stratton (new)	Base	46.4	2.3	763
	2.7 % Oxygen	46.7	2.3	751
	3.5 % Oxygen	44.5	3.1	658
EPA Briggs& Stratton (old)	Base	71.0	1.2	1079
	2.7 % Oxygen	65.0	1.3	997
	3.5 % Oxygen	65.8	1.7	949
EPA Kohler (new)	Base	5.8	3.0	339
	2.7 % Oxygen	5.4	3.2	323
	3.5 % Oxygen	4.3	5.0	239

Because only one 2-stroke gasoline engine has been tested, the effect of oxygen on exhaust emissions on 2-stroke engines will be based on the effects generated by that test. [4] Two test fuels, one with 2.7 and another with 3.4 weight percent oxygen, were tested so the average oxygen effect will be based on an average percent effect per percent oxygen from those tests. The engine used was a Yamaha two stroke moped engine. The result of these tests is shown below in Table 3.

Table 3: Emission Test Results for the Two-Stroke Engine

Fuel Used	**HC (g/kW-hr)**	**NOx (g/kW-hr)**	**CO (g/kW-hr)**
Base Gasoline	183.6	2.44	184
2.7% Oxygen	181.5	3.65	182
3.4% Oxygen	178.4	4.00	106

<u>Results</u>

Four Stroke Engines

The oxygen level for the 10 engines in the Gabele study was 2.3 and for the three engines in the Lindhjem and Charmley study was 2.0 weight percent. The average oxygen level for the 13 engines is then considered to be 2.2 weight percent by averaging the oxygen content for all of the engines.

This study calculates the effect by weighting the emission rates (g/kW-hr) by the power level of the engines shown in Table 1 to calculate an average emission rate for the engines tested on base and oxygenated fuels. The NONROAD model assumes that any given engine operates at a constant fraction of available power; therefore, to consistently reflect the overall effect on emissions, each engine in this study is assumed to also operate at a constant fraction of available power.

The effect of adding 2.2% oxygen to the fuel is calculated to reduce HC by 9.8%, increase NOx by 25.2%, and reduce carbon monoxide by 13.8%. The effect per percent of fuel oxygen is then estimated to be -4.5% for HC, +11.5% for NOx, and -6.3% for CO.

Two Stroke Engines

The percent change for the 2.7 and 3.4 weight percent oxygen is shown in Table 4. The overall effect of oxygen on two stroke gasoline engines per percent of fuel oxygen is estimated to be -0.6% for HC, +18.6% for NOx, and -6.5% for CO.

Table 4: The Effect of Fuel Oxygen on the Two Stroke Engine's Exhaust Emissions

Fuel Used	**HC (%/%Oxygen)**	**NOx (%/%Oxygen)**	**CO (%/%Oxygen)**
2.7% Oxygen	-0.4	18.4	-0.4
3.4% Oxygen	-0.8	18.8	-12.5

References

[1] EPA, "Regulation of Fuels and Fuel Additives; Standards for Reformulated and Conventional Gasoline; Final Rule," February, 16, 1994, FR-7716.
[2] Amendments to the Clean Air Act, 1990.
[3] Memo from Phil Lorang to EPA Regional Air Directors, Aug. 19, 1993.
[4] Hare, C.J. and White, J.J., "Toward the Environmentally-Friendly Small Engine: Fuel, Lubricant, and Emission Measurement Issues," SAE-911222.
[5] Memo from Lindhjem C.E. and Charmley, W.J. to Paul Machiele, July, 21, 1994.
[6] Gabele, P., "Exhaust Emissions from Four-Stroke Lawn Mower Engines," Journal of the Air and Waste Management Association, v 47, Sept., 1997.