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Global trends in motor vehicle pollution control: a 2011 update Part 2

6. A Comprehensive Vehicle Pollution Control Strategy

Reducing the pollution that comes from vehicles will usually require a comprehensive strategy. Generally, the goal of a motor vehicle pollution control program is to reduce emissions from motor vehicles in-use to the degree reasonably necessary to achieve healthy air quality as rapidly as possible or, failing that for reasons of impracticality, to the practical limits of effective technological, economic, and social feasibility. A comprehensive strategy to achieve this goal includes four key components: increasingly stringent emissions standards for new vehicles, specifications for clean fuels, programs to assure proper maintenance of in-use vehicles, and transportation planning and demand management. These emission reduction goals should be achieved in the most cost effective manner available.

7. Emissions Reduction Progress to Date

In almost every corner of the world, for every type of road vehicle and fuel, there is a clear trend toward more and more stringent emissions requirements. Over the next decade, this pattern is moving toward similar controls on off road vehicles and fuels. Driving these trends are several factors:

- Continued growth in the number of vehicles (especially in China, India and other parts of Asia and Brazil) and their concentration in urban areas where pollution levels remain unacceptably high,
- The growing accumulation of health studies that show adverse impacts at lower and lower levels and in the case of PM at virtually any level, and
- Advances in vehicle technology and clean fuels that are making it possible to achieve lower and lower emissions levels at reasonable costs.

One of the critically important lessons learned to date is that clean vehicles and high quality fuels go hand in hand; they must be treated as a system. Over approximately the last twenty years, extensive studies have been carried out to better establish the linkages between fuels, vehicles, and vehicle emissions. One major study, the Auto/Oil Air Quality Improvement Research Program (AQIRP) was established in 1989 in the US and involved 14 oil companies, three domestic automakers, and four associate members [1]. In 1992, the European Commission also initiated a vehicle emissions and air quality program. The motor industry (represented by Association des Constructeurs Européens d'Automobiles (European Automobile Manufacturers Association (ACEA)) and the oil industry (European Petroleum Industry Association (EUROPIA)) were invited to cooperate within a framework program, later known as "the tripartite activity" or European Auto/Oil Program. In June 1993, a contract was signed by the two industries to undertake a common test program, called the European Program on Emissions, Fuels, and Engine Technologies (EPEFE).

The Japan Clean Air Program (JCAP) was conducted by the Petroleum Energy Center as a joint research program of the automobile industry (as fuel users) and the petroleum industry (as fuel producers), supported by the Ministry of Economy, Trade and Industry. The program consisted of two stages: the first stage called JCAP I commenced in FY 1997 and terminated in FY 2001; the second called JCAP II commenced in FY 2002 and continued until 2007 to provide a further development of the research activities of JCAP I. In JCAP II, studies focused on future automobile and fuel technologies aimed at realizing Zero Emissions while at the same time improving fuel consumption.

A summary of the advances in vehicle technologies over recent decades and the linkages with fuel quality is provided below.

A. Diesel Vehicles and Fuels

Diesel engines emit more nitrogen oxides (NO_x) and particulate matter (PM) than equivalent gasoline engines per mile driven. Reducing PM emissions tends to be the higher priority because ambient PM levels are often above WHO recommended levels and are responsible for hundreds of thousands of premature deaths each year. Diesel particulate (soot) is thought to be particularly hazardous and has been characterized as toxic or potentially toxic by the California Air Resources Board, EPA, the International Agency for Research on Cancer (IARC) the National Institute for Occupational Safety and Health (NIOSH) and others. NO_x emissions are also important, however, since they cause or contribute to ambient nitrogen dioxide, ozone, and secondary PM (nitrates)[1)].

Modest to significant NO_x control from diesel engines can be achieved by delaying fuel injection timing and adding exhaust gas recirculation (EGR). Very high pressure, computer controlled fuel injection can also be timed to reduce PM emissions. (Modifying engine parameters to simultaneously reduce both NO_x and PM is difficult and limited since the optimal settings for one pollutant frequently increases emissions of the other.) To attain very low levels of NO_x and PM therefore requires exhaust treatment. Lean NO_x catalysts, selective catalytic reduction, NO_x storage traps with periodic reduction, PM filter traps with periodic burn-off, and oxidation catalysts with continuous burn-off are technologies

[1)] Certain pollutants which are emitted from vehicles as gases undergo transformation in the atmosphere and are converted into particles. For example, some of the gaseous nitrogen oxides (NO_x) emitted from vehicles chemically react with other gases and are converted into nitrates which contribute to urban PM air quality levels. Nitrates can account for as much as 20-30% of ambient PM in the US (although that fraction varies regionally).

that are being phased in at differing rates in various parts of the world. A new type of diesel, the homogeneous charge compression ignition engine, provides another approach to reducing NO_x and particulates that is receiving significant attention and is already being introduced on some engines for at least portions of the engine map.

Diesel fuel is a complex mixture of hydrocarbons with the main groups being paraffins, napthenes and aromatics. Organic sulfur is also naturally present at varying levels depending on the source of the crude oil. Additives are generally used to influence properties such as the flow, storage, and combustion characteristics of diesel fuel. The actual properties of commercial motor vehicle diesel depend on the refining practices employed and the nature of the crude oils from which the fuel is produced. The quality and composition of diesel fuel can significantly influence emissions from diesel engines.

To reduce PM and NO_x emissions from a diesel engine, the most important fuel characteristic is sulfur because sulfur contributes directly to PM emissions and high sulfur levels precludes the use of or impairs the performance of the most effective PM and NO_x control technologies. For the control of PM, most new vehicles in Japan and the US and a growing fraction in Europe are equipped with filters or traps which reduce over 90% of the particles. NO_x adsorbers and Selective Catalytic Reduction systems are also starting to be introduced; NO_x adsorbers are especially sensitive to sulfur levels in the fuel.

Sulfur occurs naturally in crude oil, and the sulfur content of diesel fuel depends on both the source of the crude oil and the refining process.

The contribution of the sulfur content of diesel fuel to exhaust particulate emissions has been well established with a general linear relationship between fuel sulfur levels and this regulated emission. Shown below (Fig. 6) is one estimate of this relationship provided by the US EPA. (This figure shows only the sulfur-related PM and not the total PM emitted from a diesel engine.) An indirect relationship also exists as some emissions of sulfur dioxide will eventually be converted in the atmosphere to sulfate PM[2]. Only a small fraction of the diesel fuel sulfur (1-2%) is converted to sulfate emissions in the exhaust with the remaining 98-99% emitted as gaseous SO_2; a substantial fraction of the SO_2 is lost to deposition with the remainder gradually converted in the atmosphere to sulfate PM.

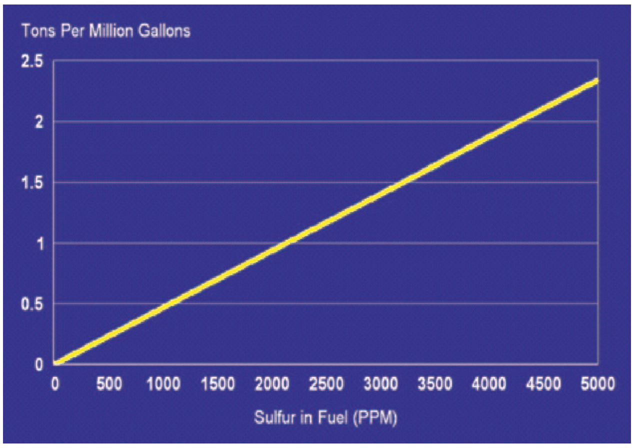

Fig. 6. Tons of directly emitted PM from diesel fuels sulfur
Notes: PPM = parts per million. Only particulate matter (PM) related to sulfur and not the total PM emitted from a diesel engine are reflected in this figure

Light duty diesel engines (< 3.5 tons gross vehicle weight (GVW)) generally require oxidation catalysts to comply with Euro 2 or more stringent vehicle emission standards. Oxidation catalysts lower hydrocarbons, carbon monoxide, and particle emissions, typically removing around 30% of total particle mass emissions through oxidation of a large proportion of the soluble organic fraction. The conversion of sulfur in the catalyst reduces the availability of active sites on the catalyst surface and therefore reduces catalyst effectiveness. This catalyst deactivation is reversible through high temperature exposure – the sulfur compounds decompose and are released from the catalyst wash coat. However, due to generally low diesel exhaust temperatures, in many diesel engine applications the conditions needed for full catalyst regeneration may rarely be reached. High sulfur content in the fuel can also lead to the formation of sulfates in the converter which are then emitted as additional particles. Therefore it is important to match fuel sulfur levels to the after-treatment technology present in the vehicle fleet.

To enable compliance with tighter particle emission standards for diesel vehicles, tighter limits on the maximum sulfur content of diesel fuel have been, or are being, introduced in many countries. While substantial reductions in particle emissions can be obtained without reducing sulfur levels, compliance with Euro 2 or tighter vehicle emission standards is generally not possible when fuel sulfur levels are greater than 500 ppm because of the relatively greater proportion of sulfates in the total mass of particle emissions.

In the case of Euro 3 and Euro 4 vehicle emission standards, even lower sulfur levels (350 ppm and 50 ppm, respectively) in diesel fuel will be required to ensure compliance with the standards. Complying with Euro 5 and 6 requirements or US Tier 2 standards will require maximum sulfur levels as low as 10-15 PPM. Apart from contributing to the effective operation of catalysts and reducing particle emissions, these further reductions in sulfur levels will enable tighter emission standards to be met by the use of next generation "de-NOx" catalysts, especially NO_x adsorber systems. These are currently extremely sensitive to sulfur. An alternative emission control technology for Euro 5 or cleaner diesel vehicles is Selective Catalytic Reduction (SCR). These systems are not particularly sensitive to sulfur levels in fuel.

Sulfur content is also known to have an effect on engine wear and deposits, particularly under low temperature, intermittent operating conditions. Under these conditions there is more moisture condensation, which combines with sulfur compounds to form acids and results in corrosion and excessive engine wear. Generally lower sulfur levels

[2] Similar to the secondary transformation of NO_x to nitrate discussed earlier.

lessen engine wear. With Euro 4+ or equivalent emission standards, the role of engine oil will also be important in ensuring sustained performance of engines/tail pipe devices. Low sulfur levels also allow the use of extended oil-change intervals reducing operating costs.

Diesel fuel has natural lubricity properties from compounds including the heavier hydrocarbons and organo-sulfur. Diesel fuel pumps (especially rotary injection pumps in light duty vehicles), without an external lubrication system, rely on the lubricating properties of the fuel to ensure proper operation. Refining processes to remove sulfur and aromatics from diesel fuel tend to also reduce the components that provide natural lubricity. In addition to excessive pump wear and, in some cases, engine failure, certain modes of deterioration in the injection system could also affect the combustion process, and hence emissions. Additives are available to improve lubricity with very low sulfur fuels and should be used with any fuels with 500-ppm sulfur or less. A brief summary of the impact of various diesel fuel parameters on diesel vehicle emissions is provided in Tables 2 and 3.

In summary, from the standpoint of emission control technology, the most important diesel parameter is the sulfur content of the fuel, mainly since it allows for better after-treatment control technologies. Once standards sufficiently stringent to require oxidation catalysts are introduced, the sulfur content should be reduced to a maximum of 500 ppm; for the most advanced NO_x and PM controls, the maximum should be 10-15 ppm sulfur. If sulfur levels are higher than these levels, the optimal performance of the pollution control systems will not be achieved and the in-use emissions will likely exceed standards. For cleaner vehicles, depending on the technology selected by the vehicle manufacturer, permanent damage could occur from the use of higher sulfur fuels.

B. Gasoline Vehicles and Fuels

Gasoline is a complex mixture of volatile hydrocarbons used as a fuel in internal combustion engines. The pollutants of greatest concern from gasoline-fueled vehicles with regard to urban and regional pollution are CO, HC, NO_x, lead and

Table 2. Impact of Fuels on Light Duty Diesel Vehicles

Diesel Fuel characteristic	Pre-Euro	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5/6[3]	Comments
Sulfur↑	SO_2, PM↑		If oxidation catalyst is used, SO_3, SO_2, PM↑		If Filter, 50 ppm maximum, 10-15 ppm better		If NO_x adsorber used requires near zero sulfur (<10 ppm) With low S, use lubricity additives
Cetane↑	Lower CO, HC, benzene, 1,3 butadiene, formaldehyde & acetaldehyde						Higher white smoke with low cetane fuels
Density↓	PM, HC, CO, formaldehyde, acetaldehyde & benzene↓, NO_x↑						
Volatility (T95 from 370 to 325 C)	NO_x, HC increase, PM, CO decrease						
Polyaromatics↓	NO_x, PM, formaldehyde & acetaldehyde↓ but HC, benzene & CO ↑						some studies show that total aromatics are important for emissions in a manner similar to polyaromatics

Notes: CO = carbon monoxide; HC = hydrocarbon; NO_x = oxides of nitrogen, PM = particulate matter; ppm = parts per million; SO_2 = sulfur dioxide; SO_3 or sulfur trioxide is an intermediate compound.

Table 3. Impact of Fuels on Heavy Duty Diesel Vehicles

Diesel	Pre-Euro	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5[4]	Comments
Sulfur↑	SO_2, PM↑		If oxidation catalyst is used, SO_3, SO_2, PM↑		If Filter, 50 ppm maximum, 10-15 ppm better		If NO_x adsorber used requires near zero sulfur (< 10 ppm) With low S, use lubricity additives
Cetane↑	Lower CO, HC, benzene, 1,3-butadiene, formaldehyde & acetaldehyde						Higher white smoke with low cetane fuels
Density↓	HC, CO ↑, NO_x↓						
Volatility (T95 from 370 to 325 C)	Slightly lower NO_x but increased HC						Too large a fraction of fuel that does not volatilize at 370 C increases smoke and PM
Polyaromatics↓	NO_x, PM, HC ↓						Some studies show that total aromatics are important

Notes: CO = carbon monoxide; HC = hydrocarbon; NO_x = oxides of nitrogen, PM = particulate matter; ppm = parts per million; S = sulfur; SO_2 = sulfur dioxide; SO_3 or sulfur trioxide is an intermediate compound.

[3] Euro 5 emissions standards for light duty diesel vehicles have been adopted by the EU for implementation in 2010; Euro 6 limits were also adopted for 2015 implementation. Both Euro 5 and Euro 6 standards are expected to mandate the use of PM filters on all light duty diesel vehicles.

[4] The EU Commission has also adopted Euro 6 emissions standards for heavy duty engines, likely mandating the use of PM filters on all heavy duty diesel vehicles from 2013 or 2014.

certain toxic hydrocarbons such as benzene[5]. Each of these can be influenced by the composition of the gasoline used by the vehicle.

The use of catalyst exhaust gas treatment required the elimination of lead from gasoline. This change, which started in the US and Japan during the 1970's and has now occurred throughout most of the world, has resulted in a dramatic reduction of ambient lead levels. Other gasoline properties that can be adjusted to reduce emissions include, roughly in order of effectiveness, sulfur level, vapor pressure, distillation characteristics, light olefin content, and aromatic content [7].

Modern gasoline engines use computer-controlled intake port fuel injection with feedback control based on an oxygen sensor to meter precisely the quantity and timing of fuel delivered to the engine. Control of in-cylinder mixing and use of high-energy ignition promote nearly complete combustion. The three-way catalyst provides greater than 90% reduction of carbon monoxide, hydrocarbons, and oxides of nitrogen. Designs for rapid warm-up minimize cold-start emissions. On-board diagnostic (OBD) systems sense emissions systems performance and identify component failures. Durability in excess of 160,000 km, with minimal maintenance, is now common in many countries.

Lead

Lead additives have been blended with gasoline, primarily to boost octane levels, since the 1920s [6]. Lead is not a natural constituent of gasoline, and is added during the refining process as either tetramethyl lead or tetraethyl lead.

Vehicles using leaded gasoline cannot use a catalytic converter because lead poisons the catalyst, and therefore have much higher levels of CO, HC, and NO_x emissions. In addition, lead itself is toxic. Lead has long been recognized as posing a serious health risk. It is absorbed after being inhaled or ingested, and can result in a wide range of biological effects depending on the level and duration of exposure. Children, especially under the age of 4, are more susceptible to the adverse effects of lead exposure than adults.

Almost every country in the world has eliminated the use of leaded gasoline; the latest estimate is that less than 10 countries continue to add lead.

Sulfur

Sulfur occurs naturally in crude oil. Its level in refined gasoline depends upon the source of the crude oil used and the extent to which the sulfur is removed during the refining process.

Sulfur in gasoline reduces the efficiency of catalysts designed to limit vehicle emissions and adversely affects heated exhaust-gas oxygen sensors. High sulfur gasoline is a barrier to the introduction of new lean burn technologies using DeNOx catalysts, while low sulfur gasoline will enable new and future conventional vehicle technologies to realize their full benefits. If sulfur levels are lowered, existing vehicles equipped with catalysts will generally have improved emissions.

Laboratory testing of catalysts has demonstrated reductions in efficiency resulting from higher sulfur levels across a full range of air/fuel ratios. The effect is greater in percentage for low-emission vehicles than for traditional vehicles. Studies have also shown that sulfur adversely affects heated exhaust-gas oxygen sensors; slows the lean-to-rich transition, thereby introducing an unintended rich bias into the emission calibration; and may affect the durability of advanced on-board diagnostic (OBD) systems.

The European Programme on Emissions, Fuels and Engine Technologies (EPEFE) study demonstrated the relationship between reduced gasoline sulfur levels and reductions in vehicle emissions. It found that reducing sulfur reduced exhaust emissions of HC, CO and NO_x (the effects were generally linear at around 8-10% reductions as fuel sulfur is reduced from 382 ppm to 18 ppm)[6]. The study results confirmed that fuel sulfur affects catalyst efficiency with the greatest effect being in the warmed up mode. In the case of air toxins, benzene and C3-12 alkanes were in line with overall hydrocarbon reductions, with larger reductions (around 18%) for methane and ethane.

The combustion of sulfur produces sulfur dioxide (SO_2), an acidic irritant that also leads to acid rain and the formation of sulfate particulate matter.

Certain other additives which are put into gasoline [generally to increase octane] can also affect vehicle emissions. Metallic-based, ash-forming, octane-enhancing additives such as Methylcyclopentadienyl manganese tricarbonyl (MMT) and ferrocene when added to gasoline will increase manganese-oxide and iron oxide emissions respectively from all categories of vehicles. Because of health concerns, participants in a workshop convened by the Scientific Committees on Neurotoxicology and Psychophysiology and Toxicology of Metals of the International Commission on Occupational Health recently published their conclusion that, "The addition of organic manganese compounds to gasoline should be halted immediately in all nations" [3]. The Health Effects Institute noted, "There is a large body of evidence that (1) under certain circumstances, manganese can accumulate in the brain [2, 4], (2) chronic exposure can cause irreversible neurotoxic damage over a lifetime of exposure, (3) manganese may cause neurobehavioral effects at relatively low doses [5], and (4) these effects follow inhalation of manganese-containing particles.

Vehicle manufacturers have expressed concerns regarding catalyst plugging and oxygen sensor damage with the use of these metallic additives which could lead to higher

[5] PM emissions from gasoline-fueled vehicles have traditionally not been regulated because their emissions are so much lower per mile driven than from diesel vehicles. However, it is now recognized that in many countries and cities where the gasoline vehicle population is much larger than the diesel population, they are a more important source. Also, health studies continue to point to lower and lower levels of ambient PM being acceptable from a public health standpoint. As a result, PM standards from gasoline-fueled vehicles may emerge.

[6] The study found that the effects tended to be larger over higher speed driving than in low speed driving.

in-use vehicle emissions especially at higher mileage. The impact seems greatest with vehicles meeting tight emissions standards and using high cell density catalyst substrates.

The Table 4 summarizes the impacts of various gasoline fuel qualities on emissions from light duty gasoline vehicles.

Table 4. Impact of Gasoline Composition on Emissions from Light Duty Vehicles

Gasoline	No Catalyst	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5/6[7])	Comments
Lead ↑	Pb, HC↑	CO, HC, NO_x all increase dramatically as catalyst destroyed					Lead is banned in China since 2000
Sulfur ↑ (50 to 450 ppm)	SO_2 ↑	CO, HC, NO_x all increase ~15-20% SO_2 and SO_3 increase					Onboard Diagnostic light may come on incorrectly
Olefins ↑	Increased 1,3 butadiene, increased HC reactivity, NO_x, small increases in HC for Euro 3 and cleaner						Potential deposit buildup
Aromatics ↑	Increased benzene in exhaust						Deposits on intake valves and combustion chamber tend to increase
	Potential increases in HC, NO_x	HC ↑, NO_x ↓, CO ↑		HC, NO_x, CO ↑			
Benzene ↑	Increased benzene exhaust and evaporative emissions						
Ethanol ↑ up to 3.5% O_2	Lower CO, HC, slight NO_x increase (when above 2% oxygen content), Higher aldehydes	Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems					Increased evaporative emissions unless RVP adjusted, potential effects on fuel system components, potential deposit issues, small fuel economy penalty
MTBE ↑ up to 2.7% O_2	Lower CO, HC, higher aldehydes	Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems					Concerns over water contamination
Distillation characteristics T50, T90↑	Probably HC ↑	HC ↑					
MMT ↑	Increased Manganese Emissions			Possible Catalyst Plugging	Likely Catalyst Plugging		O_2 sensor and OBD may be damaged, MIL light may come on incorrectly
RVP ↑	Increased evaporative HC Emissions						Most critical parameter for Asian countries because of high ambient temperatures
Deposit control additives ↑		Potential HC, NO_x emissions benefits					Help to reduce deposits on fuel injectors, carburetors, intake valves, combustion chamber

Notes: CO = carbon monoxide; HC = hydrocarbon; Pb = lead; RVP = Reid vapor pressure; MMT = methylcyclopentadienyl manganese tricarbonyl; MTBE = methyl tert-butyl ether; NO_x = oxides of nitrogen; O_2 = oxygen; SO_2 = sulfur dioxide; T50 = temperature at which 50% of the gasoline distils; T90 = temperature at which 90% of the gasoline distils.

C. Two and Three Wheeled Vehicles

There has been very little study focused on the impacts of specific fuel parameters on motorcycles and scooters. However, based on the limited available data and the combustion similarities between these and other internal combustion engines, these impacts are estimated to be as shown in the Table 5.

Concluding Remarks on Vehicles and Fuels

One of the most important lessons learned in the approximately 50-year history of vehicle pollution control worldwide is that vehicles and fuels must be treated as a system. Improvements in vehicles and fuels must proceed in parallel if significant improvements in vehicle related air pollution are to occur. A program that focuses on vehicles alone is doomed to failure; conversely, a program designed to improve fuel quality alone also will not be successful.

Reformulated diesel fuels can reduce particulate emissions from all diesel vehicles, as discussed earlier. [Approximately 70-80% of diesel PM is composed of elemental/black carbon. Gasoline PM contains only about 25% elemental/black carbon. Controls on diesel PM, especially catalyzed PM filters, greatly reduce the elemental carbon both in mass and fraction. For example, a 2007 HDD with a catalyzed PM trap has lower PM with only ~10% as elemental carbon]. Especially low sulfur fuels reduce the sulfate contribution. Certain after-treatment technologies are especially sensitive to the sulfur content of the fuel. Therefore if very stringent control of NO_x and PM was needed, sulfur levels will need to be reduced to 50 ppm or less and Euro 4 vehicle standards introduced. Euro 5 or US Tier 2 standards include a fuel sulfur limit of 10-15 ppm. Technologies to achieve these levels already exist and even more advanced technologies are being introduced for new vehicles.

[7]) Euro 5 emissions standards were adopted for implementation in 2010; Euro 6 was also adopted for 2015 implementation.

Table 5. Impact of Gasoline Composition on Emissions from Motorcycles

Gasoline	No Catalyst	India 2005	Euro 3	India 2008	China Stage 3	Comments
Lead ↑	Pb, HC ↑	CO, HC, NO_x all increase dramatically as catalyst destroyed				
Sulfur ↑ (50 to 450 ppm)	SO_2 ↑	CO, HC, NO_x all increase SO_2 and SO_3 increase				
Olefins ↑	Increased 1,3 butadiene, HC reactivity and NO_x					Potential deposit buildup
Aromatics ↑	Increased benzene exhaust					
Benzene ↑	Increased benzene exhaust and evaporative emissions					
Ethanol ↑ up to 3.5% O_2	Lower CO, HC, slight NO_x increase	Minimal effect with oxygen sensor equipped vehicles				Increased evaporative emissions unless RVP adjusted, potential effects on fuel system components, potential deposit issues, small fuel economy penalty
MTBE ↑ up to 2.7% O_2	Lower CO, HC	Minimal effect with O_2 sensor equipped vehicles				Concerns over Water Contamination small fuel economy penalty
Distillation characteristics T50, T90 ↑	Probably HC ↑	HC ↑				Not as quantifiable as in passenger cars
MMT ↑	Increased manganese emissions	Possible catalyst plugging				With low cell density, catalyst plugging risk seems small but there are concerns regarding deposits on spark plugs and in the combustion chamber
RVP ↑	Increased evaporative HC Emissions					
Deposit control additives ↑		Potential emissions benefits				Help to reduce deposits on fuel injectors, carburetors

Notes: CO = carbon monoxide; HC = hydrocarbon; Pb = lead; RVP = Reid vapor pressure; MMT = methylcyclopentadienyl manganese tricarbonyl; MTBE = methyl tert-butyl ether; NO_x = oxides of nitrogen; O_2 = oxygen; SO_2 = sulfur dioxide; T50 = temperature at which 50% of the gasoline distils; T90 = temperature at which 90% of the gasoline distils

With regard to gasoline-fueled vehicles, the use of catalyst exhaust gas treatment requires the elimination of lead from gasoline. This change, which has occurred throughout most of the world, has resulted in a dramatic reduction of ambient lead levels. Other gasoline properties that can be adjusted to reduce emissions include, roughly in order of effectiveness, sulfur level, vapor pressure, distillation characteristics, light olefin content, and aromatic content [7]. Catalyst technology is emerging for 2-3 wheeled vehicles and therefore lead free and lower sulfur gasoline will be important for these vehicles as well.

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