APPENDIX C

Diesel Fuel Aromatic Content and Exhaust Emissions of
Polycyclic Aromatic Hydrocarbons

I INTRODUCTION

This appendix discusses how changes in aromatic levels of diesel fuel affect the emissions of polycyclic aromatic hydrocarbons (PAH) in diesel exhaust (DE). Specifically, this appendix focuses on how reductions in diesel fuel aromatic content can reduce PAH and its derivatives. PAH belongs to a group of chemicals called polycyclic organic materials (POM).

A. PAH Chemistry

PAH consists of carbon and hydrogen and can be conceived as consisting of fused rings of benzene. These chemicals belong to the group of compounds commonly referred to as POM. POM includes zaarenes, oxaarenes, thiaarenes (and their derivatives), and transformation products of PAH, e.g. nitro derivatives and quinones. Azaarenes, thiaarenes and oxaarenes can be conceived as a PAH, where a carbon atom in the ring system is replaced by a nitrogen, sulfur or an oxygen atom, respectively. For the purposes of this discussion the term PAH will include all the above mentioned compounds. The chemical state, i.e. solid, liquid, or gas phase, of POM is directly associated with its molecular weight and ring structure. In diesel exhaust large molecular weight PAH (5 - 7 rings) are associated with particle matter (PM) and low molecular weight PAH (3 - 4 rings) are usually found in diesel exhaust vapor or gas phase. The major part of the mutagens in ambient air has been shown to be particle-associated (Fenger et al., 1990). Particulate matter in diesel exhaust is mainly caused by un-combusted fuel, while lubricant and other mechanisms provide a minor contribution to diesel PM.[1, 2]

PAH compounds have attracted considerable attention because of their known mutagenic and, in some cases, carcinogenic character (National Research Council, 1982[3]). POM is a class of compounds and derivatives is listed as a California Toxic Air Contaminant by the Office of Environmental Health Hazard Assessment (OEHHA), California EPA. Recently OEHHA staff reviewed PAH toxicity to identify hazards to which infants and children might be especially sensitive. This activity supported the Children's Environmental Health Protection Act (California SB25). OEHHA concluded "Apparently, children may be both more heavily exposed and also more sensitive to the toxic effects of POM[4]." One may conclude that children and infants are also more sensitive to PAHs and their derivatives.

B. Importance of Diesel Exhaust and PAH

Most industrialized countries limit emissions of four components of diesel exhaust: CO, HC, PM, and NOx. The first three are the result of incomplete combustion and NOx, is a byproduct of combustion. However, diesel exhaust (DE) is a complex mixture of thousands of gases and fine particles emitted by diesel-fueled internal combustion engines. The composition will vary depending on engine type, operating conditions, fuel composition, lubricating oil, and whether an emission control system is present. Gaseous components of DE include carbon dioxide, oxygen, nitrogen, water vapor, carbon monoxide, nitrogen compounds, sulfur compounds, and numerous

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[1] Internal Combustion Engine Fundamentals, Heywood, 1988, ISBN 0-07-028637, McGraw Hill, NY, NY
[2] Transient Emissions Comparisons of Alternative Compression Ignition Fuels, SAE 1999-01-1117, Clark, et. al.
[3] National Research Council. (1982) Diesel cars: benefits, risks and public policy. Final report of the Diesel Impacts Study Committee. Washington, DC: National Academy Press.
[4] See OEHHA web page: http://www.oehha.org/public_info/public/kids/pdf/PAHs%20on%20Children%27s%20Health.pdf

low-molecular-weight hydrocarbons. Recent studies have focused on the toxicity of diesel exhaust and diesel particulate matter (DPM)[5].

Available data for on-road engines indicate that toxicologically relevant organic components of DE (e.g., PAHs, nitro-PAHs) emitted from older vehicle engines are still present in emissions from newer engines, though relative amounts have decreased[6]. Diesel engines, however, emit more PM per mile driven compared with gasoline engines of a similar weight. Over the past decade, modifications engines have substantially reduced particle emissions from both diesel and gasoline engines[7, 8]. However, PM emitted from newer diesel engines is still about 20 times greater than from comparable gasoline engines, on an equivalent fuel energy basis. Over 90 percent of the mass of these particles are less than 2.5 microns in diameter. Because of their small size, these particles are easily inhaled into the bronchial and alveolar regions of the lung. Many of these particles have been found to contain potent mutagens and carcinogens (see Chapter III, section E of "Proposed Identification of Diesel Exhaust as a Toxic Air Contaminant" prepared by the staff of ARB and OEHHA[9]).

Available evidence indicates that there are human health hazards associated with exposure to diesel exhaust. The hazards include acute exposure-related symptoms; chronic exposure related non-cancer respiratory effects, and lung cancer. As new and cleaner diesel engines, together with different diesel fuels, replace a substantial number of existing diesel engines, the expected health hazards associated with diesel exhaust general should be reduced. New engine and fuel technology expected to produce significantly cleaner engine exhaust by 2007 (e.g., in response to new federal heavy duty engine regulations), significant reductions in public health hazards are expected for those engine uses affected by the regulations.

Reducing CO emissions to proposed regulatory levels is not a significant problem in diesel engine design. Reducing hydrocarbon emissions can be solved using proven methods used to improve fuel efficiency and reduce PM emissions. However, current federal and ARB regulations require simultaneous emission reductions in DPM and NOx emissions by 2006. This is major technical problem that requires a comprehensive approach to DPM control. Part of this control strategy includes changes in diesel fuel regulatory specifications.

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[5] Health Assessment Document for Diesel Engine Exhaust. USEPA EPA/600/8-90/057F. 01 May 2002. U.S. Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment, Washington, DC.
[6] Ibid. footnote #3
[7] Hammerle, RH; Schuetzle, D; Adams,W. (1994) A perspective on the potential development of environmentally acceptable light-duty diesel engines. Environ Health Perspect (Suppl.) 102:25-30.
[8] Sawyer, RF; Johnson, JH. (1995) Diesel emissions and control technology. In: Diesel exhaust: a critical analysis of emissions, exposure, and health effects. Cambridge, MA: Health Effects Institute, pp. 65-81.
[9] Rulemaking documents on identifying particulate emissions from diesel-fueled engines as a toxic air contaminant, http://www.arb.ca.gov/regact/diesltac/diesltac.htm.

C. Historical Trends in Diesel Fuel [10, 11]

Use of diesel fuel increased steadily in the second half of the 20th century. According to statistics from the Federal Highway Administration (1995, 1997), in 1949 diesel fuel was approximately 1% of the total motor fuel used, and in 1995 it was about 18%. Over the same time, diesel fuel consumption in the United States increased from about 400 million gallons to 26 billion gallons per year, an increase by a factor of more than 60. The chemistry and properties of diesel fuel have a direct effect on emissions of regulated pollutants from diesel engines.

The chemical makeup of diesel fuel has changed over time, in part because of new regulations and in part because of technological developments in refinery processes. EPA currently regulates on-road diesel fuel and requires the cetane index (a surrogate for actual measurements of cetane number) to be greater than or equal to 40, or the maximum aromatic content to be 35% or less (CFR 40:80.29). EPA recently finalized a regulation that will limit the sulfur content of on-road diesel fuel to 15 PPM starting in 2006 (U.S. EPA, 2000b). California has placed additional restrictions on the aromatic content of diesel fuel (California Code of Regulations, Title 13, Sections 2281-2282) and requires a minimum cetane number of 50 and an aromatics cap of 10% by volume, with some exceptions for small refiners and alternative formulations as long as equivalent emissions are demonstrated. Diesel fuel from larger refiners is limited to 10% aromatic content, and for three small refiners (a small fraction of diesel sales) to 20% aromatic content. The refiners can also certify a fuel with higher aromatic content as being emissions-equivalent to the 10% (or 20%) aromatic content fuels by performing a 7-day engine dynamometer emissions test. This method is chosen by most, if not all, California refiners, and so a typical California diesel fuel has an aromatic content above 20%. Emissions equivalence has been obtained through use of cetane enhancers, oxygenates, and other proprietary additives. Nonroad diesel fuel is not regulated, and consequently, cetane index, aromatic content, and sulfur content vary widely with nominal values for cetane number around 43, 31% aromatics, and sulfur approximately 3,000 PPM.

Studies measuring the emissions impact of changes in cetane number and aromatic content for roughly 1990 model year engine technology find that increasing the aromatic content from 20% to 30%, with an accompanying decrease in the cetane number from 50 to 44, results in a 2% to 5% increase in NOx and a 5% to 10% increase in total DPM (McCarthy et al., 1992; Ullman et al., 1990; Sienicki et al., 1990; Graboski and McCormick, 1996). These ranges may be reasonable upper bounds for the effect of changes in fuel quality on NOx and DPM emissions during the years 1960–1990. Railroad-grade diesel fuel is currently unregulated.

Fuel chemistry is also important for emission of particle-associated PAHs. In studies performed over more than a decade, Williams and Andrews of the University of Leeds have shown that the solvent-extractable PAHs from diesel particulate originate almost entirely in the fuel (Williams et al., 1987; Andrews et al., 1998; Hsiao-Hsuan et al., 2000). The PAH molecules are relatively

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[10] Comparitive Toxicity of Gasoline and Diesel Engine Emissions, SAE 2000-001-2214, Seagrave, et. al.

[11] U.S. Environmental Protection Agency (EPA). (2002) Health assessment document for diesel engine exhaust. Prepared by the National Center for Environmental Assessment, Washington, DC, for the Office of Transportation and Air Quality; EPA/600/8-90/057F. Available from: National Technical Information Service, Springfield, VA; PB2002-107661, and <http://www.epa.gov/ncea>.

refractory, so a significant fraction survive the combustion process and condense onto the DPM. These studies have been confirmed by other research groups (Crebelli et al., 1995; Tancell et al., 1995). There is a consensus among these researchers that pyrosynthesis of PAHs occurs only at the highest temperature operating conditions in a diesel engine. Under these conditions, most of the DPM and other pyrolysis products are ultimately burned before exiting the cylinder. These results indicate that emissions of PAHs are more a function of the PAH content of the fuel than of engine technology. For a given refinery and crude oil, diesel fuel PAH correlates with total aromatic content and T90.

Representative data on aromatic content for diesel fuels in the United States do not appear to be available before the mid-1980s. However, the decreasing trend in cetane number, increasing trend in T90, and the increasing use of light cycle oil from catalytic cracking beginning in the late 1950s suggest that diesel PAH content has increased over the past 40 years. Changes in PAH content of diesel fuel over time, as well as differences between diesel fuels used in different applications (on-road, nonroad, locomotive), may influence the hazards observed in exposed populations from different occupations.

D. Regulatory Context

United States, Europe, and Japan have regulated diesel and gasoline engines emissions separately due to differences in technology and combustion between each engine type. Diesels were initially regulated much less heavily than gasoline engines. As a result, diesel emissions control standards and technology lagged gasoline engine control standards and technology. As emissions from gasoline engines declined due to regulatory control measures, the relative share of diesel engine emissions has increased. This increase prompted the California Air Resources Board (ARB) and U.S. Environmental Protection Agency (EPA) to issue regulations for diesel fuel 1993. The “California” diesel fuel requirements are designed to reduce NOx emissions by 7% and DPM emissions by 25%. Current “federal” diesel fuel regulations do not reduce NOx emissions and only reduce PM emissions by 5 percent. Recently the State of Texas adopted diesel fuel regulations with diesel fuel requirements similar to California regulations. Today even greater regulatory control is being proposed for diesel exhaust. This emphasis in regulatory control is supported by numerous studies including an exhaustive 10-year scientific assessment process where ARB identified particulate matter from diesel-fueled engines as a toxic air contaminant (TAC) in 1988.

The ARB, EPA, other state and local agencies, engine and vehicle manufacturers, emission control manufacturers, and refiners have been working for the past decade to substantially reduce emissions from diesel engines. A significant area of research in this effort is determining the relationship between diesel fuel properties with diesel emissions. The chemistry and properties of diesel fuel have a direct effect on emissions of regulated pollutants from diesel engines.[12,13] Researchers have studied the NOx and DPM effect of sulfur content, total aromatic content, polyaromatic content, fuel density, oxygenate content, cetane number, and T90 on emissions of regulated pollutants, (T90 is the 90% distillation point temperature).

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[12] Strategies and Issues in Correlating Diesel Fuel Properties with Emissions, EPA420-P-01-001, July 2001.This appendix extensively cites this report.
[13] Ibid. footnote 2.

In late 1999, EPA issued its "Tier 2" motor vehicle emission standards, i.e., Control of Air Pollution From New Motor Vehicles, Tier 2 Motor vehicle Emissions Standards and Gasoline Sulfur Control Requirements, 64 Fed. Reg. 6698 (2000). The regulations focus on reductions in emissions most responsible for ozone and particulate matter pollution. Most importantly the regulations also set more stringent controls for PM, NOx, and HC emissions from diesel engines.

This staff discussion document describes technical issues related to an assessment of the effect of changes in diesel fuel parameters on the emissions of particulate matter (PM). This discussion is intended as a review of the current understanding of the relationship between diesel fuel aromatic content and emission of PAH in diesel exhaust.

1. National Regulation of Diesel Fuel Parameters

Various European and international authorities have established standards or limit values for air pollution components. With respect to the occurrence of carcinogenic PAH and other mutagens in air the regulators are faced with an extremely difficult situation as these compounds are present in complex mixtures with widely varying compositions and carcinogenic potencies depending on different sources and locations. Most often benzo(a)pyrene is used as a marker substance for the total carcinogenic potency present in ambient air in European regulations.

The Netherlands

In the Netherlands a draft (annual average) tolerable level of 5 ng/m^3 and an acceptable level of 0.5 ng/m^3 for the benzo(a)pyrene content in the outdoor air has been given in the Environmental Programme 1988-1991 (Montizaan et al., 1989).

Germany

In Germany The Umwelt Bundes Amt has stated that "Since dose-effect relationships for man do not exist, the recommended value is based on technical and economic feasibility". In view of the concentrations occurring in Western European cities an annual average of 10 ng/m^3 benzo(a)pyrene is used as an "orientating value". This value should be feasible, considering the values in other countries (Montizaan et al., 1989).

US-EPA

The US-EPA in 1984 has proposed to regulate PAH in the outdoor air by means of emission limits instead of determining a recommended value for PAH in the outdoor air.

World Health Organization (WHO)

The WHO (1987) states that because of the carcinogenic properties of PAH a safe level cannot be recommended. Various risk assessments are given using benzo(a)pyrene as an indicator. Based on benzene soluble fractions of coke oven emissions, a risk of lung cancer is given of 9x10-5 per ng benzo(a)pyrene per m^3 at lifetime exposure. It is clearly stated that this estimation is related to a mixture of PAH and other carcinogens similar to that occurring in coke emissions.

Denmark

The Danish Environmental Protection Agency has not established standards for PAH in ambient air. As PAH are carcinogenic compounds the levels should be as low as possible, and the Danish EPA regulates PAH in the outdoor air by means of emission limits for the various sources.

2. US federal and State Regulation of Diesel Fuel Parameters

Recently Texas, and other states have expressed interest in reducing criteria pollutant emissions by regulating diesel fuel properties in a manner similar to ARB diesel fuel regulations. The US EPA responded to this interest by attempting to quantify the emission effects of diesel fuel parameter changes[14]. Federal law and regulations control sulfur and aromatic content and the cetane index of highway diesel fuel introduced into commerce as of October 1, 1993[15]. Except for California[16] no state had regulated similar aspects of diesel fuel until April 2000, when Texas adopted its Low Emission Diesel (LED) rule for the Dallas metropolitan area[17], and later amended the same rule to expand the geographic scope of the covered area and to further restrict sulfur levels[18]. Like the California rule (implemented in October 1993) the Texas rule (to be implemented in April, 2005[19]) controls sulfur and aromatic hydrocarbon content of diesel fuel for both highway and nonroad engines; Texas also controls the cetane number of diesel fuel[20]. In its proposed SIP revisions, Texas claims the LED rule will provide significant reductions in emissions of oxides of nitrogen (NOx). In developing the emission reduction estimates, Texas assumed its LED fuel would be similar to California diesel fuel.

B. Overview of Current Research

1. European Studies

Danish Studies: A review of ambient air analysis confirmed that traffic emissions are the major sources for the presence of PAH, other PAC and mutagens in street air[21]. The Danish environmental study (Environmental Project # 447, 1999) confirmed that a significant reduction of PAH and mutagens took place during the period 1992-1996. The reduction of the PAH-concentration has been estimated to about 35%. It was concluded that 2/3 of the reduction is due to the use of the improved diesel quality and 1/3 to the increased use of catalytic converters. The concentration of benzo(a)pyrene turned out to be a poor indicator for the air pollution with carcinogenic and mutagenic components.

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[14] Strategies and Issues in Correlating Diesel Fuel Properties with Emissions, EPA420-P-01-001, July 2001.
[15] Clean Air Act § 211(i); 40 CFR § 80.29.
[16] Title 13 Calif. Code of Regulations, Sections 2281- 2282.
[17] Title 30 Texas Admin. Code, Chapter 114, Sections 114.6, 114.312-317, 114.319, adopted by the Texas Natural Resource Conservation Commission (TNRCC), April 19, 2000.
[18] Title 30 Texas Admin. Code, Chapter 114, Sections 114.6, 114.312-317, 114.319, as amended by the TNRCC, December 6, 2000.
[19] Texas has proposed revising the rule to delay implementation until April, 2005 http://www.tnrcc.state.tx.us/oprd/sips/houston.html.
[20] California does not set a regulatory standard for cetane number. However, it does require use of a reference fuel with a specific cetane number (identical to the Texas regulatory standard) in determining whether alternative formulations (which do not meet the 10% aromatics content standard) have equivalent emissions reductions. Alternative fuel formulations with equivalent emissions reductions can meet the California diesel fuel requirements.
[21] Impact of Regulations of Traffic Emissions on PAH Level in the Air; Evironmental project, no. 447, Nielsen, T., et. al., June 1999, www.mst.dk/udgiv/publications/1999/87-7909-281-0/html/kolofon_eng.htm.

The objective of this investigation was to determine whether the application of diesel fuel having a low distillation end point had affected the air levels of PAH and mutagens. These new diesel qualities were expected to reduce the emissions of particulates and soot (Karonis et al., 1998) and therefore, probably also the emissions of PAH and other mutagens (Westerholm and Egebäck, 1994). Most of the PAH in the diesel exhaust is carried over from the fuel and not formed by pyrosynthesis during the combustion process (Williams et al., 1989). After the introduction of the new diesel fuel occurred in Denmark a significant reduction in the levels of PAH and especially the mutagens was observed (Nielsen, 1996, Nielsen et al. 1995b and c).

EPEFE Study: The European Programmes on Emissions, Fuels and Engine Technologies (EPEFE) - Light Duty Diesel Study (SAE 961073) measured regulated and toxic emissions. The report covered work during the period between July 1993 and March 1995. The speciation measurements were made only for a single test of each fuel/vehicle combination, therefore "a statistical analysis...was not feasible." However, reductions in polyaromatics and density showed an average 2 to 10% reduction in PM. Reductions in diesel fuel density directly corresponds to reductions in diesel aromatic content. Therefore, one can infer that this and other follow up studies reinforce the conclusion that reductions in diesel aromatics decrease PM emissions.[22]

2. *ARB Studies*

ARB Study: The study performed for ARB tested three diesel fuels in a Cummins L10 engine. The three fuels included a pre-1993 diesel fuel, a low aromatic fuel (aromatics less than 10%, and an alternative formulation (Alternative fuel formulations with equivalent emissions reductions that can meet the California diesel fuel requirements[23].) Total hydrocarbon, NOx and PM emissions were all reduced for both the low aromatic fuel and the reformulated fuel compared to the Pre-1993 fuel. It should be noted that the PM emission reduction changes from the Pre-1993 fuel were deemed statistically significant[24].

3. *Recent Diesel Fuel Emissions Studies*

"Clean Diesel" Comparisons: Total PAH, including PAH derivatives, averaged between *.076 and 0.69 mg/mile* in the exhaust of a low-emitting diesel engine using <15 PPM sulfur CARB diesel fuel and a catalyzed regenerative diesel particulate filter. In comparison conventional diesel engines using CARB diesel averaged between *2.8 and 4.34 mg/mile* total PAH emissions.[25, 26, 27]

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[22] Comparisons of Exhaust Emissions from Swedish Environmental Classified Diesel Fuel (MK1) and EPEFE reference fuel, Westerholm et. al., Enviro. Sci. Technol., 2001, 35, 1748-1754

[23] Evaluation of Factors That Affect Diesel Exhaust Toxicity, Norbeck, J. M., et. Al., Contract No. 94-312, July 24, 1998.

[24] Significant at 95% confidence limit using Fisher's Protected Least Significant Difference Test.

[25] A Comparison of Emissions for Medium-Duty Diesel Trucks Operated on California In-Use Diesel, ARCO's EC-Diesel, and ARCO EC-Diesel with a Diesel Particulate Filter. Final Report. Durbin, T., Norbeck, J.M. (2002). National Renewable Energy Laboratory contract ACL-1-30110-01

[26] Speciation of Organic Compounds from the Exhaust of Trucks and Buses: Effect of Fuel and After-Treatment on VehicleEmission Profiles, SAE 2002-01-2873, Miriam Lev-On, et. al.

[27] Comparison of Exhaust Emissions, Including Toxic Air Contaminants, from School Buses in Compressed Natural Gas, Low Emitting Diesel, and Conventional Diesel Engine Configurations, SAE 2003-01-1381, Ullman T.L. et. al.

Literature Review of Diesel Fuels: This review describes typical Fischer-Tropsch, EPA, and CARB diesel fuel properties. The paper discusses how these fuel properties impact pollutant emissions, and draws together data from known engine and chassis dynamometer studies of emissions. The review shows that diesel fuels share a set of common properties and these properties can contribute to reductions in PM compared to conventional diesel fuel. Also, reductions in diesel aromatic content reduced NOx and PM emissions compared to conventional diesel fuel.[28]

Single Cylinder Research: Recent laboratory testing of a modern single-cylinder engine demonstrates that the composition of diesel exhaust organic compounds vary significantly according to engine design and as the engine load and/or speed are changed. The majority of organic compounds were observed at idling, light, and medium loads. Diesel exhaust organic compounds emission rates at high loads were negligible. This research supports the basis for changes in diesel fuel formulation to ensure reductions diesel exhaust PAH emissions for all engine types and operating regimes.[29, 30]

C. Monoaromatic versus polyaromatic effects

A number of studies investigated the emission impacts of subcategories of aromatic compounds. In these studies, the most typical approach was to separate monoaromatic compounds (hydrocarbons containing a single benzene ring) from polyaromatics (hydrocarbons containing more than one benzene ring). A smaller set of studies made further distinctions between mono, di-, and tri-aromatic compounds. In the studies that actually measured these subcategories of aromatics, some actually made efforts to control the test fuel levels of one subcategory of aromatics separately from another subcategory of aromatics. In most cases, the polyaromatics were specifically controlled while the monoaromatics were uncontrolled.

These studies offered evidence that different types of aromatic compounds may have different impacts on emissions, particularly for PM. Some studies also concluded that mono and polyaromatic compounds might exhibit different effects for NOx.

D. Application to nonroad fleet

Nonroad compression-ignition engines are an important portion of the diesel fleet and an important contributor to inventories of regulated pollutants. Therefore, in addition to understanding the correlation of diesel fuel parameters with emissions from highway engines, it is important to understand this correlation in nonroad engines. Most nonroad engines use technologies similar to those found in highway vehicle engines, although in a given year highway vehicle technology is generally more advanced. Research suggests that most technologies used in on-road fuel applications will exhibited a similar response in off-road applications. Thus, in most cases, the distinctions between nonroad and highway vehicle

[28] Fischer-Tropsch Diesel Fuels – Properties and Exhaust Emissions: A Literature Review, SAE 2003-01-0763, Teresa L. Alleman and Robert L. McCormick.

[29] Effects of Fuel Properties and Source on Emissions from Five Different Heavy Duty Diesel Engines, SAE 2000-01-2890, Ken Mitchell

[30] Effect of Engine Operating Conditions on Particle-Phase Organic Compounds in Engine Exhaust of a Heavy-Duty Direct-Injection (D.I.) Diesel Engine, SAE 2003-01-0342, Chol-Bum Kweon et. al.

technologies may not be important for the purpose of evaluating relative emission effects of fuel changes.

There are some concerns that the type of operation that nonroad engines experience may be sufficiently different from the operation of highway vehicles that extrapolations based on highway driving, may not be applicable to nonroad. However, there are a variety of test cycles that could represent nonroad applications that are currently being evaluated. The current body of data on nonroad engine cycles is insufficient to indicate whether the effect of changes in diesel fuel properties will affect emissions differently for nonroad engines than for highway engines. On the basis of the information we currently have, then, we believe that the relative effects exhibited by changes in on-road diesel fuel are applicable to nonroad.

E. Effects of Vehicle Technology and Operation

As mentioned previously, results from various research groups demonstrated that the magnitude of any diesel fuel property alone was generally not a good indicator for projecting the amount of pollutant emissions. This was especially true for determining NOx emissions. The results showed that diesel fuel properties, engine technologies, and driving cycle all played interactive roles in determining the amount of pollutants emitted.

1. DI and IDI Engines

In the EPEFE study, an increase in density resulted in a slight reduction of fleet averaged NOx emissions, shown in Table VI.C.1-1. However, individual vehicle responses to density increase were not consistent directionally, even though this group of light-duty vehicles was tested under the same protocol and fuels. They also varied considerably in magnitude. When the density was reduced, emissions data from individual vehicle showed that the half of the fleet with electronic injection responded with increased NOx emissions, while the opposite effect was seen with the remaining half of the fleet. This varying behavior from the light-duty fleet was also seen with NOx emissions when the cetane number of the fuel was varied. As the cetane number was increased, the NOx emissions reduced for DI (mostly electronically controlled) fleet, while the NOx emissions increased for the IDI (mostly mechanically controlled) fleet. The investigators reported that DI vehicles were primarily tuned to control NOx with resulting trade off of the other emissions (e.g., PM, HC, and CO). Consequently, vehicles with electronically controlled injection generally showed higher levels of PM, HC, and CO emissions than mechanically controlled vehicles. Because the engine technologies played such an integral part in how fuel properties would affect emissions, the fuel property should not be taken alone in determining its impact on the pollutant emission levels.

Although the magnitude changes due to fuel effects were generally of the same order between the DI and IDI fleets in the EPEFE study, the DI and IDI fleets displayed a very different sensitivity in cetane number effects on PM emissions. The investigators observed that from PM emissions DI vehicles were about four times more sensitive than those were from IDI vehicles, percentage wise. Therefore, their study indicated that under certain circumstances, vehicle technology changes might play an even more significant role than fuel property changes in affecting the amount of pollutant emissions.

2. *Sensitivity of Vehicle Response to Engine Parameters*

This chapter has thus far focused on fuel parameter studies with little discussions on engine effects such as changes to engine calibration or operating conditions. However, two studies that focus on these effects offer important insights for interpreting the previously discussed studies.

a. *Engine Operating Conditions*

Beatrice et al carried out an engine study over a 2-liter, turbocharged, DI engine equipped with an EGR system23. The fuel matrix examined consisted of 12 different fuels. Focusing on the engine sensitivity to fuel quality in their steady state testing at various operating (e.g., load, speed, and ambient temperature) conditions, they indicated that the engine sensitivity to fuel quality changes was very different depending on both the operating conditions and the individual pollutant emission under examination. They noticed the sensitivity to fuel quality changes increased at low load and speed, especially for HC emissions. With respect to PM emissions, all test conditions were found to be relevant, while particularly higher sensitivity was noted at retarded timings and during cold operation. However, this was not true for NOx whose behavior was quite flat over varying test conditions. Their study stressed the importance of the interplay between the engine operating conditions and fuel properties on pollutant emissions.

This study clearly illustrated the complex relationships between various engine management components that could impact pollutant emissions. Even though advanced injection timing should lead to higher NOx emissions, the net effect due to an increase in fuel density was NOx reduction by the co-existence of the more dominant EGR effect. Thus, all aspects of the engine systems need to be taken together to assess fuel effects on emissions.

F. Conclusions

Research shows a consistent trend across studies that an reduction in aromatics content results in low PM and PAH 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. Various studies demonstrated that fuel properties effect on the extent of PAH emissions clearly depended on the engine design.

Unlike results for heavy-duty vehicles, research suggests difficulty of projecting changes in light-duty vehicle emissions as a function of diesel fuel parameters. Nevertheless, there is clearly some PM benefit associated with reducing aromatics. However, the magnitude of emissions reduction is highly uncertain without a full understanding of the specific vehicle design and configurations, and such assessment would require further analysis. Diesel fuel properties, along with existing engine design or vehicle technologies, operating conditions (load, speed, ambient conditions) as well as the driving cycles all play interactive roles in influencing the amount of pollutant emissions.