Report to the Minnesota Department of Commerce

E20 Effects in Small Non-Road SI Engines
A literature and Information Search

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EXECUTIVE SUMMARY

Minnesota Statute 239.791 Subd.1a requires that on August 30, 2013, gasoline sold in the State of Minnesota shall contain at least 20% denatured ethanol by volume. If on December 31, 2010, however, it is determined that 20% of the State's gasoline volume is ethanol, then this provision expires. If 20% volume replacement is not achieved by 2010, then the 2013 requirement becomes effective provided the United States Environmental Protection Agency (US EPA) certifies E20 by December 31, 2010. In order to use E20 in non-Flex-Fuel vehicles, it will be necessary that the US EPA certify E20 as a motor fuel through a waiver under section 211(f) (4) of the Clean Air Act.

In anticipation that a 20% ethanol blend (E20) may become law in Minnesota, the State Commissioner of Commerce, in consultation with the Commissioner of Agriculture, was mandated to: (1) Report to legislative committees on E20 effects on small engines, (2) Assess fuel inventories, availability and use, and; (3) Make appropriate recommendations.

This report is a result of a literature and information search on the effects of E20 fuel on small spark-ignited (SI) engines. Just ten published reports were found specifically on E20 in small engines, however numerous other reports containing information on E20 and higher blends in automotive and other engines offer strong clues on how E20 would affect small engines. Additionally, industry trade groups were contacted to learn of their positions and research programs on the use of E20.

As defined by the US EPA, small non-road spark-ignited engines are rated below 25 horsepower (19 kW) and used in household and commercial applications, including lawn and garden equipment, utility vehicles, generators, and a variety of other construction, farm, and industrial equipment. Additionally, SI engines are used in outboard and personal watercraft engines.

In discussions with manufacturers of nonroad engines, the US Environmental Agency confirmed that using oxygenated fuels is acceptable, although some manufacturers offer special instructions when operating equipment on oxygenated fuels. Most nonroad engine manufacturers permit the use of oxygenated fuels, not to exceed 10% ethanol by volume. To summarize, the following effects on an engine can be expected when ethanol blends E20 and greater are used as an engine fuel:

(1) Engine Performance: Ethanol has a higher octane number than gasoline and when blended with gasoline can effectively operate at higher compression ratios with subsequent improvement in power output, efficiency, and fuel consumption. It may be impractical to raise the compression ratio, but if the engine is knock-limited with standard gasoline, advancing the spark may offer improvements in performance similar to those obtained with a small increase in compression ratio. The chemically correct fuel-air ratio with E20 is about 4.5% higher than that of E10, 9% higher than that of E0. With an open-loop fuel system this will lead to leaning of the fuel/air mixture, increases in exhaust temperatures, and possible drivability (operating) problems.

Ethanol also has a higher latent heat of vaporization. The blended ethanol's higher latent heat of vaporization would enable the engine volumetric efficiency to increase. But at colder temperatures, the high latent heat will lead to less vaporization of the fuel, a leaner mixture, and starting and drivability (operating) problems. This problem could be avoided by heating the intake manifold, but this solution is not practical for small engines because these engines have simple fuel induction systems that are not amenable to this modification. In addition, manifold heating offsets the volumetric efficiency gains associated with the high latent heat of vaporization.

All of these factors will influence the performance of E20 in a small engine. However, there will be considerable engine-to-engine differences, depending on detailed engine design differences. The high octane and latent heat of vaporization of ethanol offer the potential of significant performance gains, but existing small engines would need to be redesigned or modified to fully realize these gains.

(2) Cold Start: Cold starting is highly dependent on the fuels ability to vaporize effectively at low temperatures and provide an ignitable mixture at the time of ignition. For ethanol blends, cold starting depends on the vaporization of the more volatile gasoline fractions. However, when alcohol is present, the vapor contains a greater concentration of alcohol than would be expected based on the vapor pressure of the alcohol or it's concentration in the gasoline. Due to ethanol's higher heat of vaporization than gasoline, more heat is required to vaporize ethanol blends. Effectively, the mixture suffers from enleanment due to the higher concentration of alcohol (because the chemically correct fuel/air ratio is higher). These factors indicate cold starting difficulties on small engines operating with ethanol blends greater than E10.

Raising the compression ratio and valve timing optimization are considered to be practical methods to improve cold starting, but these solutions require new engine designs.

(3) Enleanment: The addition of oxygenates to gasoline has the effect of enleaning the fuel/air mixture on engines that are not adjusted to optimize this ratio. Fuel metering components are sized to deliver an fuel/air mixture that provides an optimum balance between power output, fuel economy, and durability. Engine manufacturers are aware of the fuel/air sensitivity of their engines and in some cases, they recommend alterations to certain engine models when using oxygenated gasoline. If an engine operates at a mixture that is significantly leaner than it is designed for, it will run at a higher temperature, which can lead to engine damage. Some manufacturers of recreational vehicles offer recommendations for modifying engines when operated on oxygenated fuels (i.e. choke adjustments for cold starts and installation of larger carburetor jets).

(4) Vapor Lock: Although the vapor pressure of pure ethanol is low, the Reid Vapor Pressure (RVP) of gasoline-ethanol blends rises depending on the ethanol proportion in the blend. Low RVP can cause starting problems, but high RVP can cause vapor lock in warm weather. Depending upon the degree, vapor blockage can cause engine performance problems ranging from poor to erratic power output to engine overheating to full engine stall due to fuel starvation and hot-start problems.

(5) Engine Wear: The impact of a 20% ethanol blend on engine wear is unclear. No literature was uncovered that dealt with ethanol blends exceeding 10% ethanol. The only valid conclusion that can be drawn is that further testing is required to obtain data to provide an indication of the potential impact of E20 on engine wear.

(6) Emissions: Both exhaust and evaporative emissions can be influenced by the use of oxygenates in gasoline. Because of the cooling effect on the intake charge and leaner operation when oxygenates are used, both carbon monoxide (CO) and hydrocarbons (HC) emitted from the exhaust are reduced with no significant change in NO_x. However, if an engine is designed to operate close to the lean limit of combustion on hydrocarbon fuels, misfire may occur when oxygenates are present, with a consequent increase in unburned hydrocarbons.

Other unregulated exhaust gas pollutants that have been studied and that are influenced by oxygenates in gasoline include 1,3 butadiene, benzene, and other aromatics including polynuclear aromatics (PNAs), formaldehyde and acetaldehyde.

Another important emissions concern that remains poorly understood is ethanol's ability to permeate through rubber, plastic, and other materials that are used widely in the fuel tank, fuel system hoses, seals, and other parts of the fuel handling system. Recent studies have shown these emissions can be quite significant. High vapor pressure and the presence of ethanol in gasoline also increase evaporative/diffusional emissions (and fuel loss). Permeation rates for ethanol blends of E20 and greater are largely unknown.

(7) Engine and Fuel System Deposits: Ethanol gasoline blends increase the solubility of gasoline fuel deposits lending to the release of gum-bound debris followed by blockage of filters and fuel metering components. Gum formation during equipment storage is a particular concern for equipment that does not get used on a regular basis. The majority of engine manufacturers recommend draining unused fuel from equipment or adding a fuel-stabilizing additive that prevents oxidation prior to storage of equipment. The solvent action of the oxygenated fuel may dissolve some of the fuel system deposits, which will plug fuel filters.

In regards to an E20 blend, further testing is required to obtain data to provide an indication of the potential impact of deposits on engine performance and durability.

(8) Material Compatibility: The materials used in engine fuels systems are diverse. Ethanol in gasoline can cause elastomers to swell and lose tensile strength, causing fuel pumps, accelerator pumps, and hoses to fail**.** Manufacturers are concerned that seals and gaskets on older equipment that have not been previously exposed to alcohol-oxygenated fuels could experience leakage. Manufacturers of hoses for retail gasoline dispensers have indicated their hoses are suitable for only gasoline ethanol blends containing up to 10% ethanol

Fiberglass-reinforced plastic tanks may cause problems depending on the type of resin used during fabrication. Materials such as terne plate (lead/tin-coated steel used in fuel tanks) zinc die castings, and aluminum fuel system components are attacked by alcohols and require corrosion inhibitors to minimize this effect. Corrosion of steel is accelerated by the presence of alcohols in the fuel, partly because of the increased water content of the fuel. Only testing of representative components along with long-term durability and testing with the E20 ethanol blend can provide accurate information of the possible impact.

(9) Phase Separation (of fuel): Ethanol has a high affinity for water, thus it contains a certain amount of water. Since gasoline and water do not mix, even small amounts of water in pure gasoline will result in a separate phase of water in a fuel tank, which, if pumped into the engine, could cause damage. However, years of experience have resulted in this concern being minimized. Oxygenated gasoline (ethanol blends), will tend to dry out fuel tanks by blending with the water allowing it to be combusted in the engine. Only with comparatively large amounts of water in ethanol-blended gasoline will a separate alcohol/water phase occur. There is a wide range of recommendations by manufacturers for the use of oxygenated fuels depending on the specific engine application. Water contamination can also cause corrosion on metal components. Solubility improvers, such as isopropanol, can prevent these problems.

In conclusion, only durability and emissions testing will provide accurate information on the possible impact of E20 on small engines because little specific information was uncovered during the literature search. This testing would need to be satisfactorily completed as part of the EPA E20 waiver process. Fortunately, engine manufacturers and industry trade groups are taking this matter seriously and are cooperating with federal and state agencies to address the potential issues of E20 in small SI engines (see appendices).

INTRODUCTION

At one time small engines were not considered significant contributors to air pollution, but as automobile emission controls have become more effective the relative contribution of small engine emissions to overall air pollution has increased. Emissions from small utility engines are 100 to 1,000 times higher than those from automobile engines (1). Prior to this era, design and development of small engines has been motivated predominantly by output power, cost, and durability, and optimal design solutions invariably favored operation with fuel-rich combustion with little regard to emissions.

The 1990 Clean Air Act Amendments requires the Environmental Protection Agency (EPA) to issue regulations for gasoline to be "reformulated" to result in significant reductions in vehicle emissions of air pollutants. The primary goal of the reformulated gasoline program is to reduce vehicle emissions that contribute to the formation of smog, a noxious pollutant that is harmful to human health and the environment, and reduce toxic emissions from vehicles such as benzene, a known human carcinogen. These amendments require that, beginning in November 1992, all carbon monoxide (CO) non-attainment areas implement mandatory oxygenated fuel program during certain winter months. Ethanol is the most widely used oxygenate for complying with current oxygenated fuel requirements. Because of its higher oxygen content, compliance can be achieved with less volume addition than with other oxygenates. Ethanol in gasoline can favorably impact engine emissions in five primary air quality areas: fine particulate matter, CO, toxics, ozone, and global warming (1).

In discussions with manufacturers of nonroad engines, the EPA confirmed that using oxygenated fuels is acceptable up to a point, although some manufacturers offer special instructions when operating equipment on oxygenated fuels. Most nonroad engine manufacturers permit the use of oxygenated fuels, not to exceed E10 (10% ethanol by volume) (2).

Minnesota Statute 239.791 Subd.1a requires that on August 30, 2013, gasoline sold in the State of Minnesota shall contain at least 20% denatured ethanol by volume. If on December 31, 2010, however, it is determined that 20% of the State’s gasoline volume is ethanol, then this provision expires. If 20% volume replacement is not achieved by 2010, then the 2013 requirement becomes effective provided the United States Environmental Protection Agency (US EPA) certifies E20 by December 31, 2010. In order to use E20 in non-Flex-Fuel vehicles, it will be necessary that the US EPA certify E20 as a motor fuel through a waiver under section 211(f) (4) of the Clean Air Act.

In anticipation that 20% ethanol blends (E20) may become law, the State Commissioner of Commerce, in consultation with the Commissioner of Agriculture, was mandated to: report to legislative committees on E20 effects on small engines, assess fuel inventories, availability and use, and make appropriate recommendations.

The University of Minnesota performed a literature and information search on the use of E20 (20% ethanol / 80% gasoline) in small engines. Just ten published reports (5, 10, 12, 14, 16, 19, 21, 22, 23, 25) were found specifically on E20 in small SI engines, however numerous other reports containing information (i.e. fuel blend characteristics, effects on emissions and materials) on E20 and higher blends in automotive and other engines are covered and offer strong clues on how E20 would affect small engines.

As defined by the US EPA, small non-road spark-ignition (SI) engines are those rated below 25 horsepower (19 kW) and used in household and commercial applications, including lawn and garden equipment, utility vehicles, generators, and a variety of other construction, farm, and industrial equipment. Utility engine is a term used for a particular group of general-purpose internal combustion engines. Utility engines are off-road or stationary, and mostly single-cylinder. They are commonly used in applications such lawn and garden equipment (lawn mowers, string trimmers, chainsaws, etc.) generator sets, and pump or compressor sets. Additionally, spark-ignition engines are used in marine vessels including outboard engines, personal watercraft, and stern drive/inboard engines. These engines are made in both 2-stroke and 4-stroke configurations.

Ethyl alcohol, or ethanol (C_2H_5-OH) is derived from the direct fermentation of sugars, fermentation of starches and cellulose after chemical or enzymatic pretreatment, or made from petroleum sources. Ethanol has different chemical and physical properties when compared to gasoline. These properties include octane, oxygen content, volatility, and water solubility. These differences influence the performance, combustion products, and effects on engine components of gasoline-ethanol blends. Although ethyl alcohol has low caloric value compared to gasoline, engine power output has the potential to be improved by using ethanol. That is, at the same equivalence ratio, ethanol can produce greater power as compared to gasoline. Power increases proportional to the percentage of ethanol in the blend (3). However, small engine redesign or modifications would be required to take full advantage of ethanol blends greater than E10.

The American Society for Testing and Materials (ASTM) has a standard for E85, which covers formulations ranging from E70 to E85. However, there are no standards for mid-level blends between E10-E70 (4). Without standards, users are making E20 formulations on an ad-hoc basis, typically by splash blending denatured ethanol with some type of base gasoline. Therefore, there is no comparability between properties of these mid-level ethanol blends made by various users.

ENGINE PERFORMANCE

Ethanol has a higher octane number than gasoline and when blended with gasoline can effectively operate at higher compression ratios with subsequent improvement in power output, efficiency, and fuel consumption. It may be impractical to raise the compression ratio, but if the engine is knock-limited with standard gasoline, advancing the spark may offer improvements in performance similar to those obtained with a small increase in compression ratio. The chemically correct fuel-air ratio with E20 is about 4.5% higher than that of E10, 9% higher than that of E0. With an open-loop fuel system this will lead to leaning of the fuel/air mixture, increases in exhaust temperatures, and possible drivability (operating) problems.

Ethanol also has a higher latent heat of vaporization. The blended ethanol's higher latent heat of vaporization would enable the engine volumetric efficiency to increase. But at colder temperatures, the high latent heat will lead to less vaporization of the fuel, a leaner mixture, and starting and drivability (operating) problems. This problem could be avoided by heating the intake manifold, but this solution is not practical for small engines because these engines have simple fuel induction systems that are not amenable to this modification. In addition, manifold heating offsets the volumetric efficiency gains associated with the high latent heat of vaporization.

All of these factors will influence the performance of E20 in a small engine. However, there will be considerable engine-to-engine differences, depending on detailed engine design differences. The high octane and latent heat of vaporization of ethanol offer the potential of significant performance gains, but existing small engines would need to be redesigned or modified to fully realize these gains.

Cold Start

Fuel specifications are very important both to the manufacturer of engines and to the user. Reid Vapor Pressure (RVP) is an important fuel property influencing cold start. RVP is defined as the pressure exerted by the vapors released from any material at a given controlled temperature when enclosed in a laboratory vapor tight vessel.

The ability to start an engine at low ambient temperatures is highly dependent on the fuels ability to vaporize effectively at low temperatures and provide an ignitable mixture at the time of ignition. If a gasoline's vapor pressure is unusually low (below 5.5 psi) it can cause faltering acceleration during sudden wide-open throttle applications. The lower the median temperature of an area, the higher the vapor pressure must be to properly atomize the fuel with air for proper engine combustion. Ethanol has low volatility (low values of RVP). Because the RVP at 0 degrees C (32 degrees F) is 3 to 4 times lower than that of gasoline, it is difficult to vaporize ethanol at temperatures below 10 degrees C (50 degrees F) (5, 6). Confirmed by tests, these factors indicate cold starting difficulties on engines operating with ethanol blends (7). This influence can be remedied by use of volatile additives (i.e., iso-pentane) and pre-heating the intake air (5). Due to the added complexity, preheating the intake air is not a practical solution for small engines.

Vapor Lock

Reid Vapor Pressure (RVP) is an important fuel property influencing vapor lock. Vapor lock is caused by the fuel flow to the engine being reduced as a result of vapor formation, typically caused by high temperatures, while the engine is operated.

Normal vapor pressure for street grade gasoline ranges from 9.0 to 15.0 psi depending on the air temperature of the environment. The higher the average air temperature of a locale, the lower the vapor pressure needs to be. If a gasoline's vapor pressure is excessively high, it may result in vapor lock or fuel percolation hindering fuel flow. Depending upon the degree, vapor blockage can cause engine performance problems ranging from poor to erratic power out put to engine overheating to full engine stall due to fuel starvation and hot-start problems. This problem may be exacerbated in carburetor-equipped engines. Since the addition of an alcohol to gasoline can increase the volatility of the fuel, there is a risk that it will also cause vapor lock to occur in hot weather or at high altitudes (1).

Enleanment

Because fuel delivery systems are designed to deliver a prescribed amount of fuel on a volume control basis, the fuel volume delivered is related to the volume of air introduced. Engines are calibrated to match the air/fuel ratio characteristics that a particular engine design requires. Because ethanol blended fuels require more fuel for the same amount of air to achieve stoichiometric conditions, the fuel system must adapt by introducing more fuel or the desired mixture is not achieved. The effect of this type of fuel change on an engine is called enleanment (8).

Engine manufacturers are aware of the air/fuel sensitivity of their engines and in some cases, they recommend alterations to certain engine models when using oxygenated gasoline. For example, in engines set at an air/fuel ratio of 14.7:1 on a hydrocarbon fuel, the introduction of 2.7% weight oxygen (E7.7 equivalent) in the fuel would enlean the ratio to about 15.15:1, which is a relatively small change. If an engine operates at a mixture that is significantly leaner than it is designed for (i.e. E20), it will run at a higher combustion chamber and exhaust temperatures, which can lead to engine damage (i.e. piston damage, cylinder wall scuffing, valve seat erosion) (9, Appendix B4).

Enleanment also has the potential to have a detrimental effect on cold starts, hot operation, cold operation, and wide open throttle performance. The propensity for these conditions to occur will increase as the proportion of ethanol blend is increased (7). Enleanment as a result of using E10 and E20 fuel can cause engine knock and pre-ignition in engines intended for use with regular gasoline. This effect was found to be potentially the main source of base engine component failure in a study by the Orbital Engine Company (10).

Two-stroke engines usually operate at air/fuel ratios that are rich enough to not be affected by the addition of oxygenates. However, some manufacturers of recreational vehicles, such as snowmobiles, offer recommendations for modifying engines when operated on oxygenated fuels (2). The Honda 4-stroke engines, for example, can easily be adjusted to avoid enleanment by simply re-jetting the carburetor (11). Engine-specific tests would be required to determine how ethanol blends greater than E10 would affect performance.

Engine Wear

Concerns have been expressed on how the use of alcohols in fuels would increase engine wear (6). There are concerns that gasoline-containing ethanol may not provide adequate lubricity, especially in two-stroke engines. However, there is very limited technical data to support such a position (2).

The impact of a 20% ethanol blend on engine wear in non-automotive engines in a study of the Australian non-automotive engine population is unclear. No literature was uncovered that dealt with ethanol blends exceeding 10% ethanol (7). However, in a Chinese study of nine motorcycles of three different types (six 4-stroke and three 2-stroke engines) were used to study the effects of E10 vs. neat gasoline, advanced piston wear was discovered in the 2-stroke engines (12). Overall, information on the effects of E20 on engine wear is lacking. Further testing is required to obtain data to provide an indication of the potential impact of ethanol blends on engine wear.

Emissions

Initiated by Environment Australia, the Orbital Engine Company carried out a series of investigations on vehicles fuelled with ethanol-blended gasoline (7, 10, 13, 14, 15, 16). Most of these investigations have focused on a blend of 20 % ethanol in two or three grades of gasoline produced for the Australian market. These investigations are valuable because a broad spectrum of emission data is presented in the reports and many aspects, such as fuels, vehicles, catalysts, vehicle performance and wear are discussed. One drawback with the data from the tests involved the gasoline used for the tests. The blended fuel and the neat gasoline had sulphur contents ranging from 150 and 500 ppm, respectively. Investigations and evaluations conducted for the American Lung Association of Minnesota (17) have shown that the sulphur content of the fuel has a considerable impact on both regulated and unregulated emissions. Therefore, data on emissions generated using fuels with different sulphur levels cannot be directly compared (18).

Both exhaust and evaporative emissions can be influenced by the use of oxygenates in gasoline. A leaning effect on the air/fuel ratio when oxygenates are used can mean that, for small engines with no exhaust aftertreatment, both CO and HC emitted from the exhaust are reduced with no significant change in oxides of nitrogen (NO_x). However, if an engine is designed to operate close to the lean limit of combustion on hydrocarbon fuels, misfire may occur when oxygenates are present, with a consequent increase in unburned hydrocarbons. If an engine operates in a rich region, HC emissions tend to decrease proportional to ethanol's percentage in the blend (3).

An experimental investigation of using ethanol as a fuel in a common utility engine (Honda 2.5 Hp single-cylinder, 4-stroke, spark ignition, side valve, 5.1 cu. in.) was conducted to investigate and validate the effect of ethanol and ethanol blended (E10, E20, E40, and E100) with gasoline on engine performance and exhaust emissions. The authors found that overall, CO, HC, and NO_x decreased proportional the percentage of ethanol in the blend. In these tests, however, the engine carburetor was modified to accommodate the increase in fuel flow rate of the ethanol blends. Also, a system to change the spark ignition timing was incorporated (19).

Unregulated exhaust gas pollutants that have been studied and that are influenced by oxygenates in gasoline include 1,3 butadiene, benzene, and other aromatics including polynuclear aromatics (PNAs), formaldehyde and acetaldehyde. Aldehydes are increased in the exhaust gases when oxygenates are present in gasoline mainly because of the leaning effect, so that the increase is proportional to the oxygen content of the fuel. Further, there is no standard validated method for determining aldehyde and alcohol emissions from motor vehicle (engines), so (an) appropriate method(s) must be developed (18).

Pana performed experiments on an experimental single cylinder engine (modifications were made to preheat intake air and to the carburetor). An increase in efficiency of about 12% was obtained when E20 fuel was used. This result is due to reduction of combustion event duration attributable to the ethanol addition. For the same engine power the reduction of HC emissions was about 12% with E20 and NO_x reduction was about 11%. The authors state that an E20 blend is preferred because it does not require any major engine modification (5) (in this engine configuration).

Experiments by Nakata on a modified (increased compression ratio) automotive engine on the use of ethanol fuel led to significantly less CO and HC. At the same equivalence ratio, compared to neat gasoline, ethanol generated much less NO_x and $HC+NO_x$ proportional to the percentage of ethanol in the blend. $HC+NO_x$ emissions tended to decrease proportional to the percentage of ethanol in the blend (3). But, the emissions effects of increased ethanol in gasoline are generally not linear with the amount of oxygen in the fuel. Therefore, the effects of increasing the ethanol content beyond E10 on exhaust and evaporative emissions on current small engines are not fully known (8).

One problem related to the use of ethanol in gasoline is the increased vapor pressure caused by the alcohol when mixed in relatively low proportions with gasoline. Blends of greater than 10% are of particular concern (18, 20). Evaporative emissions are strongly dependent on the RVP of the fuel and any increase due to the presence of oxygenates will give a corresponding increase in evaporative emissions (6). An increase in vapor pressure (RVP) has been shown to increase the emissions of VOCs (volatile organic components), which may in worst-case scenarios result in enhanced levels of ozone (1).

Henke measured the evaporative emissions (total hydrocarbons (THC)) from two summer gasoline fuels blended with E0, E5, E10, and E15 at various intervals. THC levels ranged from 200 ppm for neat gasoline up to 350- ppm for E15 (20).

Two-Stroke Engines**:** For outdoor products such as trimmers, blowers, and chain saws the high-performance two-stroke engine is the most commonly applied power source. It is very compact, lightweight, low-cost, easy to maintain, and yields a high specific power output.
Two-stroke engines suffer from high scavenge losses leading to high HC emissions due to incoming fuel leaving the cylinder with outgoing exhaust gas (21). In conventional 2-stroke engine designs that optimize power at low cost (such as the LawnBoy D410), roughly 25% of the fuel is exhausted in this way. When these engines are mistuned, or run without air filters, as much as 50% of the fuel is exhausted as unburned hydrocarbons (11).

Czerwinski performed emission measurements of chainsaw engines, with a special concern for particulate emissions. Particulates were analyzed via state-of-the-art techniques; gravimetry, Scanning Mobility Particle Sizer (SMPS), NanoMet, and differential analysis of sample filter residue. The variable test conditions were air/fuel ratio, lube-oil content, and fuel quality. Results show that the particulate mass and nanoparticle numbers attain very high values and consist almost exclusively of unburned lube-oil. These pollutants are strongly influenced by engine tuning and lube-oil content (composition). Recommendations for chainsaw engine emission control are the use of an oxidation catalyst, improvements of 2-stroke engine design, and substitution with small 4-stroke engines (22).

In a Chinese study, six 4-stroke and three 2-stroke motorcycles were used to study the effects of E10 vs. neat gasoline. Unfortunately in their data analysis, the authors combined the test results of both 2- and 4-stroke engines to make general conclusions. They found that E10 reduced CO (-50%) and HC (-20%) emissions with a slight decrease in top speed (12).

Four-Stroke Engines*:* Four-stroke engines are configured with two types of valve arrangements - side valve and overhead valve.

Emissions of THC, CO, NO_x, and combined $HC+NO_x$ from small utility engines were used to judge the effect of ethanol addition (E0 to E50) to a hydrocarbon fuel with factory air/fuel ratio carburetor settings. The test engines used were two 4-stroke 9.3 kW (12.5 HP) Briggs & Stratton side valve engines and one 4-stroke Kohler overhead valve engine of the same size. Emissions differences due to the differing valve arrangements were a secondary objective. The primary results indicate that increasing the concentration of ethanol in gasoline is effective in reducing regulated CO emissions from small engines designed to operate on non-oxygenated fuels but ineffective in reducing regulated combined $HC+NO_x$ emissions. This result has negative implications on one small engine emission reduction strategy – blending a specialized “lawn and garden” highly oxygenated fuel for delivery through alternative distribution outlets. The secondary results indicate that the overhead valve technology engine exhibits lower HC and CO emission characteristics but has no discernible effect on NO_x and negligible effect on combined $HC+NO_x$ emissions. This result has positive implications on small engine emissions reduction strategy – the shift from side-valve engines to overhead valve engines in small engine applications (23).

Brinkman also observed two beneficial emission characteristics of ethanol addition: The enleanment effect reduces HC and CO emissions, and the effect of more complete combustion beneficially alters the CO and NO_x emissions relationships (24).

Bayraktar investigated the effects of ethanol addition to gasoline on a SI engine (single-cylinder, 4-stroke, water-cooled, variable compression ratio) performance and exhaust emission experimentally and theoretically. Experimental applications included blends containing 1.5, 3, 4.5, 6, 7.5, 9, 10.5, and 12% ethanol. Numerical applications were performed with up to 21% ethanol. Experimental results show that among the various blends, 7.5% ethanol was the most suitable from the engine performance and CO emissions point of view. However, theoretical comparisons show that the blend containing 16.5% ethanol was the most suited blend for SI engines. The author goes on to conclude that blends up to 16.5% ethanol by volume can be used in SI engines without any modification to the engine design and fuel system (25).

Emission Control: In principle, a straightforward way to reduce emissions is to burn an almost stoichiometric air-fuel mixture and aftertreatment by catalysis, as modern automobiles do. However, gasoline-fueled small engines that have been developed predominantly for power and low cost, using fuel-rich combustion, typically knock, misfire, or overheat if operated at stoichiometric air-fuel ratios. Redesign of combustion chambers and valve-gear for operation at higher temperatures is quite feasible, as evidenced by the success of propane-fueled engines that run at a stoichiometric mixture and have become the powerplant of choice for heavy-duty indoor machines (5, 11).

Some very recent \`low-emissions' small engines run at air-fuel ratios sufficiently close to stoichiometric that NO_x emissions become problematic. In one application, Ryobi has incorporated an EGR (exhaust-gas recirculation) valve between the exhaust and intake manifolds in their Pro-4-Mor 4-stroke engine. This 3/4 hp engine is presently the only commercially available four-stroke string-trimmer in a market in which traditionally only two-stroke engines have been used (11).

In small 2-stroke engines, scavenging systems have conventionally been designed to maximize engine power. Redesigns of intake and exhaust ports, and re-optimization of the placement and overlap of these ports offer opportunities to reduce emissions through scavenging losses though the possible gains are not yet known. In specialized applications such as chainsaws, where other engines cannot match the high rpm and power-to-weight ratio of two-strokes, prototype engines using direct injection of fuel have been tested. Because re-designs of this kind could lead to significantly higher development and manufacturing costs, the most cost effective solutions will probably be some combination of re-design and aftertreatment or of more sophisticated carburetion (sensor controlled) and aftertreatment (11).

The most effective way to overcome high HC emissions is by substituting with small 4-stroke engines, however these engines cannot achieve the high performance/low weight levels of two-stroke engines. Two approaches to control HC emissions in 2-stroke engines are being taken by manufacturers (21):

-Avoiding excessive scavenging losses by controlling the scavenge cycle by stratified scavenging or charging, direct fuel injection or mixture injection.

-Aftertreatment of HC emissions by catalysts that allows leaving the core engine mostly unchanged.

Permeation: An important emissions issue that is poorly understood is ethanol's ability to permeate through rubber, plastic, and other materials used widely in the fuel tank, fuel system hoses, seals, and other parts of the fuel handling system (8). Recent studies have shown these emissions can be quite significant. The low-level ethanol blends E6 through E20, increased permeation in vehicle systems, compared to the non-ethanol fuel (E0). Permeation rates for higher ethanol blends greater than E20 are largely unknown (26).

PHASE SEPARATION (of fuel)

Since gasoline and water do not mix, even small amounts of water in pure gasoline will result in a separate phase of water in a fuel tank, which, if pumped into the engine, could cause damage. The oxygenated gasolines, primarily the alcohol blends, will tend to dry out fuel tanks by blending with the water allowing it to be combusted in the engine. This is the same principal behind the "dry gas" additives sold over the counter to prevent water in fuel from causing engine problems. Only with comparatively large amounts of water in alcohol-blended gasoline will a separate alcohol/water phase occur. Many manufacturers have specific recommendations for preparing equipment for storage during the off-season, especially if the equipment has been fueled with alcohol fuels.

When ethanol absorbs enough water (about 3/4 oz. or more per gallon), the ethanol phases out of an E10 mixture creating two stratified layers, with the gasoline on top. If the fuel lines are at he bottom of the tank, they will take in the alcohol and water first, which will cause stalling and difficult starting (6, 27).

If it was combust in the engine, the impact of the water-ethanol phase is greater in a 2-stroke engine than in a 4-stroke engine. In a 2-stroke engine the ethanol-water phase will compete with the gasoline-oil mixture and reduce the lubricating ability of the lubricating oil. However, phase separation normally only occurs in the presence of liquid water in a ethanol-gasoline blend (28).

Years of experience on essentially identical fuels have resulted in phase separation concern being minimized. In summary, there is a wide range of recommendations by manufacturers for the use of oxygenated fuels depending on the specific engine application (1, 2).

MATERIAL COMPATABILITY

The materials used in engine fuels systems are diverse. Materials used in engine and fuel system components must be compatible with the full range of expected fuel composition. Appendix 'A' lists some of the types of metals, rubbers, and plastics that are used in existing engines and fuel system components currently designed to run on E10 fuel blends. This is not an exhaustive list and is meant as an illustration of the diversity of materials presently used. The compatibility of all of these materials with greater than E10 fuel blends is not well known because there has been no reason to test (13). However, some test data is available from testing on E20 fuels by others (7).

Ethanol contains acetic acid that can corrode aluminum alloys. It also adsorbs the lead in alloys causing the surface to become porous (5). Materials such as terne plate (lead/tin-coated steel used in fuel tanks) zinc die castings, and aluminum fuel system components are attacked by alcohols and require corrosion inhibitors to minimize this effect. Corrosion of steel is accelerated by the presence of alcohols in the fuel, partly because of the increased water content of the fuel. Corrosion occurs through different mechanisms including acidic attack, galvanic activity, and chemical interaction. The first is caused by water in the fuel (6). Ethanol attracts and dissolves water, creating a slightly acidic solution. Unlike gasoline, ethanol alone or combined with water conducts electricity; this conductivity creates a galvanic cell that causes exposed metals to corrode. Another mechanism is direct chemical interaction with ethanol molecules on certain metals. Deterioration of materials would result in loss of function of critical engine components, resulting in fuel leaks, fires from fuel leaks, and equipment failure

To ensure materials compatibility at higher ethanol levels for use with flexible fuel vehicles (FFVs) manufacturers use corrosion resistant materials in any part that may contact fuel. Manufacturers of small engine products such as chain saws and lawn mowers, as well as older and antique vehicles recommend coating or anodizing aluminum carburetors or substituting a different metal not susceptible to attack (13).

Ethanol in gasoline can cause elastomers to swell and lose tensile strength, causing fuel pumps, accelerator pumps, and hoses to fail (6). Manufacturers are concerned that seals and gaskets on older equipment that have not been previously exposed to alcohol-oxygenated fuels could experience leakage (2). Manufacturers of hoses for retail gasoline dispensers have indicated their hoses are suitable for only gasoline ethanol blends containing up to 10% ethanol (9).

The Orbital Engine Company carried out performance, durability, and material compatibility testing on two different 2-stroke engine models: a 15-HP Mercury marine engine and a Stihl line trimmer with E10 and E20 fuels (10). The results for E10 were found to be acceptable, however material compatibility problems were found for E20 with both engine types, and evidence of possible long-term durability concerns was found for the marine outboard engines. A study using 2000-hour E20 immersion tests on materials found in these two engine models revealed concerns, and the effects on some polymeric materials were seemingly unacceptable (13). These studies also show E20 tarnishing and corroding brass and aluminum parts, and both these metals are avoided for E85 applications. Higher exhaust gas temperatures for E20 were observed and are considered a potential source of long-term durability problems. Performance testing of 10 of these same 15 hp marine outboard engines (10) showed minor but measurable performance degradation for E20 operation. Specifically observed were increased misfire, engine stall, and difficulty maintaining a constant engine speed. However, engines were always easily restarted after stalling (16).

Fiberglass-reinforced plastic fuel tanks may cause material compatibility problems depending on the type of resin used during fabrication. Higher blend concentrations (above 10% ethanol) may require fiberglass tanks to be constructed of a special resin. General epoxy or polyester resin based materials used in the late 1970's and earlier 1980's are not compatible with gasoline/ethanol blends (6). Boats have similar compatibility concerns. It was reported that fiberglass gas tanks could fail and cause engine damage when filled with gasoline formulated with ethanol. Reports state that more than 50 cases of fiberglass gas tanks, many of them manufactured before the mid-1980's, produced an engine-killing sludge or began leaking after being filled with a 10% ethanol gasoline (29, 30).

Three material compatibility studies on metals, elastomers, and plastics are underway at Minnesota State University, Mankato (31, 32, 33) but the results of this work (as of January 2008) are not available.

ENGINE AND FUEL SYSTEM DEPOSITS

Intake system deposits can have an effect on engine performance and fuel economy. Non-automotive 4-stroke engines are expected to experience intake system deposits in the same manner as automotive 4-stroke engines operating on ethanol gasoline blended fuels. Two-stroke engines may also experience deposit related issues when operating on ethanol blends.

Many boats use aluminum fuel tanks that are susceptible to corrosion. While sacrificial zinc anodes often are added later to the external parts of these tanks, they are not feasible for the tank's interior. The interior of some older steel tanks may have been lined to prevent small leaks and extend their useful life (6). Fiberglass tanks have a different problem. Ethanol can chemically attack some of the resins used to make these tanks causing them to dissolve. In doing so, the ethanol causes leaks, heavy black deposits on marine engine intake valves, and deformation of push rods, pistons, and valves (16).

The engine damage in boats with fiberglass tanks appears to be due to a tar-like substance - possibly from the chemical reaction between the resin and ethanol - causing hard black deposits that damage intake valves and pushrods, ultimately destroying the engine. Early symptoms may include engine backfiring and hard or sluggish starting in which the engine turns over slowly. Affected engines may not reach their rated speed. Fuel filters have not captured the substance. The only way to know for certain if deposits from deteriorating tanks are causing engine performance to degrade is to inspect the carburetor for a black, gummy film (27, 29, 30).

Gum formation during equipment storage is a particular concern for equipment that does not get used on a regular basis. Ethanol blends increase the solubility of the gum in gasoline and this may partly account for the increased intake system deposit-forming tendency. Dissolved gum causes suspended materials to plug filters. These released gum-bound deposits of rust and other types of sediment can be deposited within the engine, degrading performance. This is a problem when existing fuel tanks are converted from hydrocarbon-only duty to the storage of alcohol/gasoline blends (6).

Gumming was highlighted as a potential failure mode, due to the potential risk of fuel residues depositing on critical surfaces or causing blockages within components (10). In a Chinese study of nine motorcycles (six 4-stroke and three 2-stroke) fueled on E10 for 16,000 km (9,942 miles), sediment was found in the 4-stroke motorcycle carburetors (12).
The majority of engine manufacturers recommend draining unused fuel from equipment or adding a fuel-stabilizing additive that prevents oxidation prior to storage of equipment Changing fuel filters more frequently until the fuel system has cleaned itself is recommended (2, 7).

The literature related to non-automotive engine deposits due to use of ethanol is limited and only related to the E10 blend. With respect to the potential impacts of an E20 blend, further testing is required to obtain data to provide an indication of the potential impact of E20 on engine and fuel system deposits.

SUMMARY

As defined by the US EPA, small non-road spark-ignited (SI) engines are rated below 25 horsepower (19 kW) and used in household and commercial applications, including lawn and garden equipment, utility vehicles, generators, and a variety of other construction, farm, and industrial equipment. Additionally, SI engines are used in marine vessels including outboard engines, personal watercraft, and stern drive/inboard engines.

This class of internal combustion engine is presently the subject of exhaust-emission regulations developed by the California Air Resources Board and the U.S. Environmental Protection Agency, in accordance with the Clean Air Act Amendments of 1990. These amendments require that, beginning in November 1992, all carbon monoxide (CO) non-attainment areas implement mandatory oxygenated fuel program during certain winter months. Ethanol is the most widely used oxygenate for complying with current oxygenated fuel requirements. Because of its higher oxygen content, compliance can be achieved with less volume addition than with other oxygenates.

In discussions with manufacturers of nonroad engines, the US EPA confirmed that using oxygenated fuels is acceptable, although some manufacturers offer special instructions when operating equipment on oxygenated fuels. Most nonroad engine manufacturers permit the use of oxygenated fuels, not to exceed 10% ethanol by volume.

In anticipation that a 20% ethanol blend (E20) may become law in Minnesota, the State Commissioner of Commerce, in consultation with the Commissioner of Agriculture, was mandated to: (1) Report to legislative committees on E20 effects on small engines, (2) Assess fuel inventories, availability and use, and; (3) Make appropriate recommendations.

Reported here are the results of a literature and information search on the effects of E20 fuel on small SI engines. Only limited information (10 reports) specifically relating to small SI engines and ethanol-blended fuels was available. However, numerous other reports containing information on E20 and higher blends in automotive and other engines offer strong clues on how E20 would affect small engines. The literature reviewed were largely reports and other papers published during the last 12 years. When examining reports dealing with blended fuel, wear of the vehicles and vehicle performance it is apparent that results differ among those concerned with the use of ethanol and the impact on vehicles of using ethanol. Additionally, industry trade groups were contacted to learn of their positions and research programs on the use of E20 (see appendices).

Ethanol is an attractive alternative fuel for SI engines. It can be used as either a pure fuel or as a gasoline additive. Both options can provide some advantages for engine performance, fuel economy and exhaust emissions. Some of the changes in fuel properties due to the addition of ethanol to gasoline include octane number, fuel volatility, energy density, oxygen content and water solubility. These properties affect engine performance and emissions. Ethanol also affects the fuel’s compatibility with various materials, thus it can affect an engine’s durability. Gasoline-ethanol blends up to E10 can be used without any engine modifications. Blends containing greater than 10% ethanol in small engines will likely require engine and fuel system modifications. Specific engine and fuel system modifications need to be determined on an individual engine basis.

To summarize, the following effects on an engine can be expected when ethanol blends E20 and greater are used as an engine fuel:

(1) Engine Performance: Ethanol has a higher octane number than gasoline and when blended with gasoline can effectively operate at higher compression ratios with subsequent improvement in power output, efficiency, and fuel consumption. It may be impractical to raise the compression ratio, but if the engine is knock-limited with standard gasoline, advancing the spark may offer improvements in performance similar to those obtained with a small increase in compression ratio. The chemically correct fuel-air ratio with E20 is about 4.5% higher than that of E10, 9% higher than that of E0. With an open-loop fuel system this will lead to leaning of the mixture, increases in exhaust temperatures, and possible drivability (operating) problems.

Ethanol also has a higher latent heat of vaporization. The blended ethanol's higher latent heat of vaporization would enable the engine volumetric efficiency to increase. But at colder temperatures, the high latent heat will lead to less vaporization of the fuel, a leaner mixture, and starting and drivability (operating) problems. This problem could be avoided by heating the intake manifold, but this solution is not practical for small engines because these engines have simple fuel induction systems that are not amenable to this modification. In addition, manifold heating offsets the volumetric efficiency gains associated with the high latent heat of vaporization.

All of these factors will influence the performance of E20 in a small engine. However, there will be considerable engine-to-engine differences, depending on detailed engine design differences. The high octane and latent heat of vaporization of ethanol offer the potential of significant performance gains, but existing small engines would need to be redesigned or modified to fully realize these gains.

(2) Cold Start: Cold starting is highly dependent on the fuels ability to vaporize effectively at low temperatures and provide an ignitable mixture at the time of ignition. For ethanol blends, cold starting depends on the vaporization of the more volatile gasoline fractions. However, when alcohol is present, the vapor contains a greater concentration of alcohol than would be expected based on the vapor pressure of the alcohol or it's concentration in the gasoline. Due to ethanol's higher heat of vaporization than gasoline, more heat is required to vaporize ethanol blends. Effectively, the mixture suffers from enleanment due to the higher concentration of alcohol (because the chemically correct fuel/air ratio is higher). These factors indicate cold starting difficulties on small engines operating with ethanol blends greater than E10.

Raising the compression ratio and valve timing optimization are considered to be practical methods to improve cold starting, but these solutions require new engine designs.

(3) Enleanment: The addition of oxygenates to gasoline has the effect of enleaning the air/fuel mixture on engines that do not adjust to optimize the air/fuel ratio. Fuel metering components are sized to deliver an air/fuel mixture that provides an optimum balance between power output, fuel economy, and durability. Engine manufacturers are aware of the air/fuel sensitivity of their engines and in some cases, they recommend alterations to certain engine models when using oxygenated gasoline. If an engine operates at a mixture that is significantly leaner than it is designed for, it will run at a higher temperature, which can lead to engine damage. Some manufacturers of recreational vehicles offer recommendations for modifying engines when operated on oxygenated fuels (i.e. choke adjustments for cold starts and installation of larger carburetor jets).

(4) Vapor Lock: Although the vapor pressure of pure ethanol is low, the Reid Vapor Pressure (RVP) of gasoline-ethanol blends rises depending on the ethanol proportion in the blend. Low RVP can cause starting problems, but high RVP can cause vapor lock in warm weather. Depending upon the degree, vapor blockage can cause engine performance problems ranging from poor to erratic power output to engine overheating to full engine stall due to fuel starvation and hot-start problems.

(5) Engine Wear: The impact of a 20% ethanol blend on engine wear is unclear. No literature was uncovered that dealt with ethanol blends exceeding 10% ethanol. The only valid conclusion that can be drawn is that further testing is required to obtain data to provide an indication of the potential impact.

(6) Emissions: Both exhaust and evaporative emissions can be influenced by the use of oxygenates in gasoline. Because of the cooling effect on the intake charge and leaner operation when oxygenates are used, both carbon monoxide (CO) and hydrocarbons (HC) emitted from the exhaust are reduced with no significant change in NO_x. However, if an engine is designed to operate close to the lean limit of combustion on hydrocarbon fuels, misfire may occur when oxygenates are present, with a consequent increase in unburned hydrocarbons.

Other unregulated exhaust gas pollutants that have been studied and that are influenced by oxygenates in gasoline include 1,3 butadiene, benzene, and other aromatics including polynuclear aromatics (PNAs), formaldehyde and acetaldehyde.

Another important emissions concern that remains poorly understood is ethanol's ability to permeate through rubber, plastic, and other materials that are used widely in the fuel tank, fuel system hoses, seals, and other parts of the fuel handling system. Recent studies have shown these emissions can be quite significant. High vapor pressure and the presence of ethanol in gasoline also increase evaporative/diffusional emissions (and fuel loss). Permeation rates for higher ethanol blends greater than E20 are largely unknown.

(7) Engine and Fuel System Deposits: Engine intake system deposits may have an effect on engine performance and fuel economy. Non-automotive 2-stroke engines are expected to experience intake system deposits in the same manner as automotive 4-stroke engines operating on ethanol gasoline blended fuels. Two-stroke engines may also experience deposit-related issues when operating on ethanol blends. The literature related to non-automotive engines is limited.

Ethanol gasoline blends increase the solubility of gasoline fuel deposits lending to the release of gum-bound debris followed by blockage of filters and fuel metering components. Gum formation during equipment storage is a particular concern for equipment that does not get used on a regular basis. The majority of engine manufacturers recommend draining unused fuel from equipment or adding a fuel-stabilizing additive that prevents oxidation prior to storage of equipment. The solvent action of the oxygenated fuel may dissolve some of the fuel system deposits, which will plug fuel filters.

In regards to an E20 blend, further testing is required to obtain data to provide an indication of the potential impact of deposits on engine performance and durability.

(8) Material Compatibility: The materials used in engine fuels systems are diverse. Ethanol in gasoline can cause elastomers to swell and lose tensile strength, causing fuel pumps, accelerator pumps, and hoses to fail**.** Manufacturers are concerned that seals and gaskets on older equipment that have not been previously exposed to alcohol-oxygenated fuels could experience leakage.

Fiberglass-reinforced plastic tanks may cause problems depending on the type of resin used during fabrication. Materials such as terne plate (lead/tin-coated steel used in fuel tanks) zinc die castings, and aluminum fuel system components are attacked by alcohols and require corrosion inhibitors to minimize this effect. Corrosion of steel is accelerated by the presence of alcohols in the fuel, partly because of the increased water content of the fuel. Only testing of representative components along with long-term durability and testing with the E20 ethanol blend can provide accurate information of the possible impact.

(9) Phase Separation (of fuel): Ethanol has a high affinity for water, thus it contains a certain amount of water. Since gasoline and water do not mix, even small amounts of water in pure gasoline will result in a separate phase of water in a fuel tank, which, if pumped into the engine, could cause damage. However, years of experience have resulted in this concern being minimized. Oxygenated gasoline (ethanol blends), will tend to dry out fuel tanks by blending with the water allowing it to be combusted in the engine. Only with comparatively large amounts of water in ethanol-blended gasoline will a separate alcohol/water phase occur. There is a wide range of recommendations by manufacturers for the use of oxygenated fuels depending on the specific engine application. Many manufacturers have specific recommendations for preparing equipment for storage during the off-season, especially if the equipment has been fueled with alcohol fuels. Water contamination can also cause corrosion on metal components. Solubility improvers, such as isopropanol, can prevent these problems.

In conclusion, only durability and emissions testing will provide accurate information on the possible impact of E20 on small engines because little specific information was uncovered during the literature search. This testing would need to be satisfactorily completed as part of the EPA E20 waiver process. Fortunately, engine manufacturers and industry trade groups are taking this matter seriously and are cooperating with federal and state agencies to address the potential issues of E20 in small engines (34, Appendices B1, B2, B3, B4).

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APPENDICES

APPENDIX A - Diversity of Materials Used in Engine and Fuel Systems

(Reference - ASTM D5798-99, Standard Specification for Fuel Ethanol for Automotive Spark-Ignition Engines; Table B)

A. Metals

Aluminum (various grades)
Brass
Carbon Steel
Cast Iron
Copper
Magnesium (and alloys)
Zinc (and alloys)
Lead
Tin
Terne Plate
Solder (tin/lead)
Other metals and alloys

B. Rubbers

Buna N
Silicon Rubber (VMQ)
HNBR (Hydrogenated Nitrile Butadiene Rubber)
Others

C. Plastics/Polymers/Monomers/Elastomers

Hydrin (epichlorohydrin)
H-NBR (copolymer from butadiene and acrylonitrile)
Low Temp Viton (FKM) grades such as GFLT Nylons (various grades)
Polyester urethane foam
NBR with 16% PVC and 32% ACN content
Ozo-Paracril (blend of PVC and nitrile rubbers)
CSM - Chlorosulfonated polyethylene, such as Hypalon FVMQ –
Fluorosilicone
HDPE – High Density Polyethylene
PS - Polysulfone
PC - Polycarbonate
ABS - Acrylonitrile Butadiene Styrene
EVOH -Ethylene Vinyl Alcohol
PPA - Polyphtalamide
PBT - Polybutylene Terephthalate
PE - Polyethylene –
High Density Polyethylene (HDPE),
PE - LDPE Low Density Polyethylene (LDPE)
PET – Polyethylene Terephthalate (Mylar)
PP – Polypropylene
PPS – Polyphenylene Sulfide
PUR – Polyurethane
PVC – Polyvinyl Chloride
PEI – Polyetherimide (GE Ultem)
POM - Acetel Copolymer
HTN - DuPont™ Zytel®
HTN PTFE - Polyteraflouroethylene (Teflon)
POM - Polyoxymethylene (acetal/Delrin)
Fluorosilicones
Others

APPENDIX B - Industry and Trade Group Positions / Research

APPENDIX B1 - Minnesota E20 Fuel Research Program
(Reference Jewitt and Associates, Minnesota E20 Fuel Research Program, http://www.mma.org/lib/docs/nmma/gr/environmental/Minnesota_E_20_Fuel_Research_Program.doc.

The Minnesota-Renewable Fuels Association E20 Fuel Research Program consists of three segments:

- Vehicle Fuel System Materials Compatibility Study
- Vehicle Drivability Study
- Vehicle Exhaust and Evaporative Emissions Study

The Fuel Research Program is focused on light duty vehicles. It is recognized that small engine and marine engine issues must eventually be addressed. But, the Renewable Fuels Association chose to first focus the research program on that segment which would use the greater volumes of fuel, i.e., light-duty vehicles. If serious problems arise with automotive related testing, it would then be questionable to proceed with E20 research on small engines and marine engines.

The E20 Vehicle Emissions Study is a pilot study consisting of two fuels and three vehicles. Emissions Certification Fuel (E0) and Emissions Certification Fuel are the test fuels, which are splash blended with twenty volume percent denatured ethanol (E20). The three test vehicles represent evolved technologies from 1981 through 2007. Vehicles selected were a 1981 V8, carbureted, closed loop Buick Riviera, a 1999, V6, port fuel injected Ford Taurus meeting Tier One Emissions Standards and a 2007 L4, port fuel injected Dodge Caliber meeting Tier Two Emissions Standards.

The E20 Emissions Study consists of two sections; exhaust emissions and evaporative emissions. Each vehicle undergoes a prescribed fuel change procedure with the test fuel, followed by exhaust emissions testing after which then follows evaporative emissions testing. This project is on-going.

APPENDIX B2 - State of the Coordinating Research Council: 2007

(Reference http://www.crcao.com/2007 annual report)

The Coordinating Research Council (CRC) provides the means for the automotive and petroleum industries to work together with government in addressing mobility and environmental issues of national and, in many cases, international interest. CRC is pleased to welcome Nissan as a new member company in 2007.
The U.S. Department of Energy (DOE) through the National Renewable Energy Laboratory (NREL), the California Air Resources Board (CARB), the Engine Manufacturers Association (EMA), the U. S. Environmental Protection Agency (EPA), and the South Coast Air Quality Management District (SCAQMD) have continued their cooperation with CRC in co-sponsoring research and other activities. This cooperation results in a finer focus on the important issues and leveraging of both technical expertise and financial support to meet common goals. A special meeting was held at the start of the year with EPA and CARB staff to begin planning cooperative work on an update of the 1990's Auto/Oil emission database and the addition of other alternative fuel emissions data as stipulated in the new Energy Policy Act. CRC and CARB have joined together to lead a new technology panel on Real-Time PM Measurement Methods.

CRC research on the use of renewable fuels such as ethanol and biodiesel has increased this year. New proposals for replacement of conventional petroleum sources with renewable sources are being promoted in many sectors around the world. One such proposal is to increase the content of ethanol in gasoline from 10 volume percent (E10) to 20 volume percent (E20). It is important to understand the impacts that such a change may bring about on fuel quality and performance in the current fleet. Therefore, several studies on the potential impacts of E20 have been undertaken by the technical committees of CRC. The impacts of increased biodiesel use on fuel quality and vehicle performance are also being evaluated. CRC is coordinating this research with government agencies and other stakeholders. CRC Project E-80 will evaluate the emission performance of flexible-fuel vehicles operating on a full range of ethanol fuels from E6 to E85. This project is being conducted cooperatively with CARB and will examine what happens to emissions during a transition from one fuel to another. Evaporative emissions will also be measured.

There is a potential for gasoline-containing ethanol to increase the rate of permeation of fuel components through materials contained in vehicle fuel systems. Permeation is a diffusion process whereby fuel molecules migrate through the plastic and rubber materials that make up the vehicle fuel and fuel vapor systems. The CRC Emissions Committee and CARB co-sponsored a major study on the permeation effects of ethanol on automotive fuel systems. The final phase of this research was reported in CRC Final Report No. E-65-3, where the impacts of permeation emissions for new vehicles using E0, E10, E20, and a range of aromatics along with E6 fuel blends and E85 in flexible fuel vehicles. This expanded work previously completed on fuels containing MTBE, ethanol, and no oxygenate in a test vehicle set representing the U.S. fleet in 2001. The final report

from this year and the final report from the initial study are available on the CRC website.
An important new study (E-77) has begun to evaluate the impact of evaporative emissions from the in-use fleet emphasizing vehicles with the most advanced evaporative emission control systems. Test fuels to be evaluated in this study include E0, E10, and E20. A pilot study was conducted initially to demonstrate the new test procedures that isolate and quantify canister losses, leak rates, and other full vehicle evaporative emission levels. After a successful pilot study of 10 test vehicles the main phase of testing is now underway. The project was planned and is now being conducted in cooperation with technical staff of EPA.

The Performance Committee released a final report this year (CRC Report No. 646) on gasoline compositional effects (including ethanol concentrations up to E20) during extreme hot weather operation (105-115°F). A new study on vehicle driveability is slated for early 2008 where a fleet of flexible fuel vehicles with be tested under cold weather conditions on a variety of E85 fuel blends.
The Atmospheric Impacts Committee is looking into future air quality scenarios through the use of air quality grid models. These models evaluate not only gaseous pollutant transport and reactions, but also direct emissions of aerosols (particulate matter) and secondary aerosols formed in the atmosphere. Due to the non-linearity of atmospheric reactions, predicted future reductions in emissions may lead to only modest improvements in ozone levels. The CRC Atmospheric Impacts Committee is overseeing this work and is also developing new modeling routines (probing tools) that will delineate the important parameters that are responsible for net changes in air quality. As air quality improves across the U.S., the importance of background sources of pollutants is becoming more important and the committee is studying the impacts of background air quality under its current program scope.

The Mobile Source Air Toxics Workshop was held again in 2006, bringing together key local, state, and federal government, academic, and industry researchers and other stakeholders to discuss the state-of-the-art and future research needs. Proceedings of the workshop were published in January 2007. This workshop will continue on a biannual schedule. Supplementing this workshop, CRC has conducted a study of the fate, transport, and deposition of air toxics and is continuing to address the air toxics in its modeling studies of air quality.

Previous CRC projects resulted in the publication of two books by Oxford University Press, *The Mechanisms of Atmospheric Oxidation of the Alkenes* and *The Mechanisms of Atmospheric Oxidation of Aromatic Hydrocarbons.* The manuscript for a third book, entitled *Mechanisms of Atmospheric Oxidation of the Alkanes* was submitted and accepted for publication. A new study on the atmospheric reactions of the oxygenates is now in development.

Details on these and other CRC projects appear in Part Two of this Annual Report. Reports issued since the last *CRC Annual Report* are listed in Part Three, and organization memberships comprise Part Four.

APPENDIX B3 - Alliance for a Safe Alternative Fuels Environment (AllSAFE)

Improvements Required to Ensure the Long-Term Success of Ethanol and Renewables

(Reference http://www.allsafe-fuel.org/news.html, 6/13/07 Press Release)

AllSAFE is made up of the national consumer, manufacturing, and gasoline retailers associations (listed below) that consume gasoline and ethanol-fuel blends. AllSAFE speaks on fuel-related legislation for over 250 million Americans that own and operate over 300 million products, including recreational boats and marine engines, chainsaws, lawnmowers, motor vehicles, motorcycles, all terrain vehicles (ATVs), snowmobiles, generators, and related vehicles and equipment. As the US Congress moves forward in mandating the increased production of renewable fuels, it should direct the responsible regulatory agencies (principally, EPA and DOE) to make sure these new fuels will operate successfully with the $2 trillion dollars worth of existing and new products.
We appreciate and understand all the compelling reasons that support expanding the market for renewable fuels, including ethanol. In fact, AllSAFE supports increased ethanol use and wants to avoid potential consumer rejection of all ethanol blends (including E85) that could occur if midlevel ethanol blends (above 10% ethanol) ultimately damage consumers and their products – for example, as a result of increased heat and corrosion when mid-level ethanol fuels are used in engines, boats, equipment, and vehicles designed for *conventional* gasoline. The use of ethanol blends in these conventional vehicles is totally different from using these fuels in flexible fuel vehicles (FFVs), which are specifically designed to run on any level of ethanol up to *E85*.
To ensure the long-term success of ethanol and other renewable fuels, Congress should adopt the following improvements set forth in the enclosed amendment:
First, with $1 million in appropriated funding, the Environmental Protection Agency (EPA) and the Department of Energy (DOE) should conduct a study (with input from the affected stakeholders) on the impacts of mid-level ethanol blends on: (1) consumers and their boats, vehicles, equipment, and other products; (2) manufacturers of these affected products; (3) the environment; and (4) gasoline retailers. This study should be submitted to Congress within 24 months. This study should become part of the administrative record in any fuel waiver 2 applications specifically seeking to introduce “general purpose”, new fuels with greater than 10% ethanol.

Second, we also urge Congress to modify Section 211(f)(4) of the Clean Air Act to improve the new fuel and fuel additive waiver review process, as a simple matter of good governance. Under Section 211(f)(4), EPA must currently determine that the new fuel or fuel additive will not cause or contribute to the failure of any emission control device, or the failure of engines, vehicles, or equipment to meet the applicable evaporative and exhaust EPA emissions standards. However, Section 211(f)(4) currently states that *if EPA does not act on a waiver application for a new fuels waiver within 180 days of its submission, the application is deemed granted, even in the absence of EPA action or consideration of the application’s merits*. AllSAFE recommends modifying this provision to require EPA to make a timely decision (subject to public notice and comment) after building a complete, technical record on the merits. Pursuant to our proposed amendment, EPA should be compelled to make new fuel waiver decisions a time-sensitive priority and to approve or deny these petitions within 270 days of receiving a complete waiver application.

* * *

The AllSAFE members listed below look forward to working with the Congress, EPA, DOE and all the affected stakeholders to improve our understanding of all the impacts of ethanol fuels on consumers, manufacturers, gasoline retailers, and the environment -- *before* we undertake any rash action that would harm consumers and the long-term success of mid-level ethanol and other renewable fuels in the marketplace. Please call Greg Scott of Kelley Drye Collier Shannon, at 202-342-8646 with any questions.

Alliance of Automobile Manufacturers
American Motorcyclist Association
Association of Marina Industries
Association of International Automobile Manufacturers
Boat Owners Association of the Untied States
Engine Manufacturers Association
International Snowmobile Manufacturers Association
Motorcycle Industry Council
National Association of Convenience Stores
National Marine Manufacturers Association
Outdoor Power Equipment Institute
Personal Watercraft Industry Association
Professional Landcare Network
Specialty Vehicle Institute of America

APPENDIX B4 - Effects of Running E20 in Polaris Current Products

Effects of Running E20 in Polaris Current Products

Polaris Industries

Joe Wegleitner
James Buchwitz
Gary Simons
Kevin Ness

1-8-08

Introduction:

An initial evaluation was conducted at Polaris to understand the potential affects that running E20 (gasoline with 20% ethanol content by volume) will have on current production Polaris vehicles. Samples of Polaris' core products, a Victory motorcycle, a 4-stroke ATV and a 2 stroke snowmobile, were evaluated to quantify the effects of the added ethanol. Two key areas were focused on during the 4-stroke evaluation; air-fuel ratio fluctuation and exhaust gas temperatures. For the 2-stroke evaluation a fuel stability study focused on the ability to use the 20% blended fuel without engine damage.

Several areas of concern were not addressed in this initial evaluation including; material compatibility, drivability differences, long term durability from leaner operation and higher temps, starting, or impacts of octane changes.

Fuel Mixing:

The fuel used for the baseline testing was a non-oxygenated gasoline that is commercially available in Minnesota. The fuel used for the ethanol testing was commercially available oxygenated gasoline (10%) that was blended up to 20% ethanol content by volume with pure ethanol.

Test Results:

ATV Testing:

A 2006 Sportsman 800 was used for the ATV portion of the evaluation. This vehicle utilizes a 760cc two cylinder, four-stroke engine, with open-loop fuel injection. A similar vehicle is pictured in Figure 1. The vehicle was instrumented with a data acquisition system that allowed various engine parameters to be recorded such as engine speed, throttle position, intake air temperature and pressure, exhaust gas air-fuel ratio, exhaust gas temperatures, etc.

Figure 1:Sportsman 800

The vehicle was warmed to stable coolant temperatures and then ridden on a flat road at discrete engine speeds while recording the engine data. This was done while the vehicle was running on a non-oxygenated gasoline (E0) and then while it was running on a 20% ethanol blended fuel (E20). The fuel was siphoned from the tank between runs to ensure no contamination of one fuel with the other.

The graph in Figure 2 indicates the final air-fuel ratio differences when running on E20. The blue line in the graph depicts the percentage that the air-fuel ratio changed when running E20 compared to E0. The red line indicates the average change during the rpm sweep. The data indicates that the engine is running approximately 6.3% leaner with E20.

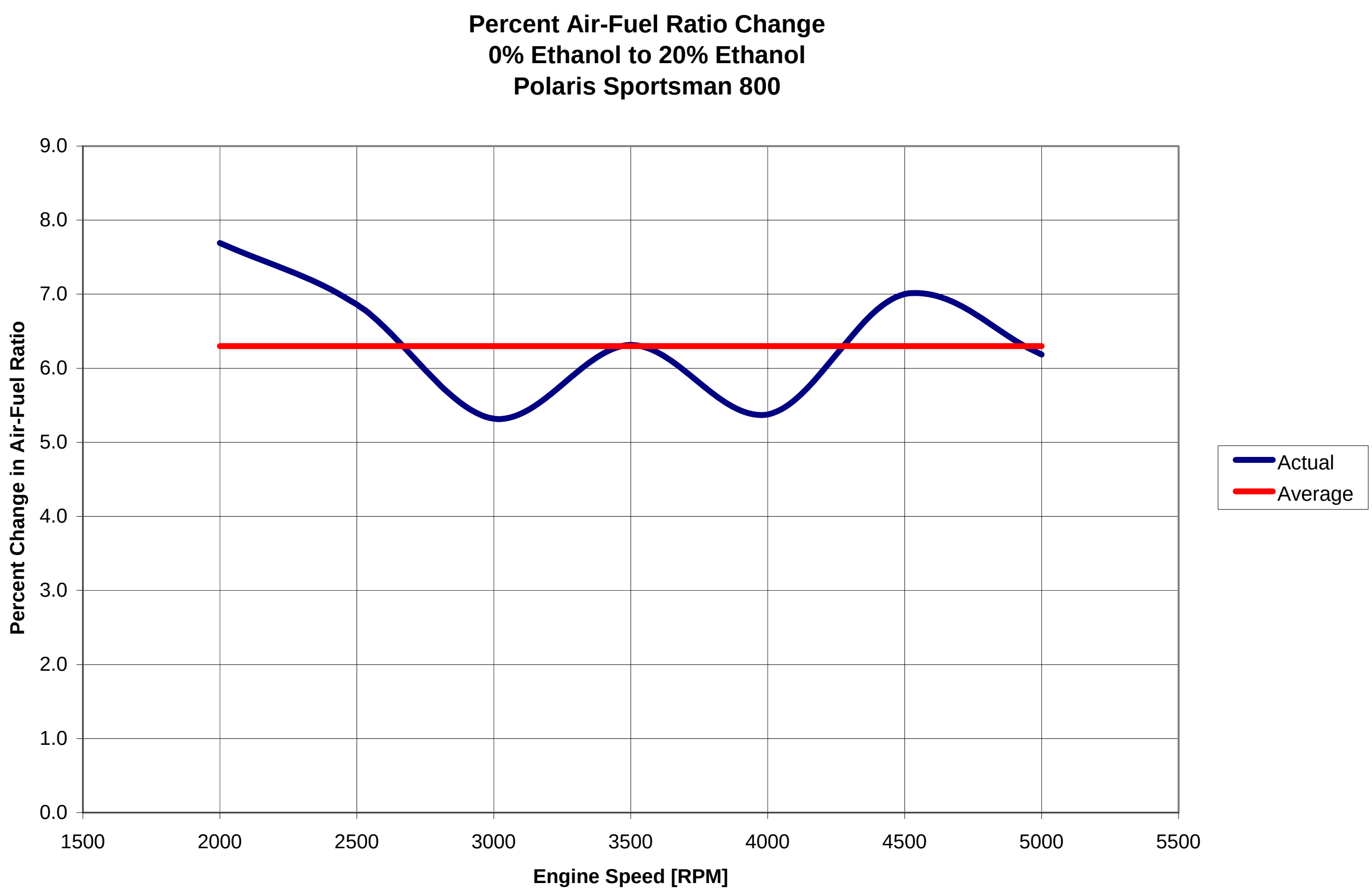

Figure 2: Percentage Air-Fuel Ratio Change When Operating on E20 Compared to E0

The graph in figure 3 indicates the exhaust gas temperature difference when running E20. The graph indicates up to a 40 degree C (72F) increase in temperatures when running on E20 over E0.

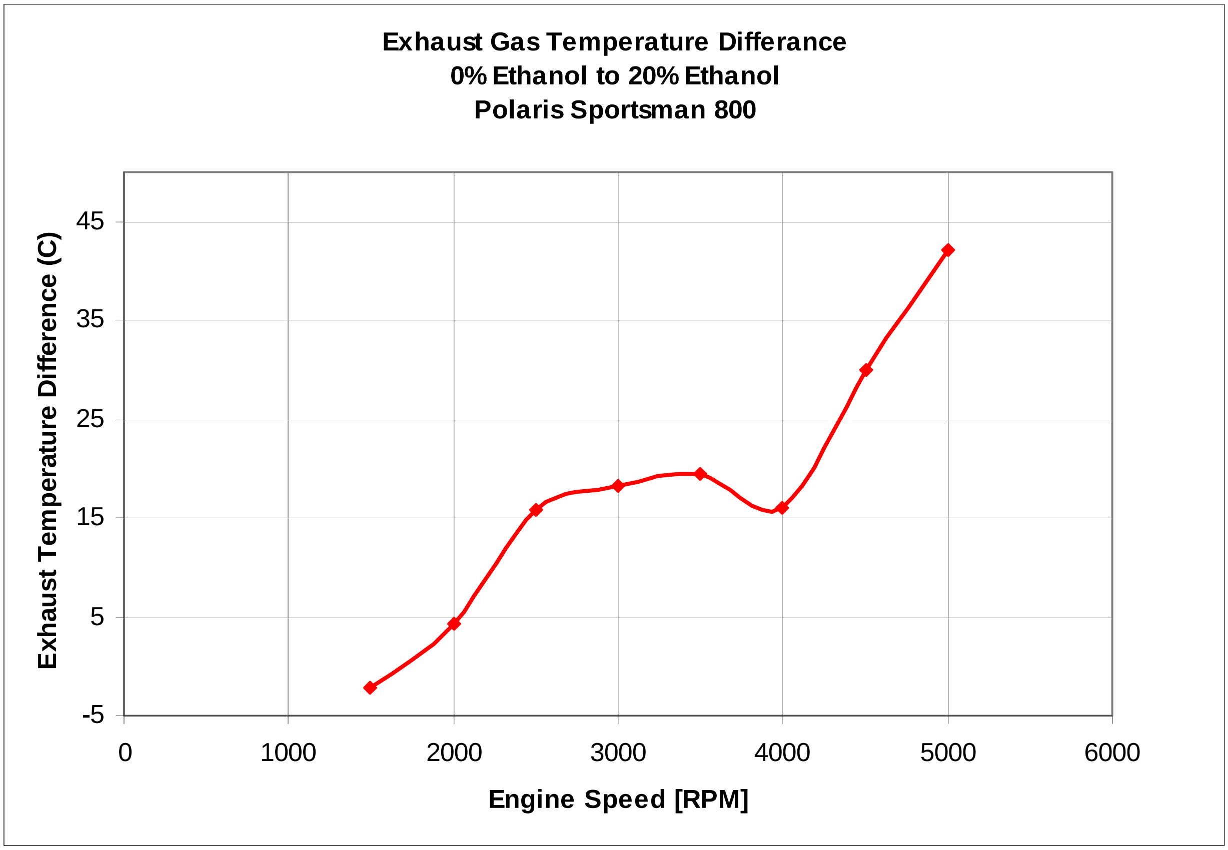

Figure 3: Exhaust Gas Temperature Difference When Operating on E20 Compared to E0

Motorcycle Testing:

A 2006 Polaris Victory Jackpot was used for the motorcycle evaluation. This vehicle utilitizes a 1.6 liter V-twin, oil cooled 4-stroke engine with open-loop electronic fuel injection. A similar vehicle is pictured in Figure 4. The vehicle was instrumented similar to the ATV. However, because of weather conditions, the motorcycle was tested on an indoor chassis dynamometer compared to the ATV which was tested in the field.

Figure 4: Polaris Victory Jackpot

The graph in Figure 5 indicates the air-fuel ratio change when running the engine on E20 over E0. The graph indicates the same average shift in air-fuel ratios as the ATV, just over 6%.

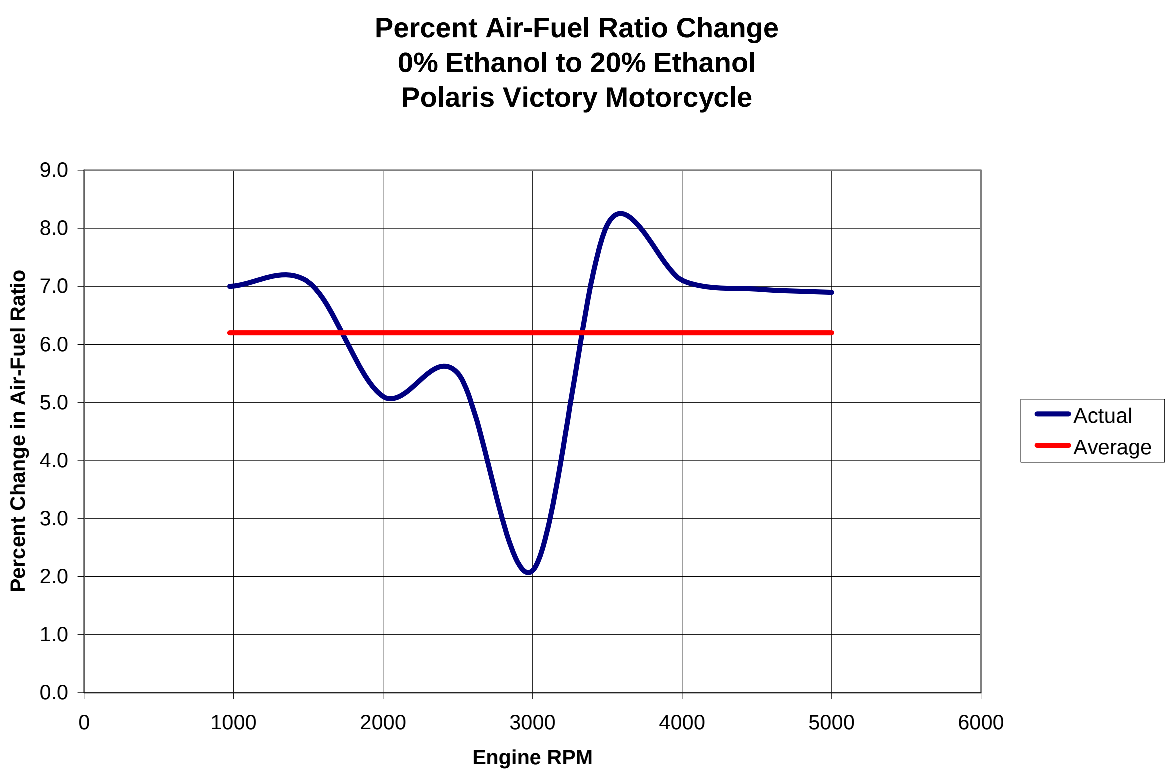

Figure 5: Percentage Air-Fuel Ratio Change When Operating on E20 vs E0

Figure 6 indicates the influence of running E20 on exhaust gas temperatures in the Victory motorcycle. The graph indicates a peak temperature difference of up to 65 degrees C (117F) when running E20 over E0.

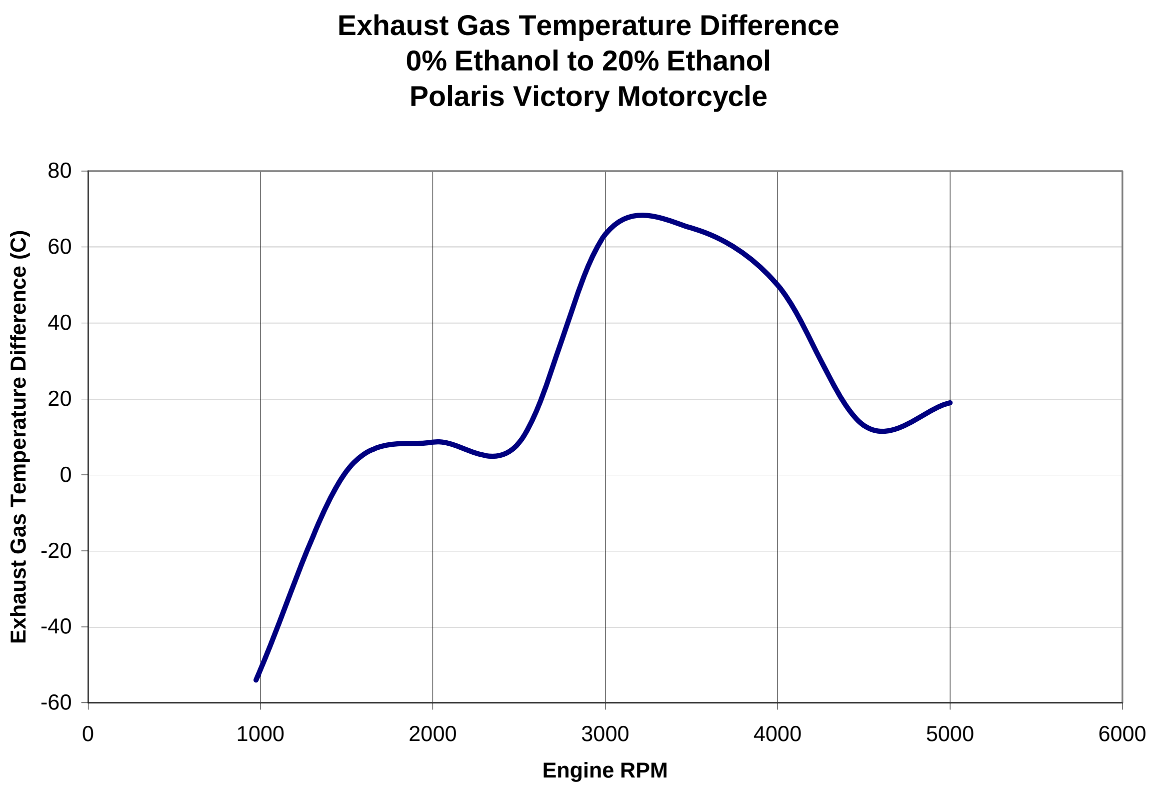

Figure 6: Exhaust Gas Temperature Difference When Operating on E20 Compared to E0

For model year 2008 and beyond, the Victory motorcycles will employ a closed-loop fuel injection system. During times when the vehicle is operating on closed loop mode, fueling will be modified to compensate for differences in ethanol content in the fuel. Although, when the vehicle is not being operated in closed-loop mode, such as cold starts, transients, etc, it is expected that the results indicated above will be experienced.

2-Stroke Snowmobile Engine Testing

A 2008 Polaris 600 Dragon IQ CFI (Cleanfire™ Fuel Injection) 2-stroke engine was operated in an engine test cell to determine the ability of the engine to operate with a fuel that contains 20% ethanol by volume. The engine used was from a production vehicle as seen in Figure 7.

Figure 7: 2008 MY 600 IQ CFI

The engine was operated at its rated speed (maximum horsepower speed) at wide open throttle and the fueling was varied from rich to lean to determine the sensitivity for each fuel. For example, the data point with E0 at fueling multiplier 1.1 reflects the addition of 10% more fuel than was called for with the production calibration. Figure 8 shows the results for that testing.

As can be seen in the graph, the engine can operate on gasoline (E0) in a window that is approximately 17% wide (fueling multiplier 0.88 to 1.05). The window is wide enough to account for production tolerances in engines, exhaust, and fuel systems. When operating on the E20, the engine has an operating window that is only 8% wide (fueling multiplier 1.02 to 1.10) and the window of acceptable operation with both fuels is 3% wide (fueling multiplier 1.02 to 1.05). The graph also shows that the engine was showing signs of detonation or knock when operating on E20 at production settings (fueling multiplier 1.0).

It is likely that if the E20 fuel were to be used in a larger sample size of production units that a percentage of them would exhibit signs of detonation and possibly piston failure.

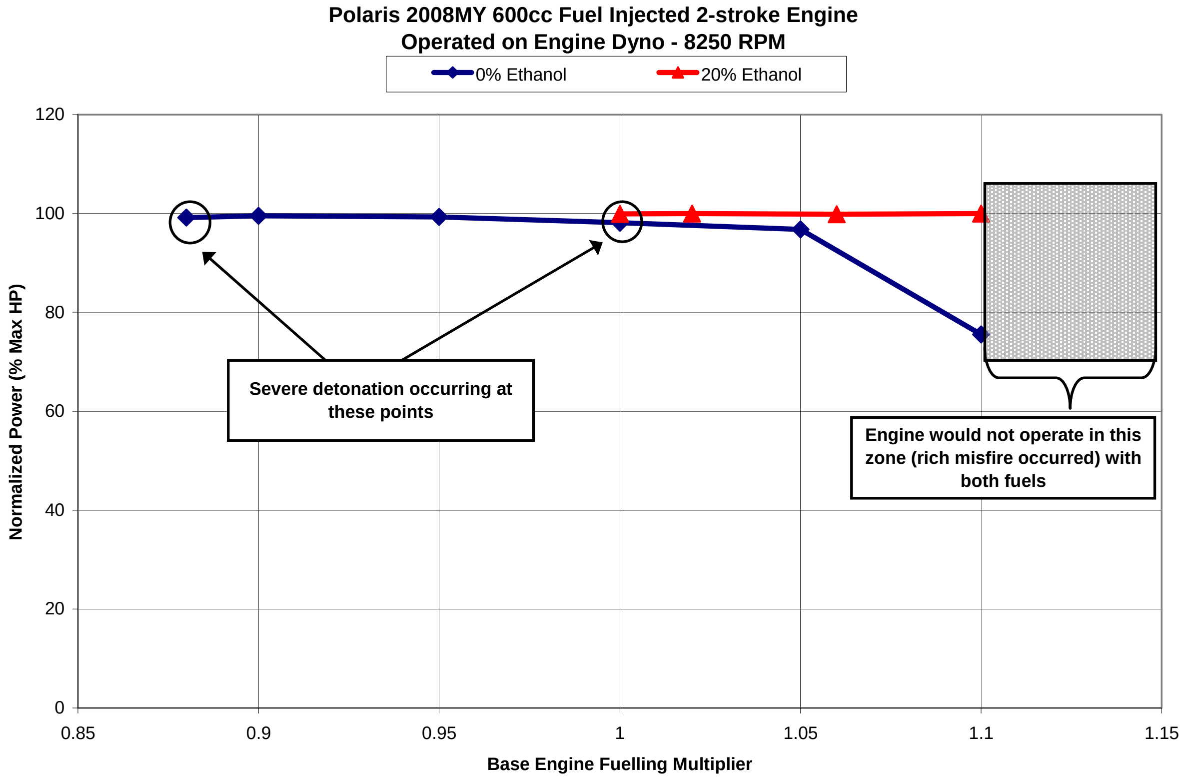

Figure 8: 600cc 2-Stroke Fuel Sensitivity

When the engine was operated leaner than the limit (Base fueling 1.0 or production settings with E20) as shown in Figure 8, the engine experienced piston failure due to detonation. Figure 9 shows the result of the piston damage due to detonation. Standard production tolerances make it nearly impossible to produce a 2-stroke product that could operate acceptably on both non-oxygenated gasoline (E0) and a 20% ethanol blend (E20).

Figure 9: 600cc 2-Stroke Piston Failure Due to Detonation

Discussion:

The data discussed previously clearly indicates that there will be a lean shift if current production Polaris 4-stroke vehicles are operated on E20 gasoline. The lean shift will result in increased exhaust gas temperatures and increased cylinder head metal temperatures. This increase in metal temperatures will likely result in decreased product life. Generally a lean shift in air-fuel ratios can cause issues such as poor vehicle drivability, poor cold starting, and reduction in performance.

The data above also shows that the current and past population of 2-stroke Polaris snowmobiles in the field would likely have a significant number of existing vehicles that would see piston damage from running on E20.

In addition, on most recreational vehicles tight packaging is a necessity. Because of this, additional exhaust heat requires careful engineering considerations to avoid excessive heat for the operator and/or heat damage to the body structure of the vehicle. The increased exhaust gas temperatures that result from using E20 would increase the potential of heat related consequences either for the operator or the vehicle. As each vehicle design is different this would need to be investigated further and mitigated on a vehicle specific basis.

The impacts on Polaris' products would be similar to the impact on other small engine manufacturers' products. These impacts are all of concern to Polaris and the severity of each would need to be investigated in future testing to ensure product durability before products could be offered that could operate on E20. The cost impact of redesigning product to operate properly on E20 is not yet quantified, but at a minimum it would require a considerable amount of engineering resources (investment dollars and time) to recalibrate, field test, and validate new product to operate on E20 to meet durability and performance standards. Polaris' current or past products will simply not allow a seamless transition from non-oxygenated gasoline (E0) to a gasoline blended with 20% ethanol (E20). The change in fueling volume that is needed to deal with the increased ethanol is larger than the production fueling tolerances of both 2-stroke and 4-stroke engines.

Availability of Non-oxygenated Gasoline 2007