LITERATURE REVIEW TO EXAMINE THE EFFECT OF SELECTED FUEL QUALITY PARAMETERS ON VEHICLE EMISSIONS

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Glossary

AIAMC	Association of International Automobile Manufacturers of Canada
ASTM	The American Society for Testing and Materials
CARB	California Air Resources Board
CCD	Combustion Chamber Deposits
CGSB	Canadian General Standards Board
CI	Cetane Index
CI	Compression Ignition
CN	Cetane Number, a measure of a fuel's ignition delay
CO	Carbon Monoxide
CONCAWE	Conservation of Clean Air and Water in Europe
CRC	Coordinating Research Council
CR-DPF	Continuous Regeneration Diesel Particulate Filter
DCA	Deposit Control Additives
DI	Direct Injection
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DTBP	Di-tertiary Butyl Peroxide
ECE	An urban driving cycle used in Europe for light-duty vehicles
EEA	European Environment Agency
EGR	Exhaust Gas Recirculation
EPEFE	European Program on Emissions, Fuels, and Emission Technology
ESC	European Stationary Cycle
EUDC	Extra Urban Driving Cycle
EURO I to VI	European Emission Standards
FIE	Fuel Injection Equipment
FQTWG	Fuel Quality Technical Working Group
FID	Fuel Injector Deposits
FTP	Federal Test Procedure (US)
GVW	Gross Vehicle Weight
HC	Hydrocarbons
HCCI	Homogeneous Charge Compression Ignition
HFRR	High-Frequency Reciprocating Rig
HPL-EGR	High Pressure Loop - Exhaust Gas Recirculation
IDI	Indirect Injection
IVD	Intake Valve Deposit
LEV	Low Emission Vehicles
LAC	Lowest Additive Concentration

LPL-EGR	Low Pressure Loop - Exhaust Gas Recirculation
MPI	Multi Port Injection
MSAT	Mobile Source Air Toxics
NEDC	New European Driving Cycle
NMHC	Non-methane Hydrocarbons
NO_X	Oxides of Nitrogen
NSR	NO_X Storage Reduction catalyst
OBD	On-Board Diagnostics
OGAED	Oil Gas and Alternative Energy Division
PCCI	Premix Charge Compression Ignition
PEA	Polyetheramine
PFID	Port Fuel Injector Deposit
PIBA	Polyisobutyl amine
PM	Particulate Matter
RIA	Regulatory Impact Analysis
SAE	Society of Automotive Engineers
SCR	Selective Catalyst Reduction
SI	Spark Ignition
SLBOCLE	Scuffing Load Ball-on-Cylinder Lubricity Evaluator
SO_2	Sulphur Dioxide
SULEV	Super Ultra Low Emission Vehicles
THC	Total Hydrocarbons
Tier 1 to 4	US EPA Emission Standards
TLEV	Transitional Low Emission Vehicle
TWC	Three-Way Catalysts
ULEV	Ultra Low Emission Vehicles
US EPA	United States Environmental Protection Agency
ULSD	Ultra Low Sulphur Diesel
VGT	Variable Geometry Turbocharger
WSD	Wear Scar Diameter

1 Introduction

In response to issues raised in a report by the Pembina Institute, commissioned by the Association of International Automobile Manufacturers of Canada (AIAMC), the Minister of Environment tasked the Oil Gas and Alternative Energy Division (OGAED) of the Environmental Stewardship Branch at Environment Canada to work in collaboration with industry to make recommendations to the Minister of the Environment on a path forward with respect to four fuel quality parameters related to on-road gasoline and diesel. These parameters include sulphur in gasoline, deposit control additives (DCAs) in gasoline, lubricity in diesel, and cetane in diesel. The Minister specified that the recommendation should be in the context of harmonization with the United States, and in the context of environmental and/or health benefits. OGAED established a government-industry Fuel Quality Technical Working Group (FQTWG) to develop the recommended path forward, which includes Health Canada, other government departments and industry stakeholders.

Health Canada (Fuel Assessment Section, Air Health Science Division) and Environment Canada (OGAED) wish to better understand the state of scientific evidence available to establish a link between potential vehicle emission reductions and possible changes in the selected fuel quality parameters.

This report documents a review of available literature on these four fuel parameters and their link with vehicle emissions.

1.1 Objectives

Four objectives were established for this assignment. The literature review was intended to:

- Evaluate the potential impact on vehicle emissions of reducing Sulphur levels in on-road gasoline;
- Evaluate the potential impact on vehicle emissions of increasing the amount of Deposit Control Additives (DCA) in on-road gasoline;
- Evaluate the potential impact on vehicle emissions of increasing the Cetane content in on-road diesel fuel; and
- Evaluate the potential impact on vehicle emissions of increasing the Lubricity rating for on-road diesel fuel.

1.2 Background

Fuel Quality in Canada is maintained through a combination of regulations (both Federal and Provincial) and a commercial approach anchored by processes and specifications developed by the Canadian General Standards Board (CGSB). Federal and Provincial statutes establish the authority under which specific fuel quality parameters are regulated. The commercial approach to maintaining fuel quality relies on private industry voluntarily adopting the CGSB specifications as a standard business practice to facilitate commercial product transactions.

1.2.1 Sulphur

High levels of sulphur in gasoline may contribute to particulate matter (PM) and sulphur dioxide (SO_2) emissions, and may interfere with after-treatment technologies (e.g. catalysts) required for effective emission controls. Interference with after-treatment can result in increased emissions of hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x).

The federal Sulphur in Gasoline Regulations (SOR/99-236) establish limits for sulphur in on-road gasoline produced, imported or sold in Canada to an average level of 30 mg/kg, with a never-to-be-exceeded maximum of 80 mg/kg. While the relatively recent imposition of this limit represents a significant reduction in historical fuel sulphur content, it has been suggested[1] that further improvement in the quantity of emissions can be achieved through further reduction of sulphur limits. For information on the current Canadian Sulphur in Gasoline Regulations refer to the following website: http://laws.justice.gc.ca/en/C-15.31/SOR-99-236/index.html.

1.2.2 Deposit Control Additives

Over time, deposits within the fuel system (e.g. injectors, etc.) can lead to reduced performance of the fuel delivery system, specifically loss of fuel flow into the engines' combustion chamber. This occurrence in turn can impact combustion, reduce the durability of the engine and negatively impact fuel economy. These impacts in turn can lead to increased emissions of $NO_{X,}$ CO and HC, particularly as vehicles age. Deposit Control Additives (DCAs), added to the fuel at specific treat rates, are intended to reduce or eliminate deposits and thereby to help limit any increase in vehicle emission levels over time. The CGSB specifications call for voluntary addition of DCAs to gasoline. It has been suggested[1] that improved detergency in fuel (i.e. increasing the amount of DCAs) will reduce vehicle emissions.

1.2.3 Cetane Number

Cetane number (CN) is used as a measure of the ignition quality of diesel fuel and influences combustion characteristics. The cetane number is actually a measure of ignition delay, from start of injection to start of combustion, and depends on the hydrocarbon composition of the fuel. This "natural" cetane number can be modified by the addition of cetane "improvers" which increase cetane number with minimal change in fuel composition.

A measure related to the CN, the Cetane Index (CI), is used as an estimate of cetane number when a test engine is not available for determining this property directly. However, the CI is based on empirical correlations of CN with certain fuel parameters, and cannot account for cetane improvers. Thus this review uses cetane number exclusively.

CGSB specifications for diesel fuel identify a voluntary lower limit on the cetane number CN of 40.

It has been suggested[1] that increasing cetane number in diesel fuel will reduce emissions of NO_x, HC, and CO.

1.2.4 Lubricity

Lubricity is a measure of the lubricating characteristics of a diesel fuel, and impacts long-term wear on fuel system components such as pumps, injectors, or other metering devices. Since precise controls are critical for proper operation of modern engines, degradation of the fuel controls can lead to increased emissions.

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[1] Row, J., Doukas, A. 2008. "Fuel Quality in Canada Impact on Tailpipe Emissions." Prepared by The Pembina Institute, Drayton Valley, Alberta, Canada T7A 1S7; Prepared for the Association of International Automobile Manufacturers of Canada

The CGSB standard specification for diesel fuel identifies a voluntary minimum level of lubricity. The standard allows demonstration of adequate lubricity in a number of different ways, but the most commonly referenced is a standard bench test resulting in a maximum wear scar diameter of 460μm at 60°C. It has been suggested[1] that a reduction in this upper limit will reduce emissions over the lifetime of a diesel vehicle.

2 Approach

This section describes the overall approach used in conducting the analysis described in this report, including the process by which relevant technical literature was identified, and the methodology for evaluating literature. The summaries of individual studies are presented in Appendix A through D, and follow the methodology and criteria described below for evaluating individual studies.

2.1 Literature Identification

The literature identification process began by examining the regulatory impact documents and other technical support documents that accompany major regulatory rulemakings in Canada, the U.S. and Europe. These regulatory impact documents frequently cited published, peer-reviewed literature as background to the proposed rulemaking. These regulatory impact documents were an initial source of literature from which further literature identification was conducted. Many of the studies cited in regulatory impact documents were included in the identified literature used in this analysis.

The studies cited in these documents were searched to identify their underlying references, and these references were in turn searched both chronologically backward and forward in time to identify other publications by the same authors or that cite the same authors.

The two steps described above provided a body of literature associated with the regulatory rulemakings in the U.S. (both the California Air Resources Board and the U.S. Environmental Protection Agency) and in Europe. In addition to this literature, a basic literature search was conducted in major peer-reviewed journals and other resource databases for key words associated with the four fuel parameters considered in this evaluation. The types of publications queried in the general search on the fuel parameters included:

- Major journals for academic research (e.g. Society of Automotive Engineers (SAE), Transportation Research, Atmospheric Environment);
- Regulatory agency-sponsored studies (e.g. US EPA, CARB, European Environment Agency);
- Industry-sponsored studies (e.g. Coordinating Research Council (CRC), Alliance of Automobile Manufacturers, Conservation of Clean Air and Water in Europe (CONCAWE); and
- Engine design journals and other specialty journals.

Articles identified by keyword searches in major journals, industry-sponsored studies or through regulatory impact documents were screened for their relevance to the four specific fuel quality parameters considered in this analysis. This initial screening was required since some studies appear to address the four fuel quality parameters through key words or title searches but do not in fact present an analysis that can link these parameters to emissions and vehicle technology.

2.2 Methodology for Literature Review

The process described above allowed the team to collect studies on each of the four fuel quality parameters from a wide variety of sources. The final list of studies that were gathered and included in this analysis is provided in the bibliography. These studies were then reviewed, their findings summarized and a brief analysis was conducted to judge the quality of the study considering several criteria.

The most important criterion used to evaluate studies is the determination of whether the studies directly address the link between the fuel quality parameter and emissions. This link could be direct, or could be indirect through impact on vehicle technology components. The majority of studies which did not provide such a link were not included in the subsequent analysis; however, some studies which discuss the underlying phenomenon of the fuel quality parameter were reviewed and analyzed (for example studies that discuss the link between deposits in engines and emissions but do not directly link deposit control additives to these emissions).

Studies that showed a direct link between a fuel quality parameter and emissions or vehicle technology effects were then reviewed considering several other attributes. The parameters of the study were reviewed, including: the test method that was used; the driving cycle and age/mileage accumulation of the vehicle; the vehicle type (model year, technology type); how fuel quality parameters were varied and which ones were examined; how results were presented and whether a robust statistical analysis was presented (standard deviation, confidence intervals); and what were the primary conclusions of the study.

The final step in review of the studies was the consideration of all of the above factors to assess the quality of a particular study. The goal of this final analysis was to determine whether the study contributes to information that would answer the question of a link between emissions/vehicle technology and the fuel quality parameter, and whether the results of the study could be generalized or were restricted by the variables of the study. Finally, each study was evaluated to determine whether sufficient data was presented in the study to address all of the factors listed above as well as the basic question of the link between emissions/vehicle technology and the study. If insufficient data was present, whether identified by our team in the review of the study or identified by the study authors themselves, these limitations/unknowns were identified.

A synthesis discussion was then developed considering all of the study reviews conducted. The aim of the synthesis was to determine whether clear trends and linkage between a fuel quality parameter and emissions or vehicle technology were observed across studies (i.e. across individual fuel quality parameters). If several high-quality studies (per attributes identified herein) produced findings that were contradictory in nature for this linkage, the synthesis analysis flagged this finding and indicated where further future work is needed to definitely address the linkage.

3 Synthesis of the Reviewed Literature

A brief summary of each relevant paper/document reviewed is included in the appendices as follows:

- Appendix A – Sulphur in Gasoline, References A1 to A23;
- Appendix B – Deposit Control Additives in Gasoline, References B1 to B29;
- Appendix C – Cetane in Diesel Fuel, References C1 to C39;
- Appendix D – Lubricity in Diesel Fuel, References D1 to D13; and
- Appendix E – A complete bibliographic list of references used

This section presents a synthesis for each fuel parameter reviewed.

3.1 Sulphur in Gasoline

3.1.1 Background

Crude oil which is refined to produce gasoline can contain significant amounts of sulphur. The extent to which sulphur is removed during the refining process is established to achieve compliance with regulatory requirements. Since 2005, Canada has required that gasoline contain an average sulphur level of less than 30 parts per million (ppm) with a maximum fuel sulphur content of 80 ppm or a fixed limit of 40 ppm per batch.

Modern vehicles using three-way or other advanced catalyst technology can be affected by sulphur through catalyst poisoning. Generally, the extent of catalyst poisoning depends on the fuel sulphur content, catalyst configuration, and engine combustion processes. Studies have mainly focused on: (1) catalyst impairment as it relates to changes in vehicle emissions on a short-term basis and long-term basis; and (2) whether fuel effects on vehicle emissions are "reversible". A catalyst that has been poisoned by sulphur will suffer impaired operation. Reversibility refers to the potential of the catalyst to return to unimpaired operation after sulphur poisoning. If a catalyst is subject to high temperatures resulting from high engine loads, the catalyst can be cleansed of impairing compounds, thereby allowing the catalyst to return to operation without sulphur impairment. The degree of reversibility that can be obtained depends on the extent that driving conditions can provide high temperatures required to cleanse the catalyst.

Vehicles equipped with three-way catalysts (TWC) were the subject of many studies in the 1990s that were used to inform fuel sulphur regulations in the U.S. which required the reduction of sulphur from the hundreds of ppm range down to the low sulphur fuel range, requiring gasoline fuel of an average sulphur level of less than 30 parts per million (ppm) with a maximum fuel sulphur content of 80 ppm. Recent studies have focused on the emissions effects of a switch from high or low sulphur fuel to "sulphur free fuel" (<10 ppm fuel sulphur content) in vehicles with conventional spark ignition engines with a three-way catalyst as well as lean burn spark ignition engines with advanced catalyst technology.

3.1.2 Key Literature

Key literature on the effects of gasoline sulphur on emissions is listed below. These studies have been primarily driven by US federal and California-specific regulations governing gasoline sulphur concentrations, and many of these studies formed part of the background literature used in regulatory impact analyses that accompany the finalization of these regulations.

It should be noted that our analysis relied on these key studies, but incorporated knowledge, data and results from many other studies which are provided in the appendix. The overall trends and conclusions with respect to the effects of fuel parameters on emissions were informed by all of the studies we considered including these key studies.

- Alliance of Automobile Manufacturers 2009. “National Clean Gasoline: An Investigation of Costs and Benefits.” June [A1].
- Shen, Y. 2008. Effects of gasoline fuel properties on engine performance. Y. Shen. SAE Paper 2008-01-0628 [A4].
- CRC 2008. “Review of Prior Studies of Fuel Effects on Vehicle Emissions.” Prepared by Dr. Albert M. Hochhauser, 12 Celler Rd., Edison, NJ 8817, Prepared for Coordinating Research Council, CRC Project E-84 [A5].
- EPA 2007. “Regulatory Impact Analysis: Control of Hazardous Air Pollutants from Mobile Sources, Chapter 6: Feasibility of the Benzene Control Program.” United States Environmental Protection Agency. EPA420-R-07-002 [A6].
- Ntziachristos, L., A. Mamakos, Z. Samaras, U. Mathis, M. Mohr, N. Thompson, R. Stradling, L. Forti, C. Serves. 2004. “Overview of the European "Particulates" Project on the Characterization of Exhaust Particulate Emissions From Road Vehicles: Results for Light-Duty Vehicles.” SAE Paper 2004-01-1985 [A7].
- Stradling, R., N., R. Thompson, D. Bazzani, S. D. Rickeard, P. M. Bjordal, P. Martinez, P. Schmelzle, G. Scorletti, P. Wolff, J. Zemroch. 2004. Fuel effects on regulated emissions from modern gasoline vehicles. SAE Paper 2004-01-1886 [A8].
- Durbin, T.D., J. W. Miller, J. T. Pisano, T. Younglove, C. G. Sauer, S. H. Rhee, T. Huai, G. I. Mackay. 2003. “The Effect of Fuel Sulphur on NH3 and Other Emissions from 2000-2001 Model Year Vehicle.” Coordinating Research Council. May [A.9].
- Saitoh, K., M. Hamasaki. 2003. Effects of sulphur, aromatics, T50, T90 and MTBE on mass exhaust emission from vehicles with advanced technology - JCAP Gasoline WG STEP II Report". SAE Paper 2003-01-1905 [A.10].
- Mohr, M.U.L., G. Margaria. 2003. ACEA program on the emissions of fine particulates from passenger cars (2) - Part 2: Effect of sampling conditions and fuel sulphur content on the particle emission. SAE Paper 2003-01-1890 [A.11]
- AECC. 2000. “Response to European Commission Consultation on the need to reduce the Sulphur Content of Petrol and Diesel Fuels Below 50 Parts Per Million.” Association for Emissions Control by Catalyst. July [A.14].
- Baronick, J., B. Heller, G. Lach. 2000. Impact of sulphur in gasoline on nitrous oxide and other exhaust gas components. SAE Paper 2000-01-0857 [A.17].
- ACEA 2000. “ACEA Data of the Sulphur Effect In Advanced Emission Control Technologies.” Association of European Automobile Manufacturers. Brussels [A.18].
- Lyons, J.M., D. Lax, S. Welstand. 1999. Investigation of sulphur sensitivity and reversibility in late-model vehicles. SAE Paper 1999-01-3676 [A.19].
- Kwon, Y.K., R. Bazzani, P. J. Bennett, O. Esmilaire, P. Scorletti, T. David, B. Morgan, C. L. Goodfellow, M. Lien, W. Broeckx, P. Liiva. 1999. Emissions response of a European specification direct- injection gasoline vehicle to a fuels matrix incorporating independent variations in both compositional and distillation parameters. SAE Paper 1999-01-3663 [A.20].
- Schleyer, C.H., K. D. Eng, R. A. Gorse, R. F. Gunst, J. Eckstrom, J. Freel, M. Natarajan, A. M. Schlenker. 1999. Reversibility of Sulphur Effects on Emissions of California Low-Emission Vehicles. SAE Paper 1999-01-1544 [A.21].
- Schleyer, C.H., R. A. Gorse Jr., R. F. Gunst, G. J. Barnes, J. Eckstrom, K. D. Eng, J. Freel, M. Natajaran, A. M. Schlenker. 1998. Effect of fuel sulphur on emissions in California low emission vehicles". SAE Paper 982726 [A.22].

3.1.3 Effect of Fuel Sulphur on Gasoline Vehicle Emissions

Three-Way Catalyst, Sulphur Free Fuel (HC, CO, NO$_X$)

U.S. EPA and the Automobile Industry performed a joint study on the effects of fuel sulphur on vehicle emissions and EPA used the results in support of EPA's Mobile Source Air Toxics (MSAT) Rulemaking [A.6]. Nine Tier 2 certified vehicles of model year 2004 to 2007, meeting Bin 5 or Bin 8 (i.e. late-model vehicles certified to Tier 2 standards which are present within the current vehicle fleet) standards were tested with both 6 ppm and 32 ppm sulphur fuel. Statistically significant emissions reductions for emissions generated with 6 ppm sulphur fuel relative to 32 ppm sulphur fuel at 90% confidence were noted for THC, CH_4, CO, and NO$_X$, but not for NMHC. Percentage reductions in emissions due to the use of 6 ppm sulphur fuel relative to 32 ppm sulphur fuel were 11, 32, 17, and 33 for THC, CH_4, CO, and NO$_X$, respectively.

A study commissioned by the Coordinating Research Council (CRC) and reported upon in 2003 [A.9] investigated the effects of fuel sulphur on advanced technology vehicles. Twelve vehicles certified to California requirements and two vehicles certified to Euro 3 standards were tested. The fleet was designed to represent some of the latest technology vehicles on the market at the time of the study, circa 2001. Fuel sulphur contents of 5 ppm, 30 ppm, and 150 ppm were evaluated. Table 1 below shows the study results for the FTP test cycle and the US06 test cycle. The FTP test cycle is used for emissions certification testing and was developed based on real-world driving in Los Angeles in California. The US06 driving cycle simulates aggressive highway driving and is a supplemental FTP procedure. Emission changes from 30 ppm fuel sulphur to 5 ppm fuel sulphur were significant for US06 NMHC and NO$_X$ emissions, but not for CO emissions while emission changes from 30 ppm fuel sulphur to 5 ppm fuel sulphur were not significant for the FTP cycle for NMHC, CO, or NO$_X$.

Table 1. Fuel average emissions results including the European vehicles (g/mi)

(source: [A.9])

Fuel Sulphur Content	FTP			US06		
	NMHC	CO	NO$_x$	NMHC	CO	NO$_x$
5	0.049	0.639	0.053^c	0.013^{b,c}	4.564	0.043^{b,c}
30	0.048^c	0.629	0.059^c	0.021^{a,c}	4.676	0.072^{a,c}
150	0.052^b	0.682	0.072^{a,b}	0.038^{a,b}	4.953	0.123^{a,b}

a: Statistically significant difference from 5 ppm
b: Statistically significant difference from 30 ppm
c: Statistically significant difference from 150 ppm

In 2008 a literature review study and synthesis was commissioned by CRC [A.5]. In this report, historical studies on the subject of the sensitivity of emissions to fuel properties, including gasoline fuel sulphur, were reviewed. The following synthesis points were noted with respect to fuel sulphur effects:

- The authors note that based upon review of studies including high sulphur fuel, low sulphur fuel and sulphur free fuel, it was concluded that lowering sulphur in gasoline will reduce emissions of HC, CO and NO$_X$. Though there is some conflicting data, reductions in HC, CO, and NO$_X$ emissions are generally linear as a function of fuel sulphur content, especially at fuel sulphur contents below 150 ppm. The authors made this point based upon review of numerous studies, many of which included evaluation of changes in emissions due to a change from low sulphur to sulphur free fuel.

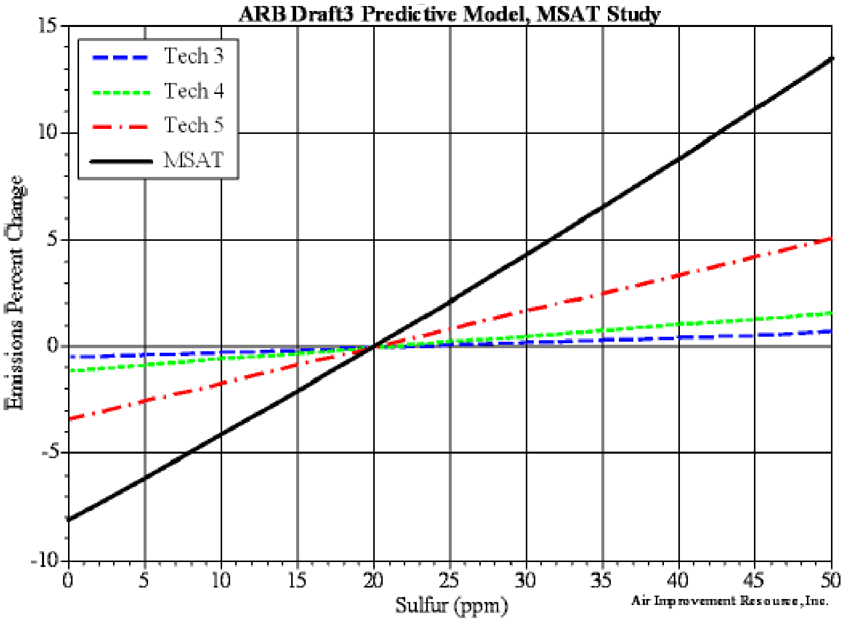
- The authors themselves note that PM emissions levels are likely impacted by sulphur content, but particulate emissions from newer vehicles are too low to be detected by instrumentation currently used to measure emissions so this direct impact could not be verified in the study.
- The authors also note that reversibility is complete under mild driving conditions such as those encountered on the FTP driving cycle for pre-1990 vehicles, but required "extreme" operation such as those encountered on the US06 driving cycle to achieve rich conditions which are required to obtain complete reversibility for newer vehicles.
- The authors also note that at the levels seen in modern gasoline, sulphur does not contribute to "vehicle performance attributes", but it does impact the TWC and other components of emissions control systems.
- The authors also note that emissions of benzene and 1,3 butadiene decrease and formaldehyde emissions may increase with reductions in fuel sulfur content while the effect on acetaldehyde is not clear. The vehicle testing studies reviewed within this literature review that contain information about fuel sulphur effects on toxic emissions were published prior to 2002. The results drawn from these studies cannot be used to draw reliable conclusions regarding fuel sulfur effects on toxics emissions for late model vehicles meeting more stringent emission standards.

In 2004 a study was published in the Society of Automotive Engineers (SAE) describing methodology and results of a testing program conducted on vehicles with conventional engines and vehicles with lean burn engines [A.8]. Fuels with sulphur contents of 4 ppm, 9 ppm, 49 ppm, and 148 ppm were evaluated. Conventional vehicles included 1) a stoichiometric DI vehicle certified to Euro III standards with a TWC, and 2) a multi port injection (MPI) vehicle with variable valve actuation certified to Euro IV standards with a TWC. It was noted that emissions were low relative to emission standards for both vehicles with conventional engines over all fuel sulphur contents evaluated. Statistically significant increases of HC emissions with increasing fuel sulphur content were found while statistically significant sensitivity of NO_X emissions to fuel sulphur content was not. One vehicle showed statistically significant CO emissions decreases with increasing fuel sulphur content, while the other vehicle showed no statistically significant sensitivity.

A study was published in SAE in 2000 describing methodology and results of a testing program conducted on three vehicles with conventional engines, one certified to each of the following California standards LEV, ULEV, and SULEV [A.15]. Fuel sulphur content was varied from <1 ppm to 600 ppm. Though no statistical analysis was performed, it was noted that HC and NO_X emissions for each of the three vehicles were found to be sensitive to fuel sulphur content, and that the SULEV was found to be most sensitive.

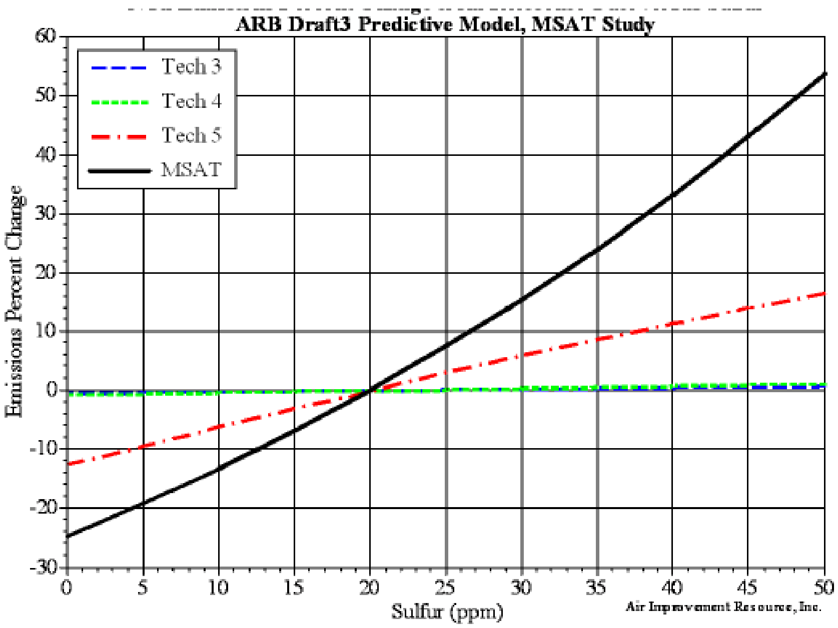
In 2000, the Association of European Automobile Manufacturers published a review of in-house vehicle data collected by vehicle manufacturers pertaining to fuel sulphur effects on emissions [A.18], with an emphasis on data relevant to advanced emissions control technology. Results for conventional spark ignition engines showed NO_X emission reductions of 13% when using 1 ppm in place of 30 ppm sulphur fuel. Regarding reversibility, after operating at 50 ppm and then 600 ppm fuel sulphur, catalysts that returned to operation at 50 ppm sulphur showed higher CO emissions relative to initial CO emissions using 50 ppm sulphur content fuel, though no such analysis was presented for a change from low sulphur to sulphur free fuel.

In 2009, the Alliance of Automobile Manufacturers published a study [A.1] in which emissions sensitivity to fuel sulphur effects were presented from various sources. The authors compared emissions sensitivity to fuel sulphur content between 0 ppm and 50 ppm as predicted by the California Predictive model for Tech 3 (1981 to 1985 model year vehicles), Tech 4 (1986 to 1995 model year vehicles) and Tech 5 (1996+) and results from the joint EPA and Automobile Industry study [A.6] for THC and NO_X as shown below in Figures 1 and 2. The sensitivity analysis presented for the joint EPA and Automobile study (*MSAT* in the figure below) represents Tier 2 vehicles only, for model years 2004 to 2007 as described above. For both THC and NO_X, it was noted that based on these results, the newer the vehicle the more sensitive the vehicle would be to fuel sulphur effects.



y-axis: Emissions Percent Change, x-axis: Sulphur (ppm)

Figure 1. THC percent change from reference fuel (20 ppm) versus sulphur
(source [A.1])



y-axis: Emissions Percent Change, x-axis: Sulphur (ppm)

Figure 2. NO_X percent change from reference fuel (20 ppm) versus sulphur
(source [A.1])

In study [A.1] it is noted that if VOC emissions were reduced by lowering fuel sulphur content, toxics species such as 1,3 butadiene and formaldehyde, which are usually estimated as a fraction of VOC emissions, would also be reduced. In study [A.6], emissions testing for toxics on the late model vehicles included in the study indicated a significant decrease of formaldehyde emissions of 16.5 percent at the 90% confidence level when fuel sulphur content was decreased from 32 ppm to 6 ppm. No significant difference at the 90% confidence level was noted for the other toxics for which emissions testing was conducted (1,3-Butadiene, Acetaldehyde, Benzene, Ethylbenzene, n-Hexane, Styrene, Toluene, M,P-Xylene, O-Xylene). The studies reviewed above for vehicles with conventional spark ignition engines with respect to fuel sulphur effects resulting from a change from low sulphur to sulphur free fuel indicate the following:

- Sensitivity: The weight of studies reviewed above generally supports the conclusion that HC and NO_X emissions increased with fuel sulphur content increases. CO emissions sensitivity to fuel sulphur effects was reported with less frequency and results were inconclusive.
- Aging: Results with respect to fuel sulphur effects on aging were not a focus of the studies reviewed above.
- Reversibility - Results with respect to fuel sulphur effects on reversibility were not a focus of the studies reviewed above.
- Technology – No vehicle operability effects resulting from the use of low sulphur relative to sulphur free fuel were noted by these studies, though TWC poisoning by sulphur is understood to be the mechanism by which fuel sulphur content affects emissions.

Three-Way Catalyst, Low Sulphur Fuel (HC, CO, NO_X)

Many studies were conducted and published regarding fuel sulphur effects resulting from a shift to low sulphur fuel in the 1990s. Below, studies reviewed are limited to those published since the late 1990s with discussion of California LEV or Euro IV vehicles, meeting late-model vehicle emissions standards and generally considered to be representative of the current light-duty gasoline vehicle fleet.

SAE published in 1997 a study commissioned by CRC [A.22] of six model year 1997 vehicles certified to LEV standards which were tested at fuel sulphur contents from 30 to 630 ppm. Statistically significant emissions reductions at 95% confidence were noted for NO_X, NMHC, and CO between fuel sulphur content of 30 ppm and 630 ppm for both low and high mileage catalysts. The responses to fuel sulphur were linear for low mileage catalyst while high mileage catalyst showed non-linear response with the largest effects on emissions occurring at lower sulphur levels. Figure 3 shows NO_X response to fuel sulphur.

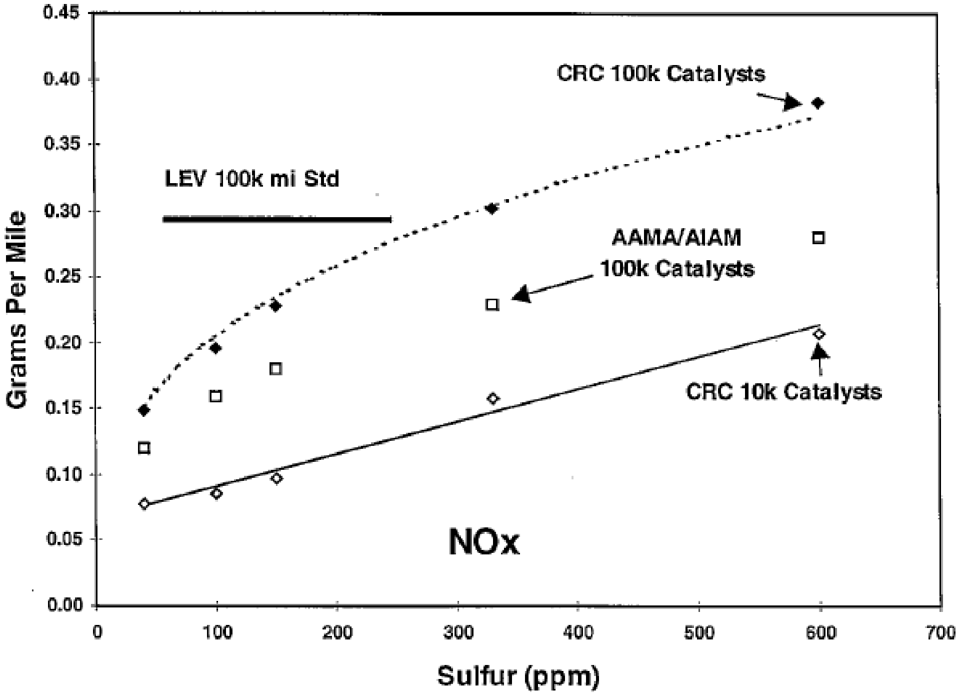


Figure 3. NO_X emissions fuel sulphur response for California LEV vehicles

(Source: [A.22])

In 2008, SAE published a paper that evaluated the impact of fuel sulphur content on Euro IV engine emissions [A.4]. Sulphur content had no effect on fresh catalyst THC, CO, or NO_X conversion efficiency for the engine tested (Euro IV) over the range of fuel sulphur contents evaluated. For the fuel sulphur contents included in this test (50 ppm and 150 ppm), the higher fuel sulphur content was associated with higher light-off temperatures and lower conversion efficiencies after catalyst aging. It is noted these results are engine bench tests which are generally used to establish emissions trends that are then confirmed by in-use vehicle testing. In this study, in-use vehicle testing was not used to confirm fuel sulphur effects.

SAE in 1999 published a study [A.19] regarding testing of eight vehicles of model year 1997 or 1998 with fuel sulphur contents of 40 ppm and 540 ppm. HC, CO, and NO_X generally showed higher emissions with the higher fuel sulphur content, but sensitivity differed from vehicle to vehicle. It was also noted that effects on emissions from high sulphur fuel were reversible by operating on low sulphur fuel, though in some cases more severe operating conditions such as those encountered in the US06 cycle were necessary to induce a return to relatively lower emissions. Aging of catalysts to the equivalent of 100,000 miles of on-road operation induced higher emissions for low and high sulphur fuel with larger increases in CO and NO_X emissions for the higher sulphur fuel.

Another study published by SAE in 1999 [A.21] evaluated the impact of fuel sulphur content on exhaust emissions as well as the reversibility of fuel sulphur effects of California LEV vehicles. Fuels with sulphur contents of 30 ppm and 630 ppm were evaluated. Significant reductions in NMHC, NO_X, and CO were observed for operation at low fuel sulphur content.

Lyons *et al* [A.23] conducted a review of literature relevant to gasoline fuel sulphur effects on emissions, focusing on California LEV vehicles and noted the following:

- When Tier 0, Tier 1, TLEV or LEV vehicles operate on higher sulphur gasoline, emissions of all regulated pollutants (i.e. VOC, CO, NO_X, PM, and SO_x) increase.
- Oxygen sensor performance may be degraded by high sulphur fuel.
- The functioning of OBD II systems may be impaired, but remain functional for vehicles operating on high sulphur fuel.
- Sulphur impacts vary from vehicle to vehicle, dependent on catalyst formation, catalyst location, emission control and OBD II design, vehicle calibration, and the gasoline fuel sulphur content.
- For pre-LEV vehicles, the effects of operating on high fuel sulphur fuel are completely reversible given operation at a rich air/fuel ratio at high temperatures for a sufficient period of time. However, for LEV vehicles the effects of operating on high fuel sulphur fuel may not be completely reversible.

The studies reviewed above for vehicles with conventional spark ignition engines with respect to fuel sulphur effects resulting from a change to low sulphur fuel indicate the following:

- Sensitivity: Studies consistently show significant emissions decreases for operation on low sulphur fuel relative to higher sulphur fuel.
- Aging: Studies show that higher fuel sulphur may induce higher emissions over mileage accumulation relative to lower fuel sulphur.
- Reversibility: It appears that fuel sulphur effects are completely reversible, although some vehicles may require extreme driving conditions to obtain complete reversibility.
- Technology: No vehicle operability effects resulting from the use of low sulphur relative to higher sulphur fuel were noted by these studies, though TWC poisoning by sulphur is understood to be the mechanism by which fuel sulphur content affects emissions.

Three-Way Catalyst, (PM, SO_X)

Particulate emissions sensitivity to fuel sulphur content was evaluated in a study published by SAE in 2004 [A.7]. The study included tests of six Euro III certified vehicles, one Euro I vehicle, and one ULEV vehicle. Results indicated that particulate emissions from vehicles with conventional spark ignition engines showed little response to fuel sulphur.

Particulate emissions sensitivity to fuel sulphur content was evaluated in a study published by SAE in 2003 [A.11]. The influence of fuel sulphur content on exhaust particulate emissions from an advanced Euro 3 certified MPI vehicle with a three-way catalyst was evaluated. Fuel with sulphur content of <10 ppm and 175 ppm were included in this study. Measurement results did not allow the authors to draw reliable conclusions, although, significantly higher particle counts were measured for some configurations for fuel with higher sulphur content. The increase in particle count while operating at higher fuel sulphur content was due to the contribution of non-solid material, a large fraction of which was found to be made up of sulphates.

For SO_X, numeric data is sparse, but based on the understanding that most fuel sulphur is converted to SO_X upon combustion, it is reasonable to infer that a reduction in fuel sulphur content would also produce a reduction in SO_X emissions.

Lean Spark Ignition Direct Injection Engines (HC, CO, NO_X)

In 2004, a study was published in SAE describing methodology and results of a testing program conducted on vehicles with conventional spark ignition engines and vehicles with lean burn engines [A.8]. Two vehicles with lean burn spark ignition direct injection engines were studied: 1) A vehicle certified to Euro III standards with a three-way catalyst (TWC) and NO_X trap, 2) A vehicle certified to Euro IV standards with a three-way catalyst (TWC) and NO_X trap. Fuels with sulphur contents of 4 ppm, 9 ppm, 49 ppm, and 148 ppm were evaluated. Results indicated that emissions were low relative to emission standards over all fuel sulphur contents evaluated. HC and NO_X emissions showed no statistically significant sensitivity to fuel sulphur content for either vehicle. CO emissions showed statistically significant increases in emissions with increases in fuel sulphur content for both vehicles.

In 2003, a study was published in SAE [A.10] on the subject fuel sulphur sensitivity of vehicles with lean burn spark ignition, direct injection engines. Three prototype experimental vehicles with lean burn engines with NO_X reduction catalysts were tested in this study. Each vehicle was designed to meet 1/6 the level of 1978 Japanese regulations. Fuels with sulphur contents of 2 ppm, 22 ppm, and 86 ppm were evaluated. Before mileage accumulation, fuel sulphur effects upon HC, CO, and NO_X emissions were found to be minimal and HC, CO, and NO_X emissions met the target of 1/6 of the 1978 Japanese regulation limit for all three vehicles. It should be noted that this is an experimental engine, and thus no direct comparison can be easily made between the emissions targets of this experimental engine and a specific existing vehicle emissions standard. After mileage accumulation of 30,000 km, all three vehicles did not meet the NO_X hot operations target at 86 ppm, and the NO_X target was met for only one of three vehicles at 2 ppm and 22 ppm. Table 2 shows that fuel sulphur sensitivity after mileage accumulation varied from vehicle to vehicle for hot operation and cold operation testing cycles.

Table 2. Influences of fuel sulphur after mileage accumulation

(source: [A.10])*

Driving Cycle		**10-15(hot operation)**			**11(cold operation)**		
Sulphur Change, ppm)		**86to22**	**86to2**	**22to2**	**86to22**	**86to2**	**22to2**
CO	GVA(MPI)	→	→	→	→	→	→
	GVB(SIDI)	→	→	→	→	↓	→
	GVC(SIDI)	→	→	→	↓	↓	→
	GVD(SIDI)	↓	↓	↓	↓	↓	↓
THC	GVA(MPI)	↓	↓	→	→	→	→
	GVB(SIDI)	↓	↓	→	→	↓	↓
	GVC(SIDI)	↓	→	→	↓	↓	→
	GVD(SIDI)	↓	↓	→	→	→	→
NO_X	GVA(MPI)	→	→	→	↓	↓	→
	GVB(SIDI)	→	↓	↓	→	↓	↓
	GVC(SIDI)	↓	↓	→	↓	↓	→
	GVD(SIDI)	→	↓	↓	↓	↓	↓
				↓ : Decrease		→ : No Change	
					95% Confidence Level		
* Note: 10-15 is the Japanese 10-15 (hot operation) driving cycle, and 11 is the Japanese 11 (cold operation) driving cycle							

In 2003 SAE published a study of fuel sulphur effects in vehicles with lean burn, spark ignition, direct injection engines [A.12]. Four vehicles were tested in this study: 1) A 2000 model year vehicle with a three way close coupled catalyst and an under floor lean NO_X catalyst, 2) A 2000 model year vehicle with port injection with a three way close coupled catalyst and an under floor lean NO_X catalyst, 3) A 2001 model year vehicle with a three way close coupled catalyst and an under floor three way and lean NO_X catalyst, and 4) A reference (older) vehicle with a three way close coupled catalyst and an under floor lean NO_X catalyst. Though no statistical analysis of emissions with respect to fuel sulphur content was presented, the authors noted the following with regard to durability under mileage accumulation: NO_X emissions increased under mileage accumulation dependent on fuel sulphur content though the three newer vehicles showed smaller increases with higher fuel sulphur content; THC emissions showed no increase with mileage accumulation; and for CO the older vehicle showed increases in emissions dependent upon fuel sulphur content, while the newer vehicles showed no such dependency. Regarding emissions sensitivity to fuel sulphur content, the authors noted the following: NO_X emissions increased with increased fuel sulphur content for the older vehicle, but not for the newer vehicles; THC emissions increased slightly with fuel sulphur content decreases; and CO emissions increased with fuel sulphur content for the older vehicle, but showed no clear trend for the newer vehicles.

A 2000 study published in SAE [A.15] reported on testing of two vehicles with lean burn, spark ignition, direct injection engines. Both vehicles were Japanese market vehicles, one of model year 1997 and the other of model year 1998. Fuel sulphur was varied from 8 to 500 ppm. Results indicated decreased NO_X storage reduction catalyst efficiency with accumulated mileage for fuels of higher sulphur content relative to those of lower sulphur content.

In 2000, the Association of European Automobile Manufacturers published a review of in-house vehicle data collected by vehicle manufacturers pertaining to fuel sulphur effects on emissions [A.18], with an emphasis on data relevant to advanced emission control technology. Results for vehicles with lean burn, spark ignition, direct injection engines showed that at lower fuel sulphur contents (to 8 ppm), NO_X conversion efficiencies remained higher for longer periods of operation, thus requiring fewer fuel consuming desulphurization events.

A study was published in SAE in 1999 [A.20] which evaluated the impact of fuel quality on exhaust emissions of a Euro II certified vehicle with a lean-burn direct-injection gasoline engine. Fuels with sulphur contents of 32 ppm and 138 ppm were evaluated. For all pollutants considered (THC, NO_X, CO, CO_2, PM), no statistically significant differences in emissions were observed between the low sulphur fuel and the high sulphur fuel at a 90% confidence level.

The studies presented above for vehicles with lean burn spark ignition, direct injection engines are inconclusive with respect to fuel sulphur effects for emissions sensitivity, catalyst aging, and reversibility. Technology effects aside from catalyst poisoning were not noted.

Lean Spark Ignition Direct Injection Engines (PM, SO_X)

Particulate emissions sensitivity to fuel sulphur content was evaluated in a study published by SAE in 2004 [A.7]. The study included tests of three Euro III certified vehicles with TWC and NO_X storage reduction catalysts. Results indicated that vehicles with lean burn direct injection spark ignition engines showed no consistent effect with respect to fuel sulphur.

Similar to conventional spark ignition engines, for SO_X, numeric data is sparse, but based on the understanding that most fuel sulphur is converted to SO_X upon combustion, it is reasonable to infer that a reduction in fuel sulphur content would also produce a reduction in SO_X emissions.

3.1.4 Summary of Sulphur Effects

General:

- The literature shows that there is an indirect link between fuel sulphur and THC, CO, and NO_X emissions based on catalyst impairment. There is a direct link between fuel sulphur and PM and SO_X emissions based on the direct effect of fuel sulphur content on SO_2 and sulphate emissions.
- Fuel sulphur impacts vehicle engine emissions by negatively affecting catalyst operation, thereby increasing tailpipe THC, CO, and NO_X emissions. The degree to which vehicle emissions are affected is dependent upon fuel sulphur content, engine type, catalyst configuration, and engine combustion processes. Catalyst operation is dependent on operating temperature; therefore the driving cycle used in a given study will affect study results. It is therefore difficult to compare study results across driving cycles. Comparison of internal trends established within each study is necessary to draw conclusions about fuel sulphur effects.
- Additionally, some studies of conventional engines with TWC technology indicate that HC, CO, and NO_X emissions increase with catalyst age for operations at higher fuel sulphur content.
- Studies of conventional engines with TWC technology also indicate that partial or complete reversibility is obtainable, though newer vehicles may require extreme driving conditions to obtain complete reversibility.

- The literature reviewed indicates no direct link between fuel sulphur and toxics emissions , with the exception of significant emissions decreases of formaldehyde for 6 ppm sulphur content relative to 32 ppm sulphur content fuel. However conclusions with respect to fuel sulphur effects on toxic emissions rely on only one study [A.6] that has identified toxics emissions response to fuel sulphur in late-model vehicles meeting stringent emission standard requirements.

Low Sulphur → Sulphur Free

- Conventional Engines: There is an indirect link between sulphur content and THC, CO, and NO_X emissions based on the potential for catalyst impairment by sulphur poisoning. Key studies of vehicles with conventional spark ignition engines generally show emissions benefits for operation with sulphur-free fuel relative to low sulphur fuel (30-50ppm sulphur vs. <10ppm sulphur) for THC, CO, and NO_X. A recent study [A.1] showed that for late model vehicles in the current vehicle fleet, conventional engines certified to Tier 2 standards, percentage reductions in emissions due to the use of 6 ppm sulphur fuel relative to 32 ppm sulphur fuel were 11, 32, 17, and 33 for THC, CH_4, CO, and NO_X, respectively.
- Lean-burn Engines: There is an indirect link between sulphur content and THC, CO, and NO_X emissions based on the potential for catalyst impairment by sulphur poisoning. However, studies of vehicles with lean burn spark ignition direct injection engines have not shown that these vehicles behave differently than vehicles with conventional spark ignition engines with sulphur-free gasoline. Some studies indicate no requirement for sulphur free fuel [A.12, A.8], while others indicate potential benefits for the use of sulphur-free fuel [A.10].
- PM and SO_X: Only two studies ([A.7] and [A.11]) relevant to fuel effects on PM emissions were evaluated; both contained testing results for conventional engines, but only one [A.7] contained testing results for lean-burn engines. For conventional engines, the studies reviewed did not contain information sufficient to establish a link between PM mass emissions and fuel sulphur content, although one study [A.11] reported a significant reduction in particle count for the use of fuel with <10 ppm fuel sulphur content relative to 175 ppm fuel sulphur content. For lean-burn engines, the study reviewed did not contain information sufficient to establish a link between PM mass emissions and fuel sulphur content. For $SO_{X,}$ numeric data is sparse for both conventional and lean-burn engines, but based on the understanding that most fuel sulphur is converted to SO_X upon combustion, it is reasonable to infer that a reduction in fuel sulphur content would also produce a reduction in SO_X emissions.

Interactions with Vehicle Technology

- Technology effects are limited to the emissions control systems (catalysts), with little data to indicate significant effects for systems/components other than the catalyst. As described above, the primary mechanism by which gasoline sulphur impacts vehicle technology is through reduced effectiveness of the three-way catalyst for traditional spark-ignition engines, and through reduced effectiveness of newer lean-burn catalysts for direct injection engines, although there is conflicting evidence as to whether lean-burn catalysts are impacted by sulphur levels in the fuel to any greater degree than traditional TWC. The details of this effect on emissions are described in the sections above.

3.1.5 Knowledge Gaps

In the existing body of literature, there is not enough information to understand whether or not vehicles with lean burn engines require sulphur free fuel to meet stringent emission standards. Additionally, there is not enough information to understand the extent of reversibility obtainable on vehicles meeting stringent emission standards under real-world driving conditions. Table 3 summarizes fuel sulphur knowledge gaps.

Table 3. Fuel sulphur knowledge gaps

Technology	Knowledge Area		Is There a Gap?	Explanation
Conventional Engine with TWC	Fuel sulphur effects (low sulphur to sulphur free fuel) on emissions of:	THC, CO & NO_X	No	Multiple studies ([A.1], [A.5], [A.6], [A.9]) identify higher THC, CO, and NO_X emissions resulting from the use of low sulfur fuel relative to sulfur free fuel.
		PM & SO_X	Yes	Studies reviewed ([A.7] and [A.11]) did not contain information sufficient to establish a link between PM mass emissions and fuel sulphur content. For $SO_{X,}$ numeric data is sparse for, but based on the understanding that most fuel sulphur is converted to SO_X upon combustion, it is reasonable to infer that a reduction in fuel sulphur content would also produce a reduction in SO_X emissions.
		Toxics	Yes	The current body of literature is not conclusive with respect to fuel sulphur effects on toxic emissions. Study [A.6] indicated no significant increases of toxics emissions (with the exception of formaldehyde) with higher fuel sulphur for late model Tier 2 certified vehicles. Study [A.1] notes the possibility of higher toxics emissions with higher fuel sulphur due to increases in VOC resulting from impaired catalyst efficiency.
	Reversibility		Yes	Studies [A.5], [A.19], and [A.23] identified the potential for complete reversibility. However, studies did not identify whether such reversibility is obtainable under real-world driving conditions.
Lean Spark Ignition Direct Injection Engines	Fuel sulphur effects (low sulphur to sulphur free fuel) on	THC, CO & NO_X	Yes	The current body of literature is not conclusive with respect to fuel sulphur effects on these engines. Some studies indicate no requirement for sulphur free fuel ([A.12] and [A.8]), while others indicate potential benefits for the use of sulphur-free fuel ([A.10]).

Technology	Knowledge Area		Is There a Gap?	Explanation
	emissions of:	PM & SO_X	Yes	The study reviewed [A.7] did not contain information sufficient to establish a link between PM mass emissions and fuel sulphur content. For SO_X, numeric data is sparse, but based on the understanding that most fuel sulphur is converted to SO_X upon combustion, it is reasonable to infer that a reduction in fuel sulphur content would also produce a reduction in SO_X emissions.
		Toxics	Yes	No studies to-date have identified fuel sulphur effects on toxic emissions from these engines.
	Reversibility		Yes	Studies did not identify the extent of reversibility obtainable for these engines.

3.2 Deposit Control Additives in Gasoline

3.2.1 Background

As on-road vehicles age and accumulate mileage, deposits tend to form throughout the fuel system of engines. These deposits are known to harm engine performance and increase exhaust emissions. Deposit control additives (DCA) are detergents that are blended into a base fuel by refiners, non-refiner marketers, or other independent retailers. Gasoline treated with DCA is intended either to maintain low deposit levels of a clean engine or to be used as clean-up on fuel systems already containing deposits. In Canada, the CGSB specifications call for voluntary addition of DCA to gasoline.

When fuel injector deposits (FID) build up they reduce volume of the ports and nozzles and thus the flow rate of gasoline that was to be mixed with air. As a result, electronic control systems are less able to achieve a stoichiometric balance of fuel and air required for complete combustion of hydrogen and carbon in the fuel, leading to engine inefficiency and the exhaust of incomplete combustion by-products. Intake valve deposit (IVD) build-up harms engine performance and is also known to increase exhaust emissions [B-9, B-28, B-29]. Research on engine deposits in the early 1990’s primarily focused on minimizing flow loss and the exhaust emissions benefits resulting from FID and IVD removal. DCA treatment to keep the injectors and intakes clean was also studied.

In 1995, the U.S. EPA promulgated an interim rulemaking that all gasoline must contain DCA to control FID and IVD. In its final rulemaking in 1996, EPA recognized that control of FID and IVD may contribute to formation of combustion chamber deposits (CCD) but that insufficient data existed to support rulemaking to control CCD. CCD build up is known to increase NO_X emissions, principally through a thermal insulation effect. When the combustion chamber is sufficiently coated with fuel deposits, heat transfer out of the combustion chamber is impeded leading to higher temperatures in the combustion chamber, which in turn lead to greater conversion of N_2 in air into NO_X.

3.2.2 Regulation in the United States

The US federal and California-specific rulemakings regarding DCA in gasoline are the drivers for much of the literature and studies that have been conducted in this area in the U.S. The final federal rulemaking for DCA in 1996 mandated that DCA manufacturers register their additive at the lowest additive concentration (LAC) required to meet performance standards for FID and IVD using test procedures specified by American Society for Testing and Materials (ASTM).

- The port fuel injector deposit (PFID) performance standard is less than 5% flow loss over a 10,000 mile test, per ASTM D 5598-94;
- The IVD performance standard is less than 100 mg average across all intake valves over a 10,000 mile test, per ASTM D 5500-94; and
- EPA stated in its rulemaking that the IVD performance standard is the more stringent of the two and that meeting IVD requirements generally also covers PFID control requirements.

California first promulgated its DCA requirements in 1992, which became the basis for the 1995 EPA interim rulemaking. California has since amended its DCA regulations twice (1996 and 1999) to reduce IVD average weight to 50 mg average using ASTM D 5500-98. The PFID standard remains at 5% maximum flow loss using ASTM D 5598-95a. California also has a CCD performance standard for DCA, which is that the DCA meeting the IVD standard must not result in more than 1300 mg total deposit weight in the combustion chamber or, alternatively, does not result in more than 140% total deposit weight relative to the gasoline formulation containing no additive. CCD is evaluated per the test method “Stationary Source Division's Test Method for Evaluating Intake Valve and Combustion Chamber Deposits in Vehicle Engines” of 1999, which is a modification of an ASTM procedure for IVD where steps are added to take CCD total weight measurements. California is the only state in the US with a specific DCA regulation covering CCD formation.

For additional information on United States federal regulations associated with Deposit Control Additives refer to the Final Rule for the Certification Standards for Deposit Control Gasoline Additives located on the US EPA Federal Register for Environmental Documents website: http://www.epa.gov/EPA-AIR/1996/July/Day-05/pr-23484.txt.html

3.2.3 Key Literature

The relationship between DCA in gasoline and emissions is two-part: (1) the emissions impacts caused by the presence of deposits and (2) the ability of DCA in gasoline to limit those deposits. Rarely in the literature are both phenomena examined within a single study. The majority of test programs are published in the Society of Automotive Engineers (SAE) technical papers or in the Coordinating Research Council (CRC) publications. The studies vary in breadth of their testing, from a single prototype engine to a fleet test of more than 20 in-use vehicles.

The chronological progression of engine deposit research has seen early studies which focused on PFID and IVD, followed by later studies focusing on CCD. Once widely accepted test procedures for PFID and IVD were developed, and with the advent of CCD-related problems, the research focus shifted to understanding CCD mechanisms, CCD effect on emissions, and controllability of CCD through use of DCA. A literature review [B-9] was prepared in 2002 for the Oil Gas & Energy Branch of Environment Canada that summarizes the current CCD research through 2001. Since that time, several papers have been published on studies conducted in the U.S., Europe and Asia.

It should be noted that our analysis relied on these key studies, but incorporated knowledge, data and results from many other studies which are provided in the appendix. The overall trends and conclusions with respect to the effects of fuel parameters on emissions were informed by all of the studies we considered including these key studies.

- Martin D.P. and J.F. Unsworth. 2002. The M111 engine CCD and emissions test: Is it relevant to real-world vehicle data? SAE Paper 2002-01-1642 [B-10].
- CRC. 2002. "Combustion Chamber Deposit Research Tool Development, Part 1, Vehicle Deposits and Emissions." CRC Report No. 630 [B-11].
- CRC. 2005. "Combustion Chamber Deposit Research Tool Development, Part 2, Engine Dynamometer Testing." CRC Report No. 644 [B-12].
- Balysky N.R., A.J. Lonardo, A.A. Millard, and K. Brunner. 2001. Vektron® 6913 gasoline additive NO_X evaluation fleet test program. SAE Paper 2001-01-1997 [B.13].
- CRC; CCD Emissions Group. 2000. "Effects of Combustion Chamber Deposits on Vehicle Emissions and Fuel Economy." CRC Project No. E-6. April [B-15].
- Aradi, A., W.J.Colucci, H.M. Scull Jr., and M.J. Openshaw. 2000. A study of fuel additives for direct injection gasoline (DIG) injector deposit control. SAE Paper 2000-01-2024 [B-16].
- Houser, K.R. and T.A. Crosby. 1992. The Impact of Intake Valve Deposits on Emissions. SAE Paper 922259 [B-28].
- U.S. EPA, 1995. Regulatory Impact Analysis for the final certification rule on DCA. Draft. August 14, 1995 [B-29].

3.2.4 Effects of DCA and FID/IVD on Emissions

As part of the Regulatory Impact Analysis (RIA) for the interim and final U.S. EPA rulemaking on DCA, EPA reviewed [B-29] a number of studies relating FID and IVD to emissions effects. Little technical detail on vehicle technology or experimental procedure is provided in these studies. The primary sources of these older studies on FID and IVD originate from the 1990 California Air Resources Board (CARB) technical support document for phase 1 reformulated gasoline, a 1992 SAE study performed by Chevron [B-28], and from a presentation to CARB by Texaco Research Center.

The CARB technical support document examined four vehicles (two from 1983, one from1985, one whose model year was unspecified) and concluded that fuel injector deposits can significantly increase HC and CO emissions, but the effect of PFID on NO_X is variable. HC emissions due to injector fouling increased between 28 and 228 percent. CO emissions increased between 16 and 668 percent. NO_X emissions change due to injector plugging ranged from a 42% decrease to a 169% increase. In a separate group of studies in the CARB technical support document, IVD impact on emissions was reported to depend on vehicle technology at the time of the study (model year 1995 vehicles) compared to late-1970s model year vehicles.

The 1992 SAE paper referenced within the RIA was a fleet test of 20 vehicles of model year 1990. IVD effects on emissions were found to be a linear function of the IVD deposit level. The fleet average effect of IVD on emissions was an 11% CO increase and a 15% NO_X increase; HC emissions over the FTP cycle were found to not be statistically significant.

The 1990 Texaco presentation for CARB reported results from two fleet tests. The first fleet test consisted of 12 cars and examined the emissions benefit of mechanical removal of IVD. These benefits were a 10.8% reduction in HC, 1.6% reduction in CO and 8.6% reduction in NO_X. The second fleet test consisted of 35 vehicles and mechanical removal of IVD. In the second study, removing IVD caused HC and CO emissions to increase by 7%, but reduced NO_X by 7.6%.

3.2.5 Effects of DCA and CCD on Emissions

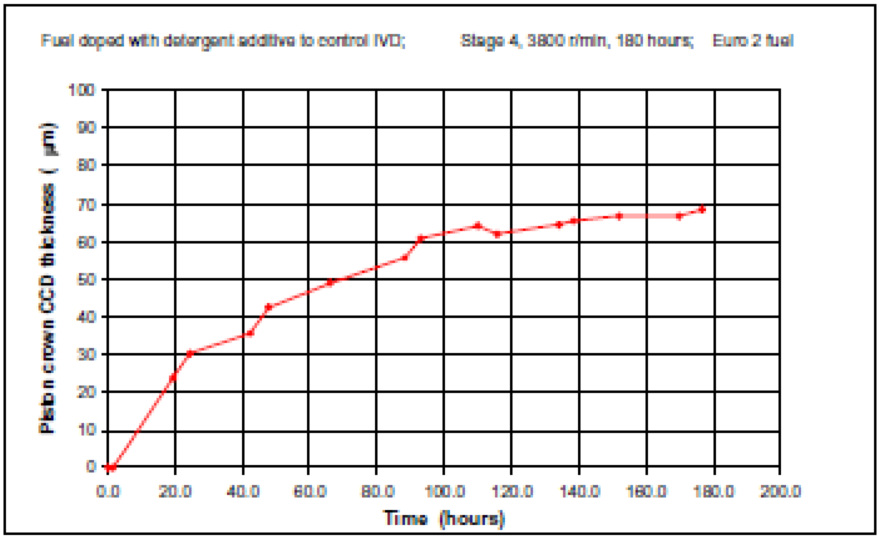
In response to an EPA request for information on the effects of CCD and emissions, CRC executed a statistically designed CCD testing program [B-15] that had the goal of determining the relationship of CCD to vehicle emissions and identifying parameters important to a potential CCD control test. Seven vehicles in four vehicle model groups (28 total) were subjected to emissions measurements at the beginning and end of a 16,000 mile deposit accumulation sequence of on-road driving. The four vehicle model groups were all 1996 vehicles certified to various California and federal emission standards.

1. Dodge Neon, certified to California TLEV
2. Dodge Caravan, certified to Federal LDT
3. Oldsmobile88, certified to Federal LDV
4. Crown Victoria, certified to TLEV

IVD and CCD were rated on the CRC 1-10 rating system at the end of mileage accumulation. CCD were subsequently removed and weighed, and emissions with the CCD-free engine were again measured. HC, CO and NO_X were all measured, but only NO_X emissions results were found to have statistically significant differences due to base fuel versus the additized fuels.

The response in the seven vehicle groups differed substantially from each other in their CCD-formation response. Dodge Caravans exhibited a CCD weight five times larger for those which accumulated miles with “high CCD” fuel compared with base fuel; for Oldsmobile 88 vehicles the factor was only 1.2. The shape of the CCD-emissions curve was not able to be defined because the two fuels for “mid-CCD” and “high-CCD” formation potential led to CCD weights that were the same.

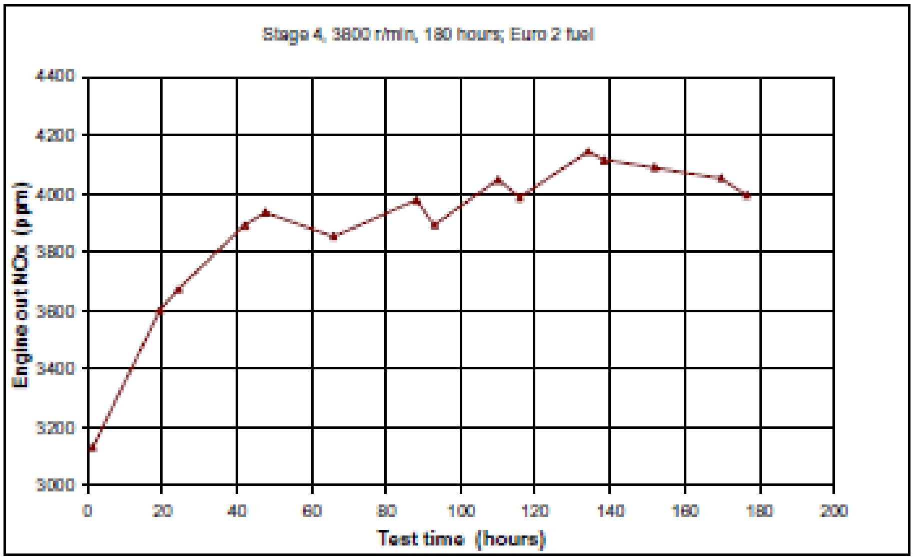
A 2002 British study published in SAE [B-10] examined the relationship between CCD and emissions from the Mercedes M111 bench engine and two road vehicles using base and DCA fuels. A European test procedure for evaluating IVD was used, a procedure that was under development in 2002 for CCD control. The base fuel was Euro 2 gasoline and the additized fuel was the base fuel dosed with DCA to control IVD. The test engine and vehicles accumulated deposits on a dynamometer for 180 hours (equivalent to 11,200 km). Piston crown CCD thickness and engine-out NO_X emissions were measured periodically throughout the deposit accumulation time. Figures 4 and 5 show the build-up of CCD and NO_X concentration as a function of time over the deposit accumulation period.



y-axis: Piston crown CCD thickness (µm), x-axis: Time (hours)

Figure 4. Build-up of piston crown CCD thickness with time

Source: [B.10]



y-axis: Engine out NO_X (ppm), x-axis: Test time (hours)

Figure 5. Engine-out increase of NO_X with time

Source: [B.10]

The fact that CCD thickness and NO_X emissions throughout the test cycle track each other well suggests the two parameters are related, but this cannot be stated with statistical certainty given the amount of data available. Both measurements are characterized by a steep initial rise followed by a plateau period.

In 2002, CRC produced a report on CCD research tool development [B-11]. The study examined effects on CCD formation of five fuels, an unadditized base fuel (Fuel E), a "high CCD" forming fuel (Fuel D) used in a previous CRC study [B-15], and three commercial additives (Fuels A, B and C). The commercial additives are not individually identified but there were one each of (1) a premium dose of polyetheramine (PEA), (2) a premium dose of polyisobutyl amine (PIBA), and (3) LAC plus 10% PIBA with synthetic carrier. The CRC identifies that a DCA treat rate of LAC plus 10% is common practice. HC, CO and NO_X exhaust emissions were measured from eight vehicles at the end of 15,000 mile tests, but no statistically significant differences were found due to differences between fuel additives. Differences in CCD weight, CCD thickness and IVD rating due to different fuel types were found to be significant at the 95% confidence level and are summarized below.

- CCD Total Weight
    - Lowest CCD weight was with Fuel E (base fuel)
    - Heaviest CCD weight caused by Fuel D ("high-CCD" fuel)
        - Fuel D produced significantly higher CCD weight compared to commercial fuels B and C, and base fuel E
        - Fuel D produced higher CCD than Fuel A
            - Not statistically significant in the Dodge Neons
            - 95% confidence in the GM Silverado vehicles
    - Comparing the three commercial detergents against base fuel (Fuel E), Total Weight of CCD,
        - Dodge Neon Vehicles
            - Increased a minimum of 57% (Fuel E to Fuel B)
            - Increased a maximum of 82% (Fuel E to Fuel A)
        - GM Silverado Vehicles
            - Increased a minimum of 59% (Fuel E to Fuel B)
            - Increased a maximum of 89% (Fuel E to Fuel A)
- CCD Thickness
    - Fuel D produced significantly higher, and Fuel E produced significantly lower deposits on the piston top than commercial fuels A, B, C
    - Fuels B and E produced significantly lower CCD cylinder head thickness than Fuels A and D (C not statistically different than other fuels)
- IVD Rating
    - The group of Fuels A, B and D kept intake valves very clean, significantly cleaner than the group of Fuels E and C, which formed heavy valve deposits. Within the two groups, the IVD ratings were not statistically different.

In Part II of the CRC study [B-12] a test cycle and engine were selected that were best able to rank additives in the first study in the same order.

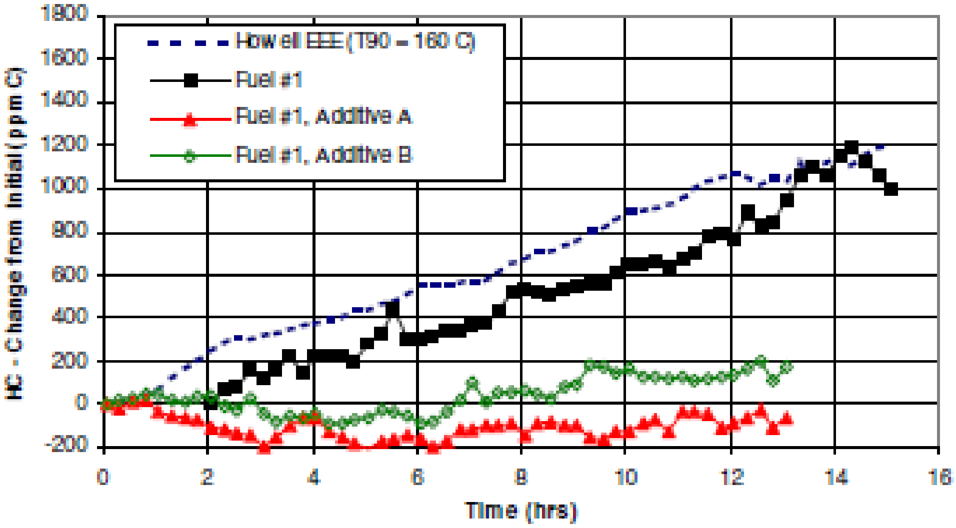
A 2001 SAE paper [B-13] reported on a vehicle fleet test program involving 28 vehicles in order to evaluate NO_X reductions achievable over a 16,000 mile accumulation comparing a base fuel to the fuel with a proprietary additive at a treat rate approximately double the LAC. Exhaust emissions of HC, CO and NO_X were measured at the end of the testing and differences in emissions due to using base or additized fuel were statistically significant at the 90% confidence level for NO_X. When the proprietary additive was used, NO_X emissions were reduced by 10% on average. Deposit measurements were not a part of this study, so the differences in CCD due to the additive use were unknown.

3.2.6 Effect of DCA in Emerging Technology: Direct Injection Engines

Direct injection engines are an emerging technology for on-road vehicles, although they currently do not represent a significant fraction of the vehicle fleets in Canada, Europe or the U.S. In direct injection engine deposit research, the focus has been on injector deposits rather than CCD.

A 2000 SAE study [B-16] using a 1982 Nissan direct injection engine was subjected to fuel flow measurements using a base fuel, five different DCAs of Mannich chemistry type and four different DCAs of PEA chemistry. Deposits were built up over six hours using base fuel, and then the fuel was switched to a batch of the base blended with each DCA. The results show that one of the Mannich additives was able to reduce the flow loss from 9.25% (from 6h of base fuel) down to 2.77% (representing 6h base fuel + 6 hours additized fuel). The PEA detergents had worse performance than the Mannichs with respect to flow loss.

A 2001 SAE study [B-26] measured HC emissions from an air-assisted direct injection research engine over two dynamometer test cycles. Figure 6 shows the fist test cycle, in which the engine was run in stratified mode at 2500 rpm engine speed for 15 hours. Stratified mode is an engine operating mode where fuel is injected near the end of the compression stroke, and the air and fuel do not completely mix. This operating mode is used under low-load vehicle conditions such as constant speed (no acceleration).



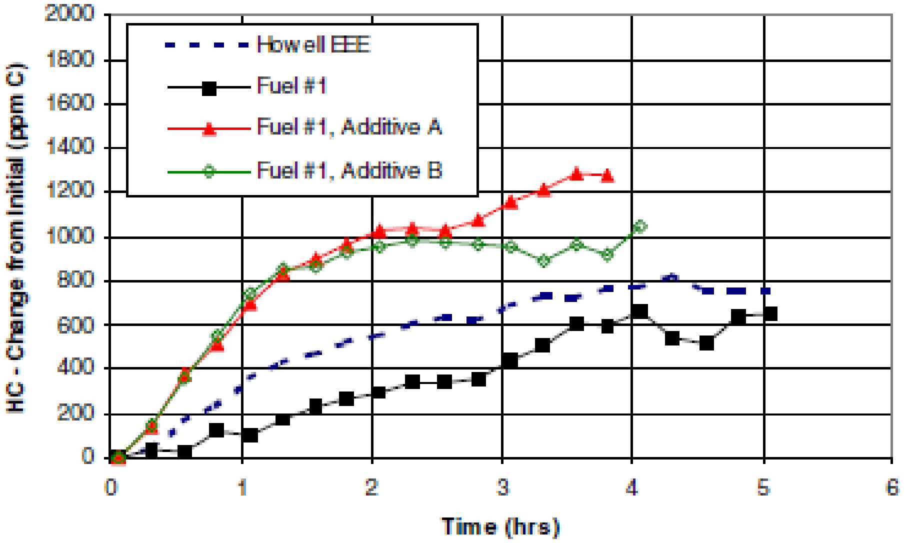
y-axis: HC change from initial (ppm C), x-axis: Time (hours)

Figure 6. HC emissions from the research engine run in stratified mode

Source: [B.26]

The second test cycle lasted five hours and the engine was run in homogeneous mode at 4000 rpm. Figure 7 reports HC emissions over the five hours. Homogenous mode is an engine operating mode where fuel is injected during the intake stroke, and the turbulence of air intake completely mixes the air and fuel. This operating mode is used under moderate and high load conditions.

It should be noted that direct-injection gasoline engines are an emerging technology and there are various experimental designs in use that run in different engine operating "modes" (i.e. stratified vs. homogeneous), however these modes are not consistent among different direct-injection engine designs nor are they easily comparable to traditional spark-ignited engines.



y-axis: HC change from initial (ppm C), x-axis: Time (hours)

Figure 7. HC emission from the research engine run in homogeneous mode

Source: [B.26]

The chemistry and dosage rates of additives A and B are unknown. These data show that the effect of DCAs relative to the base fuel varies by direct injection engine operating mode. For the stratified engine operating mode, DCA reduces HC emissions over the span of the dynamometer test. In homogeneous operating mode, the additives both increase HC emissions relative to the base fuel.

DCA effects on direct injection engines as determined from the key literature reviewed do not appear to be conclusive. Some data indicates that DCA usage can improve injector performance for this engine type, but other studies contradict this effect particularly for high mileage accumulation tests. Some studies indicate emissions benefits, particularly for CO and HC emissions but this is also contradicted by other studies. Further research would be needed on this topic to conclusively link DCA usage and emissions benefits for direct-injection engines.

3.2.7 DCA and Toxic Emissions

Only one study examined the effect of DCA on emissions of air toxics. A Taiwanese study [B-24] measured the emissions of benzene, toluene, ethylbenzene and xylene (BTEX) from an unknown model year Nissan New Sentra1.6L 4-stroke, PFI engine. Engine deposits were not measured; thus, this article does not fit into the above sections on IVD/FID or CCD. Additives GA-2, GA-3, GA-4, and GA-5 with commercial claims of intake valve cleaner, fuel injector cleaner, fuel system cleaner and carburetor cleaner, respectively, were blended into Taiwan-produced commercial base fuel 95-LFG. Emissions were measured while the vehicle was run on a chassis dynamometer over the FTP driving schedule. The original results are presented below in Figure 8 and show that all four toxic pollutants have lower emission rates with all additives (GA-2,3,4 and 5 are DCA) compared to the base fuel.

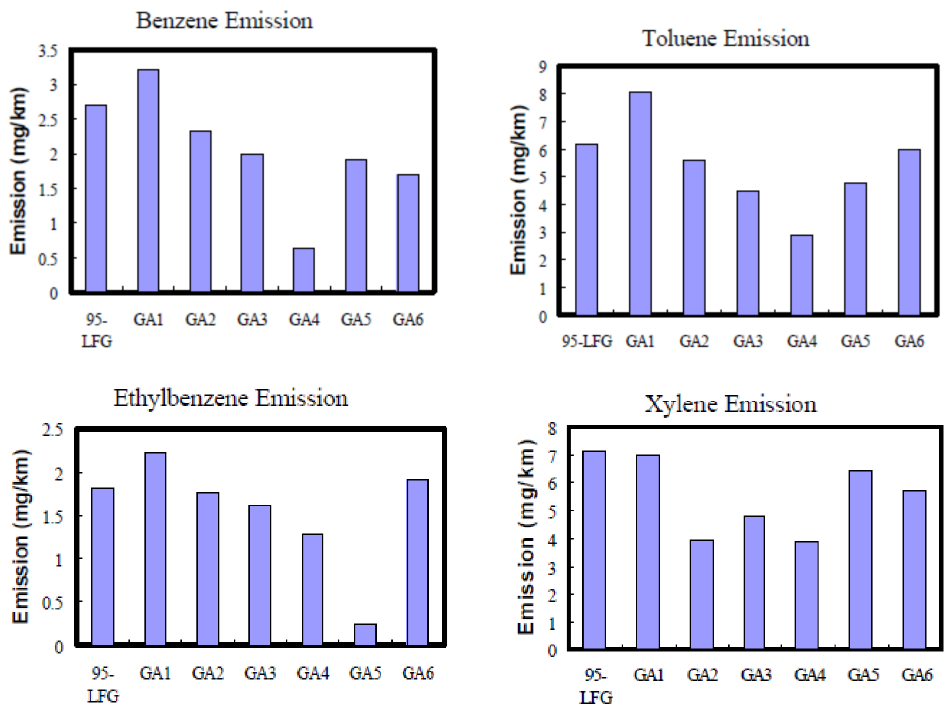


Figure 8. BTEX emissions from a Nissan Sentra engine

Source: [B.24]

3.2.8 Summary of DCA effects

General:

- A direct link between DCA and vehicle emissions cannot be established from the literature reviewed. There are indirect links between DCA and emissions, which vary depending on vehicle technology and deposit type. Quantitative data on DCA effects on emissions are therefore not possible given the extent of literature available on this subject.
- A single study [B-24] examined the effect of DCAs on emission of toxic pollutants including benzene, ethylbenzene, toluene and xylene. Neither mileage accumulation nor deposit measurements were a part of this testing program. Based on a testing program with a single engine, no repeat measurements and no statistical analysis, a conclusive link between DCA and toxic emissions is not supported in the literature.

Link with FID and IVD

- The early engine deposit studies on traditional spark-ignited (SI) engines that were considered by EPA and CARB as part of the rulemakings for DCA in the 1990’s generally found that HC and CO emissions decrease when fuel injectors were manually cleaned. The relationship between PFID and NO_X was not consistent.
- For direct injection engine technology, the key literature is less conclusive than the earlier studies on FID for SI engines. Data indicate that DCA usage reduces injector flow loss [B-16]. Other data examined use of DCA and the effect on emissions [B-26] and exhaust HC increased or decreased, depending on engine operating mode.

Link with CCD

- The more recent literature reviewed as part of this analysis focuses on studies examining the effects of CCD on emissions. These studies indicate a direct link between increasing CCD and higher NO_X emissions. Studies have demonstrated that mechanical removal of CCD results in reduced NO_X emissions [B-15]. There is insufficient data to support that DCA is able to limit deposit formation in the combustion chamber. All current evidence shows that DCA used for IVD and PFID control is effective for intake and injectors, but increases CCD.

Interactions with Vehicle Technology

- The primary interaction of DCA's with vehicle technology is to reduce deposits formed on intake valves and fuel injectors in traditional spark-ignited vehicles, which can impair the proper functioning of these vehicle components and in turn lead to impaired driveability [B-16]. However, DCA's have also been linked with an increase in combustion chamber deposits which can lead to combustion chamber deposit interference (CCDI) or "cold piston rap" [B-9] and an increase in NO_X emissions. Reduced flow through injectors and reduced flow through intake valves can lead to subsequent durability issues with the engine which can affect many other technology components of the engine system. No direct studies were found which link DCA use to interactions with vehicle emissions control systems.

3.2.9 Knowledge Gaps

The link between DCA and vehicle emissions is complex and requires knowledge of both the quantifiable relationship of engine deposits on emissions and the ability of a DCA to limit deposit formation, with degrees depending on additive chemistry and treat rate. Table 4 lists each knowledge area, whether a knowledge gap exists in the literature, and a brief explanation.

Most of the literature focused on the relationship between engine deposits and vehicle emissions. There is very little data linking DCA chemistries and treat rates required to prevent or limit engine deposit build-up. The lack of information is likely due to at least two major causes. First, DCA formulations are proprietary by nature and scientific studies comparing DCAs refer to the different formulations by numeric or other alias. Without detailed knowledge of the chemical composition of the DCA's, scientific research on their effectiveness at reducing deposits is not possible. Second, the majority of these studies were performed in the U.S. where national regulations for DCA are a performance-based standard. DCA's are required to be registered at the lowest treat rate necessary to meet the injector flow loss and IVD weight standards (explained in Section 3.2.2); thus, there is not a strong driver for research to determine the effect of variable treat rate on emissions.

Table 4. DCA gap analysis summary

Knowledge Area	Is There a Gap?	Explanation
DCA chemistry and treat rate	Yes	DCA chemical formulations of additives were proprietary. At best, studies identified test additives by chemical group name (e.g. PIBA, PEA, etc). Studies of the effects of incremental treat rate of DCA were not present in the literature.
Effect of DCA on engine deposits	No	CRC 2002 study [B-11] showed statistically significant differences in IVD and CCD between five fuels having different DCA chemistries and concentrations.
Effect of CCD on emissions	No	CRC 2000 study [B-15] showed with statistical significance that CCD causes NO_X emissions increases.
Effect of IVD and PFID on emissions	Yes	Studies [B-28, B-29] are outdated because the testing programs utilized engine technology from late 1970s through early 1990 model year.
Effect of DCA on emissions	Yes	Only one recent study examined the direct link between DCA and emissions [B-13] but the study is flawed in that no engine deposit measurements were made. Only one study examined toxic emissions [B-24] and the nature of this study is such that it is not sufficient to demonstrate a direct link between DCA and toxic emissions.
Effect of DCA on Direct Injection Engine Technology	Yes	The current body of literature is not conclusive with respect to establishing a clear link between DCA and emissions benefits for direct-injection engines.

3.3 Cetane in Diesel Fuel

3.3.1 Background

The cetane rating of a fuel, expressed as the Cetane Number (CN) is actually a measure of ignition delay, from start of injection to start of combustion. In Canada, the CGSB has established a voluntary minimum cetane number of 40. An Environment Canada survey (2003)[2]

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[2] Environment Canada 2003. Gasoline and Diesel Fuel Survey - Driveability Index (DI) and Oxygenates in Gasoline; Cetane Index, Cetane Number, Aromatics and Polyaromatic Hydrocarbons (PAH) in Diesel. Final Report

indicated that the CN of fuel sold in Canada (summer) ranged from about 40 to 56, and that the volume weighted average was about 43.

Since CN is a function of ignition delay, it affects the time available for mixing of the fuel with air prior to combustion, and also the timing of combustion relative to crankshaft angle in compression ignition engines. Thus, the CN of the fuel will have an impact on the combustion process, and has the potential to directly impact engine starting, operation, and efficiency. It also has the potential to directly impact emissions from the engine.

3.3.2 Key Literature

Cetane has generally been believed to be one of the most important fuel parameters affecting combustion of commercial diesel fuels, and there is a relatively large body of published and peer-reviewed literature available. Much of the North American research has focussed on heavy-duty engines. Most of the research on light-duty diesel engines/vehicles has been from Europe and Japan due to the wider acceptance of these vehicles in those markets.

Due to increasingly strict emission regulations around the world, a large amount of work has been directed towards identifying the effect of cetane on emissions. On-road vehicle/engine emissions standards are most stringent. Non-road engine standards are also tightening, but lag the on-road requirements. Thus, most research is directed towards on-road equipment, but the findings are applicable to both.

Of the many documents reviewed in Appendix C, the following were considered to be the key literature. It should be noted that our analysis relied on these key studies, but incorporated knowledge, data and results from many other studies which are provided in the appendix. The overall trends and conclusions with respect to the effects of fuel parameters on emissions were informed by all of the studies we considered including these key studies.

- Nuszkowski, J., Tincher, R.R., Thompson, G.J. 2009. Evaluation of the NO_X emissions from heavy-duty diesel engines with the addition of cetane improvers. *Journal of Automobile Engineering*. Vol. 223, Issue D8, pp 1049-1060 [C.3].
- CONCAWE 2008. “Advanced Combustion for Low Emissions and High Efficiency: A Literature Review of HCCI Combustion Concepts.” Report 4/08, Brussels [C.4].
- CRC 2008. “Review of Prior Studies of Fuel Effects on Vehicle Emissions.” Prepared by Dr. Albert M. Hochhauser, 12 Celler Rd., Edison, NJ 8817, Prepared for Coordinating Research Council, CRC Project E-84 [C.5].
- Massa, C.V. et al. 2007. Influence of cetane number on Euro III engine emissions, SAE Paper 2007-01-2000 [C.8].
- Kono, N., Kobayashi, Y. Takeda, H. 2005. Fuel effects on emissions from diesel vehicles equipped with advanced after-treatment devices. SAE Paper 2005-01-3700 [C.14].
- US EPA 2003. “The Effect of Cetane Number Increase Due to Additives on NO_X Emissions from Heavy-Duty Highway Engines: Final Technical Report.” Office of Transportation and Air Quality, United States Environmental Protection Agency, EPA420-R-03-002 [C.17].
- Oyama, K., Kakegawa, T. 2003. Evaluation of diesel exhaust emission of advanced emission control technologies using various diesel fuels, and sulphur effect on performance after mileage accumulation - JCAP Diesel WG (Fuel) Report for Step II Study. SAE Paper 2003-01-1907 [C.22].
- CONCAWE 2002. “Evaluation of Diesel Fuel Cetane and Aromatics Effects on Emissions from Euro-3 Engines.” Report No. 4/02, Brussels [C.24].
- Matheaus, A.C. et al. 2000. EPA HDEWG Program - Engine Tests Results. SAE Paper 2000-01-1858 [C.27].

- Mason, R.L. et al. 2000. EPA-HDEWG Program – Statistical Analysis. SAE Paper 2000-01-1859 [C.28].

3.3.3 Determination of Cetane Number

The CN is determined in accordance with a standard test method, typically ASTM D613, Standard Test Method for Cetane Number of Diesel Fuel Oil. This test method covers the determination of the rating of diesel fuel oil in terms of an arbitrary scale of cetane numbers using a standard single cylinder, four-stroke cycle, variable compression ratio, indirect injected diesel engine.

The CN scale covers the range from zero to 100, but typical testing is in the range of 30 to 65. A higher CN corresponds to a shorter ignition delay, and lower CN to a longer delay.

A measure related to the CN, the Cetane Index (CI), is used as an estimate of cetane number when a test engine is not available for determining this property directly. The CI estimation method is based on empirical correlations of CN with fuel parameters (density and distillation range), but does not account for the use of a cetane improver. It is important to understand that this measure is not an alternative to the cetane number: it is only used to estimate the cetane number of fuel prior to addition of any cetane improver. In general, the research, and therefore this review, uses cetane number exclusively due to the uncertainties that the use of the cetane index would add to any analysis.

3.3.4 Methods of Increasing Cetane Number

There are two basic methods of increasing the CN of a fuel: reformulation/reblending to alter the “natural” CN of the fuel, or addition of CN “improvers”.

The natural CN of a fuel is a function of the relative concentrations of various hydrocarbon classes within the fuel, so the feedstock, processing, and blending of a fuel will affect the CN. Further, there are practically an infinite number of fuel compositions/blends that can result in similar CN. As such, the natural CN of a fuel does not vary without other significant changes in the hydrocarbon composition of the fuel, and fuels with similar CN number can be otherwise quite different. In particular, fuel density and aromatic content frequently correlate with CN. These factors have at times confounded research into the effect of cetane on emissions, since it is difficult to separate the impact of cetane from that of the other associated changes in hydrocarbons.

Cetane enhancing additives, frequently referred to as CN improvers, can be used to increase CN in a fuel. These improvers are typically compounds such as 2-ethyl-hexyl-nitrate (2EHN), and di-tertiary butyl peroxide (DTBP) added in small amounts. These improvers increase CN without changing the relative hydrocarbon composition of the fuel or significantly impacting density, but obviously change the overall chemical composition to some extent.

These two methods of increasing CN give rise to the question of whether the effect of increasing CN on emissions will be dependent on the method used. That is, does the effect of increasing CN differ depending on whether the increase was attained by reformulation to change natural CN, or attained by addition of a cetane improver?

A number of studies have attempted to address this issue through comparison of carefully blended fuels and improved fuels of the same cetane number [C.16, C.24, C.27]. In virtually all cases the studies found no significant difference between an increase in natural CN and an increase due to addition of an improver, if other important parameters are unchanged. Other reviews reached the same conclusion [C.5, C.31]. One study [C.24] indicated there were no significant differences in emissions resulting from use of different types of improver.

3.3.5 Effect of Cetane on Heavy-Duty Diesel Engines

Many studies have made it clear that the effect of cetane is strongly dependent on engine and after-treatment technology [C.5, C.8]. An extensive review of the literature [C.5] in 2008 stated that "As engines become more sophisticated in terms of emission control, fuel effects seem to be lessened."

In the U.S., emission standards have driven engine technology development for the North American on-road market, with major step changes in 2004, 2007 and 2010. In order to meet the stringent limits on of NO_X, PM and HC, essentially all manufacturers have already adopted cooled Exhaust Gas Recirculation (EGR) and oxidizing Diesel Particulate Filters (DPF). By the 2010 model year, Selective Catalytic Reduction (SCR) or equivalent technology will also be almost universally adopted.

The US EPA Tier 4 requirements for non-road diesels phase in similar requirements from 2008 to 2015.

A recent study [C.3] showed that increasing CN through addition of improver resulted in NO_X reductions of 1 to 3.5% in older engines (1990s, without EGR), but increased NO_X slightly (1.3%) for a more modern 2004 engine with variable geometry turbocharger (VGT) and cooled EGR. These results are limited to NO_X and a small sample of engines, but the general trend seems to be present in much of the literature. That is, the effect of cetane has changed and/or diminished with the introduction of the more advanced emission controls (EGR, high pressure fuel systems, DPF, SCR, NO_X storage reduction catalysts (NSR), diesel oxidation catalysts (DOC), etc.) [C.3, C.5, C.8, C.22].

A technical analysis of previous data and literature review undertaken by the US EPA in 2003 [C.17] indicated that increasing CN in fuel will reduce NO_X emissions from heavy-duty diesel production engines built in the 1990s. However, the study specifically excluded engines with EGR, and went on to state that EGR-equipped engines are expected to exhibit no discernable NO_X response to cetane.

Other data on pre-EGR engines [C.8, C.18, C.23, C.24, C.26, C.29, C.31, C.34, C.35, C.37] from the same era show considerable variability, but the more carefully designed studies suggest that increasing CN will result in:

- A reduction in NO_X ranging from insignificant to 8%;
- No identifiable trend in PM emissions; and
- A reduction in HC and CO emissions ranging from insignificant to 50%.

It should be noted that these results are not consistent across the studies. Much of the variability may result from other differences in engine technology (fuel systems, engine controls) that are not described in the literature. Nevertheless the weight of evidence indicates that increasing CN has the potential to reduce NO_X, HC, and CO emissions from these older, pre-EGR engines.

A US EPA study [C.26] reviewed two related Arco studies that looked at the effect of increasing CN using improvers on emissions of a 1991 DDC Series 60 Engine. The studies reported that CN increases of 9 to 16 gave HC reductions of 40 to 75%, and that reductions in air toxics emissions were in line with reductions in HC. Air toxics measured included Acetaldehyde, Acetone, Acrolein, Benzaldehyde, Benzene, 1,3-Butadiene, Crotonaldehyde, Formaldehyde, Hexanaldehyde, Isobutyraldehyde + MEK, and Propionaldehyde.

In North America, EGR technology was introduced in heavy duty vehicles prior to 2004. Test data in the literature on the effect of cetane in heavy duty engines with EGR is limited. The two studies identified [C.3, C.27, C.28] both used robust methodology and reported that an increase in CN resulted in a slight increase in NO_X emission (~1%). One of these studies involved a model year 2004 production engine; one was a research version of a 1994 engine with EGR added. An increase in CN from 42 to 52 also resulted in a reduction of HC and CO emissions of 12 to 13%. No data is presented on PM emissions.

Another study involving fuel effects on heavy duty engines with advanced after-treatment included fuels with a wide range of CN (48 to 69) [C.14]. The test data was not specifically analyzed for the effect of cetane, but visual inspection of the graphs presented do not suggest a correlation of NO_X, PM, HC, or CO with cetane. These results are not inconsistent with the previously referenced studies [C.3, C.27,C.28] given that these engines are equipped with oxidizing catalysts. The authors noted that advanced engine system technologies for reduced emissions were very effective for NO_X reduction, but fuel effects were small. They also noted that, in general, fuel effects on emissions were small compared to the effect of the new technologies.

While the effects of cetane on emissions from older heavy duty engines may be significant, the limited data available suggests the introduction of EGR has changed the impact, such that only HC and CO emissions seem to correlate with CN. By inference, toxic emissions would correlate as well since these have been found to track HC emissions.

Further, the introduction of after-treatment on the latest generation of engines (2007 and newer) means that minor changes in NO_X, PM, CO, and HC (and by inference, air toxics) from the engine will have no measurable impact at the tailpipe due to after-treatment technology that is now required (DPF, DOC, SCR, NSR).

3.3.6 Effect of Cetane on Light-Duty Diesel vehicles

The bulk of the literature reporting test data has been generated on vehicles intended for the European market, and data have been generated using the standardized European vehicle test cycles. North American data was not found, likely due to limited penetration of light-duty diesels into this market.

A recent comprehensive review of the literature [C.5] found a large amount of conflicting data, but identified the following trends in emissions (prior to after-treatment) associated with an increase in CN:

- A reduction in CO emissions ranging from 17 to 50%;
- A reduction in HC emissions ranging from 7 to 25%;
- A slight (possibly insignificant) increase in PM emissions ranging from 3 to 5%; and
- No identifiable trend in NO_X emissions.

The authors pointed out that “as engines become more sophisticated in terms of emission control, fuel effects on emissions seem to be lessened” and that “The effects seem to be smaller and more difficult to measure with after-treatment systems in place.”

It is important to note that these reported effects are at the engine exhaust, prior to after-treatment. Since stringent emission standards have driven manufacturers to apply extensive after-treatment (DPF, DOC, SCR, NSR, etc.) on virtually all light-duty vehicles, minor effects at the engine exhaust would not be expected to result in measurable changes at the tailpipe in most cases.

Other test programs reviewed [C.16, C.19, C.20, C.22, C.24, C.25, C.26, C.33] generally showed a similar trend to those reported above, with considerable conflicting data. For example the change in fuel CN did not have a significant impact on CO, NO_X, HC, and PM emissions [C.8] and increasing CN slightly reduced NO_X emissions.

The European Environment Agency recently published guidance for calculating emission factors for vehicles [C.2]. Using the specified emission estimation methods, varying CN from 40 to 50 will give no significant change in NO_X and PM emissions, but will reduce CO and HC emissions for light duty diesel vehicles. That is, EEA guidance recognizes that CN impacts CO and HC emissions from the existing fleet, but has no significant predictable impact on NO_X and PM.

Of the above studies, only one [C.33] considered the impact of CN on emission of air toxics from light duty vehicles. The study involved vehicles that met 1996 European standards, and concluded that increasing CN reduced benzene and 1,3, butadiene in line with effects on total hydrocarbon emissions. It also found that increasing CN reduced formaldehyde and acetaldehyde. This is consistent with findings that toxic emissions track HC emissions in heavy duty engines [A.26].

Based on the above, there is some indication that CO and HC emissions (and by inference air toxic emissions) may be reduced by increasing CN from 40, but the magnitude of these reductions is expected to be much lower in recent and new vehicles which are equipped with extensive after-treatment. There is no clear evidence that increasing CN will reduce emissions of NO_X or PM from light-duty diesels vehicles.

3.3.7 Effect on Emerging Technologies

Homogeneous Charge Compression Ignition (HCCI) engines are the subject of a great deal of research. Using a broad definition for HCCI, there are many variants being investigated, but generally this technology differs from traditional CI engines in that the fuel/air is pre-mixed and timing of combustion is dependent on the charge properties rather than injection time. That is, timing and combustion are controlled by varying air/fuel ratio, EGR, and/or charge temperature, rather than by injection timing. In some variants, the charge is premixed prior to entering the combustion chamber, while in others it is pre-mixed by injecting early in the stroke (PCCI).

Compared to traditional diesel, these engines are of interest since early work has shown much lower NO_X and PM emissions with similar or reduced fuel consumption, although HC and CO emissions may be higher [C.4]. Reductions in engine-out emissions of NO_X and PM would reduce loads or requirements on after-treatment equipment.

Since HCCI engine operation is very dependent on charge properties, there has already been considerable published work on the effect of fuel properties, and in particular the effect of cetane number [C.1, C.4, C.7, C.9]. Due to the early stages of development, the research is more focused on the effect of CN on operation of the engine, with emissions as a secondary consideration.

To date this work is limited to single cylinder research engines, under steady state conditions, and covers a range of HCCI implementation strategies.

The work done suggests that emissions are a function of combustion phasing [C.1, C.9]. Cetane affects combustion phasing, but when combustion phasing is controlled (e.g. by EGR, fuel mix, charge temperature) to optimum conditions, CN does not affect the operation of the engine or emissions directly.

The above consideration notwithstanding, CN still remains an important fuel variable in the operation of these engines. One study found that maximum engine output was provided by CN in the range of 40 to 50, and that higher CN tended to make engine control more difficult [C.9]. A second study [C.7] found that higher CN numbers required earlier combustion phasing which was not optimal for efficiency. A recent comprehensive review of the technology concluded that the recent evidence suggests CN<45 may be the optimum choice for diesel HCCI [C.4].

It has been suggested that for fixed injection timing, pre-mix type HCCI is not compatible with a wide range of CN. This may suggest that the optimum fuel be limited to a fixed range of CN. However, with feedback control on combustion phasing, which is likely to be required to adapt changing load/speed conditions, CN is not a factor.

It should be noted that HCCI technology is not in production, and if and when it does become available it may be in a form far different from current research trends. Nevertheless, it is clear from the published work that there is no indication that increasing CN in diesel fuel will reduce emissions directly in HCCI engines. Similarly, there is no indication that increasing CN will provide indirect benefits by enabling or aiding in development of these engines.

3.3.8 Summary of Cetane Effects

Heavy-Duty Vehicles

- Pre- EGR: There is reasonable evidence that increasing CN will significantly reduce NO_X, CO and HC (including air toxics) emissions from older, pre-EGR heavy-duty vehicles (pre-2004). However, it should be noted that the results are not consistent across the studies, so quantifying the reduction is difficult. The overall impact of this effect on the North American fleet will be gradually reduced as these vehicles are removed from service.
- EGR: The introduction of EGR in heavy-duty vehicles has changed the impact of CN on emissions, such that only CO and HC (and by inference, air toxic) emissions have been correlated with CN. An increase in CN has been shown to give reductions in CO, HC (and by inference, air toxics) emissions ranging from insignificant to 50%, prior to any after-treatment.

Light-Duty Vehicles

- For light-duty vehicles, an increase in CN tends to have no significant effect on NO_X or PM emissions, but tends to reduce engine emissions of CO (17% to 50%), HC (7% to 25%) and air toxics prior to any after-treatment. The overall reduction in CO and HC (and by inference, air toxics) emissions is dependent on the level of after-treatment.

New Vehicles

- For both light- and heavy-duty vehicles, fuel effects in more modern vehicles are lessened. This is particularly true with the latest vehicles which incorporate extensive after-treatment systems. In these vehicles the effect of cetane on emissions (NO_X, PM, HC, CO, air toxics) is expected to be very small and difficult to measure.

Emerging Vehicle Technologies

- HCCI is a major emerging technology with potential to significantly reduce emissions from diesel engines with similar or lower fuel consumption. Operation of these engines is affected by CN, and early work suggests fuels with CN less than 45 may be optimal for this technology.

General

- The above indicates that CN has a direct effect on emissions of older engines/vehicles, and may still have a small direct effect on newer vehicles. There is no indication in the literature that suggests that the CN of existing fuels has indirect effects, such as impacting reliability, or creating a barrier to implementing new technology.

Interaction with Vehicle Technologies

- Cetane has the greatest impact on emissions of older, pre-EGR engines. The impact of cetane is much reduced on engines with modern controls (e.g. EGR, advanced fuel delivery systems, electronic engine controls) and is expected to be negligible on engines with advanced after-treatment systems.

3.3.9 Knowledge Gaps

The body of literature reviewed indicates a general lack of information on the effect of cetane on emissions from modern engines/vehicles with after-treatment. While it is expected that the effect of cetane is greatly reduced on these vehicles, this has not been demonstrated through a robust, well designed test program that evaluates the effect of CN on a range of vehicles/engines with modern (model year 2010) emission control and after-treatment systems.

Table 5. Cetane gap analysis summary

Knowledge Area	Is There a Gap?	Explanation
Effect of CN on older technology heavy-duty vehicles	No	The effect of cetane on emissions from older engines/vehicles has been demonstrated through multiple studies. US EPA [C.17] study provided results based on pre-EGR engines data set.
Effect of CN on modern heavy-duty engines and vehicles	Yes	Modern (model year 2007+) vehicles include advanced engine controls and exhaust after-treatment. The effect of cetane on emissions from these vehicles has not been demonstrated.
Effect of CN on light-duty vehicles	Yes	The effect of cetane on emissions is vehicle/technology specific. Most emission data is available from European and Japanese light-duty vehicles and fuels.
Effect of CN on future technology engines and vehicles	Yes	Limited studies on HCCI engines showed that fuel CN does not impact vehicle operation [C.1, C.4]. Low cetane (e.g. <45) may be beneficial.

3.4 Lubricity in Diesel Fuel

3.4.1 Background

Lubricity is the ability of a fuel to prevent or minimize wear in Fuel Injection Equipment (FIE), and has the potential to impact emissions indirectly [D.13]. The fuel injection system (e.g. pumps, injectors) is lubricated by the diesel fuel itself, so poor lubricity can increase wear in this equipment, and even cause catastrophic failure in extreme cases [D.9].

Lubricity itself does not have a direct impact on emissions, but low lubricity does lead to long term wear on critical engine parts which can contribute to a degradation of engine performance over time [D.4]. The same study suggests that emissions can be expected to rise as a result of poor lubricity due to compromised injection pump performance.

3.4.2 Key Literature

Limited literature is available linking diesel fuel lubricity measurements and FIE wear.

Of the documents reviewed in Appendix D, the key literature is listed below. It should be noted that our analysis relied on these key studies, but incorporated knowledge, data and results from many other studies which are provided in the appendix. The overall trends and conclusions with respect to the effects of fuel parameters on emissions were informed by all of the studies we considered including these key studies.

- Matzke, M. et al. 2009. Diesel lubricity requirements of future fuel injection equipment. SAE Paper 2009-01-0848 [D1].
- Caprotti, R., Takaharu, S., Masahiro, D. 2008. Impact of diesel fuel additives on vehicle performance. SAE Paper 2008-01-1600 [D.5].
- Ullmann et al. 2008. Investigation into the formation and prevention of internal diesel injector deposits. SAE Paper 2008-01-0926 [D.6].
- Knothe, G., Steidley, K.R. 2005. Lubricity of components of biodiesel and petrodiesel: the origin of biodiesel lubricity. Energy & Fuels. Vol. 19, pp. 1192-1200 [D.11].

3.4.3 Determination of Lubricity

In Canada, a minimum level of lubricity is specified by the Canadian General Standards Board (CGSB). The standard for Automotive (On-road) Diesel Fuel , CAN/CGSB-3.517-2007, allows the use of any one of five methods of measuring lubricity in diesel, together with five associated minimum levels of lubricity. The five methods and associated limits are as follows:

- Pump Wear with a Representative Fuel in a Distributor-Type Diesel Fuel Injection Pump in a Vehicle Field Test — The required vehicle field test methodology is described in SAE Paper 952370. An acceptable pump wear result is defined as an Overall Pump Rating of 4.0 or less using the rating method described in SAE Paper 961180.
- Pump Wear with a Representative Fuel in a Distributor-Type Diesel Fuel Injection Pump Rig Test — The required pump rig test methodology is described in SAE Paper 981363. SAE Papers 961180 and 952370 provide additional background information. An acceptable pump-wear result is defined as an Overall Pump Rating of 4.0 or less using the rating method described in SAE Papers 981363 and 961180.
- Pump Wear with a Representative Fuel in a Rotary-Type Diesel Fuel Injection Pump Rig Test — The required pump rig test methodology and rating method are described in SAE Paper 961944. An acceptable pump-wear result is defined as an Overall Pump Rating of 5.3 or less using the rating method described in SAE Paper 961944.
- Lab Bench Test Results with a Representative Fuel Using the High Frequency Reciprocating Rig Test — The required high frequency reciprocating rig test is described in ASTM D 6079 and shall be run at 60°C. An acceptable test result is defined as a wear scar diameter of less than or equal to 460μm at 60°C.
- Lab Bench Test Results with a Representative Fuel Using the Scuffing Load BOCLE Test — The required test is described in ASTM D 6078. An acceptable test result is defined as a scuffing load of greater than or equal to 3100 g.

Of these five methods, the first three have achieved very limited acceptance. The final two methods reference ASTM standard methods which are more commonly used in North America and abroad. Of the five, the High Frequency Reciprocating Rig test (HFRR) is by far the most commonly referenced method in the literature.

The ASTM clearly states[3] that no absolute correlation has been developed between the HFRR (ASTM D6079) and the SLBOCLE (ASTM D6078) tests. In the scope of each of these two standards, ASTM states:

“It is not known that this test method will predict the performance of all additive/fuel combinations. Additional work is underway to further establish this correlation and future revisions of this test method may be necessary once this work is complete.”

A 2007 study [D.8] reported poor correlation between the HFRR and the SLBOCLE test, Similarly, a 2002 study [D.13] evaluated lubricity of diesel fuels by five different methods including two of the above methods (HFRR and Fuel Pump Rig). The study found poor correlation between the different methods.

The HFRR test is a relatively simple, inexpensive test that can be completed within a few hours. By contrast, field and injection pump tests must be run for a period long enough to produce observable wear. The HFFR test also aligns with the European standard procedure, ISO/CD 12156-1.

3.4.4 Methods of Increasing Lubricity

In diesel fuel, the lubrication mechanism is a combination of hydrodynamic lubrication and boundary lubrication [D.9]. In hydrodynamic lubrication, a layer of liquid prevents contact between the opposing surfaces. Better hydrodynamic lubrication can be achieved by diesel fuels with higher viscosities. In boundary lubrication, some compounds form a protective anti-wear layer by adhering to the solid surfaces. If lubricity is insufficient, then boundary lubrication is not enough to prevent wear on FIE. This boundary lubrication can be improved by adding fuel additives [D-9].

There are three types of additives commonly used for lubricity, namely mono acids, amides, and esters [D-1, D-9]. Researchers have shown that some types of additives may have secondary effects, such as deposition on FIE, and that these deposits can adversely impact drivability and result in non-compliance with the emission limits [D-6].

Tests on commercially available diesel fuel additives used in the current European fleet showed that combinations of additives are responsible for deposits in FIE [D-5]. Fatty acids used as lubricity additives have been shown to readily react with metal ion impurities in the fuel to form metal soaps. The use of ester based lubricity additives were shown to be neutral when in combination with detergents. [D.5, D.6, D.11]. In one of these studies [D.5], the ester based lubricity additives were shown to have no effect on FIE over a 50,000km vehicle test.

3.4.5 Effect of Lubricity on FIE

In two recently published studies [D.1, D.2] contradictory findings were reported. CRC 2009 [D.2] results suggest the HFRR lubricity rating may not correlate well with wear in FIE, while a study published in SAE [D.1] reported that the HFRR test can be used for the modern vehicles using Common Rail (CR) fuel delivery.

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[3] ASTM D6079 - 04e1 Standard Test Method for Evaluating Lubricity of Diesel Fuels by the High-Frequency Reciprocating Rig (HFRR) Home Page. http://www.astm.org/Standards/D6078.htm Last accessed 30 October 2009.

Gray et al. [D.13] investigated the effects of fuel lubricity on diesel engine fuel injection equipment (FIE) wear and failure rates using five different test methods. They demonstrated that additives can improve the lubricity of poor lubricity diesel fuels to satisfactory levels and can substantially reduce FIE wear rates. They also found that the HFRR test is capable of distinguishing between lubricity levels of good and poor lubricity fuels, but concluded it is not capable of accurately determining the lubricity characteristics of fuels containing lubricity additives.

CRC [D.12] evaluated the level of fuel injection system degradation due to wear and failure of the boundary film, for different types of fuels. Although HFRR tests were able to distinguish between those fuels that contained lubricity additives and those that did not, there was weak correlation between lubricity rating (HFRR) and the pump durability results. In addition, High Pressure Common Rail Pumps appeared to be more sensitive to fuel lubricity in comparison to an opposed-piston, rotary-distributor, fuel-injection pump.

3.4.6 Summary of Lubricity Effects

There is no literature available that provides a direct linkage between lubricity and engine emissions. Lubricity has the potential to affect engine emissions indirectly by influencing the rate of wear in FIE. Wear in the FIE will reduce the effectiveness of the engine control system, which may result in less than optimum combustion parameters and increased engine emissions [D.1].

Fuel must have at least a minimum level of lubricity to avoid excessive wear on FIE, which can degrade effectiveness of engine controls and, in turn, increase emissions.

General

- The literature reviewed doesn’t allow a conclusion on the link between lubricity and vehicle emissions.
- There is evidence that lubricity is directly linked to FIE wear. The Swedish experience on low sulphur diesel fuel showed that inadequate lubricity can lead to excessive wear and even premature failure.
- However, there is no data available quantifying the effect of FIE wear on engine emissions. Thus it has not been established what level of FIE wear will result in a significant emissions increase.

Lubricity Test Methods

- There are several accepted methods of measuring lubricity in Canada. While there is some literature describing attempts to correlate existing measures of lubricity with wear, most studies have found poor correlation. Thus it has not been clearly established that the existing measures of lubricity can be used to reliably predict rate of wear, or the associated impact on engine emissions.

Interaction with Vehicle Technologies

- There is some indication that high pressure pumps associated with common rail fuel delivery are more sensitive to lubricity effects.

3.4.7 Knowledge Gaps

A number of technology/information gaps are identified in Table 6.

Table 6. Lubricity gap analysis summary

Knowledge Area	Is There a Gap?	Explanation
Effect of lubricity on FIE wear	Yes	Attempts to correlate existing measures of lubricity with FIE wear are conflicting.
Effect of FIE wear on engine emissions	Yes	There is no information available on the relationship between level of FIE wear and increased emissions.
Lubricity test methods	Yes	The existing literature indicates the available measures of lubricity do not correlate to one another, and do not necessarily correlate to FIE wear. There is no lubricity measurement methodology with a clear, demonstrated correlation between measured values and wear in FIE.
Secondary impact of lubricity additives	Yes	No information could be found on the secondary effects of lubricity additives (i.e. FIE deposits) on emissions.

4 Limitations

This report, which should be considered in its entirety, is based solely on a review of existing literature as reported herein. ENVIRON has assumed that the information reviewed is factual and accurate and has not independently verified the accuracy or completeness of such information.

This report was prepared by ENVIRON, and does not necessarily represent the views of Health Canada or Environment Canada.

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Appendix A: Gasoline – Fuel Sulphur Effects Reviews

Study Reference No. A.1: AAM 2009. “National Clean Gasoline: An Investigation of Costs and Benefits.” Alliance of Automobile Manufacturers, 1401 Eye St., N.W., Washington, DC 20005.

GENERAL

- The Auto Alliance report includes data from two studies on the subject of the costs and benefits of cleaner gasoline. The first study investigated refining costs while the second study investigated emissions benefits of cleaner gasoline.

TESTING PROGRAM

- This study was restricted to review of the U.S. EPA Predictive Model, the California ARB Predictive Model, and the findings of a study conducted in support of U.S. EPA Mobile Source Air Toxics Rulemaking. No testing program was performed as part of this study.

RELEVANT RESULTS

- THC and NO_X sensitivity to fuel sulphur was presented for ARB Predictive Model Tech 3, Tech 4, and Tech 5 vehicle groupings along with the results of a study performed on Tier 2 vehicles in support of the U.S. EPA Mobile Source Air Toxic rulemaking. The results showed that in the fuel sulphur content range of 0 ppm to 50 ppm, THC and NO_X emissions decreased with decreasing fuel sulphur levels for all ARB predictive model vehicle groupings as well as for the Tier 2 vehicles. Further, results showed that the newer the vehicle grouping, the greater sensitivity to fuel sulphur.

STRENGTHS/WEAKNESSES/DATA GAPS

- Fuel sulphur effects presented are only from two sources, the California Predictive Model and the Joint EPA and Automobile Industry study of Tier 2 vehicles.
- Results from other vehicle testing studies were not included.

COMMENTS

- The Tier 2/Low sulfur regulations implemented by EPA in 2004 limited maximum gasoline sulfur levels to 80 ppm and reduced average gasoline sulfur levels to 30 ppm and below.

Study Reference No. A.2: Alliance of Automobile Manufacturers 2009. “Alliance of Automobile Manufacturers Comments on Clean Air Act Waiver Application to Increase the Allowable Ethanol Content of Gasoline to 15 Percent.” Submitted to U.S. Environmental Protection Agency, July 20.

GENERAL

- Contains no information relevant to fuel sulphur effects.

Study Reference No. A.3: Row, J., Doukas, A. 2008. "Fuel Quality in Canada Impact on Tailpipe Emissions." Prepared by The Pembina Institute, Drayton Valley, Alberta, Canada T7A 1S7; Prepared for the Association of International Automobile Manufacturers of Canada.

GENERAL

- This study addresses levels of sulphur and detergency in gasoline, and cetane and lubricity in diesel fuel.
- The study compares Canadian fuel standards for these parameters to those in other jurisdictions, and reviews some test results.

TESTING PROGRAM

- This study was restricted to review of literature. No testing program was performed as part of this study.

RELEVANT RESULTS

- The Association of Emissions Control by Catalyst (AECC) conducted a review of several studies, based upon which it was concluded that significant reduction in HC, CO, and NO_X resulted from the lowering of fuel sulphur content.
- Graphical results from a training workshop from the Clean Air Initiatives for Asian Cities showed reductions of approximately 3%, 7%, and 12% for NMHC, CO, and NO_X, respectively.

STRENGTHS/WEAKNESSES/DATA GAPS

- The presentation of fuel sulphur effects was limited to cursory presentation of the results of two studies.

COMMENTS

- Results are based on limited review of the literature.

Study Reference No. A.4: Shen, Y. 2008. Effects of gasoline fuel properties on engine performance. Y. Shen. *SAE Paper* 2008-01-0628.

GENERAL

- Evaluated impact of fuel sulphur content (and other gasoline parameters not discussed herein) on Euro IV engine emissions.
- Three engines were bench tested while one vehicle was tested to confirm results of the engine bench tests.

TESTING PROGRAM

Fuels:

- Fuels with sulphur contents of 20 ppm, 50 ppm, 76 ppm, 150 ppm, and 320 ppm were used to evaluate fuel sulphur effects.

Vehicles/Engines:

- Two engines were tested in this study:
    - EQ491i certified to Euro III standards with a three way catalyst (TWC) (not used in fuel sulphur content tests); and
    - Touran 2.0 certified to Euro IV standards with a three way catalyst (TWC).
- One vehicle was tested in this study (not used in fuel sulphur content tests):
    - 2006 model year with multi port fuel injection (MPFI) with a MR20DE engine certified to Euro IV standards with a three way catalyst (TWC).

Testing Cycles:

- Vehicle testing was done using the Chinese fourth stage emission test cycle.
- Fuel sulphur effects on emissions were measured under partial load.
- Fuel sulphur effects on catalyst durability were evaluated with a rapid catalyst aging procedure.
- At least three tests were performed for each fuel type.

RELEVANT RESULTS

- Uncertainty analysis of emission results were presented and it was reported that variation between tests were less than 2-3%
- Sulphur content had no effect on fresh catalyst THC, CO, or NO_X conversion efficiency for the engine tested (Euro IV) over the range of fuel sulphur contents evaluated.
- For the fuel sulphur contents included in this test (50 ppm and 150 ppm), the higher fuel sulphur content was associated with higher light-off temperature increases and lower conversion efficiencies after catalyst aging.
- Technology effects: none aside from catalyst.

STRENGTHS/WEAKNESSES/DATA GAPS

- Vehicle testing was not used to confirm engine bench tests with respect to fuel sulphur effects.
- Results did not include emission rate analysis.

COMMENTS

- European emission standard EURO IV was implemented on January 2005.
- European emission standard EURO III was implemented on January 2000.

Study Reference No. A.5: CRC 2008. “Review of Prior Studies of Fuel Effects on Vehicle Emissions.” Prepared by Dr. Albert M. Hochhauser, 12 Celler Rd., Edison, NJ 8817, Prepared for Coordinating Research Council, CRC Project E-84.

GENERAL

- This study carried out an extensive review of published literature on the effect of fuel properties on emissions, including gasoline fuel sulphur.

TESTING PROGRAM

- This study was restricted to review of literature. No testing program was performed as part of this study.

RELEVANT RESULTS

- At the levels seen in modern gasoline, sulphur does not contribute to "vehicle performance attributes", but it does impact the three-way catalyst and other components of emissions control systems.
- Based upon review of studies including high sulphur fuel, low sulphur fuel and sulphur free fuel, it was concluded that lowering sulphur in gasoline will reduce emissions of HC, CO and NO_X. Further, the study concludes that reductions in HC, CO, and NO_X emissions "appear to be linear" as a function of fuel sulphur content, especially at fuel sulphur contents below 150 ppm. Reversibility was complete under mild driving conditions for pre-1990 vehicles, but required "extreme" operation to achieve rich conditions required to obtain complete reversibility for newer vehicles.
- PM emissions levels are likely impacted by sulphur content, but particulate emissions from newer vehicles are too low to be detected by instrumentation currently used to measure emissions.

STRENGTHS/WEAKNESSES/DATA GAPS

- Synthesized conclusions did not distinguish between three-way catalyst systems and Lean NO_X catalysts.

COMMENTS

- A comprehensive review on available literature of gasoline sulphur properties on the effect of emissions.

Study Reference No. A.6: EPA. 2007. "Regulatory Impact Analysis: Control of Hazardous Air Pollutants from Mobile Sources". United States Environmental Protection Agency. EPA420-R-07-002.

GENERAL

- This document was prepared by EPA in support of the Mobile Source Air Toxics (MSAT) Rule and includes a discussion of a testing program to evaluate fuel effects for the MSAT Rule.

TESTING PROGRAM

Fuels:

- Five fuels were included in the program. Sulphur contents of 6 ppm and 32 ppm were evaluated.

Vehicles/Engines:

- Nine Tier 2 vehicles of model year 2004 to 2007, meeting Bin 5 or Bin 8 standards were tested.
- Vehicles were fitted with an artificially aged catalyst to 120,000 miles.

Test Method:

- FTP-75 (Federal Test Procedure).

- Sulphur purges were conducted before testing on a low sulphur fuel as necessary using the EPEFE (European Programmes on Emissions, Fuels, and Engine Technologies) high speed, high load cycle.
- Sulphur loading was conducted before testing on a high sulphur fuel as necessary through mileage accumulation at 35 mph for 3 hours.
- Vehicles were tested three times on each of the five fuels.

RELEVANT RESULTS

- Statistically significant emissions reductions at 90% confidence were noted for THC, CH_4, CO, and NO_X, but not for NMHC.
- Percentage change in emissions due to the use of 32 ppm sulphur fuel relative to 6 ppm sulphur fuel was 12.07, 47.62, 20.23, and 48.44 for THC, CH_4, CO, and NO_X, respectively.
- Emissions testing for toxics indicated a significant decrease of formaldehyde emissions of 16.5 percent at the 90% confidence level when fuel sulphur content was decreased from 32 ppm to 6 ppm. No significant difference at the 90% confidence level was noted for the other toxics for which emissions testing was conducted (1,3-Butadiene, Acetaldehyde, Benzene, Ethylbenzene, n-Hexane, Styrene, Toluene, M,P-Xylene, O-Xylene).

STRENGTHS/WEAKNESSES/DATA GAPS

- Vehicle testing performed on late-model vehicles meeting stringent Tier 2 standards.
- Statistical uncertainty analysis presented.
- Testing did not consider long term effects of exposure of the catalyst to high fuel sulphur content fuel.

COMMENTS

- The Tier 2 emission standards are structured into “certification bins” (8 permanent and 3 temporary certification levels) of different stringency.

Study Reference No. A.7: Ntziachristos, L., A. Mamakos, Z. Samaras, U. Mathis, M. Mohr, N. Thompson, R. Stradling, L. Forti, C. Serves. 2004. “Overview of the European "Particulates" Project on the Characterization of Exhaust Particulate Emissions From Road Vehicles: Results for Light-Duty Vehicles.” *SAE Paper* 2004-01-1985.

GENERAL

- Evaluated particulate emissions for various vehicle types for different driving cycles and fuel sulphur contents.

TESTING PROGRAM

Fuels:

- Fuels included in this study were 6 ppm, 45 ppm, and 143 ppm fuel sulphur content.

Vehicles/Engines:

- 22 vehicles were tested in this study, including six conventional spark ignition engines, as well as five direct injection spark ignition engines, two of which operated in stoichiometric mode and three of which operated in lean mode; the remaining vehicles were diesel-fueled.

Test Method:

- The NEDC2000 driving cycle was utilized along with steady state cycles, and real world cycles developed for the Assessment and Reliability of Transport Emission Models and Inventory Systems (ARTEMIS) study.

RELEVANT RESULTS

- Particulate emissions for vehicles with conventional spark ignition engines showed little response to fuel sulphur.
- Vehicles with lean burn direct injection spark ignition engines showed no consistent effect with respect to fuel sulphur.

STRENGTHS/WEAKNESSES/DATA GAPS

- Uncertainty analysis for measurement averages is presented.
- Significance with respect to the study results was discussed, but no statistical analysis was presented.

COMMENTS

- None

Study Reference No. A.8: Stradling, R., N., R. Thompson, D. Bazzani, S. D. Rickeard, P. M. Bjordal, P. Martinez, P. Schmelzle, G. Scorletti, P. Wolff, J. Zemroch. 2004. Fuel effects on regulated emissions from modern gasoline vehicles. *SAE P*aper 2004-01-1886.

GENERAL

- Evaluated the impact of fuel quality on exhaust emissions from advanced gasoline vehicle technologies available on the market in 2002.
- Vehicle technologies included in the study were those that in 2004, appeared likely to become “significant in the near term future European car population.”

TESTING PROGRAM

Fuels:

- Fuels with sulphur contents of 4 ppm, 9 ppm, 49 ppm, and 148 ppm were evaluated.

Vehicles/Engines:

- Four vehicles were tested in this study:
    - A lean direct injection (DI) vehicle certified to Euro-3 standards with a three-way catalyst (TWC) and NO_X trap;
    - A lean DI vehicle certified to Euro-4 standards with a three-way catalyst (TWC) and NO_X trap;
    - A stoichiometric DI vehicle certified to Euro-3 standards with a TWC; and
    - A multi port fuel injection (MPFI) vehicle with variable valve actuation certified to Euro-4 standards with a TWC.

- All test vehicles had completed at least 8,000 km, were in good condition, and prior to study testing, completed the previous 500 km on a low sulphur fuel (<50 ppm) and a common lubricant.

Test Method:

- NEDC (New European Drive Cycle) test procedure.
- During the testing to evaluate fuel sulphur effects, each vehicle was tested with each fuel type at least four times, for a total of at least 16 tests.

RELEVANT RESULTS

- Over the NEDC, no statistically significant short-term fuel sulphur effects on HC, CO, or NO_X emissions were found, nor was any greater emissions sensitivity found at lower fuel sulphur contents.
- For the part of the NEDC in which there would be no cold start effects when the catalyst would be fully operational the following results were noted:
  - Emissions were low relative to emission standards over all fuel sulphur contents evaluated.
  - The following results were noted with respect to fuel sulphur (statistical significance evaluated at P<5%):
    - NO_X: No statistically significant sensitivity to fuel sulphur content.
    - HC: Emissions were sensitive to fuel sulphur content for cars #3, and #4 which showed an increase of 0.00158 and 0.00370 g/km per ppm increase in fuel sulphur content, respectively.
    - CO: Emissions were sensitive to fuel sulphur content, showing increases in emissions with increases in fuel sulphur content for car #1, and car #2, showing an increase of 0.0323 and 0.0818 g/km per ppm increase in fuel sulphur content, respectively. Car #3 showed an emissions decrease of 0.0471 g/km per ppm in fuel sulphur content.

STRENGTHS/WEAKNESSES/DATA GAPS

- Vehicle testing performed on late-model vehicles meeting Euro-3 and Euro-4 standards.
- Short-term fuel sulphur effects on emissions were evaluated and uncertainty analyses were presented.
- Long term catalyst durability and the long-term effects of operation at different fuel sulphur contents were not evaluated.

COMMENTS

- None

Study Reference No. A.9: Durbin, T.D., J. W. Miller, J. T. Pisano, T. Younglove, C. G. Sauer, S. H. Rhee, T. Huai, G. I. Mackay. 2003. “The Effect of Fuel Sulphur on NH3 and Other Emissions from 2000-2001 Model Year Vehicle.” CRC Project No. E-60: Coordinating Research Council. May.

GENERAL

- Evaluated the impact of fuel sulphur content on NH_3, N_20, HC, CO, and NO_X emissions.

TESTING PROGRAM

Fuels:

- Fuels with sulphur contents of 5 ppm, 30 ppm, and 150 ppm were evaluated.

Vehicles/Engines:

- 12 vehicles certified to California requirements (4 LEV, 6 ULEV, and 2 SULEV) and two vehicles certified to Euro 3 standards were tested. The fleet was designed to represent some of the latest technology vehicles on the market at the time of the study (circa 2001).
- Vehicles were recruited with mileages that ranged from about 5,000 miles to 30,000 miles.
- All vehicles were tested with the as-received catalyst and a bench aged catalyst.
- Vehicles were conditioned before testing by removing residual sulphur from the catalyst, changing the vehicles oil, and completing a fill and drain cycle with the fuel to be used in testing.

Test Method:

- All vehicles were tested with the FTP-75 (Federal Test Procedure) and US06 cycles.
- European vehicles were tested with the NEDC (New European Driving Cycle).
- Vehicles were tested twice for each driving cycle and fuel type unless emissions results differed by the following, in which case a triplicate test was performed: HC 33%, NO_X 29%, and CO 70%.

RELEVANT RESULTS

- NMHC: FTP cycle showed average emissions associated with 30 ppm fuel sulphur content to be statistically significantly lower than 150 ppm, with no significant differences for 5 ppm fuel sulphur content relative to 30 ppm fuel sulphur content or 150 ppm fuel sulphur content. US06 cycle average emissions showed statistically significant decreases in emissions with lower fuel sulphur contents for all fuel sulphur contents.
- CO: Neither FTP or US06 cycle average emissions showed any significant differences in average emissions for any fuel sulphur content.
- NO_X: FTP cycle emissions showed average emissions that were significantly lower for 5 ppm and 30 ppm fuel relative to 150 ppm fuel with no significant differences between average emission of 30 ppm and 5 ppm fuel sulphur content. US06 cycle emissions showed significant decreases in average emissions with fuel sulphur content for all fuels tested.

STRENGTHS/WEAKNESSES/DATA GAPS

- Short-term fuel sulphur effects on emissions were evaluated and uncertainty analyses were presented.
- Vehicle testing performed on late-model vehicles meeting LEV, ULEV, and SULEV standards.
- Reversibility of fuel sulphur effects was not evaluated.
- Fuel sulphur effects over long-term mileage accumulation were not evaluated.

COMMENTS

- None

Study Reference No. A.10: Saitoh, K., M. Hamasaki. 2003. Effects of sulphur, aromatics, T50, T90 and MTBE on mass exhaust emission from vehicles with advanced technology - JCAP Gasoline WG STEP II Report". *SAE Paper* 2003-01-1905.

GENERAL

- Evaluated impact on exhaust emissions of fuel sulphur content four prototype vehicles designed to meet emissions targets of 1/6 the level of 1978 Japanese regulations.

TESTING PROGRAM

Fuels:

- Fuels with sulphur contents of 2 ppm, 22 ppm, and 86 ppm were evaluated.

Vehicles/Engines:

- Four prototype vehicles were tested in this study that were designed to meet 1/6 the level of 1978 Japanese regulations:
  - Three spark ignition direct injection (SIDI) engines with NO_X reduction catalysts; and
  - One multi-points port injection vehicle (MPI) vehicle with a three way catalyst.

Test Method:

- Exhaust emissions were measured using the Japanese 10-15 and Japanese 11 for hot and cold operations, respectively.
- Emissions testing of HC, CO, and NO_X was carried out at zero, 15,000, and 30,000 km.
- Mileage accumulation tests were performed on each vehicle using three fuels, each with a different fuel sulphur content.
- It is assumed though not stated explicitly that for each prototype vehicle, three vehicles were tested, one at each fuel sulphur content.

RELEVANT RESULTS

- At zero, 15,000 and 30,000 km emissions testing results for each vehicle and fuel sulphur type combination, arithmetic means and 95% confidence intervals about the means were calculated in order to evaluate the influence on emissions of fuel sulphur content and mileage accumulation.
- Before mileage accumulation fuel sulphur effects upon HC, CO, and NO_X emissions were minimal and HC, CO, and NO_X emissions met the target of 1/6 of the 1978 Japanese regulation limit for all vehicles and fuel types.
- After mileage accumulation, the MPI vehicle met the targets for cold and hot operations, but SIDI vehicles did not meet the hot operations target at 86 ppm for all vehicles and only met the target for one vehicle at 2 ppm and 22 ppm, and for cold operations met all CO and NO_X targets, but did not meet the target for two vehicles at 86 ppm and one vehicle at 22 ppm.
- At the 95% confidence level, the following trends were noted with respect to fuel sulphur content:

  - NO_X emissions from SIDI: For hot operation there was a discernable effect for one of three vehicles from 86 to 22 ppm, all vehicles from 86 to 2 ppm, and 2 two vehicles from 22 to 2 ppm. For cold operation there significant were significant decreases for two of three vehicles from 86 ppm to 22 ppm and 22 ppm to 2 ppm, with all vehicles showing significant differences from 86 ppm to 2 ppm.
  - NO_X emissions from MPI: For hot operation there no discernable effect. For cold operation there were significant decreases from 86 ppm to 22 ppm and 86 ppm to 2 ppm, but not from 22 to 2 ppm.
  - HC emissions from SIDI: For hot operation there was a discernable effect for all vehicles from 86 to 22 ppm, for two of three vehicles from 86 to 2 ppm, and zero vehicles from 22 to 2 ppm. For cold operation there significant were significant decreases for one of three vehicles from 86 ppm to 22 ppm, for one of three vehicles from 86 ppm to 2 ppm, with one vehicle showing significant differences from 22 ppm to 2 ppm.
  - HC emissions from MPI: For hot operation there were significant decreases from 86 ppm to 22 ppm and 86 ppm to 2 ppm, but not from 22 to 2 ppm. For cold operation there were no discernable fuel sulphur effects.
  - CO emissions from SIDI: For hot operation there was a discernable effect for one of three vehicles from 86 to 22 ppm, 86 to 2 ppm, and 22 to 2 ppm. For cold operation there significant were significant decreases for two of three vehicles from 86 ppm to 22 ppm and for one vehicle from 22 ppm to 2 ppm, with all vehicles showing significant differences from 86 ppm to 2 ppm.
  - CO emissions from MPI: There were no significant fuel sulphur effects on emissions for cold or hot operation.
- The MPI vehicle was generally less sensitive to fuel sulphur content than the SIDI vehicles, although SIDI vehicles showed differences in sensitivity by vehicle.
- Generally, exhaust emissions decreased with decreasing sulphur content.

STRENGTHS/WEAKNESSES/DATA GAPS

- Statistically significance analysis was presented.
- Numerical relationships between fuel sulphur content and emissions were not developed or presented.

COMMENTS

- None

Study Reference No. A.11: Mohr, M.U.L., G. Margaria. 2003. ACEA program on the emissions of fine particulates from passenger cars (2) - Part 2: Effect of sampling conditions and fuel sulphur content on the particle emission. *SAE Paper* 2003-01-1890.

GENERAL

- Evaluated the influence of fuel sulphur content on exhaust emissions from advanced Euro 3 certified vehicle.
- Evaluated fine particulate emissions testing methods.

TESTING PROGRAM

Fuels:

- Fuels included in this study were <10 ppm and 175 ppm fuel sulphur content.

Vehicles/Engines:

- One gasoline MPI vehicle with a three-way catalyst certified to Euro 3 standards.

Test Method:

- The NEDC2000 driving cycle was utilized along with three steady state driving tests: 50 km/h, 100 km/h, and 120 km/h.
- The NEDC2000 test was repeated twice and the steady state tests were only conducted once for four different sampling techniques for each fuel sulphur content.

RELEVANT RESULTS

- Measurement averages along with ranges were presented graphically in the text. However, the ranges presented were not defined.
- Significance with respect to the study results was discussed, implying the application of statistical methods to access uncertainty; however, the statistical tools used to evaluate significance were not defined.
- Measurement results did not allow the authors to draw reliable conclusions, although, significantly higher particle counts were measured for some configurations for fuel with higher sulphur content. The increase in particle count while operating at higher fuel sulphur content was due to the contribution of non-solid material, a large fraction of which was found to be made up of sulphates.

STRENGTHS/WEAKNESSES/DATA GAPS

- Uncertainty analysis not defined.
- Variation in emissions with fuel sulphur level was not presented numerically.

COMMENTS

- None

Study Reference No. A.12: N.Kono, M. Hirose, K. Akasofu, H. Takeda. 2003. Gasoline sulphur effect on emissions from vehicles equipped with lean NO_X catalyst under mileage accumulation tests. *SAE Paper* 2003-01-3077.

GENERAL

- Evaluated impact on exhaust emissions of fuel sulphur content in gasoline fueled vehicles with a lean NO_X catalyst.

TESTING PROGRAM

Fuels:

- Fuels with sulphur contents of 3 ppm, 30 ppm, 50 ppm, and 80 ppm were evaluated in an older reference vehicle while fuels of 30 ppm and 50 ppm were evaluated in circa 2000 model year vehicles.

Vehicles/Engines:

- Four vehicles were tested in this study:
    - 2000 model year lean burn engine with direct injection (DI) with a three way close coupled catalyst and an under floor lean NO_X catalyst;
    - 2000 model year lean burn engine with port injection with a three way close coupled catalyst and an under floor lean NO_X catalyst;
    - 2001 model year lean burn engine with DI with a three way close coupled catalyst and an under floor three way and lean NO_X catalyst; and
    - Reference (older) lean burn engine with DI with a three way close coupled catalyst and an under floor lean NO_X catalyst.
- It is assumed, though not stated explicitly in the paper, that the vehicles were all new at study inception.
- Each vehicle accumulated 10,000 kilometers over the duration of the study, with emission testing occurring periodically.

Test Method:

- Mileage was accumulated with the Japanese Lap 11 driving cycle which complies with the Japanese governmental guidelines for evaluating durability.
- Emissions testing were done using the Japanese 10-15 test cycle.
- Mileage accumulation tests were performed with four different fuels for the older reference vehicle (#4) and two different fuels for circa 2000 model year vehicles (#1, #2, and #3).
- It is assumed though not stated explicitly that:
    - There were four reference vehicles (#4) on which mileage accumulation tests were performed for each of the four different fuel sulphur content fuels.
    - There were two of each of the circa 2000 model year vehicles (#1, #2, and #3) on which mileage accumulation tests were performed.

RELEVANT RESULTS

- Emissions were presented graphically by vehicle and fuel sulphur content over the range of mileage accumulation.
- NO_X: Older reference vehicle (#4) showed emissions increases dependent on fuel sulphur content with higher emissions at higher fuel sulphur contents. NO_X emission rates for vehicles #1, #2, and #3 also showed emission increases with an increase in sulphur content from 30 to 50, but the rate of increase in emission with respect to fuel sulphur content was less and absolute emission levels were low relative to the older reference vehicle.
- THC: Older reference vehicle showed decreases in emissions with fuel sulphur content and no discernable deterioration. Vehicles #1, #2, and #3 also showed no discernable deterioration, with no discernable trend with respect to fuel sulphur.
- CO: Older reference vehicle showed sharp deterioration after certain mileages were reached for all test fuels and increases in emissions were more significant for fuels with higher fuel sulphur content. Vehicles #1, #2, and #3 showed no fuel sulphur effect on emissions and deterioration was minimal.
- Results show potential of newer vehicles to handle fuel sulphur content of 50ppm fuel with more resiliency as a result of new lean NO_X catalyst properties as well as engine control techniques for removal of sulphur from the catalyst.

STRENGTHS/WEAKNESSES/DATA GAPS

- No rigorous statistical analysis of emissions with respect to fuel sulphur content was presented.
- Some aspects of the study methodology are unclear: Were the cars used in the study new, what standard were each of the vehicles certified to?
- Numerical analysis of fuel sulphur effects on emissions is missing.
- Fuel sulphur content effects on circa 2000 model year lean NO_X catalysts were limited to 30 ppm and 50 ppm.

COMMENTS

- Japanese 10-15 test cycle is an urban driving cycle for emission certification and fuel economy determination of light-duty vehicles.

Study Reference No. A.13: EC. 2001. "The Costs and Benefits of Lowering the Sulphur Content of Petrol & Diesel to Less Than 10 ppm." European Commission, Directorate-General Environment, Sustainable Development Unit and Air and Noise Unit.

GENERAL

- This report examined the effects of a switch to sulphur-free fuels and the incumbent costs and effects on emissions of CO_2 and other pollutants.
- In the context of this analysis, the report evaluated fuel sulphur effects on vehicular emissions with respect to HC, NO_X, and PM.

TESTING PROGRAM

- This study was restricted to review of literature. No testing program was performed as part of this study.

RELEVANT RESULTS

- Based on evaluation of evidence submitted, the following emission reductions were estimated by certification standard as a result of changing from 50 ppm to 10 ppm fuel sulphur gasoline:
    - Euro IV cars and vans: 0% effect for NO_X, HC, and PM. The report notes the potential for fuel sulphur effects on Euro IV vehicles but conservatively assumes no effect.
    - EURO I,II,III cars and vans: 10%, 10%, 0% effect for NO_X, HC, and PM.

STRENGTHS/WEAKNESSES/DATA GAPS

- This study lacked a testing program and therefore testing results as well.

COMMENTS

- Fuel sulphur effects for EURO I, II, and III vehicles should be evaluated as weight of evidence based estimates.

Study Reference No. A.14: AECC. 2000. “Response to European Commission Consultation on the need to reduce the Sulphur Content of Petrol and Diesel Fuels Below 50 Parts Per Million.” Association for Emissions Control by Catalyst. July.

GENERAL

- This report presents a review of selected publications and synthesis of fuel sulphur effects on emissions.

TESTING PROGRAM

- This study was restricted to review of literature. No testing program was performed as part of this study.

RELEVANT RESULTS

- Emissions (specific pollutants not cited) would be reduced up to 20% with a reduction from 50 ppm to 10 ppm fuel sulphur content.
- Vehicles aged and tested on a fuel with a higher sulphur content will fail to meet emission standards faster than vehicles aged and tested on a fuel with a lower fuel sulphur content.
- NO_X adsorber technology in lean burn engines requires fuel sulphur levels significantly below 10 ppm to avoid fuel consumption penalties associated with more frequent regeneration that would be required if higher sulphur content fuels were used.

STRENGTHS/WEAKNESSES/DATA GAPS

- This study lacked a testing program and therefore contains no testing results.

COMMENTS

- The conclusions drawn in this paper should be evaluated as estimates based on literature presented therein.

Study Reference No. A.15: Takei, Y., Y. Kinugasa, M. Okada, T. Tanaka, Y. Fujimoto. 2000. Fuel property requirement for advanced technology engines. *SAE Paper* 2000-01-2019.

GENERAL

- Evaluated the impact of fuel sulphur content on exhaust emissions from advanced gasoline vehicle technologies circa 1998.

TESTING PROGRAM

Fuels:

- Sulphur content used in three-way catalyst vehicle testing varied from <1 to 600 ppm.
  - LEV – test fuels with fuel sulphur contents of 38, 80, 100, 150, 330, and 600 ppm.
  - ULEV - test fuels with fuel sulphur contents of 0.03, 33, and 99 ppm.
  - SULEV - test fuels with fuel sulphur contents of 8, 33, and 150 ppm.
- Sulphur content used in NO_X storage reduction catalyst vehicle testing varied from 8 to 500 ppm.

  - 1997 model year – test fuels with fuel sulphur contents of 8, 30, 90, 200, and 500 ppm.
  - 1998 model year – test fuels with fuel sulphur contents of 10, 30, and 80 ppm.

Vehicles/Engines:

- Three-way catalyst
  - Light duty passenger vehicle certified to LEV standards with 100,000 miles
  - Light duty truck certified to LEV standards with 100,000 miles
  - Light duty passenger ULEV prototype with 100,000 miles
  - Light duty passenger SULEV prototype with 100,000 miles
- NO_X storage reduction catalyst
  - 1997 model year Japanese market production vehicle (durability mode tests with high load/speed)
  - 1998 model year Japanese market production vehicle (durability mode tests without high load/speed)

Test Method:

- Three-way catalyst
  - FTP-75 (Federal Test Procedure)
  - Each test was repeated two to six times
- NO_X storage reduction catalyst
  - Japanese 10-15 driving cycle
  - Different mileage accumulation by vehicle. One vehicle used the durability mode required for Japanese certification while the other included a high speed/high load segment in order to induce catalyst regeneration.

RELEVANT RESULTS

- Average emissions or average NO_X conversion efficiency by vehicle and fuel sulphur content were presented.
- Three-way catalyst: HC and NO_X emissions were plotted versus COMPLEX model results which the author suggested approximated older, pre-LEV vehicles. Relative to COMPLEX model results, emissions were more sensitive to fuel sulphur content, and the SULEV exhibited the most sensitivity to fuel sulphur content.
- NO_X storage reduction catalyst:
  - Durability mode without high load: Results indicated decreased NO_X storage reduction catalyst efficiency with accumulated mileage for fuels of higher sulphur content relative to those of lower sulphur content.
  - Durability mode with high load: Results indicated that the higher fuel sulphur level, the greater the NO_X emissions.

STRENGTHS/WEAKNESSES/DATA GAPS

- The lack of statistical analysis does not allow for assessment of confidence in conclusions obtained.
- There was no statistical analysis of uncertainty.

COMMENTS

- None

Study Reference No. A.16: Koseki, K., T. Uchiyama, M. Kawamura. 2000. "A study on the effects of sulphur in gasoline on exhaust emissions. *SAE Paper* 2000-01-1878.

GENERAL

- Evaluated the impact of fuel sulphur content on different types of engines for various technologies on the market from 1996 to 1999.

TESTING PROGRAM

Fuels:

- The following fuel sulphur contents were used in the study: 3 ppm, 4 ppm, 9 ppm, 11 ppm, 20 ppm, 34 ppm, 57 ppm, 80 ppm, 90 ppm and 310 ppm.

Vehicles/Engines:

- Stoichiometric Engine
  A. 1997 model year engine with a three-way catalyst.
  B. 1997 model year engine with a three-way catalyst.
  C. 1998 model year engine with a three-way catalyst.
- Lean –burn engine
  D. 1996 model year engine with a NO_X storage reduction catalyst (in latter phases of the experiment the NO_X catalyst was moved to a model year 1998 vehicle)
- Direct Injection
  E. 1999 model year engine with a NO_X selective reduction catalyst.
  F. 1999 model year engine with a NO_X storage reduction catalyst.

Test Method:

- The Japanese 10.15 cycle, which simulates urban and higher speed driving under hot mode conditions, were conducted on a chasis dynamometer. No cold start emissions testing was performed.
- Tests were repeated 10 times for each vehicle and sulphur content evaluated.

RELEVANT RESULTS

- Tests conducted on vehicle A (1997 model year with a three-way catalyst) indicated dependence of HC, CO, and NO_X emissions on fuel sulphur as emission increases were noted with increasing fuel sulphur levels (note: sulphur contents of 3 ppm, 20 ppm, and 80 ppm were evaluated).
- Tests conducted on vehicle D (1996 model year with a NO_X storage reduction catalyst) showed HC and NO_X emissions which showed slight increases in emissions with increasing fuel sulphur content while CO emissions decreased with decreasing fuel sulphur content (note: sulphur contents of 11 ppm, 34 ppm, and 90 ppm were evaluated).
- Tests conducted on vehicle E (1999 model year with NO_X selective reduction catalyst) show weak dependence on fuel sulphur concentration (note: sulphur contents of 11 ppm, 34 ppm, and 90 ppm were evaluated). It is suggested that NO_X selective reduction catalysts are sulphur tolerant because of the use of iridium.
- Tests conducted on Vehicle F (1999 model year with NO_X storage reduction catalyst) show CO emissions increases with increasing fuel sulphur content although NO_X and

HC emissions remained relatively constant (note: sulphur contents of 3 ppm, 20 ppm, and 80 ppm were evaluated).

- Based upon the results above the author suggests that new Japanese vehicles with direct injection engines and NO_X storage catalysts have weak fuel sulphur sensitivity relative to vehicles equipped with a three-way catalyst.
- When the catalyst was removed from the 1996 model year engine with 30,000 km and placed in a 1998 model year engine, no significant differences in emissions were noted. “Significance” was not defined.

STRENGTHS/WEAKNESSES/DATA GAPS

- Long term catalyst durability and the long-term effects of operation at different fuel sulphur contents were not evaluated.
- No statistical analysis of uncertainty was presented.

COMMENTS

- None

Study Reference No. A.17: Baronick, J., B. Heller, G. Lach. 2000. Impact of sulphur in gasoline on nitrous oxide and other exhaust gas components. *SAE Paper* 2000-01-0857.

GENERAL

- Evaluated the impact of fuel quality on exhaust emissions of two LEV certified vehicles on the market in 2000.

TESTING PROGRAM

Fuels:

- Fuels with sulphur contents of 1 ppm, 40 ppm, 150 ppm, and 330 ppm were evaluated.

Vehicles/Engines:

- Two vehicles were tested in this study:
  A. Model year 2000 vehicle with one three-way catalyst certified to LEV standards.
  B. Model year 2000 vehicle with two three-way catalysts in one container certified to LEV standards.
- The vehicles were equipped with aged components to simulate the 100,000 miles of road driving required for certification tests.

Test Method:

- FTP-75.

RELEVANT RESULTS

- SO_2 emissions were found to increase with increasing fuel sulphur content.
- NO_X emissions were measured before the catalyst and after the catalyst. Pre-catalyst emissions were found to show no sensitivity to fuel sulphur. Post-catalyst emissions were higher and catalyst NO_X conversion efficiency was shown to be lower at higher fuel sulphur contents.

- Significant decreases in conversion efficiency and increases in post-catalyst emissions were noted for HC and CO when tested with 330 ppm fuel, relative to lower fuel sulphur content fuel. Vehicle B showed stepwise efficiency losses with stepwise increases in fuel sulphur content. Vehicle B showed only significant differences for 330 ppm fuel sulphur fuel relative to the other fuels. It is speculated that difference in emissions sensitivity to fuel sulphur content is due to the catalyst construction; the catalyst in vehicle B is less thermally insulated and spends less time above light-off temperature.

STRENGTHS/WEAKNESSES/DATA GAPS

- In order to accomplish tests with four fuel types on two vehicles, limited pre-conditioning was used to build-up sulphur when a lower fuel sulphur content was tested previous to the testing of a higher fuel sulphur content and sulphur was removed when a higher fuel sulphur content was tested previous to the testing of a lower fuel sulphur content. Such conditions would not be encountered in real-world vehicle deterioration.
- Testing over a greater amount of mileage accumulation would be expected to yield more information about long-term effects of the use of different fuel sulphur contents.

COMMENTS

- None

Study Reference No. A.18: ACEA 2000. “ACEA Data of the Sulphur Effect in Advanced Emission Control Technologies.” Association of European Automobile Manufacturers. Brussels.

GENERAL

- Review of in-house vehicle data collected by European vehicle manufacturers pertaining to fuel sulphur effects on emissions, especially related to advanced emission control technology.

TESTING PROGRAM

- This study included literature review and presentation of the results of a vehicle testing program..

RELEVANT RESULTS

- Three-way catalysts
  - NO_X emissions are reduced by 13% when using 1 ppm in place of 30 ppm fuel sulphur fuel.
  - After operating at 50 ppm and then 600 ppm fuel sulphur, catalysts that returned to operation at 50 ppm sulphur showed higher CO emissions relative to initial CO emissions using 50 ppm sulphur content fuel.
- NO_X reduction catalysts
  - Results show NO_X conversion efficiencies with lower fuel sulphur contents (to 8 ppm) that remain higher for longer periods of operation, thus requiring fewer desulphurization events which require greater fuel consumption.

STRENGTHS/WEAKNESSES/DATA GAPS

- No uncertainty analysis is presented.

COMMENTS

- None

Study Reference No. A.19: Lyons, J.M., D. Lax, S. Welstand. 1999. Investigation of sulphur sensitivity and reversibility in late-model vehicles. *SAE Paper* 1999-01-3676.

GENERAL

- Emissions sensitivity to fuel sulphur content was evaluated in this study along with the reversibility of fuel sulphur effects in vehicles available on the market circa 1998.

TESTING PROGRAM

Fuels:

- Fuels with sulphur contents of 40 ppm and 540 ppm were evaluated.

Vehicles/Engines:

- Eight vehicles were tested as part of this study, seven of which were model year 1998, with one 1997 model year vehicle. The 1998 model year vehicles were all passenger cars with less than 7,000 miles of normal operation in customer service prior to testing while the 1997 model year vehicle was a light-duty truck with about 45,000 miles accumulated under normal operation.
- Prior to testing, a new catalyst and oxygen sensor was installed in each vehicle after which 4,000 miles were accumulated.
- Vehicle certification standards and catalyst configurations are as below:
    - Town Car: Tier 1 certified vehicle with four close coupled catalyst
    - S-10: Tier 1 certified vehicle with under floor catalyst
    - Taurus: LEV certified vehicle with dual close coupled catalyst
    - Marquis: LEV certified vehicle with four close coupled catalyst
    - Altima (two vehicles included): LEV certified vehicle with close coupled and under floor catalysts
    - Avalon: LEV certified vehicle with dual close coupled and under floor catalyst
    - Accord: LEV certified vehicle with under floor catalyst

Test Method:

- A combination of FTP, US06, and EPEFE test were used in this study to evaluate differences in emissions with respect to fuel sulphur for different cycles
- Each vehicle was tested on three to nine driving cycle/fuel sulphur content combinations. For each vehicle, each driving cycle/fuel sulphur content combination usually included two or three tests. A third test was required if NMHC, CO, and NO_X emissions ratios in the first two tests were greater than 1.33, 1.70, and 1.29, respectively.

RELEVANT RESULTS

- HC, CO, and NO_X generally showed higher emissions with the higher fuel sulphur content, but sensitivity differed from vehicle to vehicle.
- Effects on emissions from high fuel sulphur fuel were reversible by operating on low fuel sulphur fuel, though in some cases the more severe operating conditions such as those

encountered in the US06 cycle were necessary to induce a return to relatively lower emissions.
- Screening level regression analysis showed that with 95% confidence fuel sulphur sensitivity for CO emissions was related to engine-out emissions of CO and NMHC and the percent change in NMHC emissions was related to engine-out NMHC emissions.
- Screening level regression analysis showed that with 95% confidence that fuel sulphur effect reversibility for CO and NO_X emissions was related to engine-out emissions of CO and NO_X, respectively.
- Aging of catalysts to the equivalent of 100,000 miles of on-road operation induced higher emissions for low and high sulphur fuel with larger increases in CO and NO_X emissions for the higher fuel sulphur fuel.

STRENGTHS/WEAKNESSES/DATA GAPS

- The study only evaluated 40 ppm and 540 ppm fuel sulphur contents. The findings should be considered with this in mind as the evaluation of sulphur free fuel (<10 ppm) was not included.

COMMENTS

- None

Study Reference No. A.20: Kwon, Y.K., R. Bazzani, P. J. Bennett, O. Esmilaire, P. Scorletti, T. David, B. Morgan, C. L. Goodfellow, M. Lien, W. Broeckx, P. Liiva. 1999. Emissions response of a European specification direct- injection gasoline vehicle to a fuels matrix incorporating independent variations in both compositional and distillation parameters. *SAE Paper* 1999-01-3663.

GENERAL

- Evaluated the impact of fuel quality on exhaust emissions of a Euro II certified direct-injection gasoline engine.

TESTING PROGRAM

Fuels:

- Fuels with sulphur contents of 32 ppm and 138 ppm were evaluated.

Vehicles/Engines:

- All tests were performed on a vehicle with a lean-burn gasoline direct injection engine certified to meet Euro II standards with an under floor lean NO_X catalyst.
- Vehicles were received by the laboratory in new condition and were pre-conditioned by adding 6,000 kilometers using highway and urban road cycling.
- The original vehicle used in the study exhibited inconsistencies in light-off strategy that could not be explained. Tests were only accepted when an orthodox light-off pattern was observed. Due to the light-off consistency problem, an alternative engine/aftertreament was used for the latter part of the study. Consistency in emissions was used to establish the comparability of results between the original and alternative engine/aftertreatment system.

Test Method:

- Vehicles were tested on the Euro II cycle. Results were evaluated for the ECE or urban and the EUDC or highway/extra-urban parts of the Euro II cycle.
- Testing was carried out at least four times for each vehicle and fuel combination.

RELEVANT RESULTS

- For all pollutants considered, THC, NO_X, CO, CO_2, PM, no statistically significant differences in emissions were observed between the low sulphur fuel and the high sulphur fuel at a 90% confidence level.

STRENGTHS/WEAKNESSES/DATA GAPS

- Only one type of vehicle was tested in this study.
- Testing did not consider long term effects on emissions of the use of fuel of different fuel sulphur contents.

COMMENTS

- The authors suggest that consistent test repeatability was an issue throughout the study and hypothesize that consistent AFR control may not have been achieved from test to test.

Study Reference No. A.21: Schleyer, C.H., K. D. Eng, R. A. Gorse, R. F. Gunst, J. Eckstrom, J. Freel, M. Natarajan, A. M. Schlenker. 1999. Reversibility of Sulphur Effects on Emissions of California Low-Emission Vehicles. *SAE Paper* 1999-01-1544.

GENERAL

- Evaluated the impact of fuel sulphur content on exhaust emissions of LEV vehicles as well as the reversibility of fuel sulphur effects for LEV vehicles.

TESTING PROGRAM

Fuels:

- Fuels with sulphur contents of 30 ppm and 630 ppm were evaluated.

Vehicles/Engines:

- Six model year 1997 vehicles certified to LEV standards were tested in this study.
- The type of catalyst used in the vehicles is not stated explicitly, though they are likely three-way catalysts. Catalyst were aged to 100,000 miles.

Test Method:

- Vehicles were tested on the both the LA4 and US06 test cycles.
- FTP tests were taken according to the following procedure:
  - Three tests at an initial fuel sulphur content of 30 ppm to establish an initial fuel sulphur baseline.
  - Three tests at a fuel sulphur content of 630 ppm to establish emissions during exposure to high fuel sulphur.
  - Eight tests at a fuel sulphur content of 30 ppm to establish emissions after re-exposure to low fuel sulphur.

    - Three tests at a fuel sulphur content of 630 ppm to check whether high fuel sulphur exposure emissions had changed.
    - Two tests at a fuel sulphur content of 30 ppm for a repeat of test #3.
    - Six tests at a fuel sulphur content of 630 ppm with US06 cycles between tests for mileage accumulation.

RELEVANT RESULTS

- Reversibility:
    - For the LA4 cycle there was partial irreversibility of fleet NO_X and CO emissions, but statistical analysis did not show any significant irreversibility for NMHC emissions.
    - For the US06 cycle, fleet NO_X emissions showed only partial reversibility, but NMHC and CO emissions showed complete reversibility
- Differences in results for LA4 and US06 cycles indicate that driving conditions affect the reversibility of fuel sulphur effects for tested vehicles; more aggressive driving leads to greater sulphur purging from the catalyst.
- The absolute reduction over fleet average fuel sulphur as a result of changing from 630 ppm to 30 ppm fuel sulphur content was a reduction of 0.04 g/mi, 0.13 g/mi, and 0.69 g/mi for NMHC, NO_X, and CO, respectively.
- The percentage reduction over fleet average fuel sulphur as a result of changing from 630 ppm to 30 ppm fuel sulphur content was a reduction of 46%, 63%, and 57% for NMHC, NO_X, and CO, respectively.

STRENGTHS/WEAKNESSES/DATA GAPS

- Testing did not consider long term effects of exposure of the catalyst to high fuel sulphur content fuel.

COMMENTS

- None

Study Reference No. A.22: Schleyer, C.H., R. A. Gorse Jr., R. F. Gunst, G. J. Barnes, J. Eckstrom, K. D. Eng, J. Freel, M. Natajaran, A. M. Schlenker. 1998. Effect of fuel sulphur on emissions in California low emission vehicles". *SAE Paper* 982726.

GENERAL

- Evaluated the impact of fuel sulphur content on exhaust emissions of LEV vehicles.

TESTING PROGRAM

Fuels:

- Conventional fuels with sulphur contents of 30 ppm, 100 ppm, 150 ppm, and 330 ppm, and 630 ppm and California RFG fuels with sulphur contents of 30 ppm, and 150 ppm were evaluated.

Vehicles/Engines:

- Six model year 1997 vehicles certified to LEV standards were tested in this study. Vehicles tested had accumulated close to 10,000 miles.

- Catalyst were used as-is and artificially aged catalyst to 100,000 miles were also tested.

Test Method:

- Vehicles were tested on the FTP test cycles.
- Duplicate emissions testing was performed for all tests and if the ratio of highest to lowest test value was greater than or equal to 1.34 g/mi, 1.71 g/mi, and 1.30 g/mi for THC, CO, and NO_X, respectively, a triplicate test was performed.
- Fuels were tested in a random sequence with wide open throttle events between tests to ensure that testing on the new fuel started with no vehicle memory of the previous fuel.

RELEVANT RESULTS

- Statistically significant emissions reductions at 95% confidence were noted for NO_X, NMHC, and CO between fuel sulphur content of 30 ppm and 630 ppm for both low and high mileage catalysts.
- Absolute reductions in average emissions for low mileage catalysts were 0.04 g/mi, 0.13 g/mi, and 0.69 g/mi for NMHC, NO_X, and CO, respectively while reductions in average emissions for high mileage catalysts were 0.03 g/mi, 0.23 g/mi, and 0.70 g/mi for NMHC, NO_X, and CO, respectively.
- Percentage reductions in average emissions for low mileage catalysts were 46%, 63%, and 57% for NMHC, NO_X, and CO, respectively while reductions in average emissions for high mileage catalysts were 32%, 61%, and 46% for NMHC, NO_X, and CO, respectively.
- Responses to fuel sulphur were linear for the low mileage catalyst while high mileage catalyst showed non-linear response with the largest effects on emissions occurring at lower fuel sulphur.
- Fuel sulphur effects were similar for both conventional and California RFG fuels.
- Engine out emissions did not vary significantly with sulphur content changes, indicating that tail-pipe emissions response to fuel sulphur is due to catalyst efficiency.

STRENGTHS/WEAKNESSES/DATA GAPS

- Testing did not consider long term effects of exposure of the catalyst to high fuel sulphur content fuel.

COMMENTS

- None

Study Reference No. A.23: Lyons. 1997. “Initiative on the Potential Impact of Sulphur in Gasoline on Motor Vehicle Pollution Control and Monitoring Technologies - The Final Report of the Industry-Government.” Sierra Research, Inc. July.

GENERAL

- This report presents a review of literature relevant to gasoline fuel sulphur effects on emissions, focusing on LEV vehicles.

TESTING PROGRAM

- This study was restricted to review of literature. No testing program was performed as part of this study.

RELEVANT RESULTS

- When Tier 0, Tier 1, TLEV or LEV vehicles operate on higher sulphur gasoline, emissions of all regulated pollutants increase.
- Oxygen sensor performance may be degraded by high sulphur fuel.
- The functioning of OBD II systems may be impaired, but remain functional for vehicles operating on high sulphur fuel.
- Sulphur impacts vary from vehicle to vehicle, dependent on catalyst formation, catalyst location, emission control and OBD II design, vehicle calibration, and the gasoline fuel sulphur content.
- For pre-LEV vehicles the effects of operating on high fuel sulphur fuel is completely reversible given operation at a rich air/fuel ratio at high temperatures for a sufficient period of time. However, for LEV vehicle the effects of operating on high fuel sulphur fuel may not be completely reversible.

STRENGTHS/WEAKNESSES/DATA GAPS

- Above conclusions are limited to LEV and older vehicles.

COMMENTS

- None

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Appendix B: Gasoline - Deposit Control Additives Reviews

Study Reference No. B.1: Samuel S., Hassaneen A.E., Morrey D. and R. Gonzalez-Oropeza. 2009. The effect of gasoline additives on combustion generated nano-scale particulates. *SAE Paper* 2009-01-1823.

GENERAL

- Objective is to investigate effects of gasoline fuel quality on PM emissions (both nano-particle number count and size distribution) from an SI engine.

TESTING PROGRAM

Fuels:

- One base fuel and four commercially available aftermarket additives used in study.
  - Additive A (for deposit control)
  - Additive B (Octane improver)
  - Additive C (Octane and Deposit Control improver)
  - Additive D (Octane and Deposit Control improver)
- Dosage rate recommended by additive manufacturers were followed

Vehicles/Engines:

- One 4-cylinder, 4-stroke water cooled, throttle body injected SI engine,
- A CADET engine and dynamometer control system.

Test Method:

- Non-standard emissions test cycle used
- Engine tests carried out at full throttle operating conditions over entire speed range and at part throttle at 40, 70, 100 Nm loading conditions at 3000 rev/min.

RELEVANT RESULTS

- The particle number density for Type A fuel (base + DCA) in the 10 nm range and the total particle number were 3 orders of magnitude lower than the other additives. Also lower than for the base fuel, except for at 40 Nm load, where they matched.
- The Type A fuel also resulted in highest in-cylinder peak pressure and highest rate of pressure rise. Type A has noticeable role in combustion kinetics , early ignition of the mixture and higher burn rate, which may lead to higher fuel consumption.
- Type A fuel compared to the Base Fuel (all at 3000 rev/min) 40 vs. 100 Nm loading conditions summary:
  - CO: Type A causes increase at 40, decrease at 100 Nm
  - THC: Type A causes decrease at both 40 and 100 Nm
  - NO: Type A causes increase at both 40 and 100 Nm
  - NO_X: Type A causes decrease at 40, increase at 100 Nm

STRENGTHS/WEAKNESSES/DATA GAPS

- Sample size was 1 engine (and no statistical analysis)
- Chemistry and dosage of DCA not known
- Parameters of the base fuel not known

COMMENTS

- None

Study Reference No. B.2: Alliance of Automobile Manufacturers. 2009. “National Clean Gasoline: An Investigation of Costs and Benefits.” June.

GENERAL

- This publication analyzes the costs and benefits of introducing a cleaner national gasoline through two commissioned studies. The first investigated refining costs of producing the proposed fuel, and the second investigated the emissions impacts from on-road gasoline-powered vehicles that would use the proposed fuel.
- There are no relevant results because the impact on emissions portion of the report did not investigate deposit control additives (DCA) as a fuel parameter. The on-road emission baseline and future year inventories were modeled using EPA MOBILE6, which is not capable of modeling the emissions effect of DCA.

Study Reference No. B.3: Alliance of Automobile Manufacturers. 2009. “Alliance of Automobile Manufacturers Comments on Clean Air Act Waiver Application to Increase the Allowable Ethanol Content of Gasoline to 15 Percent.” Submitted to U.S. Environmental Protection Agency, July 20.

GENERAL

- This document contains the comments by the Alliance of Automobile Manufacturers on the application submitted by ethanol producers to EPA to waive Clean Air Act requirement for gasoline-ethanol blended fuels.
- Neither deposit control additives (DCA) nor engine deposits are mentioned in the document. Therefore, no results are presented for this document.

Study Reference No. B.4: CRC 2008. “Review of Prior Studies of Fuel Effects on Vehicle Emissions.” Prepared by Dr. Albert M. Hochhauser, 12 Celler Rd., Edison, NJ 8817, Prepared for Coordinating Research Council, CRC Project E-84.

GENERAL

- This CRC study summarizes the available technical literature describing the effects of fuel composition on exhaust emissions for both gasoline and diesel vehicles.
- Deposit control additive use in gasoline was not one of the parameters reviewed in CRC E-84.

Study Reference No. B.5: Row, J. and A. Doukas. 2008. “Fuel Quality in Canada Impact on Tailpipe Emissions.” Prepared by the Pembina Institute, Drayton Valley, Alberta, Canada T7A 1S7; Prepared for the Association of International Automobile Manufacturers of Canada.

GENERAL

- This study addresses levels of sulphur and detergency in gasoline, and cetane and lubricity in diesel fuel.

- The study compares Canadian fuel standards for these parameters to those in other jurisdictions, and reviews some test results.

TESTING PROGRAM

- Literature review.

RELEVANT RESULTS

- This report identifies the detergency of gasoline as one of several key gasoline parameters where there are opportunities to achieve tailpipe emission reductions.
- This study presents two references:
    - The first reference supporting gasoline detergents was a study of Russian fuels by Karpov (2007) [**Study Reference No. B.6**] showing that improving detergency improves fuel efficiency, decreases HC, CO and NO_X emissions, and reduces deposits. This study itself is not an original scientific study. Karpov references two other Russian studies that link detergents to exhaust emissions. The findings are based on old technology vehicles that may likely have little relevance to the Canadian gasoline vehicle fleet.
    - The second reference on detergency was a European study of using BP highly additized fuel versus regular fuel and the effect on pollutant emissions. The Pembina Report implies that the reductions occur when the additized fuel is used, not the base fuel, but this is not explicitly stated. HC, CO and NO_X are reduced 5%, 15% and 5%, respectively, and are presented in a bar graph. No detail on the test vehicle, procedure, fuel additive, or data uncertainty was provided. This particular study's results were presented by Ford Motor Company to the ACEA, thus it is unavailable for further review.

STRENGTHS/WEAKNESSES/DATA GAPS

- The studies that this report relied on were based on two references. No testing program details on the original studies were provided.

COMMENTS

- This report does not carry out any thorough literature review.

Study Reference No. B.6: Karpov, S.A. 2007. Improving the environmental and performance properties of automotive gasolines: detergent additives. *Chemistry and Technology of Fuels and Oils*. Vol. 43, No 3, pp 173-178.

GENERAL

- This article itself is not an original scientific study. Karpov references two other Russian studies that link detergents to exhaust emissions.
    1. A.M. Danilov, *Use of Fuel Additives* [Russian Translation], Mir, Moscow (2005).
    2. S.I. Kokhanov, Candidate Dissertation, I.M. Gubkin Russian State University of Oil and Gas, Moscow (2006).

TESTING PROGRAM

- Literature review

RELEVANT RESULTS

- Detergents reduced deposits by 60% in the carburetor and by 70% in the intake valves
- Detergents in gasoline resulted in decreased CO and HC emissions by between 50-60%, and decrease in NO_X by 20%

STRENGTHS/WEAKNESSES/DATA GAPS

- No detail concerning test engine, deposit accumulation cycle, base fuel, or additive is provided. Carbureted engines are old technology that may likely have little relevance to the Canadian gasoline vehicle fleet.

COMMENTS

- As of January 1, 2006, high octane gasoline sold in Moscow must contain detergents. Russian standards permit use of additives in all gasoline; however, refineries are not producing additized gasoline in large volumes due to low domestic production of the deposit control additives.

Study Reference No. B.7: Zand, A.D., G.N. Bidhendi, A. Mikaeili, and H. Pezeshk. 2007. The influence of deposit control additives on exhaust CO and HC emissions from gasoline engines (case study: Tehran). *Transportation Research Part D*. 12: 189-194.

GENERAL

- The Iranian vehicle study is unique in that it studies DCA used as clean-up (one time use to clear deposits), rather than for maintenance (continuous use in the fuel supply). Effects on CO and HC emissions were measured at one driving condition (idle).
- The study vehicles were all carbureted engines, and so results may have little relevance to the Canadian gasoline vehicle fleet.

TESTING PROGRAM

Fuels:

- Commercial unleaded gasoline used as the base fuel.
- “Power Clean” solvent manufactured by “Power Clean 2000 Inc.” was used as the detergent additive.
- Cleansing-fuel blended at 1:5 ratio of solvent to gasoline, injected into each of the vehicles using an EVC2000 unit (manufactured by same company) to inject the detergent gasoline mixture into the engines.

Vehicles/Engines:

- 304 Peykan and 201 Pride vehicles, all 4-cylinder vehicles
    - Peykan vehicle “based on British Hillman”
    - Pride vehicle “based on South Korea Kia motors”
- Both types are carbureted vehicles; without any emission control system.
- Model years range from then-current year 2004 back to pre-1976.

Test Method:

- This study conducted in-use measurements of emissions impacts of DCA on older carbureted vehicles.

- Measurements made before and after DCA clean-up treatment
- Tailpipe emissions measurements began in July of 2004, and were "continually measured in parallel with the decarbonization operations [i.e., DCA cleansing] for several months" until the end of January 2005.

RELEVANT RESULTS

- CO emissions from Peykan vehicles were 23.3% lower for pre-1976 vehicles and 45.4% lower for 2004 model year Peykans following the deposit control clean-up with detergent additive.
- CO emissions from Pride vehicles decreased (all vehicles), with a maximum emissions improvement of 45.7% for 2004 model year; results for model year 1996 were not statistically significant (19.8% decrease)
- HC emissions from Peykan vehicles decreased 26.5% for 2003 model year Peykans and only 9.5% for 2001 model year Peykans. The decrease for 2004 vehicles in HC emissions (15.7%) was not statistically significant.
- HC emissions from Pride vehicles decreased for almost all model year (exception was 1996 where emissions increased by 2.2%, but wasn't statistically significant). All HC measurements in Pride vehicles for model years prior to 1998 are not statistically significant; Max HC reduction in Prides was for 2001 vehicles (33.4% decrease).
- Influence of engine deposit removal on CO emissions much greater (approx. double) than on HC – observed in both vehicle types.
- There was a lot of uncertainty in the HC measurements.
- HC uncertainty could stem from fact that CCDs can act as HC-increasing agents (by absorbing and desorbing unburned HC) or as a HC-reducing agent (by plugging crevices in the cylinder and piston top). It's unclear which mechanism dominates under which operating conditions and what other factors contribute.

STRENGTHS/WEAKNESSES/DATA GAPS

- Results are reported separately for Peykan and Pride vehicles, and by model year, but variation vehicle-to-vehicle unknown
- DCA chemistry unknown.

COMMENTS

- None

Study Reference No. B.8: Aradi, A.A., Evans, J., Miller, K. and A. Hotchkiss. 2003. Direct Injection Gasoline (DIG) Injector Deposit Control with Additives. *SAE Paper* 2003-01-2024.

GENERAL

- This study investigates optimization and performance of Mannich chemistry deposit control additive effectiveness in controlling injector deposits in direct injection engines.
- Initial screening of DCAs were performed on Engine A, which was especially prone to deposit buildup due to old technology.
- Further study was done on a more representative Engine B. Engine B studies were supplemented by a prototype vehicle study on a dynamometer, Vehicle 1. Flow loss

measurements are taken throughout the drive cycle during various stages of deposit formation and clean-up.

TESTING PROGRAM

Fuels

- Howell EEE test fuel is the base for testing multiple DCAs at varying concentrations
- DCA types include 3 Mannich additives (Man-A, Man-B and Man-C), polyisobutylene amine (PIBA) and a polyether amine (PEA)
- EM-1 Mannich additive for Vehicle 1 tests

Vehicles/Engines:

- Engine A: 1982 Nissan Z22d research engine: 2.2L, dual-spark, 4-cylinder, modified to run in homogeneous direct injection mode
- Engine B: DISI engine, 4-cylinder, 1998 cm3 displacement, more advanced than the Nissan engine
- Vehicle 1: equipped with prototype DISI engine for injector coking measurements with goal of validating Engine B results

Testing Cycle:

- Non-standard emission test cycle was used
- Engine A additive tests performed over 6 hours duration at engine speed 2500 rpm, engine load 500 mg air/stroke, and173ºC injector tip temperature
- Engine B additive tests performed over a combination cycle including 3 phases
    - Warm-up phase: 1500 rpm / 40 Nm, until coolant reaches 85ºC
    - Homogeneous phase: 3600 rpm / 130 Nm load, 50 hours
    - Stratified phase: 650 rpm / 22 Nm, 50 hours
- Vehicle 1 additive tests was investigated only in homogeneous mode, on a drive cycle based on 1995 EPA survey of driving habits in Baltimore, Maryland, USA.
    - Each cycle equals 26.3 km; approximately 200 cycles were performed in sequence for each test

Injector Performance Measurements:

- “Additive keep-clean dose response” initial screenings
    - % Fuel loss was measured from Engine A injectors for 5 DCAs (Man-A to C, PIBA and PEA) at approximate dosages of 20, 80, 140, 280 and 400 ppm each
    - “Additive characterization” and optimization
    - Man-C additive from “keep-clean” study on Engine A was used on more modern Engine B with a longer, more realistic test cycle of 100h.
- “Keep-clean performance” on Vehicle 1
- “Clean-up performance” on Vehicle 1

RELEVANT RESULTS

- Mannich additive formulations can be optimized for DIG injector coking inhibition by varying on carrier fluid chemistry and detergent purity.
- The EM-1 Mannich additive proved to keep clean Vehicle 1 engine injectors over 160 test cycles of 26.3 km each.

- Following a dirty-up period of 200 cycles of Vehicle 1 on the Howell EEE base fuel, EM-1 was dosed at a European premium rate and within 40 additional cycles using the new additized fuel, flow loss returned to <5% from above 15% during the dirtying phase.

STRENGTHS/WEAKNESSES/DATA GAPS

- Chemistry and optimization parameters are not identified
- No statistical analysis.

COMMENTS

- None

Study Reference No. B.9: Environment Canada. 2002. "Combustion Chamber Deposits in Gasoline Engines: A Literature Review." Prepared by Dr. Chandra B. Prakash, Prepared for Oil, Gas & Energy Branch, Environment Canada, March.

GENERAL

- This report was prepared for Environment Canada in March 2002 that summarized to date the known research on deposit control additives (DCA). The report surveyed studies in areas of: (1) combustion chamber deposit (CCD) formation mechanisms, (2) effects of CCD on fuel octane requirement, (3) effects of CCD on fuel economy, and (4) effects of CCD on emissions.

TESTING METHOD

- Literature review.

RELEVANT RESULTS

NO_X Emissions

- Houser (1993) reported 0 to 20% increase in NO_X emissions due to CCD, with differences in NO_X emissions with different engine designs
- Bitting et al (1994) [**Study Reference No. B.22**] reported NO_X reductions averaging 20% when CCD are mechanically removed from engines
- Barnes and Stephenson (1996) [**Study Reference No. B.19**] reported CCD increased NO_X emissions by 25% on average measured at a fully warmed-up stead-state condition for 3 car models and that in a cold start European test cycle, NO_X could increase or decrease.
- Lee (1999) [**Study Reference No. B.23**] reported:
  - A non-linear step function increase in NO_X emissions with CCD thickness
    - Started with 2 clean engines
    - No emissions increase for the first 60 to 80 µm of CCD thickness
    - Above 80 µm, NO_X emissions rose steeply, then reached a plateau between 100-150 µm for both vehicles
    - Aforementioned step function was true for both operating conditions of 35 and 65 mph vehicle speed; 95% confidence level
  - The effect of reducing CCD thickness on emission through use of "cleaner fuels"
    - Reducing CCD thickness by 50% (in "fresh" unaged CCD) by switching to cleaner fuel had no effect on HC, CO, or NO_X emissions

        - NO_X can be reduced by cleaning patches of the cylinder head and piston top
        - Switching to a "cleaner fuel" (can be additized or unadditized) could either maintain or increase NO_X emissions over short to medium mileage, depending on how old the CCD are
        - Over longer mileage, NO_X emissions will likely decrease back down the step function
- Balysky et al. (2001) [**Study Reference No. B.13**] reported that NO_X reductions averaged 10% with no change in HC or CO when the Vektron® additive was used in fuel in a 28-vehicle fleet test
- CRC CCD Panel (2000) [**Study Reference No. B.15**] reported
    - Not possible to reach any conclusion about the shape of the emissions vs. CCD relationship
    - Additized fuels produced 1.2 to 5 times average more CCD mass per cylinder than the base fuel
    - The presence of CCD increased NO_X emissions and fuel economy, and the other pollutant results were not statistically significant
- A CARB staff report document (1998) reported that
    - Other studies reported NO_X reductions between 12 and 55% when CCD was removed.
    - Other studies reported that with complete CCD removal, average of 25% NO_X reductions was observed.
    - Limited data available on incremental CCD removal and emissions

HC and CO Emissions

- Bower et al. (1993) reported no trend in HC or CO emissions with increasing CCD
    - Wagner (1993) also reported no trend for HC
- Bitting et al (1994) [**Study Reference No. B.22**] reported
    - HC emissions increased by 17% in deposited engines
    - CO emissions decreased by 30% in when CCD were removed (statistically significant)
- Barnes and Stephenson (1996) [**Study Reference No. B.19**] reported that CCD have variable effects on HC and CO emissions, which can either increase or decrease due to competing mechanisms
- Haidar and Heywood (1997) [**Study Reference No. B.18**] reported
    - HC emissions rise in the first 10-15 hours of deposit accumulation
    - HC emissions stabilize after ~25 hours of deposit accumulation
    - HC increase due to CCD accounted for 10 to 20% of engine-out emissions when "deposit build-up fuel" is used
    - Benzene, isooctane, toluene and zylene emissions increased 10-30% due to CCD
    - HC emissions stabilized long before CCD thickness
- Lee (1999) [**Study Reference No. B.23**] reported
    - decrease of HC during CCD build-up between 3,000 and 6,000 miles
    - further aging of CCD and mileage accumulation between 6000 and 13,000 miles, HC emissions increased
    - beyond 13,000 miles, HC emissions comparable to a clean engine

  - reducing CCD thickness by 50% by using cleaner fuel had no effect on HC or CO emissions
- Tondelli et al. (2000) [**Study Reference No. B.14.**] reported that emissions increased with CCD using three different pure component fuels (isooctane, toluene, and 2-methyl-2-butene)

STRENGTHS/WEAKNESSES/DATA GAPS

- Experimental methods, DCA chemistry, DCA dosage not explained in this report.

COMMENTS

- Lee (1999) is the only article linking “cleaner fuels” to emissions, however the role of DCA in these fuels isn’t stated

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Study Reference No. 10: Martin, D.P., and J.F. Unsworth. 2002. The M111 engine CCD and emissions test: Is it relevant to real-world vehicle data? *SAE Paper* 2002-01-1642.

GENERAL

- This article examines the relationship between combustion chamber deposits and emissions data from the Mercedes M111 bench engine and two road vehicles using base and additized fuels.
- A European test procedure for evaluating deposits was used.

TESTING PROGRAM

Fuels

- Base fuel was typical gasoline fuel meeting European EEC specification up to Dec 31, 1999 (Euro 2 fuel)
- 4 different detergent additives were blended with the base fuel for the bench engine test; only 1 of these detergent additives was used in the road vehicles testing

Vehicle/Engines

- 1 Mercedes Benz M111 engine
- 2 Mercedes C200 vehicles with M111 engine (same engine as bench test)
  - 4-cylinder engine, 2.0L DOHC, 4 valve, PFI
- 2 Ford Mondeo vehicles with Zetec engine
  - 4-cylinder engine, 2.0L DOHC, 4 valve, PFI

Test Method

- 4 road vehicles were subjected to 11,200 km of mileage accumulation on the ECE+EUDC test cycle
- M111 bench engine subjected to 180h (equivalent to 11,200 km) operation modified and extended PF20 cycle
- NO_X emissions and CCD thickness on the piston head measured at regular intervals during 11,200-mile accumulation
  - Emissions procedures were triplicate ECE (40sec idle)15.05 + EUDC test cycles using the test fuel

  - CCD measured non-intrusively as deposit thickness on the piston crown directly underneath the spark plug through the spark plug hole
    - Fischer Dualscope measured changes in inductance which correlates to thickness

RELEVANT RESULTS

- M111 bench engine results
  - CCD thickness with time was characterized by a relatively rapid growth early in the PF20 test; later the rate of deposit growth gradually resided until a plateau was reached.
  - Engine-out NO_X with time followed similar trend as CCD thickness
- Mercedes road vehicle results
  - At approximately 9400 km, CCD piston thickness was 45 µm for the base fuel and 59 µm for the additive fuel
  - Engine-out NO_X increased with CCD thickness by an average of 14% for both fuels
- Mondeo road vehicle results
  - At approximately 11,200 km, CCD piston thickness was 106 µm for the base fuel and 94 µm for the additive fuel.
  - Engine out NO_X increase with CCD growth in the two Fords were less definite than in the Mercedes test vehicles. A NO_X reduction with CCD thickness growth was observed in the base-fueled Ford vehicle. A NO_X increase of 10% was observed in the additive-fueled vehicle.
- All road vehicle results for tailpipe NO_X
  - Tailpipe NO_X data were discarded from the Mercedes test vehicle because NO_X increased 150% for unknown reasons.
  - The remaining 3 vehicles experienced between 30% and 33% increase in NO_X tailpipe emissions over the 11200 km test.
  - The % increases for tailpipe were significantly larger than engine-out measurements and could be influenced by air:fuel ratio changes.
- Relationships correlating engine-out NO_X (g) to CCD thickness (µm) are presented in a graph and data points were fit with a linear regression
  - The two Mercedes vehicles (base and additive fuel) relationship of NO_X and CCD have R^2=0.758 and 0.885.
  - The two Ford vehicles (base and additive) relationships had R^2=0.491 for the additive fuel.

STRENGTHS/WEAKNESSES/DATA GAPS

- Chemistry and dosage of additives unknown; however, authors mention that the dosage was aimed at preventing intake valve deposits (IVD) so that IVD did not affect emissions.
- NO_X measurement instrumentation unknown.
- Direct link between effects of base vs. additive fuels were not apparent from the study results.

COMMENTS

- None

Study Reference No. B.11: CRC. 2002. “Combustion Chamber Deposit Research Tool Development, Part 1, Vehicle Deposits and Emissions.” CRC Report No. 630.

GENERAL

- CRC Report No. 630 is the first of a two-phase project to develop a research tool for evaluating combustion chamber deposits (CCD) in spark-ignition automotive engines. This first phase of the study is an on-road vehicle test program to rank five fuels based on their CCD-forming ability based on two types of 1999 vehicle models.

TESTING PROGRAM

Fuels

- Fuel E was the base fuel, unadditized RF-A
- Fuel D was the same additized fuel in CRC E-6 [Study Ref. No. 15] that was a “high-CCD” forming fuel
- Fuels A, B, C are not identified directly but are each one of the following (not necessarily in order):
    - polyetheramine (PEA), premium dose
    - polyisobutylene-amine (PIBA), premium dose with synthetic carrier
    - lowest additive concentration (LAC) plus 10% PIBA with synthetic carrier

Vehicles/Engines

- 4 GM Chevrolet Silverado pickup trucks, 1999, with V-8 6.0L engines
- 4 DaimlerChrysler Dodge Neon sedans, 1999, with 4-cylinder, 2.0L engines

Test Method

- *This study was a bench-scale research study using a modified AMA driving schedule for 15,000 miles*
- IVD visually rated after 15000 miles using a fiber scope, then cleaned/removed before emissions testing
- NMHC, CO, NO_X and fuel economy were measured before and after 15,000 mi
- Within 24h after emissions testing, CCD measurements of thickness (piston top and cylinder head) and total weight were collected

Deposit Build-up Period

- Following break-in, each fuel/vehicle combination was run for 15,000 miles on the modified AMA drive schedule described in the Study Reference No. 15 article
- Intake valve deposits (IVD) cleaned with walnut-shell blaster after 15,000 mi

RELEVANT RESULTS

- 95% confidence level was used to judge statistical significance
- Deposits in the DC Dodge Neon Vehicles
    - CCD Total Weight
        - Lowest CCD weight was with Fuel E (base fuel)
        - Heaviest CCD weight caused by Fuel D (“high-CCD” fuel)
            - Fuel D produced significantly higher CCD weight compared to commercial fuels B and C, and base fuel E

            - ➢ Fuel D produced higher CCD than Fuel A, but not with statistical significance
        - Comparing the 3 commercial detergents against base fuel (Fuel E), Total Weight of CCD,
            - ➢ Increased a minimum of 57% (from Fuel E to Fuel B)
            - ➢ Increased a maximum of 82% (from Fuel E to Fuel A)
    - CCD Thickness
        - Fuel D produced significantly higher, and Fuel E produced significantly lower deposits on the piston top than commercial fuels A, B, C
        - Fuels B and E produced significantly lower CCD cylinder head thickness than Fuels A and D (C not statistically different than other fuels)
    - IVD Rating
        - The group of Fuels A, B and D kept intake valves very clean, significantly cleaner than the group of Fuels E and C, which formed heavy valve deposits. Within the two groups, the IVD ratings were not statistically different.
- Deposits in the GM Chevrolet Silverado vehicles
    - CCD Total Weight
        - Same fuel ranking as Dodge Neon results above, except that Fuel D was significantly higher than all other fuels (incl. Fuel A)
        - Increases in CCD weight compared to the Base Fuel E, were 59% (Fuel B) up to 89% (Fuel A) for the commercial detergent packages, and 139% increase for Fuel D.
    - CCD Thickness
        - Same fuel ranking as Dodge Neon for CCD thickness, except that for piston top thickness, Fuel A was significantly greater than Fuel C.
        - Average thickness: Fuel D significantly larger than for Fuel A, which is significantly higher than Fuels B and C, which are significantly higher than Fuel E.
    - IVD Rating
        - Identical significant rankings for IVD as in the Dodge Neon
- Emissions Results in Both Vehicles
    - Analyzed emissions increments due to CCD three different ways
    - No statistical significance between emissions differences due to any fuel type
    - Results added no new insights about the effect of CCD on vehicle emissions

STRENGTHS/WEAKNESSES/DATA GAPS

- DCA type (PEA, PIBA, or LAC plus 10% PIBA) not associated with specific Fuel A, B, or C.
- Chemistry of DCA in Fuel D not known.

COMMENTS

- None

Study Reference No. B.12: CRC. 2005. “Combustion Chamber Deposit Research Tool Development, Part 2, Engine Dynamometer Testing.” CRC Report No. 644.

GENERAL

- CRC report number 644 is the second of a two-phase study to develop a research tool for evaluating combustion chamber deposits (CCD) in spark-ignition engines. The first phase of the project [Study Reference No. 11] focuses on on-road vehicle testing, while this second phase of the study has the purpose of identifying an engine/cycle/duration for a dynamometer test that ranks the additives in the same relative order as found in the on-road vehicles in phase one.

TESTING PROGRAM

Fuels

- Fuels (same as Phase 1 of the study)
- Fuel E (base), Fuels A, B, C (unknown commercial additives), Fuel D ("high-CCD" forming additive from the CRC E-6 study)

Vehicles/Engines (same as Phase 1 of the study)

- DC Dodge Neon 4-cylinder, 2.0L
- GM Chevy Silverado, V-8, 6.0L (Testing on the GM truck terminated midway through study, when results were found to be very similar to Neon)

Test Methods

- *Non-standard test cycle was used.* Dynamometer Test Cycles
- MAMA – modified AMA, designed to replicate the Phase-1 study road test cycle
- Simple – designed to be similar to MAMA, but with much fewer acceleration and deceleration ramps to provide a simpler test cycle
- MAMA with Soaks – modified MAMA to run 16 hours followed by an overnight 8h soak
- Milder – removed higher mph steady-state conditions of other cycles, but tests on this cycle were found to be inaccurate and the cycle was discontinued.
- Milder-10 – designed to duplicate fuel consumption values of the vehicles
- Simple-15 – similar to Simple Cycle but with idle to stead-state ramps changed to 15-seconds duration instead of 6 seconds.
- IVD and CCD measurements same as Phase 1 (on-road vehicle study) measurements
- CCD and IVD measurement data were analyzed using standard linear modeling methods with SAS™ statistical software
- Unwashed gum residues were prepared per ASTM D381 Standard Test Method for Gum Content in Fuels by Jet Evaporation

RELEVANT RESULTS

- Engine dynamometer testing less able to discriminate fuels than the on-road vehicle measurements of CCD
- In phase 1, Fuel E to Fuel D showed 118% increase in total CCD weight in the on-road vehicles.
- In phase 2, Fuel E to Fuel D showed approximately a 25% to 50% difference for the engine dynamometer cycles.
- The MAMA cycle provided the best ability to differentiate the 5 test fuels based on total CCD weight

- The MILDER-10 cycle ranked commercial additives A, B and C in a different order than the on-road vehicle testing. Base fuel E resulted in the lowest CCD weight and Fuel D resulted in the highest.
- Unwashed gums in the five gasoline fuels did not give useful correlations of CCD potential; the linear regressions have low R2 (0.66 for the GM truck and 0.53 for the DC Neon car)

STRENGTHS/WEAKNESSES/DATA GAPS

- No emissions testing was performed

COMMENTS

- None

Study Reference No. B.13: Balysky N.R., A.J. Lonardo, A.A. Millard, and K. Brunner. 2001. Vektron® 6913 gasoline additive NO_X evaluation fleet test program. SAE Paper 2001-01-1997.

GENERAL

- This study performed at the Southwest Research Institute is a 28-vehicle fleet test to study NO_X reductions from using Vektron®6913 additive with objectives below:
- Report NO_X reductions achieved through use of the Vektron additive
- Estimate impact of the Vektron additive on the other criteria pollutants
- Test the effect of “brand switching” between 50% Vektron blend fuel (test fuel) and 50% Infineum blend fuel (reference fuel)

TESTING PROGRAM

Fuels

- Base fuel (unadditized): approximated the physical and chemical specifications of oxygenate-free California RFG Phase 2 gasoline
- Reference fuel: Base fuel + Infineum F7721; Infineum F7721 is a conventional DCA with a synthetic carrier
- Test fuel: Base fuel + Vektron 6913; Vektron 6913 is same as Infineum detergent, but with an added “NO_X reducing functional component”
- Treat rates of reference and test fuels were selected to give the same concentration of the detergent in the finished fuel (approximately double the LAC).
  Emissions testing (tailpipe):

Vehicles/Engines:

- Models chosen to be a representative sample of vehicles in the 2001 and near-future fleet. The 28 vehicles comprise of 4 vehicles from each of the 7 following models:
  - 1999 Ford Explorer, 4.0L V-6 engine with MPFI, Automatic, LEV/LDT cert.
  - 1999 Chevrolet-1500, 5.7L V-8 engine with CSFI, Automatic, LDT certified
  - 1998 Honda Accord, 2.3L I-4, MPFI, automatic transmission, LEV/ LDV cert.
  - 1994 Ford F-150, 4.6L V-8, MPFI, Automatic, LDT cert.
  - 1996 Ford Escort, 1.9L I-4, MPFI, Automatic, LDV cert.
  - 1995 Dodge Caravan, 3.3L V-6, MPFI, Automatic, LDT cert

    - 1994 GM Buick LeSabre*/Olds 88 Royale*, 3.8L V-6, MPFI, Automatic, LDV cert. *For this group of 4 vehicles, 3 were GM Buicks/1 was an Oldsmobile 88 Royale
- No vehicle preconditioning, but each was driving 1000 random miles on the road using reference fuel and subjected to qualification checks (max allowable oil consumption and FTP emissions testing not to exceed 125% of emission standard value)
- Deposit accumulation done over 16,000 miles on the road (2x8,000 runs) on a mileage accumulation dynamometers
- Dynamometer mileage accumulation ran on a single vehicle no more than 16h/day with an 8-hour soak time. Drive cycle was 40 CFR Ch. 1 86.084-26 as modified in the Mobile Source Air Pollution Control (MSAPC) Advisory Circular A/C No. 37-A driving mode with a 70 mph top speed.
  Fuel descriptions:

Test Methods:

- FTP-75, US06, and HFET drive cycles
- NO_X, CO, HC and CO_2 tested before and after first 8,000 miles and after 16,000 miles on the mileage accumulation dynamometer

RELEVANT RESULTS

- 10% average reduction in NO_X emissions with the use of Vektron 6913 gasoline (>90% confidence)
- Result same whether Vektron fuel used intermittently (“Brand switching” with Infineum gasoline) or constantly.
- No negative impact on other criteria pollutants (CO, HC) or fuel economy (CO_2); reductions found to be not statistically significant so they’re not reported.

STRENGTHS/WEAKNESSES/DATA GAPS

- None

COMMENTS

- None

Study Reference No. B.14: Tondelli, G., M. Carriero, and A. Pedicillo. 2000. Combustion chamber deposits: Fuel and lubricant effects on exhaust hydrocarbon emissions measured by fast FID analyzer. *SAE Paper* 2000-01-2024.

GENERAL

- This article examines effect of CCD on HC emissions in a test engine using The only role of DCA in this study was in the deposit build-up period where engine ran for 60-hours.

TESTING PROGRAM

Fuels:

- 3 pure component test fuels
    - Isooctane (Paraffin chemical class),
    - 2-methyl-2-butene (mono-olefin chemical class), and

  - Toluene (aromatic chemical class).
- CEC-rf-83-a-91 fuel with DCA added at 800 ppm (higher than normal treatment)
  Deposit Accumulation
- Deposits built up over 60 hours with the high concentration DCA (800 ppm) in European fuel

Vehicles/Engines:

- The Mercedes Benz M111E engine: SI, 2.0L, 4-cylinders, multipoint fuel injection

Test Methods:

- *Non-standard test cycle was used.* Engine-out hydrocarbon emissions taken at engine operating conditions of 2500 rpm, wide open throttle engine load with and without deposits
- Fast-response FID analyzer installed in the exhaust port of cylinder #1 and #4

RELEVANT RESULTS

- CEC-rf-83-a-91 fuel with DCA added at 800 ppm resulted in a total CCD weight of 1441 mg, average IVD was 20 mg per cylinder
- HC emissions measured for the M111 engine with and without deposits. Emissions were found to vary with crank angle and to form 2 distinct peaks in HC concentration.
  - Peak 1 (crank angle 540): 1151 ppm HC without deposits; 1545 ppm HC with deposits, a 34% increase.
  - Peak 2 (crank angle 655): 678 ppm HC without deposits; 1133 ppm HC with deposits, a 67% increase.

STRENGTHS/WEAKNESSES/DATA GAPS

- No statistical analysis
- No link between DCA and CCD

COMMENTS

- None

Study Reference No. B.15: CRC; CCD Emissions Group. 2000. "Effects of Combustion Chamber Deposits on Vehicle Emissions and Fuel Economy." CRC Project No. E-6. April.

GENERAL

Regulatory Background:

- EPA in 1996 (Federal Register, Vol. 61, No. 31) established a certification program for additives to control formation of PFID and IVD in gasoline engines (CCD not regulated in US)

Motivation/objective:

- EPA mandated use of DCA to control IVD and PFID, but incremental effect of CCD on emissions not known.
- CRC goals to develop CCD/emissions relationship and identify variables important to a CCD control test.

TESTING PROGRAM

Fuels:

- “Low CCD” forming fuel: Unadditized base fuel selected was Auto/Oil Industry Average (RF-A), representative of the mid-range of unleaded regular gasoline delivered for sale in the U.S.
- “Mid CCD” forming fuel: base fuel mixed with DCA of unknown chemistry that would produce “moderate” amounts of CCD
- “High CCD” forming fuel: base fuel mixed with DCA of unknown chemistry that would produce “high” amounts of CCD
- Additives for the mid- and high-CCD forming fuels were provided by the Chemical Manufacturers’ Association and were used at the recommended treatment dosages, which are not necessarily based on commercial practices.

Vehicles/Engines:

- 28 vehicles (7 each from 4 model groups) subjected to 0-6,000 mi break-in phase, then a 6,000-15,000mi deposit accumulation phase, using a modified AMA mileage accumulation schedule.
  - 1996 Dodge Neon, L4 2.0L, certified to CA TLEV
  - 1996 Dodge Caravan, V6 3.3L, certified to 50-state LDT
  - 1996 Oldsmobile 88, V6 3.8L, certified to 50-state LDV
  - 1996 Crown Victoria, V8 4.6L, certified to CA TLEV
- Emissions testing performed at following points during vehicle operation
  - Baseline Engine clean, deposits removed; after 6000-mi
  - Engine Dirty Both CCD &IVD buildup; after 15,000 mi
  - CCD Only IVD removed, CCD in place, after 15000 mi
  - Engine Clean Same as data point 3, except CCD also removed
- Vehicles fitted with catalyst system, oxygen sensor, fuel injectors and new evaporative emission control canister

Test Methods:

- FTP tailpipe emissions determined from 3-bag collection of diluted exhaust stream for HC, NMHC, CH4, CO, NO_X, CO_2
- Engine-out emissions calculated from undiluted exhaust gases prior to treatment by vehicle catalyst system (only HC, CO, NO_X, CO_2 determined)
- Quantification of deposits during 15000 mile accumulation on the base and additized fuels
  - visual rating using CRC procedure, scale of 1-10
  - thickness measurements
  - weight measurements
- Duplicate emissions tests at each of 4 data points were performed; minimum of 224 emission tests (28 veh x 4 emission data points x 2 duplicate tests), more when poor repeatability was measured (10 instances repeated a 3rd time)

RELEVANT RESULTS

- Effects of CCD on NO_X, CO_2, and fuel economy found to be statistically significant (all increased with the additized fuels use and CCD)

- Not possible to define emissions vs. CCD curve because the two additized fuels produced the same level of CCD
- Increase in NO_X consistent with thermal barrier impact of CCD

STRENGTHS/WEAKNESSES/DATA GAPS

- DCA chemistry and dosage level in the fuel are unknown.

COMMENTS

- None

Study Reference No. B.16: Aradi, A.A., Colucci, W.J., Scull Jr., H.M., and M.J. Openshaw. 2000. A study of fuel additives for direct injection gasoline (DIG) injector deposit control. *SAE Paper* 2000-01-2020.

GENERAL

- This paper reports on a comprehensive fuel additive study where deposit control additives (DCA) of two chemistry types, Mannichs and polyetheramines, are ranked with regard to injector deposit control in a research direct injection gasoline engine.

TESTING PROGRAM

Fuels

- Base fuels:
    - Howell EEE Fuel: 20 ppm Sulphur, 5% olefins, T90 160°C
    - Fuel #7: representative of European 2000 gasoline, 153 ppm Sulphur, 19.9% olefins, T90 161°C
    - Fuel #10, representative of US gasoline but with a higher sulphur, 421 ppm Sulphur, 12.9% olefins, T90 171°C
- 9 detergent additives tested
    - 5 Mannich chemistry DCA
    - 4 Polyetheramine chemistry DCA

Vehicles/Engines:

- 1982 Nissan Z22e, 2.2L, dual-spark, 4-cylinder, modified to run in a homogeneous direct injection mode

Deposit Build-Up Procedure

- A 6-hour dynamometer test to build up injector deposits
- Constant 2500 RPM engine speed, with variable loads of 200, 300, 400, 500 and 600 mg/stroke air charge, which was found to vary the injector tip temperature
- A 95% confidence interval was calculated at injector tip temperature of 173°C (from 500 mg air/stroke loading) and also at a higher load of 184°C temperature from 600 mg air /stroke with Howell EEE fuel with and without additive
- For Fuel#10, load points of 200, 300, 400 mg air/stroke, corresponding to injector tip temperatures of 120°C, 140°C and 157°C were used, with and without additive

RELEVANT RESULTS

- Fuel #10+EM-1 (Mannich Additive) reduced flow loss through the injector at all injector temperatures compared to the unadditized Fuel #10, and this was especially pronounced at the two highest temperatures 173°C and 184°C
- Fuel #7+EM-2a (Mannich Additive) was effective as clean-up during the 6 hour test. After 3 hours of regular Fuel#7, Fuel #7+EM-2a (Mannich Additive) was introduced for 3 hours and reduced the flow loss compared to when Fuel #7 was used the entire 6 h.
- Howell EEE base gasoline was run through the engine for 6 hours and flow loss reached a maximum of 9.25% at hour 6 from deposit buildup; after 6 hours a higher than normal treat rate of Mannich additive EM-1 was blended with the Howell EEE fuel and the engine was run for 6 hours, reducing the flow loss to 2.77% at 12 hours
- Howell EEE fuel with Mannich detergent provides good injector deposit control by lowering plugging from 10.9% to 5.7% by the two hour mark of the 6 hour mark test and remained stabilized for the next 4 hours.
- The PEA detergent performed markedly worse, stabilizing the flow loss at 9.4% instead of 5.7% with Mannich

STRENGTHS/WEAKNESSES/DATA GAPS

- No emissions measurements.

COMMENTS

- None

Study Reference No. B.17: Graskow, B.R., Ahmadi, M.R., Morris, J.E., and D.B. Kittleson. 1999. Exhaust particulate emissions from two port-fuel injected, spark-ignition engines. *SAE Paper* 1999-01-1144.

GENERAL

- Two additives “A” and “B” were blended into a base fuel. Particulate number concentration and size distribution were measured from a 1993 GM engine using the base and the two deposit control additive fuels. Fuel with additive “A” reduced particulate emissions while fuel with additive “B” increased them.

TESTING PROGRAM

Fuels:

- Base fuel had the following characteristics
  - Volume Percent 28.3% aromatics, 13.2 % olefins, 58.5% paraffins/napthenes
  - Total Nitrogen 28 ppm weight
  - Sulphur 332 ppm weight
  - T10, T50, T90, EP were 57.2 ºC, 100.6 ºC, 174.4ºC, and 212.2ºC respectively
  - 0.742 specific gravity at 16ºC
  - Octane RON and MON rating of 92.2 and 82.8, respectively
  - Reid Vapor Pressure 51.0 kPa (7.4 psi)
- Two different deposit control additives (DCA) were blended into the base fuel at refinery treatment rates, approximately 300-400 ppm

Vehicles/Engines:

- 2.3L 1993 GM Quad-4 engine
- No preconditioning on this vehicle; it was previously broken-in using specific procedure for another study and had since logged significant hours on a dynamometer

Test Method:

- *Non-standard test cycle was used.* A 15-mode test consisting of 15 steady state operating conditions was used to study tailpipe particulate characteristics: 1500, 2000 and 2500 rpm with manifold absolute pressure (MAP) at 50, 60, 70, 80, and 90 kPa
- Number concentration and size distribution measurements made upstream and downstream of the exhaust catalytic converter, using two different deposit control additives.

RELEVANT RESULTS

- DCA “A” and “B” do not affect the overall trend in number emissions: break specific particle number concentrations increase exponentially as engine brake power increases regardless of fuel
- At moderate to high engine brake power, differences between the two additives become apparent: additive “B” increases total number concentration compared to the base fuel while additive “A” decreases the particle number count
- At conditions of 2500 RPM and 60kPa MPA, with reference of comparison to the base fuel size distribution,
    - Additive “B” has a higher number concentration of particles in the nuclei mode (particles <50 nm) and a slightly lower number concentration of particles in the accumulation mode (50 nm – 1 µm)
    - Additive “A” had strongly suppressed particle number concentration in both particle size modes
    - The mechanism for particle formation suppression due to additive “A” is not known

STRENGTHS/WEAKNESSES/DATA GAPS

- Chemistry of additives “A” and “B” not known.

COMMENTS

- None

Study Reference No. B.18: Haider, H.A. and J.B. Heywood. 1997. Combustion Chamber Deposit Effects on Hydrocarbon Emissions from Spark Ignition Engine. *SAE Paper* 972887.

GENERAL

- This study tests CCD accumulation on a spark ignition, port fuel injected engine and identifies the effect of CCD on HC emissions.

TESTING PROGRAM

Fuel

- All testing performed with special Chevron-blended fuel representing an oxygenated commercial gasoline, with a polyether based additive package which kept intake valves and ports virtually deposit-free

Vehicles/Engines:

- A 1991 Saturn engine, 4 cylinder, PFI, standard intake and exhaust systems present, but with no catalytic converter

Test Method:

- *Non-standard test cycle was used.* A dynamometer was used to duplicate road running conditions
- Four separate build-up tests, 100h, 50h, 25h and 35h long completed
    - Before each test, engine was disassembled and deposits removed
    - Alternating conditions of 1400 rpm at 10% load for 6 minutes and 2200 rpm at 30% load for 12 minutes, for 10 hours straight followed by overnight soak period.

RELEVANT RESULTS

- HC emissions rapidly rise between first 10-15 hours and stabilize after 25 hours, long before deposit thickness stabilized
    - At 25 h, deposit thickness was 100 µm on the cylinder head and 50 µm on the piston top
- HC increase due to CCD accumulation accounted for 10 to 20% of total engine-out HC, making CCD a significant HC emission source from this engine
- CCD in the cylinders contributed much more to HC emissions than CCD on the piston top

STRENGTHS/WEAKNESSES/DATA GAPS

- No statistical analysis.

COMMENTS

- None

Study Reference No. B.19: Barnes, J.R. and T Stephenson. 1996. Influence of Combustion Chamber Deposits on Vehicle Performance and Tailpipe Emissions. *SAE Paper* 962027.

GENERAL

- This study examines the effect of removing CCD on tailpipe emissions in several European car models before and after 16,000 km accumulation.

TESTING PROGRAM

Fuels:

- A single batch of nominal 98 RON unleaded fuel containing a DCA was used for deposit buildup

Vehicles/Engines:

- 3 pairs of vehicles (6 total) were tested, all 1994 and later model
    - A vehicle model: 2L, manual, PFI, 4 cylinder
    - B vehicle model: 1.4L, manual, PFI, 4 cylinder
    - C vehicle model: 2L, automatic, PFI, 4 cylinder

Test Method:

- After 16,000 km emissions were measured over the combined European test cycle at steady state condition
- Following the removal and measurement of CCD, emissions measurements repeated for 'CCD-clean' condition. Inlet deposits were left in-situ, so emissions effects are due solely to CCD presence.
- CCD thickness measured with a Fischer Dualscope MP4 meter on piston top and cylinder head surfaces

RELEVANT RESULTS

- Paired vehicles gave very consistent levels of CCDs; the B vehicle gave the lowest overall CCD measurements
- Removal of CCD reduced NO_X, and had smaller and less certain effects on HC and CO emissions
- NO_X benefit due to CCD removal was on average across the 6 vehicles, 25%

STRENGTHS/WEAKNESSES/DATA GAPS

- None

COMMENTS

- None

Study Reference No. B.20: Papachristos, M.J., Williams, D., Vincent, M.W., and A. Raath. 1995. Deposit Control Additive Effects on CCD formation, Engine Performance and Emissions. *SAE Paper* 952447.

GENERAL

- This study was a 2-year test program designed to discover (1) the extent emissions are affected by build-up and removal of CCD, (2) whether there are emissions benefits associated with DCA under real world conditions, and (3) whether CCD is a good predictor of fuel performance under real world conditions.

TESTING PROGRAM

Fuels:

- Base fuel was from UK refiners and was typical of pump gasoline meeting European EN228 specifications
- Base fuel blended with an EPA registered detergent package
  Deposit Accumulation

- An 80,000 km driving pattern with variable speeds was used, conducted 7 days/week over 2 years, with random down-time and soak periods to mimic “real life service conditions”

Vehicles/Engines:

- A fleet of 6 vehicles were selected to represent popular European and Japanese cars, matched pairs:
  - Manufacturer A: 1992, 1.3L, carbureted engine, no catalyst
  - Manufacturer B: 1992, 1.7L, PFI, catalyst
  - Manufacturer C: 1992, 2.0L, PFI, catalyst

Test Method:

- ECE 15 Test Cycle modified to include the Extra Urban Drive Cycle (EUDC) was used for emissions measurements
- Repeat measurements taken at all phases of the project
- Concluding 80,000 km, CCD measurements were taken
  - Coordinating Research Council (CRC) visual rating method
  - Thickness
  - Weight: using a Fischer DualScope MP4

RELEVANT RESULTS

- The additive reduced CCD thickness relative the base fuel, but increased CCD weight, but these results weren’t statistically validated
- In general HC, CO and NO_X increased directionally with deposit accumulation, but only NO_X decreased with CCD mechanical removal
- Pooling the data for the 3 base fuel cars and 3 DCA fuel cars
  - Over the deposit accumulation 80,000 km period, tailpipe NO_X increased 24%
  - Mechanical removal of CCD led to 12% drop in NO_X
- The vehicles with the additive fuel had CO and NO_X emissions that were 22% and 20% respectively, lower than vehicles with the base fuel over the 80,000 km accumulation
- No link found between CCD thickness (or rating) and emissions
- Link exists between CCD weight and NO_X emissions
- Additional testing needed to clarify influence of CCD on HC and CO emissions

STRENGTHS/WEAKNESSES/DATA GAPS

- None

COMMENTS

- None

Study Reference No. B.21: Zahalka, T.L., Kulinowski, A.M. and D.J. Malfer. A Fleet Evaluation of IVD and CCD: Emissions Effects and Correlation to the BMW 318i and Ford 2.3L IVD Tests. *SAE Paper* 952447.

GENERAL

- This study is a fleet test designed to evaluate effects of IVD and CCD on regulated tailpipe emissions (HC, CO, and NO_X) and vehicle performance.

TESTING PROGRAM

Fuels:

- Six different test fuels: 2 base gasolines and 3 commercially available DCA packages
  - DCA X: designed to control PFI and IVD (mineral carrier fluid)
  - DCA Y: designed to control PFI/IVD/CCD (all synthetic)
  - DCA Z: designed to control PFI/IVD/CCD (all synthetic)
    - Z stated as being less important to the study for unknown reason

Vehicles/Engines:

- Twenty 1994 model year vehicles powered by Ford 2.3L SI engines

Deposit Accumulation:

- The 1994 model year vehicles were driven by trained drivers for 40,225 km on a test route designed to promote intake valve deposits (70% highway, 20% secondary roads, 10% city driving)

Test Method:

- *Non-standard test cycle was used.*
- Emissions testing performed at Start, 6400 km, 37000 km and End (40225 km)
- IVD weighed at End of Test
  - Valves were subsequently cleaned with walnut shell blasting and scrubbing with wire brush. Weight of IVD was determined as the weight of the cleaned valve subtracted from the dirty valve weight.
- CCD thickness and weight taken at End of Test
  - Thickness measured by Fischer Permascope
  - Deposits scraped and weighed to the nearest 0.1 mg
- Statistical significance was evaluated using a one variable design, using the Design-Ease software

RELEVANT RESULTS

- All additives evaluated provided significant reduction in IVD
- All additives increased CCD compared to the base fuel, with 99% confidence
- Synthetic additives caused less of a CCD increase than the DCA package formulated with a mineral oil carrier fluid
- Link between NO_X emissions and CCD not statistically significant
- HC and CO emissions for the unadditized fuel were significantly higher than additized fuels with 99% confidence
  - Variations in the levels of CCD observed in the additized fuels had no effect on HC and CO, suggesting IVD control provides the most effective means to lower these emissions

STRENGTHS/WEAKNESSES/DATA GAPS

- None

COMMENTS

- None

Study Reference No. B.22: Bitting, W.H., Firmstone, G.P., and C.T. Keller. 1994. Effects of Combustion Chamber Deposits on Tailpipe Emissions. *SAE Paper* 940345.

GENERAL

- Investigated the effects of combustion chamber deposits (CCD) on tailpipe exhaust emissions of HC, CO, NO_X
- Four different model year vehicles were evaluated at four different deposit conditions

TESTING PROGRAM

Fuels:

- 3 different fuels were blended from refinery streams and were made to be typical of commonly available pump unleaded gasoline
- All fuels contained the same intake valve deposit (IVD) detergent, enough of a dosage to exceed the BMW “unlimited mileage” criteria of 100 mg average/valve in the “10,000 mile BMW test”

Vehicles/Engines:

- 1986 GM Buick Century with 3.8L engine
- 1989 GM Pontiac Grand Am with 2.3L engine
- 1990 Ford Mercury Sable with 3.0L engine
- 1992 Chrysler Plymouth Voyager with 3.0L engine
- All 4 vehicle types were equipped with port fuel injection and closed-loop exhaust emission control systems.
- A pair of each of the 4 make/models was used.

Test Methods

- FTP cycle was used for emissions testing; with measurements taken at 4 conditions
    1. BASELINE: thoroughly cleaned engine, before mileage accumulation
    2. DEPOSITED: condition of engines after the 9000-mile accumulation
    3. CCD CLEAN: after DEPOSITED condition measured, walnut shell blasting to remove CCD
    4. BASE2: following CCD CLEAN, cylinder heads and intake system were thoroughly cleaned
- Repeat measurements on each test vehicle were collected
- Engine deposits built up over 9000 miles on chassis dynamometers
- Mileage accumulation was conducted in a cyclic steady state patter with manifold absolute pressure (MAP) and vehicle speed used as control set points
    - “High cycle” steady state condition: highway speed and MAP set to slightly higher load than what it would be on level roadway
    - “Low cycle” steady state condition: city driving speed, with similar loading as the high cycle

  - Drive sequence was a 12-minute high cycle, followed by 30 second ramp down, then 6-minute low cycle, followed by a 30 second ramp up to high cycle to repeat.

RELEVANT RESULTS

- Statistical analysis of variance (ANOVA) was employed to determine the impact of the test procedure on exhaust emissions. Multiple comparison procedures were used with the Bonferroni approach and Dunnett's method.
- For HC measurements , none of the conditions (BASELINE, DEPOSITED, CCD CLEAN, BASE2) were statistically significant.
- For CO measurements, DEPOSITED condition was significantly greater than CCD CLEAN at the 90% confidence level
- For NO_X measurements, the DEPOSITED condition was statistically greater than the other 3 conditions at the 90% confidence level.
- Differences by model year were not significant; all vehicles' results were pooled into 3 charts.
- In general, HC, CO and NO_X all increase directionally with CCD removal (only NO_X statistically significant) and decrease with CCD removal (only CO and NO_X significant)
- The statistically significant average emission change results include:
  - NO_X emissions increased from BASELINE to DEPOSITED by 47%
  - NO_X emissions decreased from DEPOSITED to CCD CLEAN by 20%
  - CO emissions decreased from DEPOSITED to CCD CLEAN by 26%

STRENGTHS/WEAKNESSES/DATA GAPS

- Link between CCD and emissions established, not deposit control additive and emissions

COMMENTS

- None

Study Reference No. B.23: R. Lee. 1999. SI Engine Combustion Chamber Deposits and Their Effects Upon Emissions. SAE Paper 1999-01-3583.

GENERAL

- The effect of CCD thickness on tailpipe emissions over the FTP is measured in this study.

TESTING PROGRAM

Fuels:

- 3 market fuels were used to build CCD levels
  - Fuel A: California Reformulated Gasoline 2
  - Fuel B: EPA Reformulated Gasoline
  - Fuel C: conventional regular
- Each fuel dosed with full dosage rate of a top-tier commercial DCA package
- 2 non-market fuels also used
  - Aviation alkylate
  - Fuel D: 40/40/20 mix of isooctane, alkylate and Fuel C

Vehicles/Engines:

- 1997 Oldsmobile Achieva, with 2.4L engine
- 1997 Ford Contour, with 2.0L engine
- 1998 Chevrolet Prism, with 1.8L engine
- 6 additional 1997 Ford Contours

Test Method

- *Non-standard test cycle was used.* Road Simulation Dynamometers were run 21 of 24 hours each day used with a cycle consisting of 23.8% idle, 12.7% light accel/decal, 1.6% heavy accel, 23.8% low speed cruise and 38.1% high speed cruise
- CCD measurements were taken using a Fischer permeascope at cold engine condition, at least 2 hours after engine finished running and just prior to any emissions tests
- IVD weights taken at each valve at the end of each test
- Triplicate measurements of emissions measurements were taken at any given mileage or CCD thickness
- HC, CO and NO_X measured by a Horiba Microbench Series 200 Gas Analyser and a “Horiba AFR Mexa 110λ Analyser

RELEVANT RESULTS

- CCD builds up rapidly over low mileage and stabilizes around 4000 to 10,000 miles
- From clean engine condition, NO_X emissions vs. CCD thickness follows a non-linear “step function” and all 3 engines show a similar response
- From clean engine condition, HC increased between 20-40% at 200μm CCD thickness in two vehicles; HC increase over 3000-6000 miles in all engines was statistically significant at the 95% confidence level
- CO emissions results are mixed. From clean engine condition, CO emissions decreased 15-30% at 200 μm CCD thickness in the Ford engine, but showed no response to CCD in the Oldsmobile or Chrysler bench engine
- Reducing CCD thickness by 50% in unaged CCDs by switching to base fuel from additized fuel gave no effect on HC, CO or NO_X emissions
- Reducing CCD thickness by 30% in aged CCDs caused NO_X to rise and HC and CO emissions to decrease

STRENGTHS/WEAKNESSES/DATA GAPS

- DCA Chemistry unknown
- “Aged” versus “unaged” CCD seems to yield opposite NO_X results; classification of CCD age not clear

COMMENTS

- None

Study Reference No. B.24: Wu, T.N., Huang, Y.C., Wu, T.S., and T.D. Wu. 2007. “The Effect of Gasoline Additives on BTEX Emissions from Light-Duty Vehicle,” Proceedings of the 4th WSEAS International Conference on Fluid Mechanics, Gold Coast, Queensland, Australia, January 17-19.

GENERAL

A test study in Taiwan examined the effect of using 4 different detergent additives compared to a base gasoline fuel on HC, CO, NO_X and BTEX emissions from a Nissan passenger car engine.

TESTING PROGRAM

Fuels:

- Base fuel was Taiwanese commercial fuel 95-LFG
- Six additives (4 for deposit control) were blended into base fuel at manufacturer specifications
  - GA1: Octane Booster
  - GA2: Intake Valve Cleaner
  - GA3: Fuel Injector Cleaner
  - GA4: Fuel System Cleaner
  - GA5: Carburetor Cleaner
  - GA6: Multi-function
- Precise chemistry of each additive not given; active ingredients (and followed recommended dosages in the study) reported as:
  - Polyetheramine (PEA)
    - 357 ppm for fuel injectors or ports
    - 375 ppm for intake valve
    - 2000 ppm for combustion chamber
  - Polyether pyrolidone (PEP)
  - Polyisobutylene (PIB)
    - 140 ppm for fuel injectors or ports
    - 166 ppm for intake valve
    - 2000 ppm for combustion chamber
  - Methylcyclopentadienyl manganese tricarbonyl (MMT)

Vehicles/Engines:

- The test engine was a Nissan New Sentra1.6L jet engine with 4 cylinders, natural ventilation, port fuel injection, bore and stroke (76 x 88 mm^2), total displacement of 1597 ml, maximum horsepower of 110 HP at 6000 rpm and maximum torque 15 kg-m at 4000 rpm.
- Schenck W-130 chassis dynamometer
  - Capable of prompt switching between negative, positive torque values
  - Capable of operation in both transient cycle and steady-state modes
- Engine was cleaned prior to each emissions test with a different fuel additive

Test Method:

- US EPA 1975 Federal Test Procedure (FTP-75)
- Nissan engine's entire fuel system cleaned before each gasoline additive test; set overnight before testing

RELEVANT RESULTS

- HC, CO, NO_X measured concentrations from each fuel were weighted over the 3-phases of the FTP cycle and gram per kilometer emission rates computed

- Base fuel emission rates of HC, CO, NO_X were 0.219, 1.3, and 0.27 g/km, respectively
- HC emission rates for the 3 deposit control additives GA2, GA3, GA4 (GA5 results not reported) ranged between 0.156 g/km for GA3 to 0.169 g/km for GA2.
- CO emission rates for the 3 deposit control additives ranged between 0.16 g/km (GA4) to 1.2 (GA3)
- NO_X emission rates for the 3 deposit control additives ranged from 0.21 g/km (GA4) to 0.25 g/km (GA3)
- BTEX Emissions – also weighted FTP emission rates
    - Base fuel emissions were 2.69 mg/km for Benzene, 6.17 mg/km for Toluene, 1.81 mg/km for Ethylbenzene, and 7.13 mg/km for Xylene
    - G4 deposit control additive was superior at reducing BTEX emissions
        - 0.63 g/km Benzene
        - 2.89 g/km Toluene
        - 1.29 g/km Ethylbenzene
        - 3.85 g/km Xylene
    - G1 and G6 actually increased BTEX

STRENGTHS/WEAKNESSES/DATA GAPS

- No explanations for causes/mechanisms of increase or decrease in HC, CO, NO_X across fuel types. With a clean engine system at the start of each experiment, it is not clear that deposit formation occurred or was prevented by an additive.
- No statistical analysis reported.
    - Doesn't appear that multiple tests were repeated for fuels.
    - Not clear whether differences in emission rates are statistically significant.

COMMENTS

- None

Study Reference No. B.25: Bratsky, D. and D. Stacho. Impact of Motor Gasoline Chemical Composition and Additive Treatment on Inlet Valve and Combustion Chamber Deposits. *SAE Paper* 2000-01-2022.

GENERAL

- This Slovakian study examines, among other fuel parameters, the effect of detergent additive levels on combustion chamber deposits (CCD) using the modified CEC F-04-A-87 engine bench test. The authors developed mathematical equations to evaluate the influence of fuel parameters on CCD. The influence of detergent additives on HC exhaust emissions was also measured.
- LADA 2130 passenger car engine used because of these have a large share of the car population in Slovakia. This is a carbureted vehicle.
- Test engine was carbureted, not fuel injected, so results not relevant to Canadian fleet.

Study Reference No. B-26: Carlisle, H.W., Frew, R.W., Mills, J.R., Aradi, A.A., and N.L. Avery. 2001. The effect of fuel composition and additive content on injector deposits and performance of an air-assisted direct injection spark ignition (DISI) research engine. *SAE Paper 2001-01-2030*.

GENERAL

- This study characterizes deposits that form on injectors of an air-assisted DISI automotive engine and the effect of these deposits on engine performance with varying additive content. Also reported are raw hydrocarbon and smoke emissions with time throughout the test cycle.

TESTING PROGRAM

Fuels:

- Fuel #1 was the base fuel: T90=158°C, 18.0% aromatics, 19.7% olefins, 32 ppm Sulphur, and 89.1 octane number
- Additive A (unknown whether it is PEA or Mannich type), 115 ptb (pounds per thousand barrels) treat rate
- Additive B (unknown whether it was PEA or Mannich), 115 ptb treat rate

Vehicles/Engines:

- A multi-cylinder research engine based on a 1.8L Ford Zetec DOHC engine modified to operate with a special spray guided combustion system designed by Orbital Energy Company

Test Method:

- *Non-standard test cycle was used for a research direct-injection spark-ignited engine.* Stratified combustion mode: 2500 rpm engine speed, 13 mg/c/c fueling, 15h duration
- Homogeneous combustion mode: 4000 rpm engine speed, 30 mg/c/c fueling, 5h duration
- Maximum deposit thickness on the poppet was measured at the end of each test cycle

RELEVANT RESULTS

Stratified Mode

- With unadditized Fuel #1, HC emissions increased throughout the 15 hour test by approximately 1000 ppm compared to emissions at hour 0
- With Additive A, HC increase (from hour 0) never exceeded 200 ppm
- With Additive B, HC increase (from hour 0) never exceeded 0 ppm
- No smoke concentration reported for stratified mode combustion

Homogeneous Mode

- Additives A and B increased smoke and HC emissions relative to Fuel #1 during all 5 hours of the test cycle

STRENGTHS/WEAKNESSES/DATA GAPS

- Some statistical analysis provided for emissions measurements, but they are not clearly interpreted in terms of confidence in the results

COMMENTS

- None

Study Reference No. B.27: OACIS Deposit Workgroup. 2002. A Study of Injector Deposits, Combustion Chamber Deposits (CCD) and Intake Valve Deposits (IVD) in Direct Injection Spark Ignition (DISI) Engines. SAE Paper 2002-01-2659.

GENERAL

- This study is comprised of engine deposit tests using three representative Japanese DISI engines and seven test fuels, two of which are the base fuel and the base fuel with deposit control additives.
- The effects of the detergent (as well as other fuel additives) on injector deposits, IVD and CCD were investigated for purposes of selecting an engine for test method development.

TESTING PROGRAM

Fuels:

- Fuel A: the base fuel, with RON 100
- Fuel E: poly-butyl-amine (PBA) base, with RON 100

Vehicles/Engines:

- The 3 engines are all DISI engines equipped with TWC and lean-NO_X catalysts
  - Mitsubishi: reverse tumble flow with vertical ports, and relatively high compression ratio, cone-valve type injectors
  - Nissan: swirl flow with ball-valve type injectors
  - Toyota: cone-valve type injectors

Test Method:

- *Non-standard test cycle was used on a research direct-injection spark-ignited engine.*Two separate test phases were performed
  - Phase I: High temperatures and high engine load operating condition
    - 50 hours driving at 140 km/h
    - Homogeneous stoichiometic or richer combustion
  - Phase II: At typical load, as opposed to high load operating condition
    - 25 hours at 70 km/h
    - 25 hours at 40 km/h
    - Stratified-lean combustion
- Measurements for both phases include: fuel-flow rate, IVD weight, and CCD weight before and after the 50 hours of run time.

RELEVANT RESULTS

Phase I Results (high engine load)

- Regardless of fuel type (A or E), both the Mitsubishi and Toyota engine injectors experienced decrease in flow rate from the 50 h test. Nissan engine injectors experienced an increase in flow rate.

- Fuel E caused a greater loss in injector flow rate than the Fuel A, in the Mitsubishi and Toyota engines. Nissan injector flow rate increased more over the 50 hours of driving when Fuel E was used.
- CCD weight in both Fuel A and E was much higher in the Toyota engine than the others, likely due to the Toyota running at higher engine RPM to sustain 140 km/hr.
- CCD weight was higher in all 3 engines for Fuel E compared to Fuel A.
- IVD weight is lower for Fuel E than Fuel A in Mitsubishi and Nissan engines.
- IVD weight increases for the Toyota engine when Fuel E is used

Phase II Results (normal/typical engine load)

- Same general trend in flow rate change occurs in phase II: Mitsubishi and Toyota engine injectors experienced flow loss and Nissan experienced a flow increase, regardless of fuel type (A or E).
- Use of detergent (Fuel E) resulted in a smaller flow change over the 50 hr test in all 3 engines
- Fuel E increased CCD weight in the Mitsubishi engine, and decreased CCD weight in the Nissan and Toyota engines, compared to Fuel A.
- CCD weight is much larger in the Nissan engine than the other two.
- IVD weight is much smaller in the Toyota engine than the other two.
- Fuel E increased IVD in the Mitsubishi engine, decreased IVD in the Nissan and Toyota engines

STRENGTHS/WEAKNESSES/DATA GAPS

- No emissions testing performed
- Neither flow measurements nor deposit weights were evaluated for statistical significance

COMMENTS

- None

Study Reference No. B.28: Houser, K.R. and T.A. Crosby. The Impact of Intake Valve Deposits on Exhaust Emissions. SAE Paper 922259

GENERAL

Exhaust emissions were measured and intake valve deposits (IVD) were rated using twenty 1990 model year vehicles subjected to 80,000 km of distance accumulation.

TESTING PROGRAM

Fuels:

- Base gasoline for 4 vehicles
- Base gasoline with DCA varying in composition and concentration for 16 vehicles

Vehicles/Engines:

- Twenty similar 1990 model year midsize sedans equipped with 3.0L, V-6, PFI engines and 3-way catalytic converters

Test Method:

- Deposit Accumulation: 80,000 km on road using an AMA-type cycle
- Exhaust emissions of HC, CO and NO_X were measured using the FTP cycle before and after IVD removal after completing the 80,000 km distance
- IVD rated using the CRC 1 to 10 system, with 1 being dirtiest and 10 being clean intakes
- Statistical analyses
    - Analysis of variance (ANOVA) performed on all 3 FTP bag emission rates of HC, CO and NO_X before and after mechanical IVD removal, reported at 90% confidence level
    - ANOVA performed on all emission factors prior to IVD removal as a function of CRC weighting, reported at 90% confidence level

RELEVANT RESULTS

- Mechanical removal of IVD resulted in emissions benefits for CO and NO_X of 11% and 15% over the full FTP cycle, 90% confidence
- For all 3 pollutants FTP average emissions tend to be higher for the vehicles with low IVD ratings (high deposits)
- Emission factors are a linear function of IVD rating
    - Average, min, and max change increase in emission factors going from a CRC rating to 1 whole number higher (dirtier intakes), by FTP bag and pollutant
    - HC bag 2 (running exhaust), CO bag 1 and NO_X bag 1 (cold starts) were not significant at 90% confidence
    - FTP weighted NO_X

STRENGTHS/WEAKNESSES/DATA GAPS

- None

COMMENTS

- None

Study Reference No. B-29: U.S. Environmental Protection Agency. 1995. Relevant sections of the Regulatory Impact Analysis (RIA) for the final certification rule on DCA.

GENERAL

- This is not an original scientific study but rather a review of existing studies available at the time just prior to the U.S. EPA IVD/PFID interim rulemaking in 1995. Evidence supporting a need for IVD and PFID controls is outlined below.

TESTING PROGRAM

- Literature review.

RELEVANT RESULTS

- From reviews contained in a 1990 California Air Resources Board (CARB) document titled “Reformulated Gasoline: Proposed Phase 1 Specifications, Technical Support Document”

  - Tests on a 1983 model year vehicle with flow restrictions ranging from 20 to 25 percent (23% average) showed emissions effects of 28% HC increase, 266% CO increase and 28% NO_X decrease
  - Another 1983 model year vehicle with flow restrictions ranging from 4 to 10 percent (8% average) showed emissions effects of 26% HC increase, 16% CO increase, and 5% NO_X decrease
  - A 1985 vehicle using four different sets of injectors with various unspecified levels of fouling showed emissions effects of 63-168% HC increase, 129-668% CO increase and a 106% increase to a 42% decrease in NO_X
  - One other vehicle (unspecified model year) with fouled injectors to an unspecified level showed emissions effects of 228% HC increase, 48% CO increase and 169% NO_X increase.
  - CONCLUSION: fuel injector deposits can significantly increase HC and CO emissions, however the PFID effect on NO_X is variable.
  - Magnitude of impact of IVD on emissions depends on vehicle technology
    - Unocol study reported a NO_X emissions benefit of 33% when IVD were removed from 6 <u>modern technology [in 1995]</u> vehicles
    - Texaco study reported emissions benefits for IVD clean-up of a test fleet of unknown number of <u>modern technology [in 1995]</u> vehicles: 33% HC reduction, 1% CO reduction and 21% NO_X reduction
    - Chevron study compared emissions from 10 vehicles that were 1978 and 1979 model year operating on DCA fuel, and matched pairs that operated on base fuel without additive. Emissions benefits for DCA were reported to be 12% for HC, 15% for CO and 18% for NO_X.
- From SAE Paper 922259 **[Study Reference No. B-28]**
  - Using 20 model year 1999 vehicles
  - IVD effects on emissions may be a linear function of the deposit level.
  - The fleet average effect of IVD on emissions was an 11% CO increase and a 15% NO_X increase
  - Vehicles in the fleet with lighter IVD experienced lower than the average CO and NO_X increases
  - Vehicles in the fleet with heavy IVD showed emissions increases of 32% for CO and 54% for NO_X
  - The effect of IVD on HC emissions was not statistically significant over the entire FTP emissions test, but was significant for bag 2 emissions.
- From a presentation for CARB by Texaco Research Center in 1990 entitled “Effects of Intake and Combustion System Deposits on Regulated Exhaust Emissions”
  - Evaluated effect of cleaning up of IVD: large NO_X decrease; mixed results for HC and CO
  - In a 12-car fleet test, the emissions benefit of mechanical removal of IVD was: 10.8% HC, 1.6% CO, and 8.6% NO_X.
  - A separate 35 car fleet test showed mechanical removal of IVD increased both HC and CO by 7%, and reduced NO_X by 7.6%

STRENGTHS/WEAKNESSES/DATA GAPS

- None

COMMENTS

- None

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Appendix C: Diesel – Cetane Effects Reviews

Study Reference No. C.1: Ickes, A.M., Bohac, S.V., Assanis, D.N. 2009. Effect of fuel cetane number on a premixed diesel combustion mode. *International Journal of Engine Research*. Vol. 10, No. 4, pp 251-263.

GENERAL

- The study demonstrated the detailed combustion behaviour of variations in fuel cetane number in an HCCI engine.
- Testing was conducted under light load conditions on a modern single-cylinder test engine, fuelled with ultra-low sulphur diesel (ULSD) with cetane numbers ranging from 42 to 53.

TESTING PROGRAM

Fuels:

- Four test fuels with varying fuel properties:
    - Swedish Environmental Class 1 diesel with high cetane number (53);
    - US ultra-low sulphur diesel (ULSD) certification fuel with low cetane number (42);
    - US ULSD certification fuel with mid cetane number (47); and
    - US ULSD certification fuel with high cetane number (50).

Vehicles/Engines:

- A single-cylinder test engine.
- Based on a modern 4 cylinder, 1.7 l production diesel engine with EGR.
- Operated as an HCCI engine.

Test Method:

- No standard emission test cycle
- Experimental investigation.
- Combustion parameters studied included ignition delay and combustion phasing.

RELEVANT RESULTS

- Fuel cetane number strongly affects the ignition delay and combustion phasing.
- HC, CO and NO_X from the tested premixed diesel combustion is principally a function of the flow-rate of cooled EGR and the combustion phasing.
- Changes in fuel cetane number, and many other factors, shift the combustion phasing, which alters the gaseous emissions.
- Fixed injection timing in premixed diesel combustion is not compatible with a wide range of cetane number. A feedback control system should allow use of a wider range of cetane number.

CONCLUSION

- Fuel cetane number does not directly impact vehicle emissions.
- Fuel cetane number was not important if the combustion phasing and EGR were matched.

STRENGTHS/WEAKNESSES/DATA GAPS

- The tests were not carried out over a standard driving cycle.
- Testing was limited to light loads.

- Conclusions based on measurements of emissions per mass of fuel burned, rather than VKMT or bshp-hr.

COMMENTS

- Experimental investigation on HCCI test engine only.

Study Reference No. C.2: European Environment Agency 2009. "EMEP/EEA Air Pollutant Emission Inventory Guidebook." Technical Report 6/2009.

GENERAL

- This Guidebook details the methodology for the calculation of exhaust emissions from European road traffic.
- The estimation methods include correction factors to account for the effect of varying fuel properties, including cetane number.

TESTING PROGRAM

- Literature review

RELEVANT RESULTS

- Estimates developed for all categories of the European fleet, based on European emission standards/technologies for
  - European Light-duty (relative change is a function of base fuel/technology); and
  - European Heavy-duty (relative change is a function of base fuel/technology)
- For diesel engines, correction factors were developed to account for the following fuel properties:
  - density;
  - sulphur content;
  - polycyclic aromatics content ;
  - cetane number; and
  - back end distillation in (T95).

CONCLUSION

- Using the emission estimation methods developed in this study, and varying cetane number from 40 to 50 will:
  - reduces CO and HC emissions for both light-duty and heavy-duty European fleets, with a greater reduction in light-duty vehicles; and
  - gives no significant change in NO_X or PM emissions.

STRENGTHS/WEAKNESSES/DATA GAPS

- These methods are intended to represent the impact of cetane number on the European fleet as a whole, and do not differentiate between engine technologies.
- This work applies to range of technologies in the existing fleet, and does not address emerging technologies.

COMMENTS

- This report does is intended for a general modeling emissions for current on-road not present any tests results.

Study Reference No. C.3: Nuszkowski, J., Tincher, R.R., Thompson, G.J. 2009. Evaluation of the NO_X emissions from heavy-duty diesel engines with the addition of cetane improvers. *Journal of Automobile Engineering*. Vol. 223, Issue D8, pp 1049-1060.

GENERAL

- This study evaluated the impact of “cetane improver” additives on NO_X emissions from five heavy-duty diesel engines between model years 1991 and 2004.

TESTING PROGRAM

Fuels:

- Two common ignition improver (or cetane improver) additives were used in this study, namely nitrate-based 2-ethlyhexyl nitrate (2-EHN) and peroxide-based additive (DTBP).
- The improvers were tested in different concentrations in three base fuels: two petroleum and one B20.

Vehicles/Engines:

- Five engines were tested in an engine dynamometer test cell:
  - 1991 DDC Series 60;
  - 1992 DDC Series 60;
  - 1992 DDC Series 60;
  - 1999 Cummins ISM370; and
  - 2004 Cummins ISM370 (with Cooled Exhaust Gas Recirculation).

Test Method:

- US Federal Test Procedure (FTP).
- Triplicate tests of each fuel/engine combination.

RELEVANT RESULTS

- The additives had the most impact on reducing emissions at low engine powers, but the engine power range with an NO_X benefit varied between engines.
- The cetane improvers showed a greater reduction in NO_X emissions on the older technology engines (1.0%, 3.5%, 3.2% and 1.9% for the 1991 DDC Series 60, 1992 DDC Series 60, 1992 DDC Series 60 and 1999 Cummins ISM370, respectively). These are conventional engines without EGR.
- For the relatively new engine (2004 Cummins ISM370 with Cooled Exhaust Gas Recirculation), an increase in cetane showed an increase in NO_X emissions by 1.3%.
- The cetane improvers are beneficial in reducing NO_X in engines with low compression ratios (older technology engines) but not for NO_X reduction in newer-technology engines (higher compression ratio and EGR).

STRENGTHS/WEAKNESSES/DATA GAPS

- NO_X emissions may be impacted by effects of the additives other than just cetane number.

COMMENTS

- This study showed that cetane improvers may not reduce emissions for new technology vehicles.

Study Reference No. C.4: CONCAWE 2008. “Advanced Combustion for Low Emissions and High Efficiency: A Literature Review of HCCI Combustion Concepts.” Report 4/08, Brussels.

GENERAL

- This study carried out an extensive review of published literature of advanced combustion concepts for both gasoline and diesel engines, known as Homogeneous Charge Compression Ignition (HCCI).

TESTING PROGRAM

- Literature review

RELEVANT RESULTS

- In HCCI prototype engines, very low levels of engine-out PM and NO_X emissions have been widely demonstrated under steady-state research conditions.
- CO and HC emissions from HCCI diesel engines are higher than conventional diesel, so oxidation catalysts will still be required.
- Ignition delay is a key parameter for HCCI combustion, and one where the correct choice of fuel can have an impact. Current evidence suggests that cetane diesel fuels below 45 may be the optimum choice for diesel based HCCI.
- Fuel with a cetane number below 45 is generally beneficial in diesel HCCI since it increases ignition delay and allows improved mixing prior to ignition.
- Fuel with a lower cetane number allows operation at a lower level of EGR, and even operation without EGR.

STRENGTHS/WEAKNESSES/DATA GAPS

- It is too early to define future fuel specifications for HCCI.

COMMENTS

- HCCI technology is still emerging. While it holds promise for the future, there are significant challenges to be addressed before it will become practical.
- HCCI engines using diesel fuel has the potential for reduced emissions compared to conventional diesel, mainly in NO_X and PM, prior to the after-treatment system.
- Reducing emissions at the source will reduce after-treatment requirements for diesel engines

Study Reference No. C.5: CRC 2008. “Review of Prior Studies of Fuel Effects on Vehicle Emissions.” Prepared by Dr. Albert M. Hochhauser, 12 Celler Rd., Edison, NJ 8817, Prepared for Coordinating Research Council, CRC Project E-84.

GENERAL

- This study carried out an extensive review of published literature on the effect of fuel properties on emissions.
- 183 papers were reviewed, covering the period:
    - From 1990 to 2007 for gasoline, and light-duty diesel; and
    - From 1998 to 2007 for heavy-duty diesel
- Among many factors reviewed, the impact of fuel cetane, density and aromatics were discussed together, for light- and heavy-duty vehicles separately.
- 28 papers were reviewed involving effect of cetane on emissions
    - 15 papers on light-duty vehicles involving 86 vehicles and 267 fuels with a most recent paper of 2004; and
    - 13 papers on heavy-duty engines involving 63 vehicles and 205 fuels with a most recent paper of 2007.

TESTING PROGRAM

- Literature review.

RELEVANT RESULTS

- In many of the test programs, density, cetane and aromatics were correlated, so it was not possible to isolate the effect of cetane only.
- Several studies show no difference between natural and additized cetane.
- Based on the literature review, the general trend was summarized as follows (without after-treatment):
    - Increase in cetane number is likely to reduce CO and HC from light- and heavy-duty engines;
    - Increase in cetane number is likely to increase PM from light-duty vehicles;
    - There was no identifiable trend with respect to the effect of cetane on PM emissions from heavy-duty engines; and
    - There was no identifiable trend with respect to the effect of cetane on NO_X emissions from either light-duty or heavy-duty engines.
- “As engines become more sophisticated in terms of emission control, fuel effects on emissions seem to be lessened.”

STRENGTHS/WEAKNESSES/DATA GAPS

- There is a great deal of conflicting data, possibly due to the inability to separate the effect of cetane from other parameters.

COMMENTS

- A comprehensive review on available literature of diesel fuel properties on the effect of emissions.

Study Reference No. C.6: Row, J., Doukas, A. 2008. “Fuel Quality in Canada Impact on Tailpipe Emissions.” Prepared by The Pembina Institute, Drayton Valley, Alberta, Canada T7A 1S7; Prepared for the Association of International Automobile Manufacturers of Canada.

GENERAL

- This study addresses levels of sulphur and detergency in gasoline, and cetane and lubricity in diesel fuel.
- The study compares Canadian fuel standards for these parameters to those in other jurisdictions, and reviews some test results.

TESTING PROGRAM

- Literature review.

RELEVANT RESULTS

- The study states that low cetane values lead to higher tailpipe emissions.
- An increase in cetane number from 40 to 45, or from 40 to 55 is stated to result in a reduction of NO_X emissions of 2.7% or 5.4%, respectively (for engines without engine [*sic*] gas recirculation).
- This conclusion was based on the US EPA 2003 Report No. EPA420-R-03-002 (The Effect of Cetane Number Increase Due to Additives on NO_X Emissions from Heavy-Duty Highway Engines).
- It is stated that studies from the European Program on Emissions, Fuels and Engine technologies (EPEFE) confirm these findings and also indicate that emissions of CO and HC are also reduced with increasing cetane.
- The study references European Program on Emissions, Fuels and Engine Technology. European Program on Emissions, Fuels and Engine Technologies Report, (1995). Cross referenced from "The Department of Heritage and the Environment, Australia. Measuring Cetane Number: Options for Diesel and Alternative Diesel Fuels, (Australia, 2004)".

STRENGTHS/WEAKNESSES/DATA GAPS

- The studies that this report relied on were based on engines manufactured prior to 2000, which did not have EGR. Thus the report is based on findings for relatively old technology vehicles only.
- The EPEFE work referenced in this report includes light-duty engines only, manufactured prior to 1995. It does in fact report reductions in CO and HC emissions with increasing cetane (50 to 58), but indicates no significant change in NO_X emissions. However, it indicates a significant increase in PM emissions with increasing cetane in direct injection engines. Thus this report does not clearly confirm the US EPA findings, nor is it true that higher cetane will reduce all emissions.

COMMENTS

- This report does not carry out any thorough literature review.

Study Reference No. C.7: Bunting, B.G. *et al*. 2008. The chemistry, properties, and HCCI combustion behavior of refinery streams derived from Canadian Oil Sands crude. *SAE Paper* 2008-01-2406.

GENERAL

- This study examined the effect of sands derived fuels on an HCCI combustion engine.

- One of the main reasons for interest in HCCI engines and other low temperature combustion strategy engines is the potential for improved fuel economy combined with reduced NO_X and particulate emissions.

TESTING PROGRAM

Fuels:

- Seventeen (17) refinery streams derived 100% from Canadian oil sands crude.
- Fuel cetane number varied from 32 to 55.

Vehicles/Engines:

- A single cylinder HCCI research engine derived from a Hatz D50Z diesel engine.
- Combustion phasing controlled by temperature control of intake air.

Test Method:

- No standard emission test cycle
- Experimental investigation on HCCI technology

RELEVANT RESULTS

- Premixed HCCI engines would provide optimum performance with fuels of low cetane number combined with lower boiling points.
- Higher cetane number fuels advance combustion phasing, resulting in the need to reduce intake air temperature and an increase in air-fuel ratio. This makes combustion with higher cetane number fuels more sensitive to expansion stroke quenching and requires earlier combustion phasing, driving the engine away from the point of optimum thermodynamic efficiency.
- NO_X emissions remained low when combustion phasing was adjusted to optimum levels, regardless of cetane number.
- Fuel cetane number remains the major fuel variable controlling combustion in HCCI engines.

STRENGTHS/WEAKNESSES/DATA GAPS

- The study did not focus of the effect of cetane on emissions, but rather on the effect of cetane on operation of an HCCI engine.

COMMENTS

- The results are applicable to emerging HCCI technology.

Study Reference No. C.8: Massa, C.V. *et al*. 2007. Influence of cetane number on Euro III engine emissions, *SAE Paper* 2007-01-2000.

GENERAL

- This study investigated the effect of cetane number on heavy-duty diesel Euro III technology engines for CN ranging from 42 to 48.
- The expectation was that increasing cetane would improve performance and emissions based on previous investigations over the last 15 years on Euro I and Euro II engines
- Brazilian fuel is generally much lower cetane than Europe (42 minimum).

- The study was designed to evaluate effect of cetane number only.

TESTING PROGRAM

Fuels:

- Seven tests fuels - three base fuels, with and without cetane number improver plus one reference commercial diesel.
- Other critical fuel properties (density, sulphur, T90) were maintained within a narrow range to minimize variables other than cetane number.

Vehicles/Engines:

- Two different technology engines from different manufacturers commonly used in Brazilian bus fleets.
- Both 4 cylinder, inline that meet Euro III standard.
- One with common rail injection and another with unit pump injection.

Test Method:

- European Stationary Cycle (ESC) for the certification of 2000 standard.
- Each test was performed three times.

RELEVANT RESULTS

- Specific fuel consumption, Bosch smoke, and emissions of CO, NO_X, HC, CO_2 and PM were evaluated
- Analysis of variance (ANOVA) and correlation was applied to evaluate significance of variations.
- The change in fuel cetane number from 42 to 48 did not have a significant impact on exhaust emissions or on fuel consumption.
- Concluded that for Euro III technology, increasing cetane number in the range 42 to 48 yields no environmental or fuel economy gains.

STRENGTHS/WEAKNESSES/DATA GAPS

- Results are applicable to heavy-duty on road vehicles meeting Euro III standards.
- Well designed to isolate effect of cetane number.

COMMENTS

- Euro III engines were generally no-EGR, no-after-treatment.

Study Reference No. C.9: Bunting, B.G., Wildman, C.B., Szybist, J.P., Lewis, S., Storey, J. 2007. Fuel chemistry and cetane effects on diesel homogeneous charge compression ignition performance, combustion, and emissions. *International Journal of Engine Research*. Vol. 8, No. 1, pp 15-27

GENERAL

- This study investigated the effects of cetane number on homogeneous charge compression ignition (HCCI) engine.

- Homogeneous charge compression ignition (HCCI) is of interest for internal combustion engines because it has the potential simultaneously to produce low NO_X emissions and low particulate matter (PM) emissions with diesel-like efficiency.

TESTING PROGRAM

Fuels:

- Blends of the diesel covering a cetane number range from 19 to 76.

Vehicles/Engines:

- A single-cylinder HCCI engine with port fuel injection, using intake air temperature for control.

Test Method:

- No standard emission test cycle
- Experimental investigation

RELEVANT RESULTS

- The study focused on the effect of the different fuels on combustion characteristics over a wide range of combustion phasing.
- When tuned to the combustion phasing that produced the highest power output, all experimental fuels provided satisfactory, low-NO_X operation.
- Fuels with cetane number from 40 to 50 provided the maximum power output;
- With higher-cetane fuels it became increasingly difficult to control combustion phasing late enough at higher engine loads.
- NO_X output does not appear to correlate with fuel cetane number.

STRENGTHS/WEAKNESSES/DATA GAPS

- This study covered a large cetane number range from 19 to 76.

COMMENTS

- The results apply to emerging HCCI technology.

Study Reference No. C.10: Zannis, T.C., Hountalas, D.T. 2007. Experimental study of diesel fuel effects on direct injection (DI) diesel engine performance and pollutant emissions. *Energy & Fuels*. Vol. 21, pp 2642-2654.

GENERAL

- An experimental investigation to specify the effect of diesel fuel composition, its physical and chemical properties, engine performance and pollutant emissions on direct injection diesel engine.

TESTING PROGRAM

Fuels:

- Seven test fuels to study mainly the effect of fuel density, viscosity, and compressibility factor.

Vehicles/Engines:

- DI diesel engine, a four-stroke, naturally aspirated, air-cooled engine.

Test Method:

- No standard emission test cycle
- Experimental investigation.
- Facilities to monitor and control engine variables were installed on a single-cylinder test-bed Lister LV1 experimental engine.
- Engine tests were conducted at a constant engine speed of 2500 rpm, and three different engine loads, namely, 20, 60, and 80% of full load.

RELEVANT RESULTS

- Emphasis was given on the effect of fuel physical properties, such as density, viscosity, and compressibility factor on diesel engine combustion characteristics and pollutant emissions.

STRENGTHS/WEAKNESSES/DATA GAPS

- Although the test fuels covered a range of cetane numbers, the study was not designed to investigate the effect of cetane, and there was no attempt to correlate emissions with cetane.

COMMENTS

- No conclusions can be drawn from this study on the effect of cetane number on emissions.

Study Reference No. C.11: Hara, S. et al. 2006. Effects of fuel properties on the performance of advanced diesel NO_X after-treatment devices. *SAE Paper* 2006-01-3443.

GENERAL

- This study investigated the effects of fuel properties on the performance of two diesel NO_X after-treatment devices

TESTING PROGRAM

Fuels:

- Three test fuels with sulphur content of 0, 10 and 50 ppm.

Vehicles/Engine:

- Two heavy-duty diesel engines with after-treatment devices: SCR and NCR

Test Method:

- Diesel 13 Mode Cycle (The 13-mode cycle replaced the older 6-mode cycle for the testing of heavy duty engines in Japan)
- JE05 mode (New transient driving cycle for emission testing from heavy-duty vehicles which replaced the 13-mode cycle.)
- Experimental investigation

RELEVANT RESULTS

- No discussion on cetane number effect on emissions.

STRENGTHS/WEAKNESSES/DATA GAPS

- No discussion on cetane number effect on emissions.

COMMENTS

- This study did not present any results on cetane number investigation.

Study Reference No. C.12: Li, D. *et al*. 2005. Physico-chemical properties of ethanol–diesel blend fuel and its effect on performance and emissions of diesel engines. *Renewable Energy*. Vol. 30, Issue 6, pp 967-976.

GENERAL

- This work evaluated the effects of different ethanol-diesel blended fuels on the performance and emissions.

TESTING PROGRAM

Fuels:

- Commercial diesel fuel and analysis-grade anhydrous ethanol.
- The presence of ethanol generates different physico-chemical modifications of the diesel fuel such as reductions of cetane number.

Vehicles/Engine:

- A single-cylinder Direct Injection (DI) diesel

Test Method:

- No standard emission test cycle.
- Experimental investigation

RELEVANT RESULTS

- When the engine is fueled with ethanol-diesel blend, the cetane number of the fuel will be reduced since ethanol has very low cetane number in comparison to diesel.
- Emissions were observed to change with the ethanol-diesel blend, but there was no assertion that this was a function of cetane number.

STRENGTHS/WEAKNESSES/DATA GAPS

- No conclusion with regard to cetane effects can be drawn from this study as the any changes in emissions may be dominated by the effect of oxygenated fuel rather than cetane number.

COMMENTS

- No conclusion can be drawn on the effect of cetane number on emissions.

Study Reference No. C.13: Lu, X.C. *et al*. 2005. Improving the combustion and emissions of direct injection compression ignition engines using oxygenated fuel additives combined with a cetane number improver. *Energy & Fuels*. Vol. 19, Issue 5, pp 1879-1888.

GENERAL

- Investigation of the effects of oxygen content in the blend fuels on diesel engine combustion and emissions.
- Also investigated the influence of a cetane improver on combustion of an ethanol-diesel blend

TESTING PROGRAM

Fuels:

- Three oxygenated fuels including ethanol, dimethyl carbonate (DMC), and dimethoxy methane (DMM) were selected to mix with diesel fuel.
- A cetane number improver was also tested with a 15%ethanol-diesel blend

Vehicles/Engine:

- A four-cylinder, four-stroke, direct injection compression ignition, 58kW diesel engine, with standard pump injection.
- No changes to injection timing or volume; i.e. standard diesel engine.

Test Method:

- No standard emission test cycle.
- Experimental investigation

RELEVANT RESULTS

- NO_X emissions decreased with addition of the oxygenated fuels, but CO and HC emissions increased. CO emissions decreased at high loads but increased at low and medium loads
- Adding a CN improver to the 15%ethanol-diesel blend gave a further reduction in NO_X, and reduced CO and HC emissions compared to the 15%ethanol-diesel blend.

STRENGTHS/WEAKNESSES/DATA GAPS

- The findings are applicable only to oxygenated fuel blends in standard diesel engines.
- There was no measurement or calculation of the cetane number of the blended fuels or of the blend with cetane number improver.
- It is difficult to distinguish whether the impact on emissions is due to oxygenated fuel or cetane number, therefore not relevant to the work.

COMMENTS

- No conclusion can be drawn on the effect of cetane number on emissions.

Study Reference No. C.14: Kono, N., Kobayashi, Y. Takeda, H. 2005. Fuel effects on emissions from diesel vehicles equipped with advanced after-treatment devices. *SAE Paper* 2005-01-3700.

GENERAL

- This study examined fuel effects on exhaust emissions from diesel vehicles equipped with advanced emission reduction technologies.

TESTING PROGRAM

Fuels:

- Eight test fuels with different fuel properties.
- Main focus was to vary properties of distillation range, aromatics content, and sulphur content.
- Cetane ranged from 48 to 69 (only two below 60, both at 48)

Vehicles/Engine:

- Three two tonne cargo trucks (GVW>3.5ton, heavy duty diesel category)vehicles were tested in this study:
    - Compliant to the Japanese Long Term Regulation (J-1998 Regulation) – equipped with distributor type high pressure fuel injection and EGR;
    - Compliant to the Japanese New Short Term Regulation (J-2003 Regulation) – common rail high pressure fuel injection, cooled EGR and diesel oxidation catalyst (DOC); and
    - Compliant to the J-2003 Regulation - common rail high pressure fuel injection, cooled EGR, and NSR.

Test Method:

- JC08 chassis dynamometer test cycle (New Japanese urban driving cycle for emission and fuel economy measurements of light-duty vehicles, which will fully replace the 10-15 mode cycle by 2011).

RELEVANT RESULTS

- In general, fuel effects on emissions are small compared to the effect of the new technologies.
- The main conclusions were:
    - Advanced engine system technologies for reduced emissions are very effective for NO_X reduction but the fuel effects are very small;
    - Fuel parameters can reduce PM at engine outlet, and improve the reliability and durability of a DPF due to reduced loading;
    - An oxidation catalyst is effective for reducing THC and NMHC, while some reformulated fuels showed higher emissions; and
    - An oxidation catalyst with sufficient activity is effective for reducing CO, while some reformulated fuels showed higher emissions.

STRENGTHS/WEAKNESSES/DATA GAPS

- The evaluation of fuel properties was limited to distillation ranges, aromatic content and sulphur content.
- The authors did not comment on the influence of cetane on emissions, since the variations in cetane number corresponded to other important changes in fuel parameters.

- This study did not isolate the effect of cetane number; other parameters were varied to a large degree in the test fuels.

COMMENTS

- Although cetane number varied widely (two fuels at 48 and remainder above 60) visual inspection of graphical presentations does not show clear correlation with emissions.

Study Reference No. C.15: Murphy, M.J, Taylor, J.D., McCormick, R.L. 2004. “Compendium of Experimental Cetane Number Data.” National Renewable Energy Laboratory, Report No. NREL/SR-540-36805.

GENERAL

- This report presents a compilation of reported cetane numbers for pure chemical compounds.
- No discussion on the effect of emissions relative to cetane number.

Study Reference No. C.16: CRC 2004. “The Effect of Fuel Cetane Quality on Light-Duty Diesel Performance.” Prepared by Shell Global Solutions (UK), Prepared for Coordinating Research Council, CRC Project No. AVFL-11.

GENERAL

- To determine the effect of fuel cetane number on light-duty diesel performance.

TESTING PROGRAM

Fuels:

- Eight fuels with cetane number from 40 to 55

Vehicles/Engine:

- Four High Speed Direct Injection (HSDI) passenger vehicles for the European market:
    - Toyota Avensis D-4D Euro IV 2003
    - Mazda 6 TS Euro III 2003
    - VW Lupo TDi PD Euro III 2003
    - VW Golf TDI PD Euro III 2003

Test Method:

- The testing uses CEC-M-11-T-91 (cold weather performance test procedure for diesel vehicles), subsequently referred to as M11, to evaluate cold start-ability and CEC M-08-T-83 (cold weather drivability test procedure), and subsequently referred to as M08, directly after the cold start to evaluate cold drivability.

RELEVANT RESULTS

- Modern vehicles equipped with solenoid controlled, high pressure DI fuel systems are less sensitive to changes in cetane number than older technology vehicles.
- Lowering cetane number increases cold start smoke. This correlation is stronger at lower temperatures.

- As the test time increases, the smoke/cetane relationship changes. Smoke values from a partially warmed engine are more likely to be higher with higher cetane number fuels.
- There was some indication that additized cetane gave better performance than natural cetane, but the data was limited and the authors concluded the result was coincidental.

STRENGTHS/WEAKNESSES/DATA GAPS

- No measurements of HC, CO, or NO_X.

COMMENTS

- The study was focused on engine performance only.

Study Reference No. C.17: US EPA 2003. "The Effect of Cetane Number Increase Due to Additives on NO_X Emissions from Heavy-Duty Highway Engines: Final Technical Report." Office of Transportation and Air Quality, United States Environmental Protection Agency, EPA420-R-03-002.

GENERAL

- A technical analysis of the NO_X emissions impacts due to increases in cetane number through the use of diesel fuel additives.
- The purpose is to provide information to parties who may be evaluating the value, effectiveness, and appropriateness of the use of cetane improver additives.

TESTING PROGRAM

- No test program was carried out.
- Results are based on existing data set and literature review.

RELEVANT RESULTS

- Based on statistical analysis of the data, NO_X emissions decreased with increase in cetane number.
- This does not apply to two cycle engines or engines with EGR.
- The study states EGR-equipped engines are expected to exhibit no discernable NO_X response to cetane, based on testing done by the Heavy-Duty Engines Workgroup under the auspices of the Mobile Source Technical Review Subcommittee.

STRENGTHS/WEAKNESSES/DATA GAPS

- All data was from heavy-duty engines built in the 1990s (average model year of 1994), and specifically excluded any 2 cycle engines and engines with EGR
- No detailed description of engines in database – prior work referenced.

COMMENTS

- This study is based on relatively old engines (1990s).
- The results do not apply to engines with EGR, so do not apply to the bulk of engines in production today.

Study Reference No. C.18: Içngür, Y., Altiparmak, D. 2003. Effect of fuel cetane number and injection pressure on a DI diesel engine performance and emissions. *Energy Conversion and Management*. Vol. 44, Issue 3, pp 389-397.

GENERAL

- This study investigated the effects of different fuel cetane number and fuel injection pressures on a diesel engine emission and performance.

TESTING PROGRAM

Fuels:

- Fuel cetane number with 46, 51, 54.5 and 61.5. All with sulphur >250ppm.

Vehicles/Engine:

- A four cycle, four cylinders DI Diesel engine.

Test Method:

- No standard Emission Test Cycle.
- Experimental Investigation
- Measurements were conducted for each of the injection pressures 100, 150, 200 and 250 bar.

RELEVANT RESULTS

- NO_X, SO_2 emissions were reduced when the fuel cetane number was increased for the standard injection pressure (150 bar).
- CO emissions were increased at some engine speeds when the fuel cetane number was increased for the standard injection pressure (150 bar).
- Smoke level increases with increasing cetane.
- Reduction in emissions and improvement in performance are more sensitive to cetane number values between 46 and 54.5

STRENGTHS/WEAKNESSES/DATA GAPS

- The presented data showed substantial scatter, with no analysis for significance.

COMMENTS

- The study may be representative of old technology vehicles (no EGR) vehicles.
- There is no indication of engine technology, other than four cycle, direct injection: therefore assume that it must be typical of pre-2000 DI engines (paper was submitted in 2001) with no EGR.

Study Reference No. C.19: Bielaczyc, P., Kozak, M., Merkisz, J. 2003. Effects of fuel properties on exhaust emissions from the latest light duty DI diesel engine. *SAE Paper* 2003-01-1882.

GENERAL

- This experimental program was carried out to investigate the effects of varying fuel properties on emissions.

- The fuel properties include variations in cetane number.

TESTING PROGRAM

Fuels:

- Four different fuels for cetane number: 45, 50, 55 and 63.

Vehicles/Engine:

- Passenger car equipped with a 2.0 l, 4 cylinder engine, with common rail direct injection (DI), turbocharger (intercooled), EGR, and oxidation catalysts. Calibrated to the Euro III standard.

Test Method:

- ECE+EUDC test cycle (This cycle is used for emission certification of light duty vehicles in Europe).

RELEVANT RESULTS

- Increasing cetane from 45 to 63 reduced CO emissions by 26%.
- Increasing cetane from 45 to 63 reduced HC emissions by 25%.
- Increasing cetane from 45 to 63 slightly reduced NO_X emissions (3 to 4%). NO_X emissions reduced only for UDC phase (The UDC cycle is an urban driving cycle).
- There was no direct correlation relation between cetane number and PM emissions, but lowest emissions were from the lower cetane fuel.

STRENGTHS/WEAKNESSES/DATA GAPS

- A single test vehicle was used.
- Cetane number was varied through use of different fuels. Other parameters varied as well, and may have influenced results.

COMMENTS

- Based on inspection of the graphical presentation, increasing cetane from 45 to 55 had no impact on NO_X emission. NO_X emission was slightly lower for the 63 CN fuel test. Thus the conclusion is based on one data point.

Study Reference No. C.20: Nakakita, K. et al. 2003 Effect of hydrocarbon molecular structure in diesel fuel on in-cylinder soot formation and exhaust emissions. *SAE paper* 2003-01-1914.

GENERAL

- This study evaluated exhausts emissions and combustion characteristics using three single-cylinder high speed direct-injection (HSDI) diesel engines.

TESTING PROGRAM

Fuels:

- Six fuels with cetane number ranging from 48.9 to 80.5.
- Other fuel parameters varied as well.

Vehicles/Engines:

- Two types of common rail, high-speed, direct injection single-cylinder engines; one supercharged and intercooled
- One optically accessible diesel engine.

Test Method:

- ECE+EUDC test cycle (This cycle is used for emission certification of light duty vehicles in Europe).
- Experimental investigation

RELEVANT RESULTS

- Equations were fit to the test data, with the best fit for regression variables for cetane, aromatic rings and naphthalene rings.
- The regression coefficient for cetane was positive, indicating an increase in cetane will result in an increase in PM emission, all other variables held constant.

STRENGTHS/WEAKNESSES/DATA GAPS

- The test program is limited to single cylinder research engines.

COMMENTS

- None

Study Reference No. C.21: Neill, W.S. et al. 2003 Emissions from heavy-duty diesel engine with EGR using fuels derived from oil sands and conventional crude. *SAE Paper* 2003-01-3144

GENERAL

- This study compared the emissions behavior of the 12 test fuels in a prototype year 2004 heavy-duty diesel engine.
- The objectives were to determine whether or not PM and NO_X emissions from a modern diesel engine are influenced by crude oil source and total aromatic content.

TESTING PROGRAM

Fuels:

- 12 diesel fuels derived from oil sands and conventional sources.
- The cetane numbers were held constant at 43.

Vehicles/Engines:

- A single-cylinder version of Caterpillar’s 3400-series heavy-duty diesel engine
- The base engine is representative of Caterpillar’s engine technology for the 1994-1997 model years.
- Engine was equipped with electronic fuel injection, high levels of turbo-charging, and EGR.

Test Method::

- The AVL eight-mode steady-state simulation

- The AVL 8-Mode is designed to closely correlate with the exhaust emission results over the US FTP heavy-duty engine transient cycle.

RELEVANT RESULTS

- PM and NO_X emissions from the research engine were affected by key fuel compositional properties.
- PM and NO_X emissions from the research engine were not affected by the crude oil source.

STRENGTHS/WEAKNESSES/DATA GAPS

- This study did not evaluate the effect of cetane number on emissions, therefore not relevant to the study.

COMMENTS

- None

Study Reference No. C.22: Oyama, K., Kakegawa, T. 2003. Evaluation of diesel exhaust emission of advanced emission control technologies using various diesel fuels, and sulphur effect on performance after mileage accumulation - JCAP Diesel WG (Fuel) Report for Step II Study. *SAE Paper* 2003-01-1907.

GENERAL

- This study investigated different diesel emission control and fuel technologies as well as emissions tests using various fuels.

TESTING PROGRAM

Fuels:

- Eleven test fuels.
- Cetane number of 47 and 54 compared by two kerosene fuels of otherwise similar composition, in vehicles 1 to 3 below, only.

Vehicles/Engines:

- Six engines/vehicles were tested
  - One passenger car vehicle with NSR catalyst, common rail injection, and cooled EGR.
  - One passenger car vehicle with Fibre type CR-DPF, VGT, distributor injection, and EGR.
  - One passenger car vehicle with NSR catalyst + CR-DPF, common rail injection, and cooled EGR.
  - One small truck engine with LPL-EGR, CR-DPF, distributor injection, and LPL cooled EGR.
  - One large truck engine with CR-DPF + Urea-SCR, and common rail injection (no EGR).
  - One small truck engine with NSR catalyst, common rail injection, and LPL cooled EGR.

Test Method:

- 10-15 mode (vehicles)
- D13 mode (engines)
- European Transient Cycle
- World-wide Heavy-Duty Engine Cycle
- New Japanese Heavy-Duty Transient Cycle

RELEVANT RESULTS

- The results for passenger cars with the change in cetane number from 47 to 54 were as follows:
    - No significant change in NO_X and PM emissions for the vehicle with NSR catalyst and cooled EGR.
    - No significant change in NO_X emissions while PM emissions increased by 13% for passenger car vehicle with Fibre type CR-DPF and EGR
    - No significant change in NO_X and PM emissions passenger car vehicle with NSR catalyst, CR-DPF and cooled EGR

STRENGTHS/WEAKNESSES/DATA GAPS

- None

COMMENTS

- The influence of cetane number is vehicle/technology specific.
- No significant change is a change less than 10%. Visual inspection of the graphical presentation indicates that where "no significant change" is reported, some emissions increased and some decreased with increasing cetane number.

Study Reference No. C.23: Khalek, I.A., Ullman, T. L., Vasquez, L., Guerrero, M. 2002. Hot-start transient emissions from a Mercedes OM 366 LA and a Detroit Diesel operated on Chilean, California, and US 2D fuels. *SAE Paper* 2002-01-2827.

GENERAL

- This study investigated the emission performance of a 1997 Mercedes OM 366 LA medium heavy-duty diesel engine and a 1998 Detroit Diesel Corporation (DDC) series heavy heavy-duty diesel engine

TESTING PROGRAM

Fuels:

- Fourteen test fuels with cetane number varying from 45.1 to 62.3.

Vehicles/Engines:

- In this program two on-road heavy-duty diesel engines were tested:
    - 1997 Mercedes OM 366 LA medium heavy-duty diesel engine – 210hp, turbocharged, mechanical distributor injection pump.
    - 1998 Detroit Diesel Corporation (DDC) Series 60 heavy-duty diesel engine – 400hp, turbocharged, electronic unit injector.

Test Method:

- US EPA Heavy-Duty FTP Transient Cycle

RELEVANT RESULTS

- Decreasing trend in NO_X and HC emissions for increasing cetane number from 49 to 63
    - Mercedes engine showed greater NO_X reduction in comparison to DDC
    - DDC engine showed greater HC reduction in comparison to Mercedes engine.
- No general trend for PM emissions
    - Mercedes engine showed an increase in PM emissions with increase in cetane number.
    - DDC engine showed poor correlation between PM emissions and cetane number.

STRENGTHS/WEAKNESSES/DATA GAPS

- Results are applicable to older technology heavy-duty diesel engines.

COMMENTS

- None

Study Reference No. C.24: CONCAWE 2002. “Evaluation of Diesel Fuel Cetane and Aromatics Effects on Emissions from Euro-3 Engines.” Report No. 4/02, Brussels.

GENERAL

- This study investigated impact on emissions of aromatics content (mono- versus poly) and cetane number (natural versus additive-derived) on Euro III vehicles.

TESTING PROGRAM

Fuels:

- Six test fuels with cetane number ranging from 51.1 to 58.3

Vehicles:

- Three light duty vehicles for the European market:
    - All with direct injection technology, non-cooled EGR, and enhanced oxidation catalysts; and
    - One with each of common rail fuel injection, unit injectors, and a mechanical pump.
- Two heavy duty engine vehicles for the European market:
    - both direct injection, turbocharged and after-cooled;
    - one with in-line pump and no EGR; and
    - one with unit injectors and cooled EGR.

Test Method:

- Euro-3 MVEG test cycle for passenger cars;
- ESC cycle (European Steady-state Cycle);
- ELR cycle (dynamic load response test for smoke); and
- ETC cycle (European Transient Cycle).

RELEVANT RESULTS

- The fuel effects studied (cetane and aromatics) were generally small compared to engine technology effects and test variability.
- Different vehicles may respond to the same fuel changes in different ways.
- Increasing cetane number (from 53 to 58) had no significant effect on NO_X or PM emissions in either the heavy-duty engines or light-duty vehicles tested.
- Increasing cetane number directionally reduced HC and CO emissions.
  - For the heavy-duty engines, cetane effects on HC emissions were not significant, and only one engine showed a significant cetane effect on CO emissions.
  - For the light-duty vehicles statistically significant reductions were seen in all but one case.
- No emissions differences were seen between natural cetane fuels and those where the cetane number was boosted using ignition improver additive.

STRENGTHS/WEAKNESSES/DATA GAPS

- None

COMMENTS

- The results apply to only Euro III or newer technology vehicles.

Study Reference No. C.25: Kwon, Y. et al. 2001. Fuel effects on diesel emissions - a new understanding. *SAE Paper* 2001-01-3522.

GENERAL

- This study describes fuel effects on engine-out emissions from a European light-duty diesel engine.

TESTING PROGRAM

Fuels:

- Four fuel matrices including one for cetane number ranging from 40 to 70.

Vehicles/Engine:

- A Rover, L-Series, turbocharged, 4 cylinder, in-line, direct injection (DI) light-duty engine with rotary fuel injection and EGR.
- Bosch electronic control retained, but feedback replaced by test bed controls to maintain injection timing and EGR rate strictly at manufacturer’s settings for each speed and load.

Test Method:

- ECE+EUDC test cycle (This cycle is used for emission certification of light duty vehicles in Europe).
- Special test bed to maintain constant timing and EGR rate.

RELEVANT RESULTS

- “Large changes in the fuel parameters investigated in this study resulted in relatively small engine-out emissions.”

- Increasing cetane number resulted in increased PM emissions.
- Increasing cetane number showed a slight reduction in NO_X emissions in some cases, but the authors concluded that NO_X emissions were relatively insensitive to fuel changes.
- Increasing cetane number resulted in reduced HC and CO emissions.
- The type of cetane number improver used had little influence on results.

STRENGTHS/WEAKNESSES/DATA GAPS

- A single test engine, but sophisticated controls that should eliminate the distorting effects of engine calibration changes within fuels. Therefore results should be less dependent on engine make and type.

COMMENTS

- None

Study Reference No. C.26: US EPA 2001. "Strategies and Issues in Correlating Diesel Fuel Properties with Emissions: Staff Discussion Document." Office of Transportation and Air Quality, United States Environmental Protection Agency, EPA420-P-01-001.

GENERAL

- This report describes technical issues related to an assessment of the effect of changes in diesel fuel parameters on the emissions of HC, CO, PM, NO_X, and toxics.
- This report analyzed a large data set (75 engine tests) to model the effect of fuel properties on emissions of heavy-duty engines.
- The report reviewed other studies for findings on light duty engines.

TESTING PROGRAM

- Literature review.

RELEVANT RESULTS

- Light-Duty Conclusions:
    - Some investigators found a correlation between cetane number and NO_X emissions, while other research groups found no significant fuel effects for NO_X emissions over a wide variation in fuel composition.
    - In addition to fuel effects on PM and NO_X emissions, several investigators observed that an increase in the cetane number resulted in a reduction of both HC and CO emissions.
    - The studies also showed that engines with different technologies would respond differently to changes in fuel properties.
    - The varied engine responses may have partly attributed to inconsistencies among various findings in fuel effects on pollutant emissions.
    - The EPEFE study demonstrated that fuel properties such as density or cetane number on the extent of NO_X emissions clearly depended on the engine design: DI engine fleets (mostly electronically controlled) had responded in the opposite direction compared to the IDI (mostly mechanically controlled) engines.
    - The investigators also presented results indicating that the amount of pollutant emissions would, in some instances, strongly depend on the engine technologies on the vehicle.

  - A 1996 EPEFE study [see also reference C.33] was reviewed, which concluded that increasing CN decreased benzene and 1,3 butadiene in line with THC, and also decreased acetaldehyde and formaldehyde emissions.
- Heavy-Duty Conclusions:
  - Model predicts cetane number increase of 5 will give 0 to 1.5% reduction in NO_X, 2% reduction in PM, and 15 to 17% reduction in HC.
  - Two related studies (1993,1994) that were reviewed looked at effect of increasing cetane number using improvers on emissions of a 1991 DDC Series 60 Engine. CN increases of 9 to 16 gave HC reductions of 40 to 75%. Toxic reductions were in line with reductions in hydrocarbon emissions. Toxics measured included Acetaldehyde, Acetone, Acrolein, Benzaldehyde, Benzene, 1,3-Butadiene, Crotonaldehyde, Formaldehyde, Hexanaldehyde, Isobutyraldehyde + MEK, and Propionaldehyde

STRENGTHS/WEAKNESSES/DATA GAPS

- Applicability is extremely limited due to the age of the dataset.
- Although this report presents findings from a large dataset, it included only one engine with EGR.

COMMENTS

- This study is based on relatively old engines (1990s).
- The results do not apply to engines with EGR, so do not apply to the bulk of engines in production today.

Study Reference No. C.27: Matheaus, A.C. et al. 2000. EPA HDEWG Program - Engine Tests Results. *SAE Paper* 2000-01-1858.

&

Study Reference No. C.28: Mason, R.L. et al. 2000. EPA-HDEWG Program – Statistical Analysis. *SAE Paper* 2000-01-1859.

GENERAL

- This study was designed to determine the effects of fuel properties on NO_X emissions from heavy-duty diesel engines, designed to meet 2004 emissions standards
- A goal was to identify key fuel parameters, including cetane, and their effects on emissions.

TESTING PROGRAM

Fuels:

- A statistically designed fuel matrix of 18 fuels.
- Cetane numbers were varied from 42 to 52

Vehicles/Engines:

- Caterpillar 3176 truck engine with 1994 calibration.
- Turbocharged, after cooled, 4 valve/cyl., unit injector.
- Modified to add LPL-EGR

- Most tests with EGR, a few tests without EGR.

Test Method:

- AVL 8-Mode (The AVL 8-Mode test is a steady-state engine test procedure, designed to closely correlate with the exhaust emission results over the US FTP heavy-duty engine transient cycle).

RELEVANT RESULTS

- An increase in fuel cetane number from 42 to 52 (with EGR) resulted in:
  - an increase in NO_X emissions of 1.3%;
  - a decrease in HC and CO emissions of 12 and 13% respectively; and
  - no impact on fuel consumption.
- There was no significant difference between emissions from otherwise identical natural or boosted cetane fuels, with or without EGR.
- The effect of EGR is very large in comparison to fuel effects.
- The author states that a very low sensitivity to cetane number was demonstrated for the engine with EGR, which differs significantly from other studies on engines without EGR.

STRENGTHS/WEAKNESSES/DATA GAPS

- A single test engine, but prior work done to establish it is characteristic of several manufacturers' prototype engines.
- A very detailed test design and statistical analysis to isolate effects of individual fuel parameters.

COMMENTS

- None

Study Reference No. C.29: Mitchell, K. 2000. Effects of fuel properties and source on emissions from five different heavy-duty diesel engines. *SAE Paper* 2000-01-2890.

GENERAL

- This study reviewed the results of three programs to evaluate effects of fuel properties and source on exhaust emissions from post 1994 heavy-duty diesels.

TESTING PROGRAM

Fuels:

- Review of other test programs only.
- Fifteen fuels, varying in aromatics content and source (oil sands crude or conventional).

Vehicles/Engines:

- All heavy-duty engines with Direct Injection
- Three production engines, turbocharged with unit injectors:
  - One 1996 Detroit Diesel Series 50, 8.5 L, 4 cylinder
  - One 1995 Caterpillar 3406E, 14.6L, 6 cylinder
  - One 1995 Cummins N14-460, 14L, 6 cylinder
- One modified 1994 (DI) Caterpillar 3476, turbocharged with unit injectors and LPL-EGR added. Designed to meet 2004 emission standards.

- One single –cylinder research engine, with pump-line-nozzle injection

Test Method:

- AVL 8-Mode (The AVL 8-Mode test is a steady-state engine test procedure, designed to closely correlate with the exhaust emission results over the US FTP heavy-duty engine transient cycle)..

RELEVANT RESULTS

- NO_X emissions correlated with cetane number in all five engines, but there was no consistent trend: two engines showed increase in NO_X with increase in cetane number while three showed a reduction in NO_X emissions.
- The use of EGR can reduce NO_X emissions by half.
- There was little commonality in the effect of fuel quality on HC and CO emissions measured in any of the engines.
- PM emissions were related to sulphur and density, but there was no fuel effect in two engines.

STRENGTHS/WEAKNESSES/DATA GAPS

- For some test results in this review, several fuel parameters varied simultaneously, therefore it is difficult to conclude that any reported effect is due to cetane number only

COMMENTS

- None

Study Reference No. C.30: CONCAWE 1999. “Fuel Quality, Vehicle Technology and Their Interactions.” Report No. 99/55, Brussels.

GENERAL

- The report reviews the interactions between fuels, vehicle technology, test cycles and reference fuels with regard to their relative influences on vehicle emissions, fuel consumption, CO_2, durability and customer acceptance.

TESTING PROGRAM

- Literature review

RELEVANT RESULTS

- The study concludes that effects of fuel changes alone on emissions and performance are relatively small, but benefits arise when they are used to enable new technologies.
- The fuels and engines need to be developed together as a common system.

STRENGTHS/WEAKNESSES/DATA GAPS

- This work is based on pre-1999 data, so may no longer be applicable in some aspects.

COMMENTS

- None

Study Reference No. C.31: Lee, R., Pedley, J., Hobbs, C. 1998. Fuel quality impact on heavy duty diesel emissions - a literature review." *SAE Paper* 982649.

GENERAL

- The purpose of the study was to review the available literature on the effects of diesel fuel quality on regulated emissions.
- Focuses on fuel property changes on heavy-duty diesel engines designed to meet 1991 to 1998 emission limits.

TESTING PROGRAM

- Literature review.

RELEVANT RESULTS

- The paper specifically excludes consideration of non-production (at that time) technologies such as oxidation catalysts or EGR.
- Most studies show that both natural and improved cetane (through additives) have similar results.
- Literature showed that increasing cetane number either reduced HC emissions or has no effect.
- Their analysis showed that those engines designed to emit less than 0.2 g/bhp-hr HC were largely insensitive to cetane number while engines with less stringent standards values showed reduction in HC emissions.
- Similar to HC, engines certify to emit less CO shows very small or no reduction while engines with less stringent emission standard shows greater CO reduction with increase in cetane number.
- There is no trend in cetane number versus PM emissions.
- In high NO_X producing engines increasing cetane number will reduce NO_X, but in low NO_X producing engines the reduction will be smaller, or there will be no effect.

STRENGTHS/WEAKNESSES/DATA GAPS

- The review is outdated, and does not include current or recent engine technologies.

COMMENTS

- None

Study Reference No. C.32: Ryan, T.W., Buckingham, J., Dodge, L. G., Olikara, C. 1998. The effects of fuel properties on emissions from a 2.5 gm NOX heavy duty diesel engine. *SAE Paper* 982491.

GENERAL

- This study evaluated different technologies to meet future emission standards, and the effect of fuel properties on emissions.

TESTING PROGRAM

Fuels:

- Thirteen different fuels with varying cetane number 35 to 45, aromatic content and poly-aromatic contents.

Vehicles/Engines:

- Modified Caterpillar 3176 engine with LPL-EGR added.
- Electronic unit injector with modified timing.

Test Method:

- US EPA Heavy-Duty FTP Transient Cycle.

RELEVANT RESULTS

- There was no correlation between cetane number and NO_X or PM emissions

STRENGTHS/WEAKNESSES/DATA GAPS

- Results are based on one research engine only.
- More than one fuel properties varied therefore difficult to assess the impact of cetane number alone.

COMMENTS

- None

Study Reference No. C.33: Hublin, M., Gadd, P. G., Hall, D. E., Schindler, K. P. 1996. European Programs on Emissions, Fuels and Engine Technologies (EPEFE) light duty diesel study. *SAE Paper* 961073.

GENERAL

- This study reported the results obtained in the European Programs on Emissions, Fuels and Engine Technologies (EPEFE) program on the relationship between diesel fuel properties and light-duty vehicle technologies.
- The following area were investigated:
    - Effect of fuel properties on engine parameters; and
    - Effect on exhaust emissions of new vehicle technology

TESTING PROGRAM

Fuels:

- Eleven test fuels with fuel cetane number from 50 to 58

Vehicles/Engines:

- Nineteen light-duty European vehicles with a wide range of technology with emission level below 1996 European standards.
- Both DI and IDI vehicles with and without EGR were included.

Test Method:

- ECE15+EUDC test cycle

RELEVANT RESULTS

- Increasing cetane number from 51 to 58 decreased CO and HC.
- Increasing cetane number from 51 to 58 increased PM.
- Increasing cetane number from 51 to 58 has no effect on NO_X.
- Increasing cetane number reduces benzene and 1,3 butadiene emissions in line with effects on THC.
- Increasing cetane number reduces aldehyde emissions (formaldehyde and acetaldehyde).

STRENGTHS/WEAKNESSES/DATA GAPS

- Applicable to older technology anticipated to meet emissions standards in beyond 1996.

COMMENTS

- One of the few studies to consider effect of cetane number on toxics.

Study Reference No. C.34: Signer, M., Heinze, P., Mercogliano, R., Stein, H.J. 1996. European Program on Emissions, Fuels and Engine Technologies (EPEFE) Heavy Duty Diesel Study *SAE Paper* 961074.

GENERAL

- This study reported the results obtained in the European Programs on Emissions, Fuels and Engine Technologies (EPEFE) program on the relationship between diesel fuel properties and heavy-duty vehicle technologies.

TESTING PROGRAM

Fuels:

- Eleven test fuels with fuel cetane number from 50 to 58

Vehicles/Engines:

- Five 1996 heavy-duty diesel engines with advanced technology – most prototype.
- All direct injection (pump-line-nozzle), turbocharged and intercooled.

Test Method:

- 88/77 EEC test cycle

RELEVANT RESULTS

- Increasing cetane number from 51 to 58 decreased CO and HC
- Increasing cetane number from 51 to 58 had no significant effect on PM or NO_X emissions.

STRENGTHS/WEAKNESSES/DATA GAPS

- Applicable to older technology anticipated to meet emissions standards in beyond 1996.

COMMENTS

- None

Study Reference No. C.35: Ladommatos, N., Parsi, M., Knowles, A. 1996. The effect of fuel cetane improver on diesel pollutant emissions. *Fuel.* Vol. 75, Issue 1, pp 8-14.

GENERAL

- This study investigated the effect of fuel cetane improver on diesel pollutant emissions.

TESTING PROGRAM

Fuels:

- One base fuel of cetane number 40.2, cetane improver ethyl hexyl nitrate was added progressively.
- Nine batches of fuel.
- Cetane number varied between 40.2 to 62.

Vehicles:

- A single cylinder, indirect injection (IDI) research engine.

Test Method:

- Experimental investigation

RELEVANT RESULTS

- The increase in cetane number reduced NO_X and HC emissions
- The increase in cetane increased smoke emissions

STRENGTHS/WEAKNESSES/DATA GAPS

- A single, non-production test engine
- The study does not represent recent engine technology.

COMMENTS

- None

Study Reference No. C.36: Tsurutani, K., Takei, Y., Fujimoto, Y., Matsudaira, J., Kumamoto, M. 1995. The effects of fuel properties and oxygenates on diesel exhaust emissions. *SAE Paper* 952349.

GENERAL

- This study carried out investigation of the effects of diesel fuel properties on emissions for a light-duty vehicle.

TESTING PROGRAM

Fuels:

- Eight test fuels with varying fuel parameters including cetane number.
- Effect of cetane evaluated by addition of cetane improver.

Vehicles/Engines:

- A Toyota Corolla with a 2.0L, direct injection(DI) diesel with EGR, and
- A 4.0L direct injection (DI) light-duty diesel engine without EGR.

Test Method:

- Japanese 10-15 urban driving cycle for emission certification and fuel economy determination of light-duty vehicles
- ECE+EUDC

RELEVANT RESULTS

- In the DI engine, cetane improver had no effect on PM and NO_X emissions.
- In the IDI vehicle:
    - there was limited reduction on PM emissions for the ECE+EUDC cycle using cetane improver for low cetane number fuels; and
    - cetane level had no effect on NO_X emissions.

STRENGTHS/WEAKNESSES/DATA GAPS

- The test vehicle and engine represent relatively old technology.

COMMENTS

- The results may have influenced by other fuel properties rather than cetane number alone.

Study Reference No. C.37: Den Ouden, C.J.J. et al. 1994. Fuel quality effects on particulate matter emissions from light- and heavy-duty diesel engines. *SAE Paper* 942022.

GENERAL

- This study provides an update on correlations between diesel fuel quality and particulate emissions for light- and heavy-duty vehicles.
- The study reviews previous work, and adds some new test data.

TESTING PROGRAM

Fuels:

- For heavy-duty engines 30 fuels
- For light-duty vehicles over 40 fuels

Vehicles/Engines:

- Mix of turbocharged, catalysts/non-catalysts 20 IDI and 2 DI light-duty vehicles
- Five heavy-duty diesel engines

Test Method:

- Japanese 13-mode steady-state test cycle for heavy-duty engines
- EUC-EUDC European light-duty cycle
- US EPA UDDS (FTP)

RELEVANT RESULTS

- Increase in cetane number for light-duty vehicles:
    - Increased cetane number did not significantly change PM emissions from catalyst or no-catalyst vehicles.

- For heavy-duty engines, the effect of CN was engine dependent. Increase in CN reduced PM emissions on three of five engines, with no effect on the other two.

STRENGTHS/WEAKNESSES/DATA GAPS

- The test vehicle and engine represent relatively old technology.

COMMENTS

- None

Study Reference No. C.38: CONCAWE 1994. "The Effect of Diesel Fuel Properties on Exhaust Emissions from Catalyst Equipped Diesel Passenger Vehicles - Part 2." Report 94/56, Brussels.

GENERAL

- This study evaluated the influence of diesel fuel properties and oxidation catalyst on emissions.

TESTING PROGRAM

Fuels:

- Six blends based on European commercial fuel.
- Cetane improver used to vary cetane

Vehicles/Engines:

- Six European light-duty vehicles, 1.8 to 2.5L, mainly IDI and turbocharged.

Test Method:

- ECE-15+ EUDC

RELEVANT RESULTS

- Without the catalyst in place, increasing cetane reduced PM emissions.
- With the catalyst in place, the effect of increasing cetane on PM emissions was negligible.
- Without the catalyst in place, increasing cetane reduced HC and CO emissions in most vehicles. The effect was reduced with the catalyst in place. Two vehicles were insensitive to cetane number with or without catalyst.

STRENGTHS/WEAKNESSES/DATA GAPS

- The test vehicle and engine represent relatively old technology.

COMMENTS

- None

Study Reference No. C.39: Tritthart, P., Cichocki, R., Cartellieri, W. 1993. Fuel effects on emissions in various test cycles in advanced passenger car diesel vehicles. *SAE Paper* 932684, 1993.

GENERAL

- This study evaluated the influence of diesel fuel properties and oxidation catalyst on emissions.
- No conclusion drawn on linking exhaust emissions to cetane number.

Appendix D: Diesel – Lubricity Effects Reviews

Study Reference No. D.1: Matzke, M. *et al*. 2009. Diesel Lubricity Requirements of Future Fuel Injection Equipment. *SAE Paper* 2009-01-0848.

GENERAL

- The composition of diesel fuel has a strong impact on fuel injection equipment.
- Several different types of lubricity additives are added to the diesel fuel to increase its lubricity.
- Modern diesel engines in light-duty vehicles are equipped with common rail fuel injection systems.
- Modern diesel equipments are no longer use distributor type fuel pumps.
- The aim of this study was to investigate:
    - the tribological behaviour and the failure mechanism of different fuel compositions in a highly-loaded contact;
    - whether current fuels and lubricity additives can provide wear protection under more severe tribological conditions; and
    - assess whether the HFRR test has the potential to reproduce these more severe tribological conditions..

TESTING PROGRAM

Fuels:

- Four different commercial base fuel:
    - One Swedish Class I diesel fuel (Class 1) – WSD on HFFR = 699 µm;
    - Two ultra low sulphur diesel (ULSD) – exceeded European standard for lubricity, i.e. < 460 µm WSD on HFFR (WSD on HFFR were approximately between 520 and 600µm; and
    - One ULSD with a biodiesel content of 5% (B5) Rapeseed-Methyl Ester (RME) – WSD on HFFR = 236 µm.
- Four different commercially available lubricity additives:
    - Acid based;
    - Amide based;
    - Ester based; and
    - Ester based designed for regions with extremely cold climates.

Testing Method:

- Two test methods were used for lubricity determination:
    - The High-Frequency Reciprocating Rig (HFRR); and
    - The critical load of incipient scuffing (load carrying capacity) in the High-Temperature Oscillating Machine (HiTOM) using real components of a Common Rail (CR) pump. This test rig is designed by BOSCH.
- Four different commercial base fuel were tested with wear scar diameter (WSD) on High Frequency Reciprocating Rig (HFRR) ranging from 699 to 236 µm.

RELEVANT RESULTS

- There is a good correlation between the HiTOM test that uses real components of a Common Rail pump as test samples and the HFRR test.
- The HFRR could successfully be used for the extra lubricity added by lubricity additives.

- The lubrication measured using the HFRR and HiTOM test methods is dependent on the composition of the base fuels and the treat rate and type of lubricity additives used.
- A content of 5 % RME in fuel increases the load carrying capacity (HiTOM test) and decreases the lubricity rating in HFRR test (WSD).
- Hydrodesulphurization decreases the lubricity by 80 -200 µm (HFRR) and the load-carrying capacity by 1500 N in the HiTOM.
- The removal of sulphurised compounds is not the major reason for the loss of lubrication of ultra low sulphur diesel fuels.
- The dibenzothiophene can increase the load-carrying capacity (i.e. increase lubricity properties).
- The removal of nitrogen containing compounds is likely to result in a diesel fuel with poorer lubricity performance.
- There is a good correlation between the HiTOM test and the HFRR.
- The HFRR test can be used for the modern vehicles using Common Rail (CR) pump.

STRENGTHS/WEAKNESSES/DATA GAPS

- This study provides very good insight on the diesel fuel components and lubricity additives.
- Established a good correlation for wear on Common Rail (CR) pump and HFRR test.

COMMENTS

- None

Study Reference No. D.2: CRC. 2009. “Diesel Fuel Lubricity Requirements for LDD Vehicles.” Prepared by Southeast Research Institute SwRI Project 08.11250, Prepared for Coordinating Research Council, CRC Contract No. DP-1-03.

GENERAL

- This is an Interim Phase final report.
- The main objective of the study was to determine the relationship between diesel fuel lubricity and diesel engine injection equipment durability for the current and near future light-duty diesel injection equipment used in vehicles in the U.S.

TESTING PROGRAM

Fuels:

- Two fuels of about 400 and 600µm lubricity HFRR

Testing Method:

- Testing program was carried out on a specified cycle (related to lubricity measurements) with one type of fuel injection pump, and the two fuels.

RELEVANT RESULTS

- Range of responses from immediate failure to long term operation with no degradation.
- Inspection results from the pumps showed that the wear mechanisms do not strongly correlate with fuel lubricity.

STRENGTHS/WEAKNESSES/DATA GAPS

- This study did not report any results between fuel lubricity and emissions.
- This is not a final result. Variations could be the result of test methodology, and further work is ongoing.
- However, the interim result suggests the HFRR lubricity rating may not correlate well with wear.

COMMENTS

- Based on results, further work would be required before the test system can reliably produce data required to address the project objectives. Additional changes to the test apparatus and procedures are recommended.

Study Reference No. D.3: CRC 2008. “Review of Prior Studies of Fuel Effects on Vehicle Emissions.” Prepared by Dr. Albert M. Hochhauser, 12 Celler Rd., Edison, NJ 8817, Prepared for Coordinating Research Council, CRC Project E-84.

GENERAL

- This study carried out an extensive review of published literature on the effect of fuel properties on emissions.
- This study did not discuss fuel lubricity effect on emissions.

Study Reference No. D.4: Row, J., Doukas, A. 2008. “Fuel Quality in Canada Impact on Tailpipe Emissions.” Prepared by The Pembina Institute, Drayton Valley, Alberta, Canada T7A 1S7; Prepared for the Association of International Automobile Manufacturers of Canada.

GENERAL

- This study addresses levels of sulphur and detergency in gasoline, and cetane and lubricity in diesel fuel.
- The study compares Canadian fuel standards for these parameters to those in other jurisdictions, and quotes other discussions.

TESTING PROGRAM

- Literature review.

RELEVANT RESULTS

- Lubricity itself does not have a direct impact on emissions, but low lubricity does lead to long term wear on critical engine parts which can contribute to a degradation of engine performance over time.
- The wear occurs mainly in fuel injection systems, which in turn impact engine performance.
- The conclusion that lubricity is considered to be an important issue was based on the California Environmental Protection’s two Staff Reports
  - California Environmental Protection Agency Air Resources Board, Proposed Amendments to the California Diesel Fuel Regulations — Staff Report: Initial Statement of Reasons, (2003);

  - California Environmental Protection Agency Air Resources Board, Proposed Amendments to the California Diesel Fuel Regulations — Staff Report: Final Statement of Reasons, (2004).
  - "CARB also states that current lubricity levels are not adequate for future low emissions technology."

STRENGTHS/WEAKNESSES/DATA GAPS

- The references cited in this report, and the quotation above, were made prior to a lubricity standard being set by California Environmental Protection Agency. That is, "current lubricity levels" were completely undefined at the time. These discussion papers lead to setting lubricity standard of 0.520mm in diesel fuel in California.
- Comments on sulphur as a natural lubricant are not technically correct.

COMMENTS

- Currently, California has one of the lowest standards for lubricity (highest rating), i.e. 0.520mm in comparison to EU, Australia and Japan (0.460 mm). Canada has the same voluntarily limit of 0.460 mm as of other countries.
- This report does not carry out any thorough literature review.

Study Reference No. D.5: Caprotti, R., Takaharu, S., Masahiro, D. 2008. Impact of diesel fuel additives on vehicle performance. *SAE Paper* 2008-01-1600.

GENERAL

- This study was carried out to assess the potential impact of diesel fuel additives (e.g. lubricity additives and cold flow improvers) on vehicle performance.
- An additive free fuel was treated with very high levels of all the diesel fuel additives currently used to meet specification limits and to enhance diesel fuel performance.
- A common rail vehicle using an advanced common rail system was driven in a controlled manner for 50,000 km.

TESTING PROGRAM

Fuels:

- Test fuel analyses were carried out every 10.000km, sampling the fuel from the vehicle tank.
- The lubricity of the fuel for this work was 0.542 µm.

Testing Method:

- Emissions and driveability tests were carried out at 0km to provide baseline data.
- Further tests were then performed at 15,000km and 50,000km to determine any changes from the baseline data.
- At every 5,000km the vehicle/engine parameters were assessed following ECU protocol.

RELEVANT RESULTS

- This work demonstrated that using a particular fuel with lubricity 0.542 µm attained through additives will not have any adverse effect on modern fuel injection equipments used in current fleet at 50,000km.

- The data obtained on the test fuel show that there have been essentially no changes throughout this test possibly due to use of ester based lubricity additive.
- The use of ester based lubricity additive chemistry is harm free even in the most severe Fuel Injection Equipment (FIE) environments. This applies to the pump, fuel lines, injector body, injector spray holes and the nozzle tip.
- These results are consistent with other test results:
    - Graupner, O. *et. al*. 2005. "Injector Deposit Test for Modern Diesel Engines" TAE Symposium, 2005.
    - Caprotti, R., Breakspear, A., Graupner, O., Klaua, T. 2005. Detergency requirements of future diesel injection systems. SAE Paper 2005-01-3901.
    - Caprotti, R.: Leedham, A., Graupner, O., Klaua, T. 2004. Impact of fuel additives on diesel injector deposits. *SAE Paper* 2004-01-2935.

STRENGTHS/WEAKNESSES/DATA GAPS

- These results apply to ester based lubricity additives only.

COMMENTS

- 50,000 is relatively low mileage, and does not necessarily represent life cycle.

Study Reference No. D.6: Ullmann *et al*. 2008. Investigation into the Formation and Prevention of Internal Diesel Injector Deposits. *SAE Paper* 2008-01-0926.

GENERAL

- A new type of injector deposit has been observed on internal injector components and assemblies with increased frequency during the last three years.
- The fuel injection equipment (FIE) systems typically being considered in this study were of the common rail type, which rely on the diesel fuel to provide lubrication.
- This study was carried out to understand deposits composition and their formation mechanism.
- This study focused on internal injector deposits that can occur in common rail fuel injection systems.
- The methodology used and the data generated that support the proposed mechanisms are described in the paper.

TESTING PROGRAM

- Analysis of the deposits and laboratory investigation.

RELEVANT RESULTS

- Two new types of deposits have been observed on internal injector components
- These new deposits can adversely impact driveability and result in noncompliance with the Euro4 or Euro5 emission limits.
- Analysis of the deposits and laboratory investigation has identified:
    - Metal based deposits, particularly those containing sodium. Sodium ions in the fuel react with fatty acids to form a soap.
    - Ashless polymeric deposits derived from the reaction of typical PIBSI detergents and acidic fatty acid based materials in the market today. The resulting polymer

  is characterized by the presence of a strong peptide bond due to the reaction of the detergent with acidic materials, particularly di-fatty acids.
- Fatty acids are commonly used as lubricity additives in diesel fuel with different degrees of un-saturation that has shown to readily react with metal ion impurities in the fuel to form metal soaps.
- The use of ester based lubricity additives has been shown to be neutral when in combination with detergents.

STRENGTHS/WEAKNESSES/DATA GAPS

- This work demonstrated that the choice of lubricity additive/method is important to avoid deposition on FIE.

COMMENTS

- This paper confirmed the finding of earlier paper that ester based additives will not have any adverse effect on modern fuel injection equipments used in current fleet.

Study Reference No. D.7: DOE 2007. “The Advanced Petroleum-Based Fuels—Diesel Emission Control (APBF-DEC) Program: 2,000-Hour Performance of a NO_X Absorber Catalyst and Diesel Particle Filter System for a Medium-Duty, Pick-Up Truck Diesel Engine Platform, Final Report.” U.S. Department of Energy, DOE/GO-102007-2377

GENERAL

- The objectives of this project were to:
  - Demonstrate the emissions potential of advanced fuels, engines, and ECSs for meeting federal Tier 2-Bin 5 emissions standards
  - Evaluate the effect of fuel sulphur level on emissions and fuel economy, ECS performance, and catalyst degradation.
- This study did not discuss issues related to diesel fuel lubricity.

Study Reference No. D.8: Gallant, T., Franz, J., Ainajjar, M. 2007. “The Influence of Molecular Structure of Distillate Fuels on HRFF Lubricity”. Diesel Engine-Efficiency and Emissions Research Conference, Technical Session 7: Fuels and Lubricants, Part 2.

GENERAL

- A collaboration was formed between CANMET, NCUT, ORNL and PNNL to:
  - Investigate analytical chemistry methods which would be applicable to distillate fuel chemistry, and
  - Demonstrate the value of these advanced analytical methods by identifying research areas, e.g., HCCI combustion, emissions, lubricity, or after treatment technologies, which the analytical data may provide improved understanding.

TESTING PROGRAM

- None

RELEVANT RESULTS

- There are numerous factors affecting lubricity, e.g.,
    - viscosity,
    - sulphur,
    - nitrogen, and
    - di-aromatics.
- None of these factors by themselves completely explain all the wear results. For example:
    - Increasing viscosity showed a decrease in wear scar using HFRR test; and
    - Increasing 1H alkane showed an increase in wear scar using HFRR test.
- Lubricity is a complex mechanism that has a molecular structure component.
- Variety of analytical methods is required to adequately explore different theories regarding lubricity.
- The two lubricity tests HFRR and SBOCLE did not correlate well.

STRENGTHS/WEAKNESSES/DATA GAPS

- Conference presentation. No details are available on this work

COMMENTS

- CANMET: Natural Resources Canada's CanmetENERGY is the Canadian leader in clean energy research and technology development.
- NCUT: The National Centre for Upgrading Technology (NCUT) is Canada-Alberta's premier science and technology (S&T) organization for upgrading bitumen and heavy oil into synthetic crude oil.
- ORNL: Oak Ridge National Laboratory is a multi-program science and technology laboratory managed for the U.S. Department of Energy
- PNNL: Pacific Northwest National Laboratory in Richland Washington is a US Department of Energy government research laboratory

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Study Reference No. D.9: Chevron Corporation.2007. “Diesel Fuels Technical Review”. Chevron Products Company 6001 Bollinger Canyon Road, San Ramon, CA 94583.

GENERAL

- This report reviewed diesel fuel performance, properties, refining, and testing.
    - A chapter discussed diesel engines, especially the heavy-duty diesel engines used in trucks and buses.
    - The review examines their impact on both fuel and engine.

TESTING PROGRAM

- Literature review.

RELEVANT RESULTS

- The diesel fuel must have some minimum level of lubricity to avoid excessive wear as some moving parts of diesel fuel pumps and injectors are protected from wear by the fuel.

- The use of fuels with poor lubricity can increase fuel pump and injector wear and, at the extreme, cause catastrophic failure.
- Any benefit provided by lubricity additives is typically seen over the long term.
- Three type of additive commonly used for lubricity are:
    - mono acids,
    - amides, and
    - esters.
- Most ultra-low sulphur diesel fuels need a lubricity additive to meet the ASTM D 975 lubricity specifications
- The lubrication mechanism is a combination of hydrodynamic lubrication and boundary lubrication.
    - Hydrodynamic lubrication:
        - A layer of liquid prevents contact between the opposing surfaces,
        - The fuel itself and viscosity is the key fuel property for diesel fuel pumps and injectors wear, and
        - Diesel fuels with higher viscosities will provide better hydrodynamic lubrication.
    - Boundary lubrication:
        - Compounds that form a protective anti-wear layer by adhering to the solid surfaces, and
        - Important when high load and/or low speed have squeezed out much of the liquid that provides hydrodynamic lubrication, leaving small areas of the opposing surfaces in contact.
- Lubricity additives contain a polar group that is attracted to metal surfaces that causes the additive to form a thin surface film. The film acts as a boundary lubricant when two metal surfaces come in contact.
- The HFRR and the SLBOCLE tests can indicate that fuels treated with an effective lubricity additive have poor lubricity, while the more accurate fuel injection equipment bench test rates them acceptable.
- Because of pipeline regulations in the U.S., lubricity additives are added at the terminals.

STRENGTHS/WEAKNESSES/DATA GAPS

- None

COMMENTS

- This report provides good overview of the lubricity in diesel fuel.

Study Reference No. D.10: ASTM International Standard for Lubricity ASTM D 6078 and D 6079.

GENERAL

- ASTM International approved the addition of a lubricity requirement in 2005 to its standard for diesel fuel oils (ASTM D 975). There are two test methods accepted for lubricity test:
    - ASTM D6079 - 04e1: ASTM D6079 - 04e1 Standard Test Method for Evaluating Lubricity of Diesel Fuels by the High-Frequency Reciprocating Rig (HFRR), and

   - ASTM D6078 – 04: ASTM D6078 - 04 Standard Test Method for Evaluating Lubricity of Diesel Fuels by the Scuffing Load Ball-on-Cylinder Lubricity Evaluator (SLBOCLE).

TESTING PROGRAM

- Detailed protocol to carry out lubricity measurements.

RELEVANT RESULTS

- HFRR test is more commonly used than SLBOCLE.
- HFRR requires that all grades of diesel fuel Grade 1-D and Grade 2-D have wear scar diameters no larger than 520 microns at 60°C. Lower value represents better fuel lubricity.
- ASTM mentioned that “It is not known that these test method will predict the performance of all additive/fuel combinations. Additional work is underway to further establish this correlation and future revisions of this test method may be necessary once this work is complete.”
- There is no absolute correlation between the two test methods.

STRENGTHS/WEAKNESSES/DATA GAPS

- None

COMMENTS

- In the HFRR test, a lower value represents better fuel lubricity.
- In the SLBOCLE test, a higher value represents better fuel lubricity.
- Engine Manufacturing Associations (EMA) recommended guideline for lubricity:
  - HFRR test: a wear scar of less than 0.450 mm at 60°C; or
  - SBOCLE test: minimum of 3100 g.

Study Reference No. D.11: Knothe, G., Steidley, K.R. 2005. Lubricity of Components of Biodiesel and Petrodiesel. The Origin of Biodiesel Lubricity. *Energy & Fuels*. Vol. 19, pp. 1192-1200.

GENERAL

- This study discussed and correlated structural features of biodiesel and petrodiesel components influencing lubricity.
- One of the objective was to define the components and structural features that impart the best lubricity properties to a diesel fuel.
- A variety of compounds were studied neat (including fatty esters, fatty alcohols, fatty acids, and hydrocarbons), as well as in blends or as additives with diesel fuels.

TESTING PROGRAM

- Lubricity determinations were performed at 25 and 60 °C using an HFRR lubricity test.

RELEVANT RESULTS

- The range of wear scars for all samples tested were greater at 60 °C than at 25 °C

- The two diesel (DF1 and ULSD) exhibit poor lubricity in neat form while the commercial biodiesel showed excellent lubricity.
- Consistent with several research papers cited in the paper, adding 1%-2% biodiesel to the two low-lubricity diesel fuels used here improved their lubricity.
- The main conclusion is that at least two features must be present in a molecule to impart lubricity:
    - the presence of a polarity-imparting heteroatom, preferably oxygen, with the nature (and number) of the oxygen moiety having a significant role; and
    - a carbon chain of sufficient length, which also increases viscosity.
- The lubricity of low-level blends (1%-2%) of biodiesel with low-lubricity diesel is largely caused by free fatty acid and monoacylglycerol contaminants present in the biodiesel.

STRENGTHS/WEAKNESSES/DATA GAPS

- None

COMMENTS

- This study discussed important aspects of the diesel fuel responsible for lubricity.

Study Reference No. D.12: CRC 2002. “Operability and Compatibility Characteristics of Advanced Technology Diesel Fuels.” Prepared by Southwest Research Institute (SWRI Project No. 03-02476), Prepared for Coordinating Research Council, CRC Project No. AVFL-2

GENERAL

- Endurance tests were performed using a motorized pump stand to define the effects of diesel fuel composition on full-scale fuel injection equipment durability.
- The test series attempted to determine the level of fuel injection system degradation due to wear and failure of the boundary film for each of the test fuels.

TESTING PROGRAM

Fuels:

- Four test fuels were chosen for the study:
    - A highly hydrocracked petroleum-based fuel with very low levels of sulphur and aromatic compounds (LSLA);
    - California Reference Diesel Fuel (CA);
    - Neat Fischer-Tropsch Diesel (FT100); and
    - Blend: 15% Dimethoxymethane (DMM) with 85% LSLA (DMM15).

Testing Mehtod:

- The test series attempted to determine the level of fuel injection system degradation due to wear and failure of the boundary film for each of the test fuels.
- A 500-hour pump operating procedure was used.

RELEVANT RESULTS

- Stanadyne Automotive and Bosch indicated that the 500 hours would be sufficient to see fuel injection pump wear with low lubricity fuels. Both manufacturers indicated that with insufficient lubricity fuels, a decrease in fuel injector performance can also occur in 500 hours.

- The Stanadyne pump is an opposed-piston, rotary-distributor, fuel-injection pump. Rotary distributor fuel injection pumps are fuel lubricated, thus sensitive to fuel lubricity.
- The Bosch system evaluated was a high pressure Common Rail fuel injection system.
- Lubricity evaluations were performed on the highly hydrocracked petroleum-based fuel with very low levels of sulphur and aromatic compounds (LSLA) to determine if lubricity additives were present.
    - The HFRR wear scar was 0.585 μm
    - The BOCLE scuffing load was 1850 grams.
    - These results appear to indicate that a lubricity additive was not present.
- The conclusions from this study included:
    - The variability in the data and the small sample size make it difficult to assess the impact of fuel lubricity.
    - Bosch High Pressure Common Rail Pumps appear to be more sensitive to fuel lubricity.
- Although the laboratory high frequency reciprocating rig (HFRR) tests were able to distinguish between those fuels that contained lubricity additives and those that did not, there was little correlation with pump durability results.

STRENGTHS/WEAKNESSES/DATA GAPS

- None

COMMENTS

- Experimental set up to determine the impact of fuel lubricity.

Study Reference No. D.13: Gray, C. *et al*. 2002. Investigation of diesel fuel lubricity and evaluation of bench tests to correlate with medium and heavy duty diesel fuel injection component wear - Part 1. *SAE Paper.* 2002-01-1700.

GENERAL

- This study was conducted to investigate the effects of diesel fuel lubricity on diesel engine fuel injection equipment (FIE) wear and failure rates.

TESTING PROGRAM

Fuels:

- Seven test fuel used in the study showed the HFRR wear scars of 0.603 (base fuel), 0.423, 0.410, 0.352, 0.320, 0.196 and 0.103 μm

Testing Mehtod:

- Five tests were used to evaluate diesel fuel lubricity characteristics:
    - a modified Falex Corporation Ball-on-Three-Disk (BOTD) lubricity test rig;
    - a high-speed Detroit Diesel Corporation (DOC) 8V71T engine test rig operated at maximum load and speed conditions under elevated fuel, coolant and ambient temperatures;

  - a Wartsila VASA 9R32, medium-speed, diesel engine electric power generation unit in Iqaluit, Nunavut, Canada;
  - a fuel pump rig (FPR); and
  - a high frequency reciprocating rig (HFRR).

RELEVANT RESULTS

- Several commercially available fuel lubricity additives are capable of significantly improving the lubricity of poor lubricity diesel fuel.
- The improvement in diesel fuel lubricity can be obtained by using relatively low concentrations of lubricity additives.
- The lubricity additives would markedly reduce FIE component wear.
- The HFRR appeared to be capable of
  - distinguishing between lubricity levels of good and poor lubricity fuels in heavy duty, medium and high speed diesel engines.
  - not capable of accurately determining the lubricity characteristics of fuels containing lubricity additives for the fuels used in the study.

STRENGTHS/WEAKNESSES/DATA GAPS

- No data is presented linking FIE wear rates versus lubricity levels.

COMMENTS

- This paper demonstrated that lubricity additives will improve the lubricity of poor lubricity diesel fuels to satisfactory levels and will substantially reduce FIE wear rates.

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Appendix E: BIBLIOGRAPHY

Gasoline – Fuel Sulphur Effects

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