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DIESEL EXHAUST STANDARD PHASE I: CRC PROJECT NO. AVFL-10A

By

Patrick M. Merritt

FINAL REPORT

Prepared for

Coordinating Research Council, Inc.
3650 Mansell Road, Suite 140
Alpharetta, Georgia 30022

August 2003

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DEPARTMENT OF EMISSIONS RESEARCH
AUTOMOTIVE PRODUCTS AND EMISSIONS RESEARCH DIVISION

AVFL-10a Committee Summary

This project is the first phase of a program to develop a reproducible standard mixture that suitably captures the nature of actual diesel exhaust. An in-depth literature survey was conducted to gather information about engine-out emissions composition for a variety of diesel engine applications, fuel types, manufacturers, power outputs, and test cycles. A Microsoft Access database was created to store these data. This information will eventually be used to establish a diesel exhaust standard that can be used for evaluating after-treatment devices.

The bulk of the literature found in this study was published from 1999 to 2003 and about half (72) of the total turned out to be useful for this task. Although the over-whelming majority of papers were published by the Society of Automotive Engineers, a truly global perspective was maintained with papers from Europe, the U.K., Asia, and Japan.

Studies in the literature represent the more commonly used test cycles, such as U.S. light-duty (LD) and heavy-duty (HD) chassis cycles, U.S. HD engine test cycles, European and Japanese test cycles, plus studies of idle emissions, and a number of specialty cycles.

Engines representing almost all the world's major manufacturers are included. The bulk of the studies reporting useful data utilized 1991-2000 engines representing those found in class eight, over-the-highway trucks. Very little detail was presented on engine technology.

Fuels represented in this study included conventional and reformulated diesel, water emulsions of diesel fuel, Fischer-Tropsch synthetic fuels, neat biodiesel fuels and biodiesel blends, and fuels with various additives and catalyst materials added.

Most studies reported regulated emissions: hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), and total particulate matter (PM). The data set encompassing the regulated emissions is by far the largest set in the database. There are data from more than 767 individual tests. Average emission rates for each type of test cycle were calculated. Generally NOx and CO emissions rates are much higher than HC.

The best mix of information for heavy-duty engines was over the heavy-duty Federal Test Procedure (HD FTP). The data for the HD FTP come from seven studies and represent a variety of engines, but only four of the engines were of 1999 or newer vintage. Detailed hydrocarbon speciation data exist for a variety of heavy-duty engines, operating over a variety of duty cycles and fuels. Only six studies reported light-duty FTP (FTP-75) speciated hydrocarbons, with four representing engines manufactured in 1999 or later. Other cycles for light-duty diesels were sparse.

For the HD FTP, the predominant hydrocarbon compounds are the lighter olefins (ethene, propene), substituted cyclics, and heavier alkanes (undecane). For the FTP-

75, which is used for light- and medium-duty vehicles, the overall profile was not much different than that for the HD FTP.

Data are fairly plentiful on the carbonyl compounds for a variety of engines and duty cycles. The database contains 180 records, which report aldehydes and ketones. The majority of the data were for HD FTP. The predominant carbonyl species were formaldehyde and acetaldehyde.

Polynuclear aromatic hydrocarbons and nitro-polynuclear aromatic hydrocarbon emissions were averaged for various cycles and presented. Their mass contribution to the total particulate matter is on the order of 0.1 percent.

The “metals and inorganics” data came from fifty-four tests. The concentrations of metals did not appear to vary much with cycle, engine, or fuel. Sulfur is typically attributed to lubricating oil and fuel. Aluminum and iron are likely due to engine wear. Zinc, phosphorus, calcium, and magnesium are components of oil additives.

For PM characterization, there were a number of different parameters reported, but only total PM and soluble organic fraction (SOF) had enough observations for analysis.

While this database represents a large and varied data set, it is still not adequate to fully define emissions as a function of speed, load, fuel, and engine technology. The primary reasons are that there is insufficient coverage of LD engines, and the bulk of the data was reported as composite values rather than as discrete power/load points. Analysis of the data shows that there are relatively few observations for a number of the test conditions, and engines. In some cases, the available observations are from a single or a small number of engines. There is also some uncertainty in comparing results; it is unclear if the various laboratories used sample collection and analysis methods that yield comparable results.

Because most data represent composite results from either transient cycles or multiple, steady state points, it is not possible to define a standard gas related to a full matrix of speed and load conditions. Nevertheless, these data can be used to define a “generic” standard diesel exhaust with a reasonable level of confidence for a number of operating conditions. A scalable approach is suggested, by focusing not on the magnitude of the emissions, but on the relative amounts of the significant components. By defining the gas composition in terms of ratios of the components, the complexity of taking into account various confounding factors is avoided. Using this approach, an example of a synthetic diesel exhaust was proposed.

Analysis of the database shows that there are not sufficient data for LD vehicles. The AVFL committee believes that further testing is needed to extend the state of knowledge of LD diesel engine emissions, to permit the creation of a standard mixture that will adequately mimic the key characteristics of both LD and HD diesel exhaust, and thus greatly enhance the value in lab screening of catalysts.

FOREWORD

This project, entitled "Diesel Exhaust Standard Phase I: CRC Project No. AVFL-10a," was performed for Coordinating Research Council (CRC) by the Department of Emissions Research at Southwest Research Institute® (SwRI®). The period of performance was from January 16 through May 29, 2003. The project was based on SwRI Proposal 08.035939-A. The projector director for CRC was Mr. Brent Bailey. The project manager for Southwest Research Institute was Dr. Lawrence Smith, and the project leader was Mr. Patrick M. Merritt.

ABSTRACT

This report describes the effort to conduct an in-depth literature review to identify the state of knowledge of regulated and unregulated exhaust emissions from current, advanced technology diesel engines. The focus of this effort is to gather engine-out emissions data without regard to engine application, fuel type, manufacturer, after treatment device employed, power output, or other factors.

These data were used to create a relational database utilizing Microsoft Access® software. This database of engine-out diesel exhaust emissions will facilitate examination of the body of data based on different query criteria. In addition, a bibliography of each source reviewed has been prepared, with a brief synopsis of the content of each individual paper.

At the outset, emphasis was placed on advanced technology engines, that is to say, those developed to meet 2007 and future standards. As a result, it was anticipated that the majority of the effort would concentrate on reports published after the 1996 time frame. In fact, data from sources as old as 1991 were compiled. The bulk of studies, however, was published from 1998 to 2003. In total, 155 sources were reviewed and data were extracted from 72 of them. Most of the studies utilized to create the database were published by the Society of Automotive Engineers (SAE), yet represent a global perspective with good representation from Asia and Europe.

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I. INTRODUCTION

Development of exhaust after-treatment systems is facilitated with laboratory bench reactors in which a gas mixture is fed to a device while the feedgas and exhaust are monitored. Synthetic gas reactors have proven useful in gasoline applications, where a simple gas mixture will suffice. Some laboratories have used such a system for development of diesel aftertreatment, with propene as the primary hydrocarbon. Obviously, diesel exhaust gas is of inherently different composition than gasoline-derived exhaust from spark ignited engines; in addition, particulate matter is present in significant quantities. The lower temperatures of diesel exhaust also dictate different approaches to aftertreatment technology. For these reasons, there is impetus to develop a synthetic exhaust standard for diesel engines analogous to that used for gasoline applications. To establish such a standard composition, it is first necessary to develop a specification based on data from a variety of diesel engines and fuels. This study focused on engine-out exhaust emissions data from advanced technology diesel engines.

II. WORK PLAN

A. Objective

The objective of this research was to review, compile, and summarize data available in the open literature related to speciated, engine-out exhaust emissions from advanced technology diesel engines as a function of engine size, speed, load, fuel, technology type, and other significant variables. This summary includes an analysis of the major chemical species and particulate matter found under various operational modes. This analysis attempts to differentiate between compounds and particulate types that are generally found regardless of conditions and those that are found only under a limited set of conditions. By focusing on engine-out emissions data, this study is neutral to any after-treatment devices employed. All data collected have been put into a relational database using Microsoft Access®. Additionally, a bibliography has been prepared. An attempt has been made to identify gaps in the available literature and to make recommendations for an approach to achieve a standard non-particulate diesel exhaust mixture and an exhaust plus particulate diesel exhaust mixture.

B. Statement of Work

The principal task was to conduct an in-depth literature search to identify studies in which measurements of speciated diesel exhaust emissions from advanced technology engines on an engine-out basis are reported. Because the emphasis was on advanced technology engines, that is to say, those developed to meet 2007 and future standards, it was anticipated that efforts would concentrate on reports published after the 1996 time frame.

Many contemporary studies have reported emissions reductions brought about with the aid of after-treatment technology. Because of our charge to acquire only engine-out data, studies which did not include engine-out data were naturally excluded. Because this study was directed solely toward engine-out data, it was neutral to type of after-treatment employed and does not comment on related factors such as fuel economy penalties, durability issues, etc.

To achieve this literature search, the Department of Emissions Research (DER) accessed unrestricted, peer-reviewed materials such as technical papers [Society of Automotive Engineers (SAE), American Society of Mechanical Engineers (ASME), etc.) and reports (National Technical Information Service (NTIS), Coordinating Research Council, Inc. (CRC), and others] through our own abstracts and files, and by conducting wide-ranging searches of scientific literature utilizing our library's comprehensive Global Voyager™ electronic search capabilities. The bulk of the reports was published by SAE. In addition, CRC requested the inclusion of data from two CRC projects that were in final reporting stages at the time of this review.

Copies of the source materials identified were procured by purchase, download from the Internet, or from interlibrary loan. After review and analysis of the content and methodology employed, each source was briefly summarized as to its suitability.

A Microsoft Access® relational database has been prepared to permit analysis of emissions data reported in all the reviewed sources and to facilitate in the identification of trends. Relevant data were extracted and put into various tables. Tables were organized by engine, fuel, and emissions data. Emissions data were subdivided into tables for regulated emissions, elements and inorganic compounds, carbonyl compounds, PAH and NPAH compounds, dioxins and furans, hopanes and steranes, nitrosamines, speciated hydrocarbons, and heavy hydrocarbons. The database can be used to execute queries based on (where available) engine, fuel, duty cycle, and emissions parameter. One simply needs to structure a query to extract the data of one's choosing.

A summary which includes a detailed analysis of the major chemical species and particulate matter found under various operational modes has been prepared. This analysis attempts to differentiate between compounds and particulate types that are generally found regardless of conditions, and those that are found only under a limited set of conditions. The report includes a bibliography with a brief synopsis of each document.

SwRI anticipated that the extant literature would not contain data to cover all combinations of fuel properties, engine sizes and operating conditions, etc., and that indeed, turned out to be the case. Recommendations have been made for additional data collection programs for situations in which sufficient, reliable data do not exist.

Finally, a method was proposed to derive an appropriate synthetic diesel exhaust gas mixture. Through illustration by example, a synthetic exhaust gas mixture was derived taking into account the predominant species present in the HD transient cycle (for which there was the most abundant data) and issues of practicality.

III. RESULTS AND DISCUSSION

A total of 155 documents was reviewed for this study. It was anticipated that the primary source of information would be studies published after the 1996 time frame. In fact, sources as old as 1991 were compiled. The bulk of studies (113), however was published from 1999 to 2003. Almost half of the total (72) turned out to be useful. Of those, 47 were published from 1999 to 2003. Although the overwhelming majority of papers were published by SAE, a truly global perspective was maintained. Fully one-third (53 in all) originated in Europe, the U.K., or Scandinavia. Fourteen originated in Asia or Japan. In fact, the only continent not represented was Australia. A summary of countries of origin is presented in Table 1.

A bibliography of the documents that were included in the database is made in Appendix A. Appendix B presents a bibliography of the documents that were reviewed but not included in the database. In these tables, the title, lead author, publisher, publication date, country of origin, and citation information are included. In addition, a brief comment on the applicability and content of each article has been included.

A relational database prepared with Microsoft Access® software has been created, and is being supplied on an accompanying CD. Persons who are familiar with Microsoft Access® should be able to use this database to execute various queries to extract data of interest to them. The data tables have been named to be self-explanatory for the most part, to facilitate use of this database by individuals who may not be familiar with it. Please refer to Appendix C for a description of the layout of this database.

TABLE 1. SUMMARY OF COUNTRIES OF ORIGIN

COUNTRY	NUMBER OF STUDIES REPRESENTED
AFRICA	
South Africa	1
ASIA	
Bangladesh	1
China	2
Japan	10
India	1
EUROPE AND U.K.	
Denmark	3
European Collaborations	9
Germany	2
Greece	1
Finland	2
France	7
Italy	6
The Netherlands	1
Norway	1
Poland	1
Sweden	6
United Kingdom	13
Yugoslavia	1
NORTH AMERICA	
Canada	2
United States	81
SOUTH AMERICA	
Venezuela	1

The data contained in this database represents a wealth of information on a wide variety of engines, vehicles, applications (duty cycles), and fuels. There is not yet a great deal of information on what would be considered the latest technology, that is to say, those engines developed to meet 2007 or later emissions standards. However, there is a good deal of information about engines that were manufactured in the 1990s. Several in-depth studies are included in which detailed characterization of gaseous and particulate emissions were performed. Detailed hydrocarbon speciation data, including carbonyl compounds, have been included from studies representing light- and heavy-duty diesel engines in a variety of applications. In addition, several studies reported polynuclear aromatic hydrocarbons (PAH) and nitro-polynuclear aromatic hydrocarbons (NPAH), as well as less often reported classes such as dioxins, hopanes and steranes, and heavy hydrocarbons (> 12 carbons). Although there is a large amount of data in the database, it is not always possible to organize it in ways to represent a robust characterization of a particular mode. In particular, most data are derived from either transient cycles or represent a composite of multiple, steady-state points. Thus it is difficult to characterize discrete speed and load conditions.

A. Test Cycles

Studies represent the more commonly used test cycles, such as various steady-state modes, U.S. light-duty and heavy-duty chassis cycles, U.S. heavy-duty engine test cycles, and European test cycles. Also represented are the Japanese 10.15 and D13 cycles, studies of idle emissions, and a number of specialty cycles.

B. Engines

Engines representing almost all the world's major manufacturers are included, ranging from one and two cylinder research engines to very large marine diesel engines, with power ratings ranging from 8.2 to 6400 kilowatts. The bulk of the studies reporting useful data utilized engines representing those found in class eight, over-the-highway trucks. There are approximately* thirteen 1997, seven 1998, twenty-one 1999, eight 2000, and two 2001 model year engines represented. (*A number of studies did not report detailed engine information.) Please see Table 2 and Figure 1 for summary information on the engines for which complete descriptive information was given. Unfortunately, not all authors included much detail about the engines used in their studies. Where stated, almost all the engines were described as having direct injection and turbochargers. Little elaboration was made about the type of exhaust gas recirculation (EGR) employed (if any) except the amount of EGR being used, but only in studies where rate of EGR was a variable. Only one record states the pressure used for fuel injection. Over sixty engines were not identified by model year and 24 were not identified by manufacturer. This situation makes it difficult in some cases to derive what type of technology was being employed. Table 3 presents a summary of 1999 and newer engines by manufacturer and model designation, with application and duty cycle tested. Finally, Figure 2 shows engine size distribution.

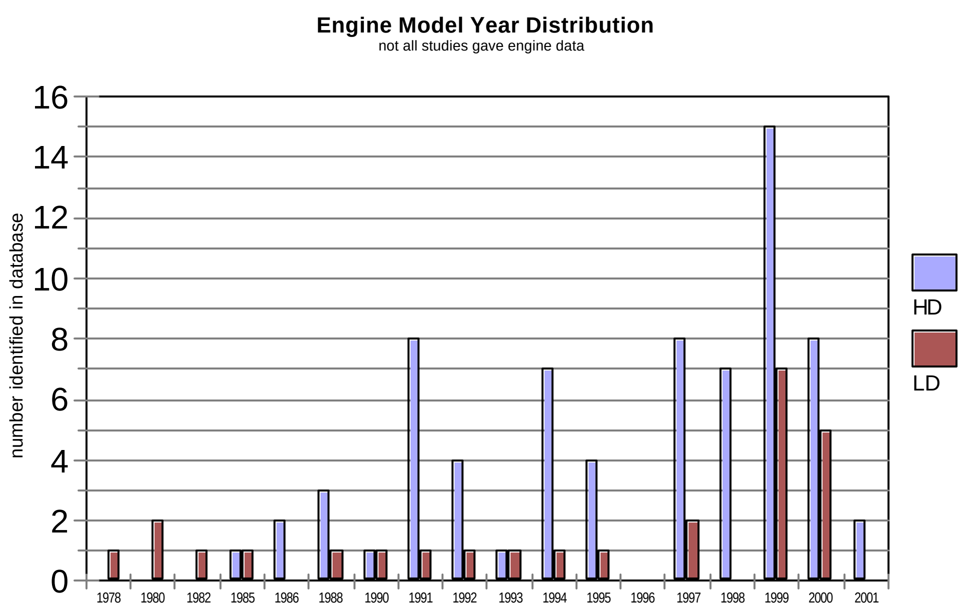

FIGURE 1. ENGINE MODEL YEAR DISTRIBUTION

TABLE 2. ENGINE MODEL YEAR SUMMARY

MANUFACTURER	MODEL YEAR / NUMBER REPRESENTED
Audi	1980/1, 1979/2, not stated/1; total 4
Caterpillar	1998/1 1997/4, 1995/1, 1994/1, 1992/2, 1986/1; total 10
Cummins	2000/6, 1999/8, 1998/1, 1997/3, 1995/3, 1993/2, 1991/2, 1990/1, 1988/2, 1986/1, 1985/1; total 32
Detroit Diesel	2001/1, 2000/1, 1999/6, 1998/3, 1997/1, 1994/2, 1991/4, not stated/1; total 19
Fiat	not stated/1
Ford	1997/1, not stated/3; total 4
Hatz	not stated/1
IMR	not stated/1
International	2001/1, 1998/2, not stated/1; total 4
Kubota	2000/1, not stated/1; total 2
Mercedes	1999/5, 1990/1, not stated/2; total 7
MWM	not stated/1
Navistar	1999/1 1994/3, 1991/1, not stated/1; total 6
Nissan	1995/1, 1994/1, 1992/1, not stated/1, total 4
OM	not stated/1
Perkins	1991/1
Peugeot	not stated/2
Phaser	not stated/1
Rover	not stated/1
Scania	not stated/1
Sulzer	not stated/1
Valmet	1 not stated/1
Volkswagen	1999/1, 1997/3, 1985/1, 1982/1, 1980/1, 1978/1, not stated/2; total 10
Volvo	1997/1, not stated/2; total 3
Wartsila Vasa	not stated/1

TABLE 3. NEWER ENGINES BY MANUFACTURER AND MODEL

Study ID	Model Year	Manufacturer	Model Designation	Engine Application	Test Cycle	Displace-ment
35	1999	Cummins	B-series	Heavy-Duty On-Road	HD FTP	5.9 L
56	1999	Cummins	ISM 370	Heavy-Duty On-Road	4 steady state OICA modes	10.8 L
56	1999	Navistar	T444E	Heavy-Duty On-Road	4 steady state Navistar modes	7.3 L
49	1999	Cummins	ISM370 ESP	Heavy-Duty On-Road	HD FTP, steady states	10.8 L
50	1999	Cummins	ISB	Light-Duty	AVL 8-mode	5.9 L
53	1999	Cummins	B-series	Heavy-Duty On-Road	HD FTP	5.9 L
10	1999	DDC	Series 60	Heavy-Duty On-Road	CSHVR	12.7
118	1999	DDC	Series 60	Heavy-Duty On-Road	CSHVR	not stated
44	1999	DDC	Series 60	Heavy-Duty On-Road	hot transient	12.7 L
137	1999	DDC	Series 60	Heavy-Duty On-Road	idle	not stated
29	1999	DDC	Series 60	Heavy-Duty On-Road	CSHVR	12.7
132	1999	Mercedes	OM611	Light-Duty	FTP-75, US06 steady states	2.2 L
119	1999	Mercedes	A170	Light-Duty	FTP-75	1.7 L
19	1999	Mercedes	OM668DE17	Light-Duty	steady states	2.2 L
26	1999	Volkswagen	1.9L TDI	Light-Duty	steady states	1.9 L
53	2000	Cummins	B-series	Light-Duty	FTP-75, US06, HFET	5.9 L
35	2000	Cummins	B-series	Light-Duty	FTP-75, US06, HFET	5.9 L
136	2000	DDC	Series 60	Heavy-Duty On-Road	idle	12.7 L
136	2000	Kubota	Z482	Aux Power unit	rated speed	0.482 L
137	2001	DDC	Series 60	Heavy-Duty On-Road	idle	not stated
152	2001	International	C275	Heavy-Duty On-Road	CSHVR	8.7 L

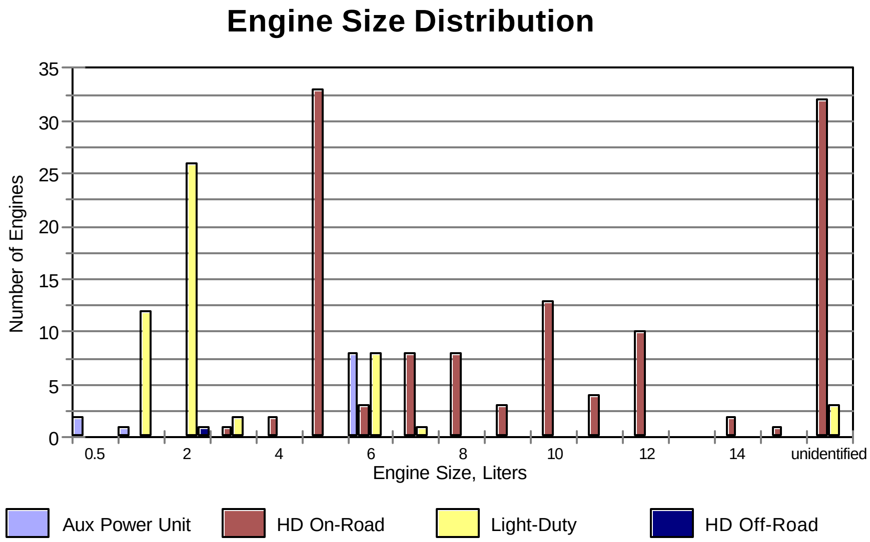

FIGURE 2. ENGINE SIZE DISTRIBUTION

C. Fuels

Fuels represented in this database included conventional and reformulated diesel with varying levels of sulfur and aromatics, water emulsions of diesel fuel, Fischer-Tropsch synthetic fuels, biodiesel fuels and biodiesel blends, and fuels with various additives and catalyst materials added. A summary of the fuels represented in this database is presented in Table 4.

TABLE 4. SUMMARY OF FUELS

FUEL DESIGNATION	SULFUR CONTENT
2D	3 ppm to 0.47 weight percent
CARB	115 ppm to 175 ppm
Biodiesel [a]	<0.005 to 0.1 weight percent
DMM (dimethoxy methane)	< 2 ppm
EC-1	0.7 ppm
Fischer-Tropsch	< 1 ppm to < 0.05 weight percent
Kerosene	0.005 weight percent
JP-8	96 ppm

[a] various biodiesel fuels are represented, mainly methyl esters of plant-derived oils.

D. Exhaust Emissions

Most studies reported regulated emissions (hydrocarbons, carbon monoxide, oxides of nitrogen, and total particulate matter), although a few reported only CO and NO_x or only PM and NO_x. There were several that reported a breakdown of particulate matter composition, but only one gave a detailed breakdown of particulate size fractions. Another presented a lengthy discussion of particulate size and particle number by size fraction but only a limited amount of data could be extracted for the database. Those studies can be identified by reading the synopses of the articles in Appendix B. Several studies included reports of the greenhouse gases (methane, carbon dioxide, and nitrous oxide). Only a few reported metals and inorganic compounds. There appears to have been much study of PAH and NPAH compounds. Only one study reported dioxins. Similarly, only two studies reported nitrosamines. Detailed hydrocarbon speciation data exist for a variety of light-duty and heavy-duty engines, operating over a variety of duty cycles and fuels. However, the bulk of the data are for the US heavy-duty FTP cycle. Data are fairly plentiful on the carbonyl compounds for a variety of engines, duty cycles, and fuels.

An analysis of compounds by class is made in the following sections. An attempt has been made to relate compounds to duty cycle and/or engine class, where possible. There are few data related to steady-state power/load points. Most information was collected using a transient test mode or was reported as some weighted composite of multiple, steady-state points.

1. Regulated Emissions

The data set encompassing the regulated emissions is by far the largest set in the database. There are data from more than 767 individual tests. Sorting these records by duty cycle permitted an analysis of both gaseous and particulate emission rates. A summary of the average emission rates reported for regulated emissions by duty cycle is presented in Table 5.

It should be immediately noted that these data represent the averages for those studies reporting data for a particular cycle and they may not relate to average results for other cycles. That is to say, for example, that the “hot-start HD FTP” data do not necessarily come from the same set of studies as those contained in “HD FTP” results.

Several of the duty cycles in the table above may not be familiar to all readers. For instance, “creep,” “laden cruise,” and “laden transient” are cycles used only in one study (No. 153, WVU-DRI CRC E-55/E-59), in which three class eight trucks were operated on a transportable chassis dynamometer. One should consult the CRC report for E-55/E-59 for a discussion of the cycles to understand how they should be interpreted.

Looking at the values in the table, it is interesting to note a number of factors. Idle emissions remain significant. It is not surprising that the “high idle” emissions are of greater magnitude than the “low idle” emissions, especially when one considers that “high idle” is usually used for operating accessories such cabin air-conditioning or heating, as well as simply running at higher engine speed. Some of the measurements of idle emissions were made at low ambient temperatures. When one considers the amount of time a typical class eight truck operates at idle, it is clear that idle emissions contribute significantly to the emissions inventory.

Emissions of oxides of nitrogen during the Creep, Laden Cruise, Laden Transient, UDDS, HFET, and CSHVR cycles are substantial. These generally represent high load cycles. On a per-mile basis, all the regulated emissions during the Creep cycle were substantially higher than those over the UDDS (in this case, the data for both cycles was from the same study with the same vehicles), an indicator that this mode of operation generates higher emissions on a per-mile basis, and affirms that urban congestion is not only a contributor to air pollution, but may cause a “snowball” effect.

“CSHVR” is the City-Suburban Heavy Vehicle Route. The data presented in Table 5 come from two similar programs in which emissions from school buses and tanker trucks were studied. Significant emissions of nitrogen oxides are evident. “ECE (MVEG)” refers to the European light-duty chassis dynamometer driving cycle.

Comparing the light-duty results to the heavy-duty chassis values, also in g/mi, it is clear that the lighter vehicles emit a fraction of the larger, heavier ones. Also, among the LD vehicles, the US06 NOx results are almost double those for the FTP-75. NOx was also elevated for the highway cycle, but it produced the lowest particulate emissions. The highest values across the board were for the Japan 10.15 cycle. There may have been other factors as well as the cycle which resulted in the higher results. All those data are from a single study in which some of the vehicles were classified as commercial.

TABLE 5. AVERAGE REGULATED EMISSION RATES BY DUTY CYCLE

CYCLE	TOTAL HYDRO-CARBONS	CARBON MONOXIDE	OXIDES OF NITROGEN	TOTAL PARTICULATE MATTER	NUMBER OF OBSERVATIONS
HEAVY DUTY ENGINE DYNAMOMETER RESULTS					
HD FTP	0.148 g/bhp-hr	1.179 g/bhp-hr	4.403 g/bhp-hr	0.102 g/bhp-hr	74
Hot-Start HD FTP	0.043 g/bhp-hr	0.434 g/bhp-hr	1.003 g/bhp-hr	0.031 g/bhp-hr	12
IDLE EMISSIONS					
High Idle (1200 rpm)	50.09 g/hr	108.9 g/hr	197.0 g/hr	6.247 g/hr	17
Low Idle (600 rpm)	25.99 g/hr	47.51 g/hr	97.96 g/hr	1.603 g/hr	17
HEAVY DUTY CHASSIS DYNAMOMETER RESULTS					
Creep	8.984 g/mi	30.07 g/mi	60.58 g/mi	3.953 g/mi	6
Laden Cruise	0.767 g/mi	2.207 g/mi	18.46 g/mi	0.303 g/mi	3
Laden Transient	2.390 g/mi	8.930 g/mi	24.07 g/mi	1.397 g/mi	3
UDDS	1.273 g/mi	10.52 g/mi	22.74 g/mi	0.883 g/mi	3
CSHVR	0.736 g/mi	3.744 g/mi	21.78 g/mi	0.287 g/mi	10
LIGHT-DUTY AND MEDIUM-DUTY VEHICLE RESULTS					
FTP 75	0.298 g/mi	1.381 g/mi	3.323 g/mi	0.142 g/mi	12
US06	0.264 g/mi	1.454 g/mi	6.498 g/mi	0.138 g/mi	8
HFET	0.160 g/mi	0.400 g/mi	4.452 g/mi	0.024 g/mi	4
Japan 10.15	2.769 g/mi	9.224 g/mi	19.36 g/mi	0.132 g/mi	41
ECE (MVEG)	0.088 g/km 0.128 g/mi	0.680 g/km 1.088 g/mi	1.565 g/km 2.504 g/mi	0.155 g/km 0.248 g/mi	12

2. Speciated Hydrocarbons

A detailed review was undertaken of the speciated hydrocarbons data. One difficulty with examining the speciated hydrocarbons data becomes evident only when the entire set is printed out: many studies that report "speciated hydrocarbons" report only a small number of compounds, such as benzene and 1,3-butadiene. Only a few laboratories, West Virginia University/Desert Research Institute of the University of Nevada, Southwest Research Institute, and the Swedish Environmental Institute reported "full" speciation.

The records were first sorted by duty cycle. This sort indicated that the best mix of information for heavy-duty engines was over the heavy-duty FTP. The data for the HD FTP come from seven studies (35, 53, 62, 89, 98, 100, 108) and represent a variety of engines, but only four of the engines were of 1999 or newer vintage. There were, of course, other cycles represented in the speciated hydrocarbons data set, but for most of the other duty cycles, there were not many studies or observations. There was only one study reporting each of the following cycles: cold-start transient (4 observations), central business district (CBD, 2 observations), city suburban heavy vehicle route (CSHVR, 6 observations). Two studies reported data from the hot-start transient cycle, with 8 observations. The predominant compounds seen over several duty cycles is presented in Table 6.

One study (No. 153) reported data on idle and creep emissions. Because of the recent interest in idle emissions, a presentation of the predominant compounds present in this mode has been made. The creep, cruise, and UDDS data from this study are also presented in Table 6 for comparison. These data represent three different class 8 trucks of model years 1985, 1994, and 1995.

Six studies reported light-duty FTP (FTP-75) speciated hydrocarbons, with four representing engines manufactured in 1999 or later. Other cycles for light-duty diesels were sparse: only two observations were recorded for the European (ECE or MVEG) cycle and there were three steady-state points reported in one other study. The speciation results for the FTP-75 are presented in Table 7. Although there were only two engines observed, data were also presented in Table 7 from a study of large ferry boats operating in the Bering Sea. When comparing the emissions rates to the on-road truck engines, consider that the two ferry engines were rated at 2460 and 6000 kW.

Figure 3 was prepared to illustrate the frequency of occurrence and magnitude of various emissions for selected cycles represented in the database. For the heavy-duty FTP, the predominant compounds are the lighter olefins, substituted cyclics, and heavier alkanes: ethene, propene, ethyne, 1,3-butadiene, butene, pentene, methyl-butene, benzene, toluene, xylenes, styrene; methyl-, ethyl-, and propyl-benzenes; and the C_9 through C_{12} alkanes. During idling, ethene and undecane are by far the most prominent components; also, propene, ethyne, butene, toluene, and dodecane are significant but substantially less apparent than the first two listed. Between the cold- and hot-start transient cycles, the only apparent difference was a greater amount of xylenes in the cold-start. For the FTP-75, which is used for light- and medium-duty vehicles, the overall profile was not much different than that for the HD FTP. One cannot make direct comparisons because of the different units for reporting, yet the incidence and relative magnitude of individual emissions is not too different.

Given the fact that:

- there are relatively few observations for a number of the test conditions,
- most available data are from transient cycles and not from discrete speed/load points,
- in some cases the available observations are from a single or a small number of engines,
- there is some uncertainty that the various laboratories used sample collection and analysis methods that yield comparable results, one should use caution and be aware of the limitations of the data set.

Further, the information on specific engine technology is scarce, so it is not possible to relate emissions to a particular design feature. With regards to differences in speciated emissions due to fuel type, heavy hydrocarbons were not reported for biodiesel or Fischer-Tropsch Fuel.

TABLE 6. SPECIATED HYDROCARBON EMISSIONS PROFILE FOR VARIOUS TEST CYCLES

TEST CYCLE	HD FTP		COLD TRANSIENT		HOT TRANSIENT		IDLE		UDDS		CREEP		CRUISE	
COMPOUND	CONCENTRATION mg/bhp-hr	No. of Observations	CONCENTRATION mg/bhp-hr	No. of Observations	CONCENTRATION mg/bhp-hr	No. of Observations	CONCENTRATION mg/mi	No. of Observations	CONCENTRATION mg/mi	No. of Observations	CONCENTRATION mg/mi	No. of Observations	CONCENTRATION mg/mi	No. of Observations
ethane	0.27	3	-	-	-	-	13.4	6	1.68	5	21.81	5	0.77	5
ethene (ethylene)	16.62	18	8.54	5	7.26	5	305.7	6	60.3	5	607.1	5	33.66	5
propane	0	3	-	-	2.20	5	7.94	6	0.74	5	10.62	5	0.59	5
propene (propylene)	6.02	18	-	-	-	-	92.1	6	25.7	5	196.1	5	13.85	5
propyne	0.20	12	-	-	-	-	7.51	6	3.09	5	13.12	5	0.59	5
ethyne	1.88	18	-	-	-	-	68.4	6	10.87	5	113.1	5	5.97	5
1,3-butadiene	1.70	23	1.18	5	0.98	8	27.1	6	6.49	5	55.86	5	1.61	5
benzene	1.82	23	1.32	-	0.93	8	38.0	6	7.32	5	59.89	5	3.99	5
toluene	0.64	18	-	-	0.30	3	18.99	6	2.98	5	25.45	5	1.29	5
butane	0	3	0.02	5	-	-	3.87	6	0.40	5	5.42	5	0.27	5
trans-2-butene	0.44	9	-	-	-	-	3.61	6	1.04	5	7.33	5	0.51	5
butene (butylene)	2.43	12	0.1	5	0.70	5	28.2	6	4.33	5	60.0	5	4.29	5
cis-2-butene	0.34	9	-	-	-	-	2.52	6	0.73	5	4.99	5	0.38	5
pentene	0.54	18	-	-	-	-	11.67	6	4.14	5	25.31	5	2.56	5
pentane	0.13	3	-	-	-	-	2.84	6	0.32	5	3.95	5	0.35	5
2-methyl-1-butene	0.57	3	0.3	5	-	-	5.07	6	1.30	5	10.41	5	0.89	5
cyclopentene	0.30	3	-	-	-	-	1.74	6	0.76	5	4.56	5	0.42	5
cyclopentane	0.45	3	-	-	-	-	0.69	6	0	3	0.12	5	0.01	4

TABLE 6 (CONTD.) SPECIATED HYDROCARBON EMISSIONS PROFILE FOR VARIOUS TEST CYCLES

TEST CYCLE	HD FTP		COLD TRANSIENT		HOT TRANSIENT		IDLE		UDDS		CREEP		CRUISE	
COMPOUND	CONCENTRATION mg/bhp-hr	No. of Observations	CONCENTRATION mg/bhp-hr	No. of Observations	CONCENTRATION mg/bhp-hr	No. of Observations	CONCENTRATION mg/mi	No. of Observations	CONCENTRATION mg/mi	No. of Observations	CONCENTRATION mg/mi	No. of Observations	CONCENTRATION mg/mi	No. of Observations
3-methylpentane	0.80	3	-	-	-	-	2.92	6	0.28	5	4.04	5	0.17	5
hexane	-	-	-	-	-	-	5.69	6	0.85	5	6.10	5	0.21	5
methylcyclopentane	0.30	3	-	-	-	-	2.81	6	0.37	5	4.03	5	0.19	5
2,3-dimethylpentane	0.10	3	-	-	-	-	0.95	6	0.1	5	1.46	5	0.06	5
heptane	0.27	3	-	-	-	-	2.36	6	0.31	5	3.37	5	0.18	5
methylcyclohexane	0.30	3	-	-	-	-	2.81	6	0.38	5	4.03	5	0.19	5
2,3-dimethylhexane	0.49	9	-	-	-	-	0.33	6	0.08	5	0.62	5	0.06	5
ethyl benzene	0.49	12	-	-	0.37	3	3.19	6	0.51	5	4.56	5	0.23	5
styrene	0.73	9	-	-	-	-	8.03	6	1.52	5	12.21	5	0.65	5
m/p-xylenes	1.21	15	4.46	5	1.58	8	6.60	6	1.11	5	9.93	5	0.52	5
o-xylene	0.99	9	-	-	-	-	2.71	6	0.47	5	4.08	5	0.21	5
dimethyloctane	1.08	9	3.68	5	2.25	5	-	-	-	-	-	-	-	-
nonene	1.57	9	-	-	-	-	-	-	-	-	-	-	-	-
nonane	0.91	9	-	-	-	-	13.51	6	1.89	5	18.48	5	0.98	5
propylbenzene	0.58	9	-	-	-	-	0.76	6	0.12	5	1.18	5	0.05	5
trimethylbenzene	2.06	9	1.54	5	2.90	5	2.67	6	0.45	5	3.66	5	0.21	5
decane	1.39	9	-	-	-	-	-	-	3.53	5	22.49	5	1.73	5
undecane	2.67	9	-	-	-	-	504.3	6	75.97	5	663.2	5	37.27	5
dodecane	2.46	9	-	-	-	-	47.72	5	7.82	5	177.0	5	7.81	5
unident. C9-C12+	12.72	9	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 7. SPECIATED HYDROCARBON EMISSIONS PROFILE FOR SELECTED TEST CYCLES

COMPOUND	Compound Number	FTP-75		Ferry at Cruise	
		Rate, mg/mi	No. of Observations	Rate, mg/kW-hr	No. of Observations
ethane	1	1.85	2	-	-
ethene (ethylene)	2	32.2	4	11.35	2
propane	3	0.3	1	-	-
propene (propylene)	4	-	-	4.2	2
propyne	5	-	-	-	-
ethyne	6	9.8	3	0.15	2
1,3-butadiene	7	1.84	8	-	-
benzene	8	2.68	9	12.1	2
toluene	9	2.65	3	10.35	2
butane	10	0.6	1	-	-
trans-2-butene	11	0.4	1	-	-
butene (butylene)	12	2.2	1	0.5	2
cis-2-butene	13	0.8	1	-	-
pentene	14	-	-	0.5	2
pentane	15	-	-	-	-
2-methyl-1-butene	16	0.6	1	-	-
cyclopentene	17	-	-	-	-
cyclopentane	18	0.2	1	-	-
2-methylpentane	19	0.3	1	-	-
hexene	20	0.6	1	-	-
hexane	21	-	-	-	-
methylcyclopentane	22	0.1	1	-	-
2,3-dimethylpentane	23	-	-	-	-
2,2,4-trimethylpentane	24	1.6	1	-	-
heptane	25	0.1	1	-	-
octane	26	0.5	1	-	-
methylcyclohexane	27	0.5	1	-	-
2,3-dimethylhexane	28	2.2	1	-	-
ethyl benzene	29	0.5	1	-	-
styrene	30	-	-	-	-
m/p-xylenes	31	2.35	2	13.5	2
o-xylene	32	1.1	1	-	-
dimethyloctane	33	0.4	1	-	-
nonene	34	1.5	1	-	-
nonane	35	1.5	1	-	-
ethylbenzene	36	-	-	1.25	2
propylbenzene	37	0.5	1	-	-
trimethylbenzene	38	0.7	1	-	-
methylethylbenzene	39	1.3	1	-	-
diethylmethylbenzene	40	0.4	1	-	-
tetramethylbenzene	41	0.5	1	-	-
decane	42	2.8	1	-	-
undecane	43	2.3	1	-	-
dodecane	44	1.1	1	-	-
unidentified C12	45	-	-	-	-

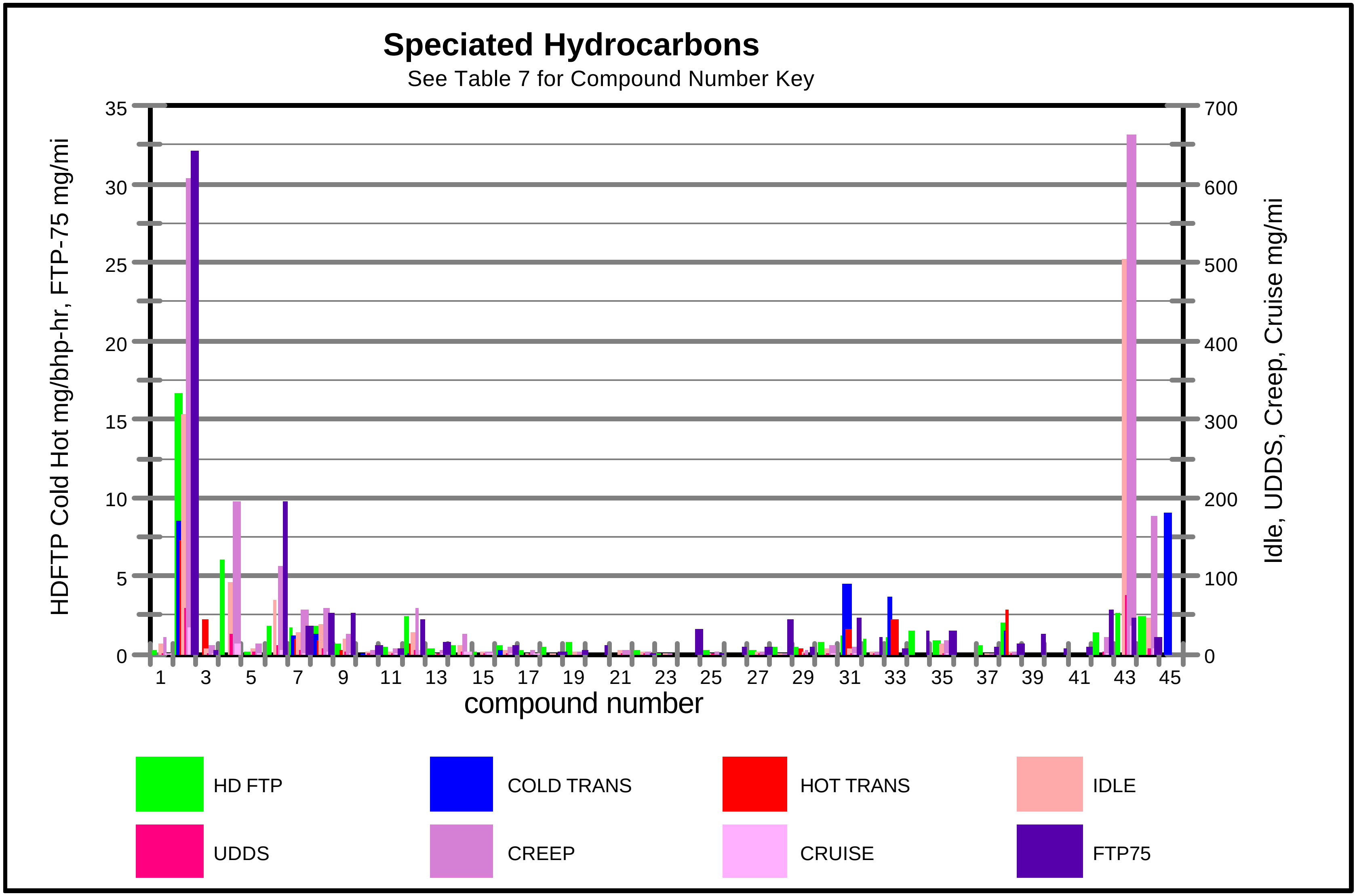

FIGURE 3. INCIDENCE OF SPECIATED HYDROCARBONS

3. Carbonyl Compounds

The database contains 180 records which report aldehydes and ketones. Table 8 presents a summary of averaged values by duty cycle along with the number of observations. Be aware that with the exception of the HD FTP, Hot Start, and FTP-75, most averages represent only one or two studies/engines, despite the number of observations recorded. Figures 4 through 7 illustrate the relative abundance of the carbonyl compounds by duty cycle. In almost every case, formaldehyde dominates by a margin of about 2:1 over the next most abundant compound, acetaldehyde.

Thirty-one observations from seven separate studies reported heavy-duty FTP carbonyl compound emissions. Formaldehyde emissions ranged from 9 to 70 mg/bhp-hr, and averaged 25.4 mg/bhp-hr. Acetaldehyde ranged from 4 to 25 mg/bhp-hr and averaged 10.3 mg/bhp-hr. Average emissions for the remaining carbonyl compounds ranged from about 0.3 to 2.7 mg/bhp-hr. The emissions profile is shown in Figure 4.

Cold-start test results were available from two studies representing eight individual test runs. For these cold-start tests, formaldehyde emissions averaged 18.5 mg/bhp-hr, acetaldehyde emissions averaged 7.1 mg/bhp-hr, and the emission rates for the remaining components ranged from approximately 0.6 to 2.7 mg/bhp-hr.

Three studies reported a total of 14 tests in which hot-start tests were performed. Three engines were represented, and conventional fuels, water emulsions, and conventional fuel doped with various levels of a Cerium fuel-born catalyst, were utilized. Hot-start emissions of formaldehyde averaged 25.4 mg/bhp-hr, acetaldehyde emissions averaged 10.3 mg/bhp-hr, acetone emissions averaged 2.4 mg/bhp-hr, acrolein averaged 2.4 mg/bhp-hr. The experiments with the Cerium fuel-born catalyst did not give results for the carbonyl compounds that were substantially different from the base fuel. For the study utilizing the water emulsions, one gave results substantially higher than the base fuel, but another water emulsion was essentially the same as the base fuel. The carbonyl compound emissions profile over the hot-start was similar to the cold-start cycle, as seen in Figure 4 (although the plots represent different populations; likewise for the HD FTP).

For light-duty vehicles operating over the FTP-75, formaldehyde emissions averaged 21.7 mg/mi and acetaldehyde emissions averaged 9.7 mg/mi. Acetone, acrolein and propionaldehyde were significant at 3.7, 4.4, and 3.8 mg/mi, respectively. Please refer to Figure 5.

Two studies evaluated a Dodge pickup with a Cummins engine operating over the US06 and the HFET. Four fuels were represented in the studies: conventional diesel, CARB diesel, Fischer-Tropsch fuel, and one termed Swedish diesel. For the US06 cycle, carbonyl emissions were virtually the same for all four fuels. Formaldehyde averaged 8.6 mg/mi, acetaldehyde averaged 4.1 mg/mi. Propionaldehyde was the next highest at 1.6 mg/mi. The carbonyl compound emissions profile over the highway fuel economy test was similar to the US06 cycle, but slightly lower in magnitude. Bear in mind that these two cycles were representative of a different population than for the FTP-75 which is shown on the same plot.

TABLE 8. SUMMARY OF AVERAGE CARBONYL COMPOUND EMISSION RATES

Test Procedure	Units	No. Observations	formaldehyde	acetaldehyde	acetone	acrolein	propionaldehyde	crotonaldehyde	butyraldehyde	benzaldehyde	isovaleraldehyde	valeraldehyde	o-tolualdehyde	m/p-tolualdehyde	hexanaldehyde	2,5-dimethylbenzaldehyde
FTP-75	mg/mi	8.0	21.7	9.7	1.3	3.7	4.4	3.8	0.4	1.0	0.2	0.4	0.1	0.2	0.1	0.1
HFET	mg/mi	5.0	5.8	2.6	0.2	0.2	1.2	0.7	0.2	0.3	0.2	0.1	0.0	0.1	0.1	0.1
US06	mg/mi	5.0	8.6	4.1	0.3	0.6	1.6	0.9	0.4	0.8	0.1	0.2	0.0	0.2	0.2	0.2
MVEG	mg/mi	5.0	43.9	10.0	–	11.2	–	–	–	–	–	–	–	–	–	–
HD FTP	mg/bhp-hr	31.0	25.4	10.3	2.4	2.7	1.8	1.3	0.4	0.8	1.4	1.3	0.6	1.8	0.6	0.3
Cold Start	mg/bhp-hr	8.0	18.5	7.1	2.5	2.7	1.5	0.9	0.8	1.7	–	–	–	–	0.6	–
Hot Start	mg/bhp-hr	14.0	16.6	6.2	1.7	2.4	1.4	0.8	0.7	1.0	–	–	–	–	0.5	–
UDDS	mg/mi	4.0	50.8	16.5	4.8	0.5	0.1	1.1	0.0	0.0	–	0.3	–	1.4	0.0	–
CSHVR	mg/mi	7.0	39.4	14.3	–	0.8	3.0	–	0.5	0.0	–	–	–	–	–	–
Cruise	mg/mi	6.0	17.5	32.0	0.0	0.7	0.2	0.3	–	–	–	0.0	–	0.1	0.0	–
Idle	mg/mi	7.0	507.1	200.7	117.6	7.0	31.1	11.4	0.0	0.0	–	7.2	–	2.0	0.7	–
Creep	mg/mi	6.0	875.3	364.7	168.7	4.7	46.7	13.7	0.0	0.0	–	15.4	–	1.4	0.1	–
high idle (1200 rpm) COLD	mg/hr	8.0	2433.1	1485.8	–	–	–	–	–	–	–	–	–	–	–	–
low idle (600 rpm)	mg/hr	10.0	974.5	618.4	–	–	–	–	–	–	–	–	–	–	–	–

" – " indicates no value reported

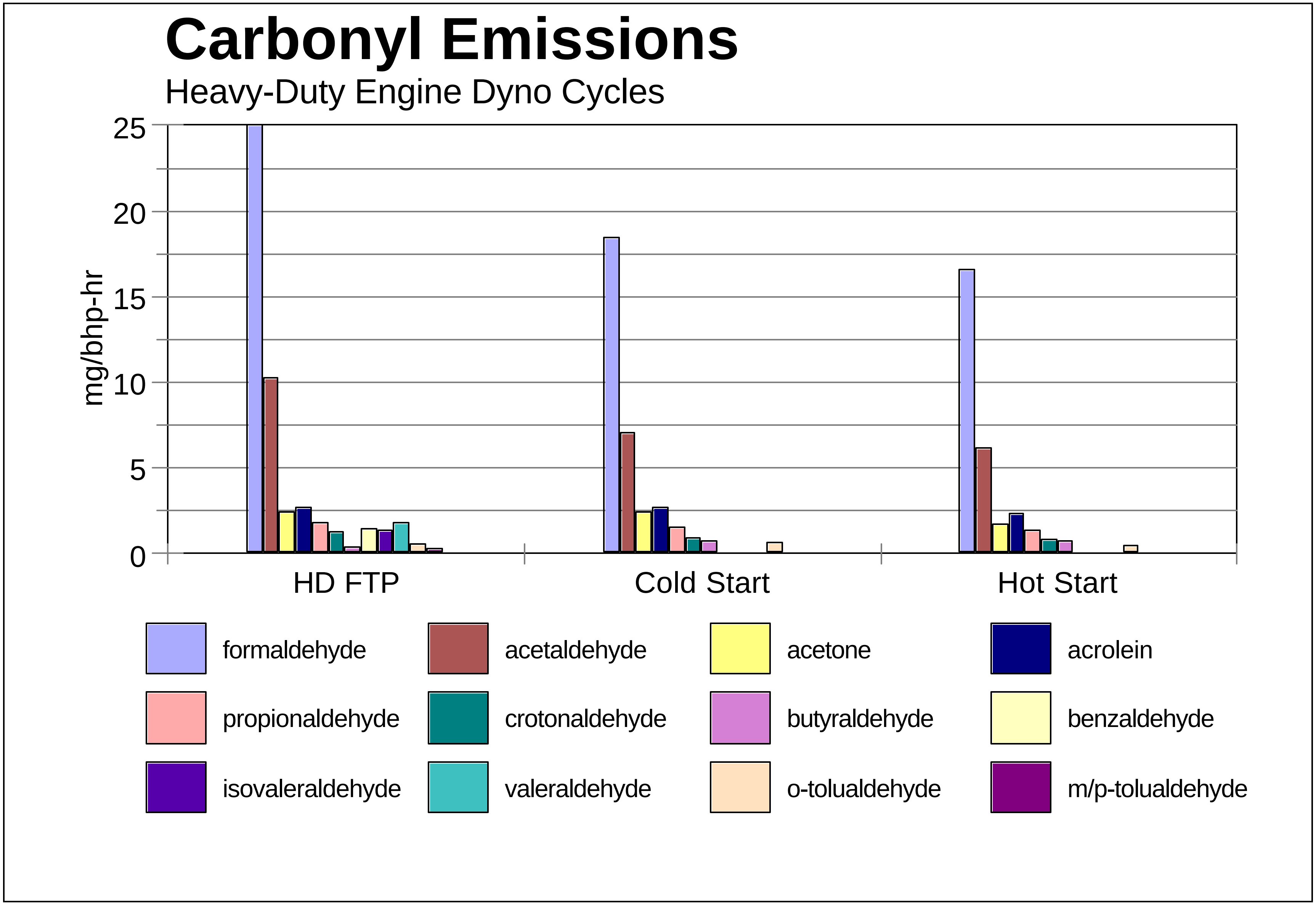

FIGURE 4. CARBONYL EMISSIONS FOR HD ENGINE DYNO CYCLES

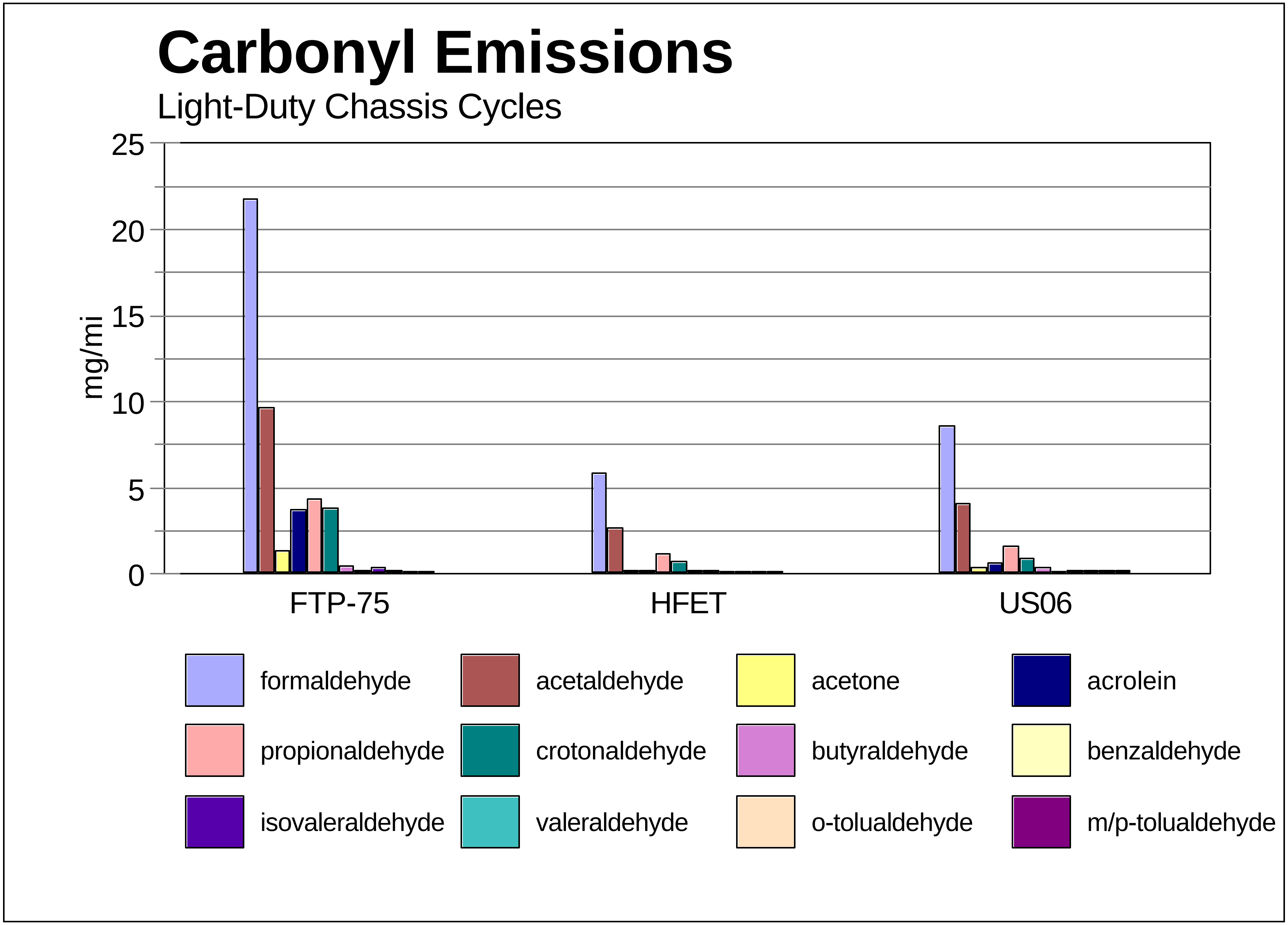

FIGURE 5. CARBONYL EMISSIONS FOR LD CHASSIS CYCLES

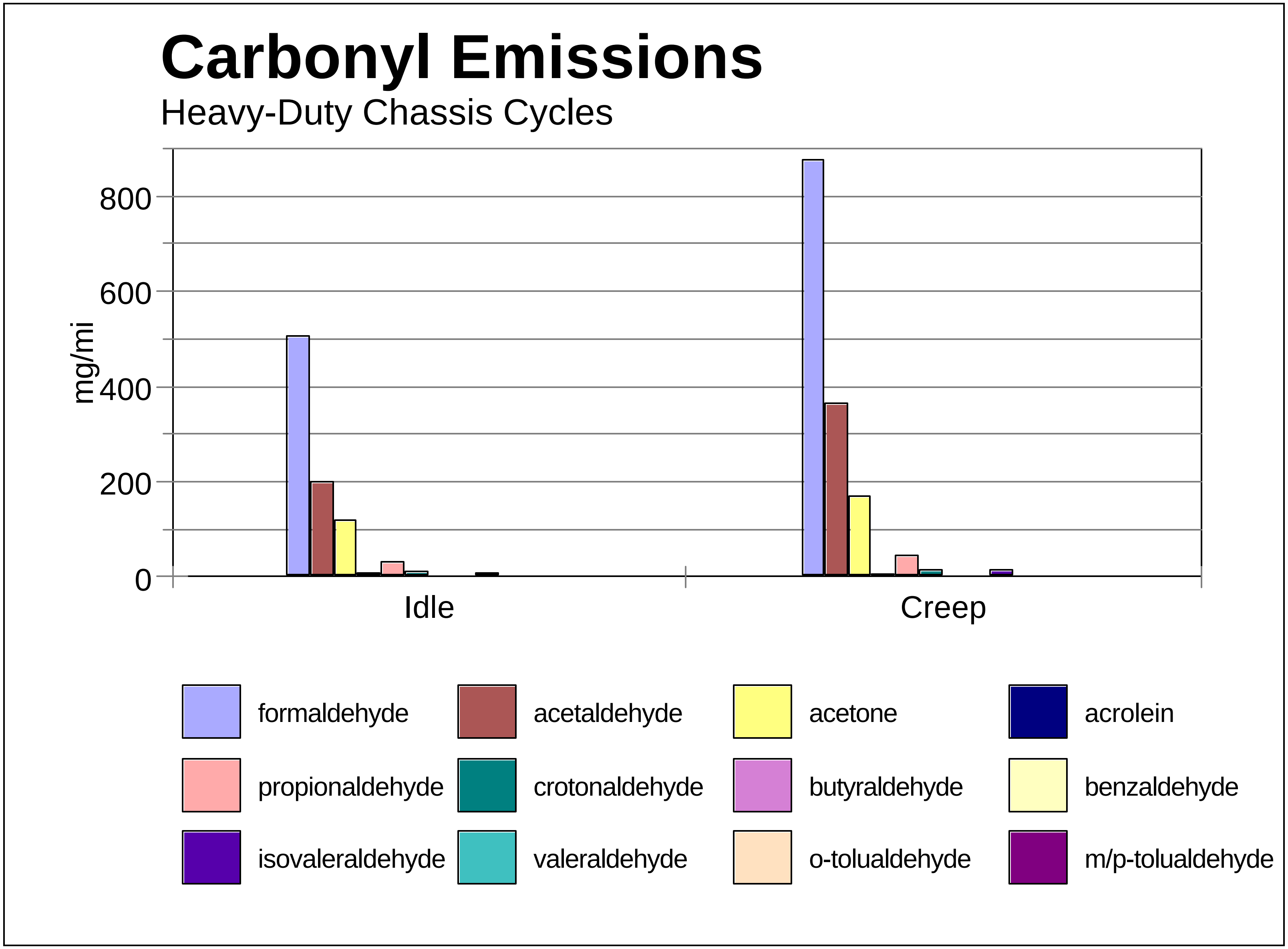

FIGURE 6. CARBONYL EMISSIONS FOR HD CHASSIS CYCLES

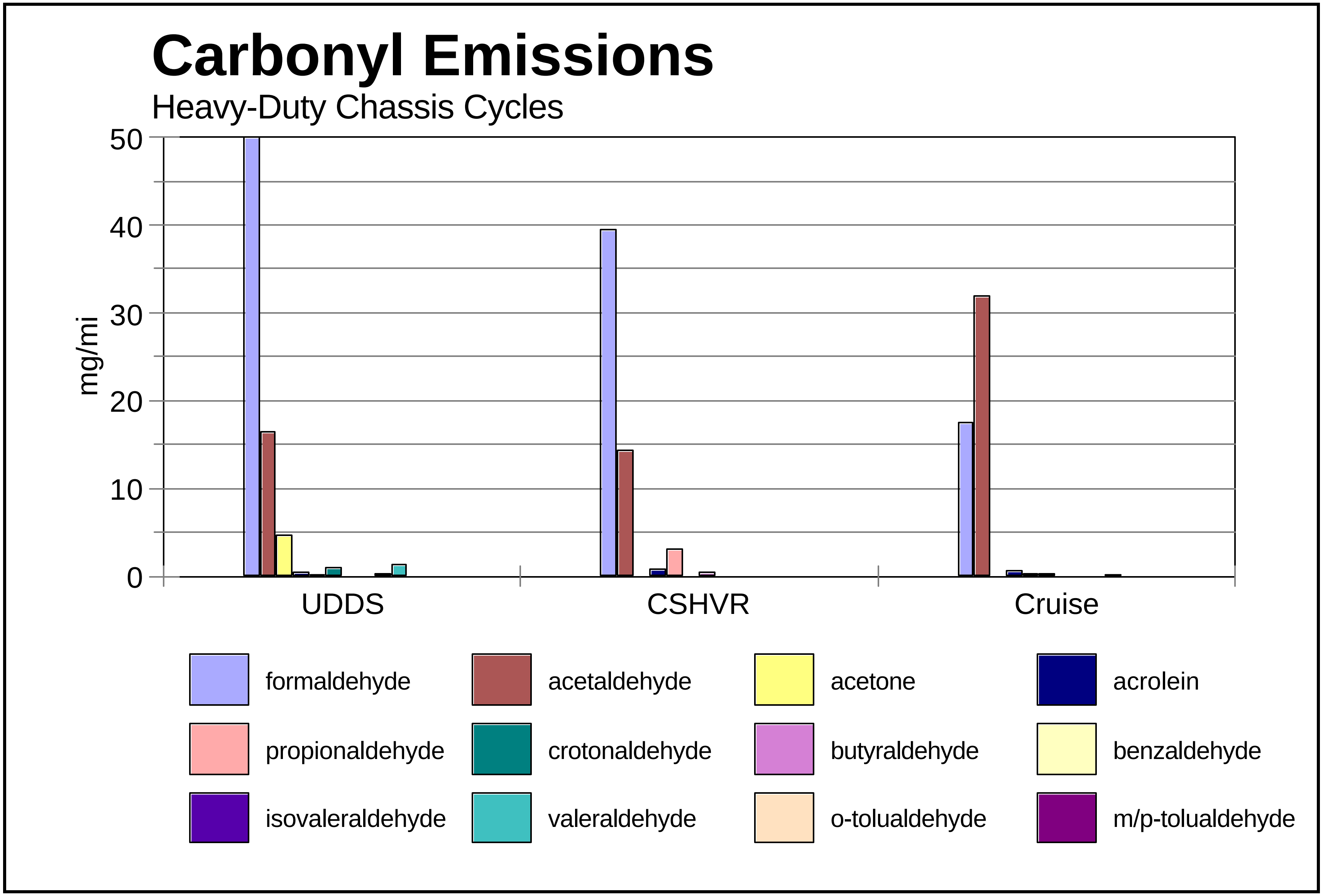

FIGURE 7. CARBONYL EMISSIONS FOR HD CHASSIS CYCLES

In the study discussed in Section 3 above, which reported idle and creep emissions for class eight trucks, formaldehyde idle emissions averaged 507 mg/mi. Acetaldehyde idle emissions averaged 201 mg/mi. (Study authors reported idle emissions in mass per mile.) Significant amounts of acetone were also reported. Please refer to Table 8 and Figure 6 for more detail. Emissions were also very high for the creep duty cycle. These data indicate that prolonged idling and operation in heavy congestion contribute substantially.

A study of airport ground support equipment operating at low idle (600 rpm) indicated formaldehyde emissions ranging from 27 to nearly 4,000 mg/hr, averaging 974 mg/hr. Acetaldehyde emissions ranged from 12 to nearly 2,200 mg/hr, averaging 618. At high idle (1200 rpm) and cold ambient temperature (-18°C), formaldehyde emissions averaged 2433 mg/hr and acetaldehyde averaged 1485 mg/hr. Only these two compounds were reported in this particular study.

4. PAH and NPAH

Polynuclear aromatic hydrocarbons and nitro-polynuclear aromatic hydrocarbon emissions were averaged for various cycles and presented in Table 9 below. While the health effects of these compounds have been widely discussed, their mass contribution to the total particulate matter is on the order only 0.1 percent. With different units for the cycles presented, it is difficult to make comparisons across cycles without making gross assumptions. The "idle" emissions data came from a single study, and again were reported as mass per mile.

5. Metals and Inorganics

Fifty-four tests comprise the "metals and inorganics" table of the database, with different studies reporting different combinations of elements and compounds. The concentrations of metals did not appear to vary much with cycle, engine, or fuel. A summary of the average concentrations is presented in Table 10. The predominant metals reported are included, and the data were separated into two categories, those reported in mass per work, and in mass per distance traveled. Sulfur is typically attributed to lubricating oil and fuel. Aluminum and iron are likely due to engine wear. Zinc, phosphorus, calcium, and magnesium are components of oil additives.

6. Particulate Matter Characterization

For particulate matter characterization, there were a number of different parameters reported, but only total PM and soluble organic fraction (SOF) had enough observations reported to warrant discussion. Over the heavy-duty FTP, total PM averaged 0.102 g/bhp-hr over 59 observations, and SOF averaged 0.036 g/bhp-hr over 36 observations.

One study, CRC AVFL-3 (study number 132), reported a detailed breakdown of particle size. In all cycles, the size range 0.09 – 0.17 micrometers dominated the profile of engine-out emissions by mass. Results were from a 1999 Mercedes 2.2 L engine.

TABLE 9. SUMMARY OF AVERAGE PAH AND NPAH EMISSIONS FOR SELECTED CYCLES

COMPOUND	HD FTP	ECE15 + EUDC	R49	CSHVR	Creep	Cruise	Idle	FTP-75	mode 9	mode 11
	ug/bph-hr	ug/bph-hr	ug/bph-hr	ug/mi	ug/mi	ug/mi	ug/mi	ug/mi	ng/m3	ng/m3
Total PAH *	187			353				149.3		
acenaphthalene	15.2	8.94	12.2	241	1175	55.0	1371			
acenaphthene	7.5			241	399	3.80	59.7			
fluorene	21.0	5.97	20.8	204	399	3.80	59.7			
phenanthrene	61.5	2.97	75.9	18.8	1134	97.8	3527			
anthracene	1.8	3.65	2.40	32.0	55.7	9.80	35.0			
fluoranthene	4.1	0.64	17.5	68.7	55.8	25.4	43.2		3.34	924
pyrene	15.3	9.96	25.4	2.30	184	34.6	85.3		5.71	1075
benzo(a)anthracene	0.96	2.57	2.91	2.84	230	4.34	41.8	2.37	0.82	1270
chrysene	1.29	4.66	5.30		19.0	16.8	13.88	4.16	1.43	337
benzo(a)fluorene	1.85							1.38		
benzo(b)fluorene	0.83		1.41					0.56	0.83	303
benzo(k)fluoranthene	0.83	0.23						1.20	0.03	41
benzo(a)pyrene	0.64	.21	0.71	2.31	972	12.8	238	4.35	0.30	50
ideno(1,2,3)pyrene	0.51		1.13	9.59	19.5	0.1	55.5			
dibenzo(a,h)anthracene	0.16		0.34	60.0		0.34	1.67			
benzo(g,h,i)pyrelene	0.69	0.49	2.40	12.0	24.0	0.16	73.7			
Total Nitro-PAH *	0.95									
9-nitroanthracene	0.23									
2-nitrofluorene	0.29			0.96					0.05	1520
3-nitrofluorene	0.11			7.07						
1-nitropyrene	0.40			1.51						
7-nitrobenzo(a) anthracene	0.02	0.23		0.19					0.58	38
6-nitrochrysene				0.17					0.10	40
6-nitrobenzo(a)pyrene	0.01									

* Because some studies reported "total PAH" or "total NPAH" only, these values will not equal the sum of the individual compounds reported.

TABLE 10. SUMMARY OF AVERAGE CONCENTRATIONS OF METALS AND INORGANICS

	Chassis Cycles		Engine Cycles	
Constituent	Concentration, mg/mi	No. of Observations	Concentration, mg/bhp-hr	No. of Observations
Zinc	1.04	39	1.16	9
Phosphorus	0.08	39	–	–
Sulfur	3.07	39	2.89	9
Calcium	7.52	39	0.02	9
Silicon	1.34	39	0.02	9
Copper	0.11	30	0.78	9
Lead	0.05	16	1.83	9
Iron	0.21	39	1.66	9
Chloride	4.22	36	0.18	9
Ammonia	2.14	34	11.5	9
Nitrate	1.89	37	–	–

E. Gap Analysis

While this database represents a large and varied data set, it does not meet the committee's desires to have defined emissions for a four-dimensional matrix of speed, load, fuel, and engine technology. The primary reason is the bulk of the data was reported as composite values rather than as discrete power/load points.

The committee desired information on the very latest technology engines; that is to say, those which were designed towards meeting the increasingly stringent emissions regulations. Very little detail on engine technology was presented in the documents reviewed. As shown in Table 2 and in Figure 1, there was good representation for model years 1999 and 2000. Whether these engines posses the latest advances being considered to reduce engine-out emissions is debatable because so little detailed information on engine technology was available in these papers.

Information on particulate matter was, for the most part, limited to chemical characterization. There were only a few studies with discussions on particle number and size. Additional study on the particulate characteristics of the most modern engines, taking into account issues such as exhaust gas recirculation, will be necessary prior to any simulations of particulate generation are attempted.

The database characterizes regulated emissions and speciated hydrocarbons, including carbonyl compounds, reasonably well for a number of cycles. There are sufficient measurements at a variety of duty cycles to permit a general characterization of exhaust composition in terms of relative ratios of various compounds. For the regulated emissions, these relative ratios varied considerably for different duty cycles, as shown in Table 11 below.

However, as was shown in the preceding sections, there was substantial similarity in the profiles of speciated hydrocarbons and carbonyl compounds over a large variety of operational cycles. These profiles of unregulated emissions did not differ materially for light-duty versus heavy-duty applications. It is the opinion of the author that the information in this database is sufficient for an informed approach to deriving a synthetic diesel exhaust mixture, excluding particulate matter. Such an approach is discussed in the following section.

F. Method to Derive a Standard Exhaust Mixture

The database that has been compiled contains data from 72 studies, most of which were published between 1998 and 2003. There are sufficient data to characterize all but the most esoteric diesel exhaust emission parameter under a limited set of operating conditions. Because most data represent composite results from either transient cycles or multiple, steady state points, it is not possible to define a standard gas related to a full matrix of speed and load conditions. Nevertheless, these data can be used to define a standard diesel exhaust with a reasonable level of confidence for a number of operating conditions.

Right away, one is confronted with the fact that engines of all sizes and applications, as well as different fuels are represented in this data set. Any simulation will need to take these factors into account, as well. Thus, a scalable approach is needed. By focusing not only on the magnitude of the emissions, but the relative amounts of the significant components, a useful, and achievable, standard can be defined.

A method to derive a representative exhaust mixture is desired and can be accomplished by approaching the problem systematically. By defining the gas composition in terms of ratios of the components, the complexity of taking into account various confounding factors is avoided. The researcher is then free to adjust concentration of the gas to fit the experiment just as would be done for factors such as gas temperature and space velocity. Selection of the components is guided by knowledge of what is present and knowledge of the chemical properties exhibited by those species. The number of components must be narrowed for practical reasons. Understanding the properties of the species one seeks to model allows selection of a few components that will suffice to represent a group.

This method may be used as shown in the following illustration. The average emissions can be used to compute ratios of each parameter relative to the others. Table 11 below presents various ways to look at these ratios by normalizing to one of the four parameters. In preparing a synthetic gas mixture, one can use these ratios to adjust the relative amounts of each parameter. Thus, a mixture where the NOx and CO are 30 and 8 times the HC concentration, respectively, would be representative of the average emission rate seen over the HD FTP cycle. Following a similar process, one can easily derive ratios for the other cycles shown in Table 11. Using the data for the FTP-75 as another example, the NOx and CO would be 11 and 4.6 times the HC concentration, respectively, to be representative of the average emission rate. For the other cycles shown, the CO tends to be about 8 times greater than the HC, and the NOx ranges from about 17 to 25 times the HC concentration.

TABLE 11. RATIOS OF AVERAGED EMISSIONS

Compound	Cycle	Average Value	Ratio, When Normalized To:			
			HC	NOx	CO	PM
NOx	HD FTP g/bhp-hr	4.40	29.73	1.00	3.73	43.14
HC		0.15	1.00	0.03	0.13	1.45
CO		1.18	7.97	0.27	1.00	11.56
PM		0.10	0.69	0.02	0.09	1.00
NOx	FTP-75 g/mi	3.32	11.15	1.00	2.41	23.40
HC		0.30	1.00	0.09	0.22	2.10
CO		1.38	4.63	0.42	1.00	9.73
PM		0.14	0.48	0.04	0.10	1.00
NOx	US06 g/mi	6.50	24.61	1.00	4.47	47.09
HC		0.26	1.00	0.04	0.18	1.91
CO		1.45	5.51	0.22	1.00	10.54
PM		0.14	0.52	0.02	0.09	1.00
NOx	MVEG g/mi	2.50	19.56	1.00	2.30	10.10
HC		0.13	1.00	0.05	0.12	0.52
CO		1.09	8.50	0.43	1.00	4.39
PM		0.25	1.94	0.10	0.23	1.00
NOx	UDDS g/mi	21.78	17.11	1.00	2.07	24.67
HC		1.27	1.00	0.06	0.12	1.44
CO		10.52	8.26	0.48	1.00	11.91
PM		0.88	0.69	0.04	0.08	1.00

The predominant compounds making up the hydrocarbons and their average concentrations were presented in Tables 6 and 7. Examining the profile for the HD FTP reveals that the dominant compounds are as shown in Table 12. A review of the information presented in Tables 6 and 7 reveals that a similar profile exists for most of the other cycles. A notable exception is the appearance of trimethylpentane and dimethylhexane over the LD FTP.

TABLE 12. DOMINANT HYDROCARBON SPECIES

COMPOUND	EMISSION RATE OVER HD FTP, mg/bhp-hr	FRACTION, NORMALIZED TO TOTAL
ethene (ethylene)	16.6	0.19
propene (propylene)	6.0	0.07
ethyne (acetylene)	1.9	0.02
butene (butylene)	2.4	0.03
1,3-butadiene	1.7	0.02
benzene	1.8	0.02
nonene	1.6	0.02
trimethylbenzene	2.1	0.02
undecane	2.7	0.03
dodecane	2.5	0.03
unidentified C9 – C12+	12.7	0.14
formaldehyde	25.4	0.29
acetaldehyde	10.3	0.12

For the sake of practicality, a synthetic gas mixture would need to be fairly simple in composition. A gas with eleven hydrocarbon components would be a challenge to prepare, and likely, would be expensive to manufacture or to purchase. As can be seen in Table 12, the composition is dominated by C_2 and C_3 combustion products (47 percent), and unburned or partially burned fuel in the C_9 – C_{12} range (42 percent). A logical approach, therefore, would be to prepare a simple mix containing a compound such as ethylene to represent the combustion products and one such as undecane to represent the light ends of the unburned fuel.

The carbonyls, while only partially "visible" to the FIDs used in hydrocarbon determinations, are another significant group of hydrocarbon related components and should be represented in any synthetic gas mix. Referring back to Figures 4 through 7, it is readily apparent that the emission profile for the carbonyl compounds is quite constant regardless of duty cycle. Formaldehyde dominates by at least a two to one margin over acetaldehyde for all but the "cruise" cycle (which represents only three measurements).

Again using the HD FTP as an example, total carbonyls averaged 44.8 mg/bhp-hr, roughly one-third of the total hydrocarbon emission rate. Formaldehyde or acetaldehyde, the most abundant carbonyl species present in exhaust, would be logical selections to represent the carbonyls in a synthetic gas mix. Formaldehyde would also win out for practical reasons. Although all carbonyl compounds are inherently unstable, aqueous solutions of formaldehyde are readily available, and it would be a relatively simple matter to design an induction system for it. Because of its highly reactive nature, however, the physical point or location in the simulation system where it is injected will be crucial to achieving the desired concentration at the proper zone. Formaldehyde and acetaldehyde are toxic and considered carcinogenic so due care must be made in handling regardless of which is utilized.

Specifying the composition of particulate matter is not as straightforward. Despite keen interest in recent years, the data set is not as large or consistent in the parameters reported. Sulfate content, for example, would be highly dependent on the sulfur concentration in the fuel. Size distribution also varies depending on a number of factors, but the available data from just one study showed a Gaussian distribution, peaking in the size range of 0.09 - 0.17 micrometers. As mentioned earlier, additional studies discuss particle size, mass concentrations, and number of particles by size, but these data were presented in graphical form. Data representative of the engine type and duty cycle to be modeled should be sought for an accurate specification. Soluble organic fraction averaged about 25 percent of the total particulate mass over the HD FTP. A reliable means of properly introducing representative particulate matter (size, organic fraction, etc.) into a synthetic exhaust mix is at this point unknown and needs considerable attention.

Many approaches have been taken in the past for synthetic *gasoline* exhaust. One approach has been to prepare two cylinders of gas, one containing 10 percent CO2 and about 1 percent CO, 4,000 ppm H2, 300 ppm propane, and 700 ppm propene, with the balance nitrogen. A second cylinder contains 1000 ppm NO in nitrogen. These gases are blended to achieve approximately 1400 ppm HC and 500 ppm NO. Water, an important component of a synthetic exhaust because of its effect on some catalyst systems, has been added by bubbling the mixture through water. Alternatively, steam can be co-injected to achieve the desired dewpoint. Other approaches have used multiple cylinders of gas where each has a simple composition, and coupling them together with an elaborate metering and manifold system.

Using the information discussed in the preceding paragraphs as a starting point, the composition in Table 13 is shown as an example method for making up the “active” components of a synthetic diesel exhaust. Of course, this mixture would be diluted with CO_2, O_2, and N_2 to achieve appropriate final concentrations, depending on the platform and load or cycle being simulated. Also, one would want to include an appropriate amount of H_20, through one of the methods discussed above, to simulate exhaust gas.

TABLE 13. EXAMPLE COMPOSITION OF REGULATED COMPONENTS FOR A SYNTHETIC DIESEL EXHAUST

CLASS	COMPOUND	RELATIVE FRACTION *
HYDROCARBONS	ETHENE	0.0144
	UNDECANE	0.0108
CARBONYLS	FORMALDEHYDE	0.0083
NITROGEN OXIDES	NO	0.7485
CARBON MONOXIDE	CO	0.2007
PARTICULATE MATTER	N/A	0.0174

*Note that these components would need to be diluted with nitrogen, oxygen, carbon dioxide, and waterto achieve appropriate final concentration.

Depending on the researcher's objectives, additional components might be included. Selection of additional components relates to the aftertreatment technology proposed for evaluation and the particular concerns related to such technology. No one is interested in creating new problems so at some point it might be appropriate to include additional toxics, for example, to show that they are mitigated or at least not amplified by the technology under evaluation. Likewise, for technologies susceptible to "poisons" such as sulfur or phosphorus, then it would be appropriate to include a representative amount in the synthetic exhaust. Sulfur could be included as SO_2 gas and unburned oil could possibly be injected to contribute phosphorus. Inclusion of PAH compounds is important, but great care would be required as these compounds are generally quite carcinogenic.

IV. CONCLUSIONS

To achieve a robust definition of engine-out emissions under the desired, four-dimensional matrix, for state-of-the-art technology engines, using a variety of fuels, speeds, and loads, it would be necessary to design a program specifically to do so. Yet, by carefully piecing together data from disparate sources, a general characterization has been enabled by this work for a variety of conditions. Given the fact that:

- there are relatively few observations for a number of the test conditions,
- most available data are from transient cycles and not from discrete speed/load points,
- in some cases the available observations are from a single or a small number of engines,
- there is some uncertainty that the various laboratories used sample collection and analysis methods that yield comparable results, one should use caution and be aware of the limitations of the data set.

Further, the information on specific engine technology is scarce, so it is not possible to relate emissions to a particular design feature.

In conclusion, the gaseous component of a synthetic diesel exhaust can be specified in a general sense for a number of duty cycles, based on the available data. A method to synthesize such a definition has been made in terms of the relative amounts of significant components. Specifications for the particulate component are less certain, as fewer data exist. In this area, it would be beneficial for future work to be more uniform in reporting parameters such as particle size distribution, elemental vs. organic carbon, soluble organic fraction, and sulfate. It is particularly important that uniform sampling conditions be utilized for particulate sampling in order for results to be comparable between studies. No attempt has been made to describe how a synthetic particulate could be prepared, as it is beyond the scope of this project. It will be a challenge to prepare sufficient quantities of particulate matter which have a defined set of characteristics, to ensure its consistency batch-to-batch, and to deliver it uniformly. The database prepared under this project will allow other researchers:

- to conveniently review data from a broad variety of sources,
- to readily observe the amount of information available for a particular condition, fuel, or engine, and
- to derive composition for a number of duty cycles.

It represents a valuable resource for future research and development of diesel aftertreatment devices.

APPENDIX A

DOCUMENTS UTILIZED IN DATABASE

Appendix A. Documents Utilized

Title	Characterization of Submicron Exhaust Particles from Engines Operating without Load on Diesel and JP-8 Fuels				
Publisher	Aerosol Science and Technology			Lead Author	C. Fred Rogers
Year	2003	Study ID	1	Citatio	37:355-368
Comments	Particle size distribution data from ground support equipment operating on diesel and JP-8 fuels at low and high idle settings was no load. Average size distribution peaked between 21 and 84nm.				

Title	Chemical Speciation of Exhaust Emissions from Trucks and Buses Fueled on Ultra-Low Sulfur Diesel and CNG				
Publisher	SAE			Lead Author	Miriam Lev-On
Year	2002	Study ID	10	Citatio	2002-01-0432
Comments	PM10, PM2.5, Dioxins, PAH, NPAH, Elements, inorganic ions, Carbonyls, VOCs from 1197-98 trucks and buses running ULSD, CARB, F-T, and CNG fuels.				

Title	Particulate Emissions From a Modern Light Duty CIDI Engine				
Publisher	SAE			Lead Author	S. Gupta
Year	2002	Study ID	19	Citatio	2002-01-1869
Comments	Particulate emissions are strongly dependent on the engine speed, load, and EGR conditions. Acquired data on particle size and mass concentration from graphs.				

Title	Evaluating a Fischer-Tropsch Fuel, Eco-Par, in a Valmet Diesel Engine				
Publisher	SAE			Lead Author	Kent Nord
Year	2002	Study ID	22	Citatio	2002-01-2726
Comments	Limited speciated HC, carbonyl emissions from HDD running EC-1 and F-T fuels over ISO 8178 cycles.				

Title	Experience of Fitting London Black Cabs With Fuel Borne Catalyst Assisted Diesel Particulate Filters - Part 2 Non-Regulated Emissions Measurements				
Publisher	SAE			Lead Author	P. Richards
Year	2002	Study ID	25	Citatio	2002-01-2785
Comments	Regulated emissions from four LD vehicles of unknown age in taxi service, operating with fuel born catalyst assisted diesel particulate filters.				

Title	Fuel Sulfur Effect on Membrane Coated Diesel Particulate Filter				
Publisher	SAE			Lead Author	Juhun Song
Year	2002	Study ID	26	Citatio	2002-01-2788
Comments	4 cylinder Volkswagen TDI engine under four different engine load conditions at constant speed was used to evaluate membrane coated and conventional uncoated silicon carbide diesel particulate filters. Limited regulated emissions gleaned from graphs				

Title	Speciation of Organic Compounds from the Exhaust of Trucks and Buses: Effect of Fuel and After-Treatment on Vehicle Emission Profiles				
Publisher	SAE			Lead Author	Miriam Lev-On
Year	2002	Study ID	29	Citatio	2002-01-2873
Comments	Speciated HC, PAH, NPAH, Dioxins from Trucks and Buses running four fuels (CARB, ECD, EC-1, F-T) over CBD and CSHVR cycles.				

Title	Performance of a Urea SCR System Combined with a PM and Fuel Optimized Heavy-Duty Diesel Engine Able to Achieve the Euro V Emission Limits				
Publisher	SAE			Lead Author	Ioannis Gekas
Year	2002	Study ID	31	Citatio	2002-01-2885
Comments	Limited engine-out data on HDD engine running 230 ppm S and 10 ppm S fuels over ETC and ESC cycles.				

Title	Effects of PuriNOx (TM) Water-Diesel Fuel Emulsions on Emissions and Fuel Economy in a Heavy-Duty Diesel Engine				
Publisher	SAE			Lead Author	Andrew C. Matheaus
Year	2002	Study ID	33	Citatio	2002-01-2891
Comments	Regulated engine-out emissions from 1998-calibration HDD engine running diesel and water emulsion fuels over AVL 8-mode test.				

Title	Heavy-Duty and Heavy Light-Duty Engine Exhaust Emission Comparisons with a Fischer-Tropsch and a Conventional Diesel Fuel				
Publisher	ASME			Lead Author	E. Robert Fanick
Year	2001	Study ID	35	Citatio	ICE Vol 36-1
Comments	Regulated, Toxics, Carbonyls, GHG emissions from 1999 HLD engine running F-T and 0.03 wt% S diesel fuels.				

Title	Evaluation of Some Alternative Diesel Fuels for Low Emissions and Improved Fuel Economy
Publisher	SAE
Lead Author	Timothy P. Gardner
Year	2001
Study ID	39
Citatio	2001-01-0149
Comments	Regulated and PM emissions from 1.2L engine running cert, LSD, DMM, and F-T fuels; various EGR and beginning of injection timings were studied.

Title	Emission Reductions and Operational Experiences with Heavy Duty Diesel Fleet Vehicles Retrofitted with Continuously Regenerated Diesel Particulate Filters in Southern California
Publisher	SAE
Lead Author	Sougato Chatterjee
Year	2001
Study ID	42
Citatio	2001-01-0512
Comments	Study of eight fleets representing 32 vehicles. Operational durability and emissions, exhaust back pressure and temperature. Gathered regulated emissions data from summary plots of engine out emissions.

Title	Maximizing the Effectiveness of Water Blended Fuel in Reducing Emissions by Varying Injection Timing or Using After-Treatment Device
Publisher	SAE
Lead Author	Deborah A. Langer
Year	2001
Study ID	43
Citatio	2001-01-0513
Comments	NOx and PM only; 1986 HDD running ISO marine 4-mode steady state; low sulfur ~150ppm and water emulsion fuels.

Title	Dynamometer Testing of a Heavy Duty Diesel Engine Equipped with a Urea-SCR System
Publisher	SAE
Lead Author	M. Farshchi
Year	2001
Study ID	44
Citatio	2001-01-0516
Comments	Limited engine-out regulated emissions; 1999 HDD running cert fuel with 300-500 ppm S over FTP and 13 mode ESC.

Title	Effects of Ethanol Additives on Diesel Particulate and NOx Emissions
Publisher	SAE
Lead Author	Roger L. Cole
Year	2001
Study ID	48
Citatio	2001-01-1937
Comments	PM and NOx emissions from a light-duty diesel engine were measured for 3 fuels: diesel with 10 percent ethanol, diesel with 15 percent ethanol, and neet diesel. PM emissions can be reduced over 2/3 of engine map using ethanol. Steady state only, graphs

Title	Measuring Diesel Emissions with a Split Exhaust Configuration
Publisher	SAE
Lead Author	W. Scott Wayne
Year	2001
Study ID	49
Citatio	2001-01-1949
Comments	Regulated emissions from 1999 HDD engine running 30 ppm S fuel over HD FTP and steady state cycles.

Title	Exhaust Aftertreatment Research for Heavy Vehicles
Publisher	SAE
Lead Author	Ronald L. Graves
Year	2001
Study ID	50
Citatio	2001-01-2064
Comments	Overview of diesel aftertreatment; limited engine out regulated emissions data from 1999 HLD engine running AVL 8-mode.

Title	Emissions from a Cummins B5.9 Diesel Engine Fueled with Oxygenate-in-Diesel Blends
Publisher	SAE
Lead Author	A. S. Cheng
Year	2001
Study ID	51
Citatio	2001-01-2505
Comments	Regulated, PM, SOF emissions from 1993 HDD running 125 ppm S diesel with four levels of cetane improver.

Title	Emissions from Fischer-Tropsch Diesel Fuels
Publisher	SAE
Lead Author	Jack W. Johnson
Year	2001
Study ID	52
Citatio	2001-01-3518
Comments	Most data presented only in graphical format; very limited regulated emissions data on US and UK LSD fuel running on 1991 HDD engine.

Title	Comparison of Emission Characteristics of Conventional, Hydrotreated, and Fischer-Tropsch Diesel Fuels in a Heavy-Duty Diesel Engine
Publisher	SAE
Lead Author	E. Robert Fanick
Year	2001
Study ID	53
Citatio	2001-01-3519
Comments	Extensive PM number and size information, toxics emissions from HLD and HDD engines on conventional and F-T fuels.

Title	Fuel Effects on Diesel Emissions – A New Understanding
Publisher	SAE
Lead Author	Y. Kwon
Year	2001
Study ID	54
Citatio	2001-01-3522
Comments	This paper describes fuel effects on engine-out emissions from a European light-duty diesel engine. Averaged, regulated emissions data for 4- and 14-mode tests. Data gleaned from graphs.

Title	Performance and Emissions Using Water in Diesel Fuel Microemulsion
Publisher	SAE
Lead Author	Manual A. Gonzalez D.
Year	2001
Study ID	55
Citatio	2001-01-3525
Comments	Regulated, Toxics, SOF and SO4 emissions from 1991 engine on base diesel and water emulsions.

Title	Research Approach for Aging and Evaluating Diesel Lean-NOx Catalysts
Publisher	SAE
Lead Author	W. Scott Wayne
Year	2001
Study ID	56
Citatio	2001-01-3620
Comments	HC, NOx, and PM data only. DECSE program. Evaluations of lean-NOx catalysts to determine the effects of fuel sulfur content on emissions reduction efficiency and catalyst durability. Data gleaned from graphs.

Title	Relative Impact on Environment and Health from the Introduction of Low Emission City Buses in Sweden
Publisher	SAE
Lead Author	Peter J.E. Ahlvik
Year	2000
Study ID	59
Citatio	2000-01-1882
Comments	Study of various engine/fuel/aftertreatment combinations; database entries only for a Euro 2 spec engine running EC1 fuel. Reg. Total PAH, toxics.

Title	Evaluation of Water-blend Fuels in a City Bus and an Assessment of Performance with Emission Control Devices
Publisher	SAE
Lead Author	Allyson Barnes
Year	2000
Study ID	61
Citatio	2000-01-1915
Comments	Regulated emissions from Euro 2 spec engine on ultra-low sulfur diesel and water emulsion fuel.

Title The Effect of Biodiesel Fuels on Transient Emissions from Modern Diesel Engines, Part I Regulated Emissions and Performance

Publisher SAE **Lead Author** Christopher A. Sharp

Year 2000 **Study ID** 62 **Citatio** 2000-01-1967

Comments Regulated and detailed PM characterization for diesel & biodiesel fuels on two 1997 and one 1995 engines.

Title Japan Clean Air Program - Step I Study of Diesel Vehicle and Fuel Influence on Emissions

Publisher SAE **Lead Author** K. Oyama

Year 2000 **Study ID** 64 **Citatio** 2000-01-1973

Comments Toxics, BaP, regulated & PM characterization; several engine/vehicle and fuel combinations.

Title A 322,000 kilometer (200,000 mile) Over the Road Test with HySEE Biodiesel in a Heavy Duty Truck

Publisher SAE **Lead Author** Craig L. Chase

Year 2000 **Study ID** 66 **Citatio** 2000-01-2647

Comments Regulated, PAH, NPAH emissions from 1997 HDD running biodiesel and conventional fuels.

Title Unregulated Exhaust Gas Components of Modern Diesel Passenger Cars

Publisher SAE **Lead Author** K.-H. Neumann

Year 1999 **Study ID** 72 **Citatio** 1999-01-0514

Comments Regulated and unregulated exhaust from a fleet of 1978-85 passenger cars are compared with modern direct injection diesel vehicles. PAH, nitro PAH, air toxic components, particulate number and size distribution are reported. Only older cars are non-cat

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Title Transient Emissions Comparisons of Alternative Compression Ignition Fuels

Publisher SAE **Lead Author** Nigel N. Clark

Year 1999 **Study ID** 73 **Citatio** 1999-01-1117

Comments Regulated emissions on various fuels; 1994 HDD engine.

Title	Methodology for Hydrocarbon Speciation for Heavy Duty Diesel Engines Operating Over the European ECE R49 Cycle
Publisher	SAE
Lead Author	E. G. Reynolds
Year	1999
Study ID	74
Citatio	1999-01-1466
Comments	Toxics, very limited HC speciation; one Euro 1 and one Euro 2 engine; 470 ppm fuel.

Title	In-Cylinder Combustion Pressure Characteristics of Fischer-Tropsch and Conventional Diesel Fuels in a Heavy Duty CI Engine
Publisher	SAE
Lead Author	Christopher M. Atkinson
Year	1999
Study ID	75
Citatio	1999-01-1472
Comments	Regulated emissions only; F-T and conventional fuels

Title	Emissions Performance of Oxygenate-in-Diesel Blends and Fisher-Tropsch Diesel in a Compression Ignition Engine
Publisher	SAE
Lead Author	Adelbert S. Cheng
Year	1999
Study ID	77
Citatio	1999-01-3606
Comments	Regulated emissions only from F-T fuels and oxygenated blends with a 1993 engine.

Title	The Influence of Speciated Diesel Fuel Composition on Speciated Particulate SOF Emissions
Publisher	SAE
Lead Author	G.E. Andrews
Year	1998
Study ID	78
Citatio	980527
Comments	PM data only, including limited PAH; 1991 engine with three fuels.

Title	Effect of Fuel Compositions on PAH in Particulate Matter from DI Diesel Engine
Publisher	SAE
Lead Author	Shigeyuki Tanaka
Year	1998
Study ID	79
Citatio	982648
Comments	PAH, regulated, and PM emissions from 27 fuels. 1994 spec engine.

Title	Transient Performance of a Urea deNOx Catalyst for Low Emissions Heavy-Duty Diesel Engines				
Publisher	SAE			Lead Author	Cornelis Havenith
Year	1997	Study ID	82	Citatio	970185
Comments	A urea SCR deNOx catalyst system for heavy-duty diesel engines was developed. Urea is injected upstream of the SCR catalyst system by means of an open-loop controlled injection system. Limited N2O engine-out data reported				

Title	Automotive Direct Injection Diesel Engine Sensitivity to Diesel Fuel Characteristics				
Publisher	SAE			Lead Author	Andrea Gerini
Year	1997	Study ID	83	Citatio	972963
Comments	Limited carbonyl and PAH data from a LD engine operating on 7 fuels.				

Title	Effect of Upgraded Diesel Fuels and Oxidation Catalysts on Emission Properties, Especially PAH and Genotoxicity				
Publisher	SAE			Lead Author	Keld Johansen
Year	1997	Study ID	86	Citatio	973001
Comments	Total PAH and regulated emissions from a LD and a HD engine on three fuels; genotoxicity also discussed.				

Title	Hydrocarbon, PAH and PCB Emissions from Ferries: A Case Study in the Skagerak-Kattegatt-Oresund Region				
Publisher	Atmospheric Environment			Lead Author	D.A. Cooper
Year	1996	Study ID	87	Citatio	V30, No14, 2463-2473
Comments	Regulated, PCB, PAH emissions from very large marine engines; fuels described as "gas oil" and "fuel oil" (possibly low quality)				

Title	Speciation of Hydrocarbon Emissions from a Medium Duty Diesel Engine				
Publisher	SAE			Lead Author	Nigel N. Clark
Year	1996	Study ID	89	Citatio	960322
Comments	Speciated HC from MDD engine on EPA cert fuel.				

Title	Effect of Reformulated Diesel Fuel on Unregulated Emissions of Light Duty Vehicles
Publisher	SAE
Lead Author	Leena Rantanen
Year	1996
Study ID	92
Citatio	961970
Comments	PAH and regulated emissions on LD vehicles over five fuels, including low temperature tests.

Title	The Influence of Fuel Formulations on Pollutant of a Light Duty D.I. Diesel Engine
Publisher	SAE
Lead Author	C. Beatrice
Year	1996
Study ID	93
Citatio	961972
Comments	Regulated and unregulated emissions of a LDD with EGR were studied under steady-state conditions. Additional tests were performed under cold conditions. PAH, SOF, IOF, and carbonyls are reported. Limited data could be extracted from graphs

Title	Introduction of Rapeseed Methyl Ester in Diesel Fuel - The French National Program
Publisher	SAE
Lead Author	X. Montagne
Year	1996
Study ID	95
Citatio	962065
Comments	This paper presents a synthesis of the results obtained during a program which lasted from 1990 to 1995, in which aging, fouling, and emissions with RME fuel were studied. Reg. Emissions, PAH, carbonyls extracted from graphs

Title	Speciation of Heavy Duty Diesel Exhaust Emissions under Steady State Operating Conditions
Publisher	SAE
Lead Author	Mridul Gautam
Year	1996
Study ID	97
Citatio	962159
Comments	Speciation of exhaust from naturally aspirated HDD running commercial diesel fuel; steady states and idle.

Title	Effects of Fuel Oxygenates, Cetane Number, and Aromatic Content on Emissions from 1994 and 1998 Prototype Heavy-Duty Diesel Engines
Publisher	Southwest Research Institute for CRC
Lead Author	Kent B. Spreen
Year	1995
Study ID	98
Citatio	SwRI 4127, CRC VE-10
Comments	Regulated and speciated emissions as function of oxygenates, cetane, and aromatic content from 1994 and 1998 HDD engines.

Title	Reactivity Comparison of Exhaust Emissions from Heavy-Duty Engines Operating on Gasoline, Diesel, and Alternative Fuels
Publisher	SAE
Lead Author	Matthew S. Newkirk
Year	1995
Study ID	100
Citatio	952442
Comments	Toxics and regulated emissions from HDD on 330 ppm S fuel. Other fuels and engines also reported.

Title	The Influence of an Oxidation Catalytic Converter on the Chemical and Biological Characteristics of Diesel Exhaust Emissions
Publisher	SAE
Lead Author	K.F. Hansen
Year	1994
Study ID	103
Citatio	940241
Comments	Regulated emissions reported in tabular form. Study reported PAH and SOF, mutagenicity graphically. Danish ultra-light fuel.

Title	Effects of an Oxidation Catalytic Converter on Regulated and Unregulated Diesel Emissions
Publisher	SAE
Lead Author	Gregory M. Pataky
Year	1994
Study ID	104
Citatio	940243
Comments	Regulated emissions; PAH and NPAH as PM-bound and vapor phase; 1991 engine with 0.01 wt% S fuel.

Title	Methods to Analyze Non-Regulated Emissions from Diesel Engines
Publisher	SAE
Lead Author	G. Lepperhoff
Year	1994
Study ID	105
Citatio	941952
Comments	Speciated HC from LDD on European Ford light-duty diesel truck operating over FTP.

Title	Emissions from Current Diesel Vehicles
Publisher	SAE
Lead Author	R. H. Hammerle
Year	1994
Study ID	106
Citatio	942043
Comments	Toxics and regulated emissions from 1994 vehicles; only one could be included as others had aftertreatment.

Title	Impact of Diesel Fuel Aromatics on Particulate, PAH and Nitro-PAH Emissions				
Publisher	SAE			Lead Author	K. Mitchell
Year	1994	Study ID	107	Citatio	942053
Comments	PM, PAH, NPAH, carbonyl emissions as function of fuel aromatic content; two 1994 engines.				

Title	Effect of Cerium Fuel Additive on the Emissions Characteristics of a Heavy-Duty Diesel Engine				
Publisher	SAE			Lead Author	Jacques LeMaire
Year	1994	Study ID	108	Citatio	942067
Comments	HC speciation, carbonyls, metals, PM characterization, PAH, nitrosamines with and without Ce fuel additive.				

Title	The Effects of Fuel Sulfur Concentration on Regulated and Unregulated Heavy-Duty Diesel Emissions				
Publisher	SAE			Lead Author	Cornelius N. Opris
Year	1993	Study ID	111	Citatio	930730
Comments	Effects of sulfur on regulated and unregulated HDD emissions were studied. PAH reported on particulate and vapor phase.				

Title	Speciation of Hydrocarbon Emissions from European Vehicles				
Publisher	SAE			Lead Author	C. A. Jemma
Year	1992	Study ID	114	Citatio	922376
Comments	Limited speciation data from European LD vehicles.				

Title	The Effect of a Ceramic Particulate Trap on the Particulate and Vapor Phase Emissions of a Heavy-Duty Diesel Engine				
Publisher	SAE			Lead Author	L. D. Gratz
Year	1991	Study ID	115	Citatio	910609
Comments	Effect of a ceramic PM trap on PM and vapor phase emissions. PAH and NPAH included.				

Title	Class 8 Trucks Operating on Ultra-Low Sulfur Diesel with Particulate Filter Systems: Regulated Emissions				
Publisher	SAE			Lead Author	Nigel N. Clark
Year	2000	Study ID	118	Citatio	2000-1-2815
Comments	Regulated emissions from class 8 trucks on ULSD. Engine out data. Paper includes study of CRT and DPF.				

Title	Catalyzed Diesel Particulate Filter Performance in a Light-Duty Vehicle				
Publisher	SAE			Lead Author	C. Scott Sluder
Year	2000	Study ID	119	Citatio	2000-01-2848
Comments	Regulated emissions only from a Mercedes A170 research vehicle with and without catalyzed DPF.				

Title	EC-Diesel Technology Validation Program Interim Report				
Publisher	SAE			Lead Author	Chuck LeTavec
Year	2000	Study ID	120	Citatio	2000-01-1854
Comments	Study of EC-Diesel in HDD trucks, buses, refuse haulers; entered only data with no aftertreatment.				

Title	EPA HDEWG Program – Engine Tests Results				
Publisher	SAE			Lead Author	Andrew C. Matheaus
Year	2000	Study ID	121	Citatio	2000-01-1858
Comments	Analysis of varying fuel parameters on emissions - cetane, aromatic content and type, density; HC, CO and NOx only.				

Title	Effect of a Non-Metallic Combustion Enhancer Diesel Additive on Mass and Number Particulate Emissions from Light-Duty Vehicles and Heavy-Duty Engines				
Publisher	SAE			Lead Author	S.H. Ahmed
Year	2000	Study ID	123	Citatio	2000-01-1910
Comments	Regulated emissions for LDD and HDD engines over ECE R49 13 mode. PAH and NPAH presented for one engine.				

Title	Identification of Toxic Parameters of Unregulated Diesel-Engine Emission
Publisher	ISATA
Lead Author	L. Markovic
Year	2000
Study ID	127
Citatio	ISATA 2000: Automotive & Transportation Technol
Comments	Emissions of three PAH compounds from 2.5L diesel over ISO 8178 8-mode test.

Title	Emissions from Trucks using Fischer-Tropsch Diesel Fuels
Publisher	SAE
Lead Author	Paul Norton
Year	1998
Study ID	131
Citatio	982526
Comments	Regulated emissions from 1994 HDD running F-T, 2D, and 50:50 blend of F-T and 2D; hot start of FTP.

Title	CRC AVFL-3 progress reports
Publisher	SwRI
Lead Author	Keith A. Shaw
Year	2002
Study ID	132
Citatio	-
Comments	Comprehensive characterization; 1999 LDD engine running EC-1 Diesel fuel.

Title	Diesel Exhaust Emissions Control for Light Duty Vehicles
Publisher	SAE
Lead Author	R. Mital
Year	2003
Study ID	134
Citatio	2003-01-0041
Comments	Regulated emissions only from LD vehicle on 15ppm S fuel.

Title	Effects of a Catalyzed Particulate Filter on Emission from a Diesel Engine: Chemical Characterization Data and Particulate Emissions Measured with Thermal Optical and Gravimetric Methods
Publisher	SAE
Lead Author	James R. Warner
Year	2003
Study ID	135
Citatio	2003-01-0049
Comments	Regulated emissions, metals, carbonyls, PM characterization; HDD engine; 375 ppm S fuel.

Title	Study of Exhaust Emissions from Idling Heavy Duty Diesel Trucks and Commercially Available Idle Reducing Devices
Publisher	SAE
Lead Author	Han Lim
Year	2003
Study ID	136
Citatio	2003-01-0288
Comments	NOx and CO2 under idling conditions for six trucks and one generator

Title	Particulate Matter and Aldehyde Emissions from Idling Heavy-Duty Diesel Trucks
Publisher	SAE
Lead Author	John M. E. Storey
Year	2003
Study ID	137
Citatio	2003-01-0289
Comments	Regulated Emissions, Formaldehyde and Acetaldehyde under idling conditions for five HD trucks and one generator.

Title	The Effect of Ambient Temperature, Humidity, and Engine Speed on Idling Emissions from Heavy-Duty Diesel Trucks
Publisher	SAE
Lead Author	N. Pekula
Year	2003
Study ID	138
Citatio	2003-01-0290
Comments	Very limited: NOx and CO2 only, for idling emissions. Most data in graphical form only.

Title	Demonstration of the Benefits of DPF/FBC Systems on London Black Cabs
Publisher	SAE
Lead Author	P. Richards
Year	2003
Study ID	144
Citatio	2003-01-0375
Comments	Regulated emissions only from four London Taxis. Paper also reviewed improvements due to DPF/FBC.

Title	Comparison of Exhaust Emissions, Including Toxic Air Contaminants, from School Buses in Compressed Natural Gas, Low Emitting Diesel, and Conventional Diesel Configurations
Publisher	SAE
Lead Author	Terry L. Ullman
Year	2003
Study ID	152
Citatio	2003-01-1381
Comments	Comprehensive characterization; 1998 HDD running 371 ppm S fuel.

Title	CRC Project No. E-55/E-59, Heavy-Duty Vehicle Chassis Dynamometer Testing for Emissions Inventory, Air Quality Modeling, Source Apportionment and Air Toxics Emissions Inventory				
Publisher	West Virginia University			Lead Author	Mridul Gautam
Year	2003	Study ID	153	Citatio	Phase 1 Report
Comments	Comprehensive characterization from 3 HHD trucks over various chassis cycles.				

Title	Size and Composition Distribution of Fine Particulate Matter Emitted from Motor Vehicles				
Publisher	Environmental Science and Technology			Lead Author	Michael J. Kleeman
Year	2000	Study ID	155	Citatio	34, No. 7, 1132-1142
Comments	An optical particle counter and a differential mobility analyzer were used to measure the size-distributed fine particles from motor vehicles. Very limited size distribution data from two LDD vehicles.				

APPENDIX B

DOCUMENTS REVIEWED BUT NOT INCLUDED IN DATABASE

Appendix B. Documents Not Utilized

Title	Exhaust Emission Toxicity Evaluation for Heavy-duty Diesel and Natural Gas Engines, Part 1: Regulated and Unregulated Emissions with Diesel Fuel and Blend of Diesel Fuel and Biodiesel				
Publisher	SAE			**Lead Author**	M. Gambino
Year	2001	**Study ID**	2	**Citatio**	2001-24-0044
Comment	Interlibrary loan service was unable to get this document. It was also unavailable from SAE.				

Title	Chemical Analysis of Diesel Nanoparticles Using a Non-DMA/Thermal Desorption Particle Beam Mass Spectrometer				
Publisher	CRC			**Lead Author**	Paul J. Ziemann
Year	2002	**Study ID**	3	**Citatio**	E-43-4
Comment	Detailed information on diesel nanoparticle measurement, particle properties and formation processes. Nano-DMA/TDPBMS and TDMA of particle volatility and hygroscopicity. Two engines (1998 & 1999). No chemical compounds reported.				

Title	Characterization of Fine Particle Material in Ambient Air and Personal Samples from an Underground Mine				
Publisher	Aerosol Science and Technology			**Lead Author**	Jacob D. McDonald
Year	2002	**Study ID**	4	**Citatio**	36: 1033-1044
Comment	Ambient measurements: not applicable. Personal samples and stationery samplers in an underground mine. Size-segregated chemistry of diesel particulate matter. PAH, hopanes, steranes, elements, ions, speciated hydrocarbons.				

Title	Brassica carnata as an Alternative Oil Crop for the Production of Biodiesel in Italy: Engine Performance and Regulated and Unregulated Exhaust Emissions				
Publisher	Environmental Science and Technology			**Lead Author**	Massimo Cardone
Year	2002	**Study ID**	5	**Citatio**	36: 4656-4662
Comment	Unregulated, PM characterization, PAH, carbonyl emissions from 1.9 l LDD engine fueled with biodiesel at different loads				

Title	Homogeneous Charge Compression Ignition Engine-Out Emissions - Does Flame Propagation Occur in Homogenous Charge Compression Ignition?				
Publisher	International Journal of Engine Research			**Lead Author**	E. W. Kaiser
Year	2002	**Study ID**	6	**Citatio**	Vol 3 No 4 185-195
Comment	Not applicable: combustion ignition with gasoline fuel. Engine-out emissions data of regulated compounds and particulate matter (size and number density).				

Title	Diesel Emission Control: 2001 in Review				
Publisher	SAE			Lead Author	Timothy V. Johnson
Year	2002	Study ID	7	Citatio	2002-01-0285
Comment	No data presented. A review of developments from all major conferences in the year 2001. Filter retrofit and durability, DeNOx catalysts, SCR, NOx traps for diesel, and nonthermal plasma methods. Nano particle studies.				

Title	Optimizing the Low Temperature Performance and Regeneration Efficiency of the Continuously Regenerating Diesel Particulate Filter System				
Publisher	SAE			Lead Author	Ronny Allanson
Year	2002	Study ID	8	Citatio	2002-01-0428
Comment	No engine-out data presented. Compares the performance of CR-DPF, catalyzed soot filter, and an Oxy cat plus catalyzed soot filter.				

Title	Performance and Durability Evaluation of Continuously Regenerating Particulate Filters on Diesel Powered Urban Buses at NY City Transit – Part II				
Publisher	SAE			Lead Author	Sougato Chatterjee
Year	2002	Study ID	9	Citatio	2002-01-0430
Comment	No engine-out data presented. Study of 25 New York City transit buses equipped with continuously regenerating diesel particular filters operating with the Ultra low sulfur fuel. No engine-out data presented.				

Title	Contribution of Highway and Nonroad Mobil Source Categories to Ambient Concentrations of 20 Hazardous Air Pollutants in 1996				
Publisher	SAE			Lead Author	Rich Cook
Year	2002	Study ID	11	Citatio	2002-01-0650
Comment	Not applicable: ambient measurements. Analysis of 20 hazardous air pollutants. Concludes that gasoline vehicles and equipment are greatest contributors.				

Title	Common Rail HSDI Diesel Engine Combustion and Emissions with Fossil/Bio-Derived Fuel Blends				
Publisher	SAE			Lead Author	Carlo N. Grimaldi
Year	2002	Study ID	12	Citatio	2002-01-0865
Comment	Regulated emissions and combustion properties of various fuels at 2 engine speeds and various loads. Mean in cylinder pressure and heat release. Emissions plotted as function of lambda.				

Title	Combustion of the Rape-Seed Oil in a Diesel Engine				
Publisher	SAE			Lead Author	Masataka Hashimoto
Year	2002	Study ID	13	Citatio	2002-01-0867
Comment	Study focuses on combustion characteristics, droplet and flame shapes of various gas oil and rapeseed oil combinations.				

Title	CFD Optimization of DI Diesel Engine Performance and Emissions Using Variable Intake Valve Actuation with Boost Pressure, EGR, and Multiple Injections				
Publisher	SAE			Lead Author	R. Shrivastava
Year	2002	Study ID	14	Citatio	2002-01-0959
Comment	No emissions data. Modeling of DI engine performance with varied intakes activation, boost pressure, EGR, multiple injections.				

Title	Effect of EFR on Autoignition, Combustion, Regulated Emissions and Aldehydes in DI Diesel Engines				
Publisher	SAE			Lead Author	Bogdam Nitu
Year	2002	Study ID	15	Citatio	2002-1-1153
Comment	Regulated emissions, hydrocarbon speciation with aldehydes. Single cylinder diesel engines, wide range of operating speeds and EGR ratios, but no engine load is specified.				

Title	Modeling the Effect of Late Cycle Oxygen Enrichment on Diesel Engine Combustion and Emissions				
Publisher	SAE			Lead Author	D.K. Mather
Year	2002	Study ID	16	Citatio	2002-01-1158
Comment	No engine data presented. Study discusses modeling the effects of oxygen enrichment on soot and NOx emissions.				

Title	Mutagenic Potential of Particulate Matter from Diesel Engine Operation on Fischer-Tropsch Fuel as a Function of Engine Operating Conditions and Particle Size				
Publisher	SAE			Lead Author	Michael H. McMillian
Year	2002	Study ID	17	Citatio	2002-01-1699
Comment	No engine emissions data presented. The mutantagenicity of particulate matter derived from F- and diesel fuel combustion in a single cylinder diesel engine by relating to the in vitro mutagenic activity of the PM to engine operating conditions & speed.				

Title	Diesel and CNG Heavy-Duty Transit Bus Emissions over Multiple Driving Schedules: Regulated Pollutants and Project Overview				
Publisher	SAE			Lead Author	Alberto Ayala
Year	2002	Study ID	18	Citatio	2002-01-1722
Comment	No engine-out data from diesel engine. Regulated emissions, greenhouse gases, carbonyl compounds, PAH, elements, elemental and organic carbon were measured. Size-resolved particulate mass and number emissions measurements were conducted from diesel & CNG				

Title	Analysis of the Influence of Fuel Sulphur Content on Diesel Engine Particulate Emissions				
Publisher	SAE			Lead Author	Piotr Bielaczyc
Year	2002	Study ID	20	Citatio	2002-01-2219
Comment	No engine-out data. Particulate emissions from diesel engines equipped with oxidation catalysts fueled with research fuels of differing sulfur content are reported.				

Title	Impact of Ultra-Clean Fischer-Tropsch Diesel Fuel on Emissions in a Light-Duty Passenger Car Diesel Engine
Publisher	SAE
Lead Author	Paul F. Schubert
Year	2002
Study ID	21
Citatio	2002-01-2725
Comment	No engine-out data. Post-oxidation catalyst speciated hydrocarbons, carbonyls, and particle size distribution reported for F-T fuel in a LDD engine.

Title	Low Pressure EGR Calibration Strategies for Reliable Diesel Particulate Filter Regeneration on HDD Engines
Publisher	SAE
Lead Author	Soren Andersson
Year	2002
Study ID	23
Citatio	2002-01-2780
Comment	No engine-out data. The objective was to obtain a better understanding of soot oxidation and to develop EGR calibration strategies that would ensure reliable DPF regeneration.

Title	Passenger Car Series Application of a New Diesel Particulate Filter System Using a New Ceria-Based Fuel-Borne Catalyst: From the Engine Test Bench to European Vehicle Certification
Publisher	SAE
Lead Author	G. Blanchard
Year	2002
Study ID	24
Citatio	2002-01-2781
Comment	Regulated, toxics, very limited speciated HC data on Euro 3 spec LDD engine over MVEG.

Title	Performances and Durability of a DPF Tested on a Fleet of Peugeot 607 Taxis First and Second Test Phases Results
Publisher	SAE
Lead Author	N. Jeuland
Year	2002
Study ID	27
Citatio	2002-01-2790
Comment	No engine-out data. Five taxis were studied for 80,000 kilometers. Regulated gaseous emissions on the new European driving cycle, particle number and size measurement with SMPS, and hydrocarbon speciation was performed on vehicle with DPF.

Title	Nature of Fundamental Parameters Related to Engine Combustion for a Wide Range of Oxygenated Fuels
Publisher	SAE
Lead Author	Md. Nurum Nabi
Year	2002
Study ID	28
Citatio	2002-01-2853
Comment	No engine emissions data presented. Fundamental combustion parameters such as heating value, air to fuel ratio, adiabatic flame temperature, C02 and NO2 emissions, specific heat, and thermal efficiency were studied.

Title	Impact of Engine Operating Conditions on Low-NOx Emissions in a Light-Duty CIDI Engine Using Advanced Fuels
Publisher	SAE
Lead Author	Mani Natarajan
Year	2002
Study ID	30
Citatio	2002-01-2884
Comment	Modal analysis was performed for developing an engine control strategy to take advantage of fuel properties to minimize engine and NOx emissions. Emission indices shown as functions of various parameters but no values per work, distance, or concentration.

Title	A Fundamental Consideration on NOx Adsorber Technology for DI Diesel Application
Publisher	SAE
Lead Author	Howard L. Fang
Year	2002
Study ID	32
Citatio	2002-01-2889
Comment	No engine-out emissions data presented. Spectroscopic techniques are applied to understand the underlying chemical reactions over the catalyst surface during NOx trapping and regeneration periods.

Title	Effects of Water-Fuel Emulsions on Spray and Combustion Processes in a Heavy-Duty DI Diesel Engine
Publisher	SAE
Lead Author	Mark P. B. Musculus
Year	2002
Study ID	34
Citatio	2002-01-2892
Comment	No engine-out data presented. Laser based chemiluminescence imaging experiments were performed in an optically accessible heavy-duty diesel engine, using standard diesel and a 20 percent water emulsion.

Title	Effects of Advanced Fuel Injection Strategies on DI Diesel Emissions
Publisher	NTIS
Lead Author	A. M. Mellor
Year	2001
Study ID	36
Citatio	ADP012097
Comment	Modeling Study. No engine emissions data presented. Development of engineering models for diesel emissions and performance for algorithms for control of smart engines.

Title	On-Road Emissions of Carbonyls from Light-Duty and Heavy-Duty Vehicles
Publisher	Environmental Science and Technology
Lead Author	Daniel Grosjean
Year	2001
Study ID	37
Citatio	35: 45-53
Comment	Ambient, tunnel measurements only. Speciated carbonyls were measured in May 1999 at the Tuscarora Mountain Tunnel, Pennsylvania.

Title	Effects of Advanced Fuels on the Particulate and NOx Emissions from an Optimized Light-Duty CIDI Engine
Publisher	SAE
Lead Author	Patrick G. Szymkowicz
Year	2001
Study ID	38
Citatio	2001-01-0148
Comment	No raw data presented - only emissions "indices." CARB fuel was compared to low aromatic hydro cracked fuel blended with dimethoxymethane and F-T fuel. Five steady-state modes were studied. EGR rates and combustion phasing were optimized.

Title	Single-Stage Dilution Tunnel Performance
Publisher	SAE
Lead Author	Qiang Wei
Year	2001
Study ID	40
Citatio	2001-01-0201
Comment	An evaluation of single stage dilution tunnel performance; discussion of apparatus design and procedure. Analysis of particle count and size by residence time, dilution air temperature.

Title	Performance and Durability Evaluation of Continuously Regenerating Particulate Filters on Diesel Powered Urban Buses at NY City Transit				
Publisher	SAE			Lead Author	Christopher Bush
Year	2001	Study ID	41	Citatio	2001-01-0511
Comment	No engine-out data. Performance and durability evaluation of continuously regenerating filters. Regulated emissions, Carbonyls, speciated hydrocarbons, PAH and nitro PAH, organic and elemental carbon, soluble organic fraction. No engine-out data.				

Title	Numerical Analysis of Passenger Car HSDI Diesel Engines with the 2nd Generation of Common Rail Injection Systems: The Effect of Multiple Injections on Emissions				
Publisher	SAE			Lead Author	G. M. Bianchi
Year	2001	Study ID	45	Citatio	2001-01-1068
Comment	No emissions data presented. Multiple injection strategies are modeled to assess the capability of multiple injection in reducing NOx and soot emissions of HSDI engines.				

Title	The Effect of Fuel-Vapor Concentration on the Process of Initial Combustion and Soot Formation in a DI Diesel Engine Using LII and LIEF				
Publisher	SAE			Lead Author	Dea Choi
Year	2001	Study ID	46	Citatio	2001-01-1255
Comment	A study of laser-induced incandescence and laser-induced exciplex fluorescence for visualization of the liquid and vapor phases of the field jet in a diesel engine. No engine-out emissions data presented.				

Title	Time-Resolved Behavior of Unburned Hydrocarbon Components in Diesel Exhaust under Transient Operations				
Publisher	SAE			Lead Author	Khandoker Abu Raihan
Year	2001	Study ID	47	Citatio	2001-01-1259
Comment	A study of combustion properties during high fueling at startup. Shortening high fueling duration is effective to reduce total hydrocarbon emissions as long as sufficient startability is maintained. Emissions reported as conc. vs. cycle no. (strokes).				

Title	Measurement of In-Use, On Board Emissions from Heavy-Duty Diesel Vehicles: Mobile Emissions Measurement System				
Publisher	SAE			Lead Author	Mridul Gautam
Year	2001	Study ID	57	Citatio	2001-01-3643
Comment	This paper reports the development of on-road emissions measurement systems. Measurements of break specific NOx and CO2 recorded by the MEMS over an FTP test were found to be within five percent of laboratory results. Only comparative (% diff) data incl.				

Title	Hydrocarbon Emission in a Highway Tunnel in the Paris Area				
Publisher	Atmospheric Environment			Lead Author	M. Touaty
Year	2000	Study ID	58	Citatio	v. 34 no6 985-96
Comment	Ambient, tunnel measurements. Hydrocarbon speciation of general vehicle emissions in a tunnel in the Paris area was performed.				

Title	Comparative Emissions Performance of Sasol Fischer-Tropsch Diesel Fuel in Current and Older Technology Heavy-Duty Engines				
Publisher	SAE			Lead Author	Paul W. Schaberg
Year	2000	Study ID	60	Citatio	2000-01-1912
Comment	Hot-start and cold-start HD transient emissions tests were performed using a 1999 model year engine with F-T fuel. Regulated emissions and particulate characterization was performed, but only relative % differences were reported - no hard data.				

Title	The Effect of Biodiesel Fuels on Transient Emissions from Modern Diesel Engines, Part II Unregulated Emissions and Chemical Characterization				
Publisher	SAE			Lead Author	Christopher A. Sharp
Year	2000	Study ID	63	Citatio	2000-01-1968
Comment	Speciated HC, aldehydes & ketones, PAH, NPAH for diesel & biodiesel fuels on two 1997 and one 1995 engines.				

Title	Comparative Toxicity of Gasoline and Diesel Engine Emissions				
Publisher	SAE			Lead Author	JeanClare Seagrave
Year	2000	Study ID	65	Citatio	2000-01-2241
Comment	This is an update of a study to assess comparative toxicity of vehicle exhaust particles and semi volatile organic compounds. No emissions data are presented.				

Title	A Before Treatment Method for Reduction of Emissions in Diesel Engines				
Publisher	SAE			Lead Author	S. O. Bade Shrestha
Year	2000	Study ID	67	Citatio	2000-01-2791
Comment	A discussion of the benefits of hydrogen pretreatment of exhaust emissions. Hydrogen provided by and electrical dissociation of water. Performance relative to baseline reported (no hard data).				

Title	A New Method for Diesel HC Collection and Speciation				
Publisher	SAE			Lead Author	Lisa A. Lanning
Year	2000	Study ID	68	Citatio	2000-01-2951
Comment	Methods for gas chromatography and impinger trapping for collecting hydrocarbons through C24 in diesel exhaust are reported. Only bag concentration data are reported - not useful to database.				

Title	Screening of Aerosol Filter Samples for PAHs and Nitro-PAHs by Laser Desorption Ionization TOF Mass Spectrometry				
Publisher	Aerosol Science and Technology			Lead Author	Dawit Z. Bezabeh
Year	1999	Study ID	69	Citatio	30: 288-299
Comment	A method for Laser desorption ionization TOF mass spectrometry is reported for screening of aerosol filter samples for PAH and Nitro-PAH compounds. Engine emissions data are not reported.				

Title	Organic Emissions Profile for a Light-Duty Diesel Vehicle
Publisher	Atmospheric Environment
Lead Author	Walter O. Siegl
Year	1999
Study ID	70
Citatio	33 (1999) 797-805
Comment	No engine-out data. The speciated gas phase hydrocarbon and carbonyl emissions collected from a light-duty indirect injection diesel engine with oxidation catalyst are reported.

Title	The Reduction of Diesel Engine Emissions by Using the Oxidation Catalysts of Japan Diesel 13 Mode Cycle
Publisher	SAE
Lead Author	Hironobu Mogi
Year	1999
Study ID	71
Citatio	1999-01-0471
Comment	The effectiveness of several oxidation catalysts on both the regulated and unregulated emissions was evaluated. The relative conversion efficiencies for benzene, formaldehyde, acetaldehyde, and BaP emissions are reported. (No hard data)

Title	Analysis of Semivolatile Organic Compounds in Diesel Exhaust Using a Novel Sorption and Extraction Method
Publisher	SAE
Lead Author	John M. E. Storey
Year	1999
Study ID	76
Citatio	1999-01-3534
Comment	A sample trapping and analysis procedure was described utilizing Tenax, PUF, and XAD-type resins, with thermal desorption. No emissions data presented.

Title	Characterization of Vehicle Emissions in Vancouver BC During the 1993 Lower Fraser Valley Oxidants Study
Publisher	Atmospheric Environment
Lead Author	Alan W. Gertler
Year	1997
Study ID	80
Citatio	31 (1997) 2107-2112
Comment	Tunnel ambient measurements; no engine-out data. Studies of C02 and speciated hydrocarbons and regulated emissions in Vancouver's Cassair Tunnel.

Title	Non-Thermal Plasma Discharge Based NOx Removal System for Diesel Engine Exhaust
Publisher	Air & Waste Management Association
Lead Author	Glenn E. Rolader
Year	1997
Study ID	81
Citatio	97-MP5.07
Comment	A description is made of a pilot scale NOx removal system based on non-thermal plasma discharge. No engine emissions data are presented.

Title	Evaluating Alternative Fuels for Light-Duty Applications
Publisher	SAE
Lead Author	Nils-Olof Nylund
Year	1997
Study ID	84
Citatio	972974
Comment	14 light-duty vehicles were tested on gasoline, diesel, alcohol, and gaseous fuels. Low-temperature tests were performed. Hydrocarbon speciation, carbonyls, particulate- and semivolatile-phase PAH compounds were reported. No diesel engine-out data.

Title The Effect of Hydrocarbon Composition on Lean NOx Catalysis

Publisher SAE | Lead Author Anthony R. Collier
Year 1997 | Study ID 85 | Citatio 973000

Comment 9 model fuels and a diesel fuel were injected into the exhaust stream of a medium duty diesel engine prior to a DeNOx catalyst. Only relative conversion efficiencies were reported.

Title Measurement Procedures of Polycyclic Aromatic Hydrocarbons in Undiluted Diesel Exhaust Gases

Publisher SAE | Lead Author Joel Wajsman
Year 1996 | Study ID 88 | Citatio 960248

Comment Analytical methodology only; no engine data. Procedures for the measurements of PAH using solid traps and thermal desorption with analysis by GC/FID and HPLC/fluorescence are reported.

Title European Programme on Emissions, Fuels and Engine Technologies (EPEFE) – Fuel and Exhaust Gas Analysis Methodology

Publisher SAE | Lead Author T. D. B. Morgan
Year 1996 | Study ID 90 | Citatio 961070

Comment Analytical methodology only. This paper describes how analytical methods for fuels an exhaust gases were selected and developed for the EPEFE study, including round-robin studies.

Title European Programme on Emissions, Fuels and Engine Technologies (EPEFE) – Light Duty Diesel Study

Publisher SAE | Lead Author M. Hublin
Year 1996 | Study ID 91 | Citatio 961073

Comment Regulated emissions and toxics on LD vehicles on 11fuels, but reported data averaged over 15 vehicle models. Test vehicles were selected to cover a wide range of technologies with performance levels below the 1996 limit.

Title Laboratory Screening of Diesel Oxidation Catalysts and Validation with Vehicle Testing: The Importance of Hydrocarbon Storage

Publisher SAE | Lead Author Karen M. Adams
Year 1996 | Study ID 94 | Citatio 962049

Comment The importance of hydrocarbon storage in diesel oxidation catalysts was studied. N-decane was used as feedgas in bench reactors. CO light off and SO2 oxidation activity has been evaluated. No engine emissions data reported, just comparative efficiencies.

Title Review: Utilization of Rapeseed Oil, Rapeseed Oil Methyl Ester or Diesel Fuel: Exhaust Gas Emissions and Estimation of Environmental Effects

Publisher SAE | Lead Author Jurgen Krahl
Year 1996 | Study ID 96 | Citatio 962096

Comment This paper reviews and summarizes the published emissions measurements from different authors, compares their results, and attempts to identify trends. Only relative changes reported -- no hard data.

Title	A Method for the Speciation of Diesel Fuel and the Semi-Volatile Hydrocarbon Fraction of Diesel-Fueled Vehicle Exhaust Emissions
Publisher	SAE
Lead Author	Robert H. Hammerle
Year	1995
Study ID	99
Citatio	952353
Comment	New methodology for the collection and analysis of the >C12 fraction of hydrocarbon exhaust is detailed.

Title	Development of Sampling and Analytical Techniques for Speciation of Heavy-Duty Diesel Hydrocarbon Emissions
Publisher	Southwest Research Institute
Lead Author	Matthew S. Newkirk
Year	1994
Study ID	101
Citatio	SwRI 9701
Comment	Analytical methodology only. This document describes the design and development of a sampling and analysis system for speciation of hydrocarbons >C12.

Title	A review of Diesel Particulate Control Technology and Emissions Effects – 1992 Horning Memorial Award Lecture
Publisher	SAE
Lead Author	John H. Johnson
Year	1994
Study ID	102
Citatio	940233
Comment	No engine-out data. 1992 Horning Memorial Award Lecture. Aftertreatment, engine design, and modified fuel formulations, as well as methods for dilution total sampling, particle size analysis, and chemical analysis (PAH and nitro PAH) are reported.

Title	Effects of a Ceramic Particle Trap and Copper Fuel Additive on Heavy-Duty Diesel Emissions
Publisher	SAE
Lead Author	George D. Harvey
Year	1994
Study ID	109
Citatio	942068
Comment	NPAH and PAH data by particulate and vapor phase; 1988 technology engine used.

Title	Sampling Strategies for Characterization of the Reactive Components of Heavy Duty Diesel Exhaust Emissions
Publisher	SAE
Lead Author	Mridul Gautam
Year	1994
Study ID	110
Citatio	942262
Comment	No engine data. This paper focus on sampling protocols for the gas phase, semi-volatile and particulate matter from the exhaust of engines operating on different kinds of diesel fuel.

Title	The Influence of Fuel Composition on Particulate Emissions of DI Diesel Engines
Publisher	SAE
Lead Author	C. Bertolli
Year	1993
Study ID	112
Citatio	932733
Comment	14 fuels designed to obtain large variations in cetane number, sulfur, and aromatic contents of diesel fuel are reported. Relative differences reported.

Title	A Diesel Oxidation Catalyst for Exhaust Emissions Reduction
Publisher	SAE
Lead Author	Izumi Fukano
Year	1993
Study ID	113
Citatio	932958
Comment	A mass spectrometer was used to determine a mechanism for reduction of SOF through a diesel oxidation catalyst. Carbonyl compounds, PAH, and nitro PAH were sampled. Relative efficiencies only were reported.

Title	Monitoring of Particulate Matter-Bound Polynuclear Aromatic Hydrocarbons from Diesel Vehicles by Photoelectric Aerosol Sensor (PAS)
Publisher	SAE
Lead Author	Shida Tang
Year	2001
Study ID	116
Citatio	2001-1-3578
Comment	Particulate-bound total PAH emissions.

Title	Quantitative Diesel Particulate Analysis using GC/MS
Publisher	Proceedings, Inst. of Mechanical Engineers
Lead Author	J.R. Farrar-Khan
Year	1993
Study ID	117
Citatio	1993 V207.A2 95-100
Comment	This paper describes a method for the analysis of PAH of diesel fuel and exhaust particulate with, and without, preseparation into the aliphatic and aromatic fractions. No engine emissions data presented.

Title	EPA HDEWG Program – Statistical Analysis
Publisher	SAE
Lead Author	Robert L. Mason
Year	2000
Study ID	122
Citatio	2000-01-1859
Comment	Same data as document number 121; statistical analysis.

Title	Determination of Polycyclic Aromatic Hydrocarbons in Size Fractionated Diesel Particles from a Light Duty Vehicle
Publisher	SAE
Lead Author	Roger Westerholm
Year	1999
Study ID	124
Citatio	1999-01-3533
Comment	All data from LD vehicle with an oxidation catalyst. No engine-out emissions were reported.

Title	Characterization and Study of Actual Emissions of Buses During Operation
Publisher	Technical University of Graz
Lead Author	C. Parfait
Year	2000
Study ID	125
Citatio	1999-23-0003
Comment	Article not found by inter-library loan system, as cited.

Title	Fuel Property Effects on Polyaromatic Hydrocarbon Emissions From Modern Heavy-Duty Engines				
Publisher	Inst. of Mech Engr			Lead Author	R.C. Doel
Year	1996	Study ID	126	Citatio	IMechE transactions, 1356-1448; 1996-5
Comment	PAH emissions over R49 cycle from modern HDD with five fuels.				

Title	A Method for Collecting Cold-Start Particulate Emissions During the Warm-Up Transient Phase of a Two Litre Direct Injection Diesel Engine to Allow Periodic Hydrocarbon Speciation				
Publisher				Lead Author	A. Blackwood
Year		Study ID	128	Citatio	C524/034/97
Comment	This paper demonstrates an alternative method of particulate collection which allows meaningful samples to be trapped in 30 seconds or less. It also presents preliminary results of PM emission rates during the first two minutes. No engine-out data.				

Title	Spectroscopic Properties of Unburned Species in Combustion Processes				
Publisher	SAE			Lead Author	B. Apicella
Year	1999	Study ID	129	Citatio	1999-24-0009
Comment	Chemical and spectroscopic analysis of high molecular wt organic species was performed on a controlled system, a pre-mixed flame, to interpret the spectroscopic features obtained using optical techniques on a diesel engine. No engine-out emissions data.				

Title	Exhaust Emission and Fuel Consumption from Otto Engine Fuels and Some Petrol Components				
Publisher	SAE			Lead Author	A. Laveskog
Year	1999	Study ID	130	Citatio	1999-24-0046
Comment	No diesel engine-out emissions reported. Unregulated emissions, including carbonyls, alcohols, ethers, aromatics, paraffins, and olefins are reported for thirteen different Otto cycle engine fuels.				

Title	Diesel Emission Control in Review - The Last 12 Months				
Publisher	SAE			Lead Author	Timothy V. Johnson
Year	2003	Study ID	133	Citatio	2003-01-0039
Comment	The author reviews advances in aftertreatment and system integration during the last 12 months. No engine-out data are presented.				

Title	Effect of Injection Pressure on the Performance and Exhaust Emissions of a Heavy Duty DI Diesel Engine				
Publisher	SAE			Lead Author	D. T. Hountalas
Year	2003	Study ID	139	Citatio	2003-01-0340
Comment	The effect of injection peak pressure on peak combustion pressure and the heat release rate mechanism is studied. NO and soot production studied as functions of injection timing. No reporting of emissions by cycle.				

Title	Effect of Engine Operating Conditions on Particle-Phase Organic Compounds in Engine Exhaust of a Heavy-Duty Direct Injection (D.I.) Diesel Engine				
Publisher	SAE			Lead Author	Chol-Bum Kweon
Year	2003	Study ID	140	Citatio	2003-01-0342
Comment	Particle-bound PAH, hopanes, steranes, alkycyclohexanes, and heavy n-alkanes over CARB 8-mode cycle from one HDD on 350 ppm S fuel.				

Title	An Experimental Investigation of PCCI-DI Combustion and Emissions in a Heavy-Duty Diesel Engine				
Publisher	SAE			Lead Author	Stefan Simescu
Year	2003	Study ID	141	Citatio	2003-01-0345
Comment	Partial premixed charge compression ignition in combination with direct fuel injection was studied on a HDD engine to investigate the performance, emissions, and efficiency of the concept. Only normalized data comparisons were presented.				

Title	An Experimental Study on Emissions Optimization Using Micro-Genetic Algorithms in a HSDI Diesel Engine				
Publisher	SAE			Lead Author	Hanho Yun
Year	2003	Study ID	142	Citatio	2003-01-0347
Comment	Micro-genetic algorithm optimization technique, which locates a global Ottoman via the law of survival of the fittest was applied to a high-speed DI, single cylinder diesel engine. Only comparative data presented, no emissions by cycle.				

Title	Experimental Research on EGR in a Diesel Engine Equipped with Common Rail Injection System				
Publisher	SAE			Lead Author	Fuyuan Yang
Year	2003	Study ID	143	Citatio	2003-01-0351
Comment	The effects of cold and hot EGR on exhaust emissions in a light-duty, high-speed direct injection diesel engine were studied. Comparative emissions by EGR rates and coolant temps.				

Title	The Effect of Cooled EGR on Emissions and Performance of a Turbocharged HCCI Engine				
Publisher	SAE			Lead Author	Jan-Ola Olsson
Year	2003	Study ID	145	Citatio	2003-01-0743
Comment	The effects of cooled exhaust gas recirculation on a turbocharged, multi-cylinder HCCI engine are reported, focusing on combustion efficiency, unburned hydrocarbons, and CO. Normalized data and efficiency plots. No raw data.				

Title	Effects of Air/Fuel Rations and EGR Rates on HCCI Combustion of n-Heptane, a Diesel Type Fuel				
Publisher	SAE			Lead Author	Zhijun Peng
Year	2003	Study ID	146	Citatio	2003-01-0747
Comment	Investigations concentrate on HCCI combustion of n-heptane at different air fuel ratios (lambda) and EGR rates. Data is mapped according to lambda vs. EGR rate; no raw emissions data reported.				

Title	A Parametric Study of HCCI Combustion -- the Sources of Emissions a Low Loads and the Effects of GDI Fuel Injection				
Publisher	SAE			Lead Author	John E. Dec
Year	2003	Study ID	147	Citatio	2003-01-0752
Comment	A combined experimental and modeling study conducted to investigate the sources of CO and HC emissions at low loads. Comparative computations using a single-zone model with full chemistry mechanisms to predict bulk gases for case with no heat transfer.				

Title	Effect of Boiling Point Differences of Two-Component Normal Paraffin Fuels on Combustion and Emission in CI Engines				
Publisher	SAE			Lead Author	Montajir M. Rahman
Year	2003	Study ID	148	Citatio	2003-01-0757
Comment	The effect of boiling point differences and flashpoint of two-component normal paraffin fuels on combustion and exhaust emissions was examined under different test conditions. Relative emissions rates compared by engine timing and load. No raw data.				

Title	Effect of Diethyl Ether on the Performance and Emission of a 4-S DI Diesel Engine				
Publisher	SAE			Lead Author	P. Mohanan
Year	2003	Study ID	149	Citatio	2003-01-0760
Comment	The effect of diethyl ether on the performance and emissions of a four stroke DI diesel engine was studied. Five percent diethyl ether gives better performance and lower commissions than other blends of DEE. Comparative plots of smoke and CO vol % only.				

Title	A Study of Direct Injection Diesel Engine Fueled with Hydrogen				
Publisher	SAE			Lead Author	Taku Tsujimura
Year	2003	Study ID	150	Citatio	2003-01-0761
Comment	Development and characteristics of auto ignition/combustion of hydrogen jets were investigated in a constant-volume vessel. Effects of jet developing process and thermodynamic states on auto-ignition delays of H2 jets were studied. No engine-out data.				

Title	Study on Combustion and Emission Characteristics of Diesel Engines Using Ethanol Blended Diesel Fuels				
Publisher	SAE			Lead Author	Bang-Quan He
Year	2003	Study ID	151	Citatio	2003-01-0762
Comment	The effect of ethanol blended diesel fuels on brake specific fuel consumption, energy consumption, smoke, and NOx emissions was investigated. Carbonyl, smoke, NOx, and ethanol emissions are reported as a function of engine load.				

Title	PM and exhaust emissions purification performance of diesel particulate filter system regenerated turns for heavy-duty diesel truck				
Publisher	SAE			Lead Author	Yoshiyuki Ko
Year	2001	Study ID	154	Citatio	2001-08-0364
Comment	This document was published in Japanese.				

APPENDIX C

LAYOUT DESCRIPTION OF DATABASE

LAYOUT DESCRIPTION OF DATABASE

The database supplied with this report was prepared with Microsoft Access® software. Because it contains a great deal of information, it was necessary to arrange information in a number of tables. The principal Table is entitled “documents reviewed”. In this Table, every document reviewed for this study is listed along with the citation, publisher, year it was published, and the name of the primary author. Associated with every document is a unique study ID number. This unique study ID number is repeated in every Table. Thus for every piece of data, one can refer back to the original source for that information.

There are 12 tables overall. Their names give an indication of the information contained in each. The tables are named as follows:

- Carbonyls
- Dioxins & Furans
- Documents Reviewed
- Emissions Data
- Engine Data
- Fuel Data
- Heavy Hydrocarbons
- Hopanes & Steranes
- Metals and Inorganics
- Nitrosamines
- PAH, NPAH
- Speciated HC

For example, “Carbonyls” contains information related to aldehydes and ketones, such as formaldehyde and acetaldehyde, and methyl ethyl ketone. “Emissions Data” contains all the regulated gaseous emissions, particulate matter mass and size information, particulate breakdown (VOF, SOF, elemental and organic carbon, etc.), greenhouse gases (carbon dioxide, nitrous oxide, methane), and miscellaneous gases like hydrogen sulfide. “Engine Data” contains all descriptive information that provided by the authors. Similarly, “Fuel Data” contains all the information provided by the authors related to the fuels used in the study. “PAH, NPAH” contains information on polycyclic, or polynuclear, aromatic hydrocarbons and their nitro- derivatives.