NIOSH

TECHNICAL REPORT

Evaluation of Exhaust Emissions Data for Diesel Engines used in Underground Mines

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Center for Disease Control
National Institute for Occupational Safety and Health

EVALUATION OF EXHAUST EMISSIONS DATA FOR DIESEL ENGINES USED IN UNDERGROUND MINES

John W. Sheehy, P.E.
Division of Physical Sciences and Engineering

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Center for Disease Control
National Institute for Occupational Safety and Health
4676 Columbia Parkway
Cincinnati, Ohio 45226

September 1980

DISCLAIMER

DHHS (NIOSH) Publication No. 80-146

ABSTRACT

This report presents an evaluation by the National Institute for Occupational Safety and Health of exhaust emissions data for diesel engines used in underground mines in the United States. The data were collected by the Mine Enforcement and Safety Administration (MESA) during the period of 1974 through 1977. (MESA became the Mine Safety and Health Administration (MSHA) on March 9, 1978). Diesel exhaust pollutants evaluated were nitrogen oxide (NO), carbon monoxide (CO), and carbon dioxide (CO_2). The pollutants were collected from 4-, 6-, 8-, and 12-cylinder indirect injection engines prior to installation of any emission control device.

Findings include: NO emissions were higher from turbocharged aftercooled engines than from naturally aspirated engines. CO emissions were considerably less from turbocharged aftercooled engines than from naturally aspirated engines. NO emissions (gm/bhphr) averaged over modes 3, 6, 9, and 10 of the Environmental Protection Agency (EPA) 13-mode cycle were higher than NO levels at peak torque or at rated load/speed.

Since exhaust emission levels varied among diesel engines that were alike as to fuel injection system, air intake system, and numbers of cylinders, the use of several makes and models of engines is recommended when testing the effectiveness of emission control devices.

CONTENTS

FIGURES

TABLLES

ACKNOWLEDGMENTS

We are grateful to Messrs. Fred Sharp, Allen Nagel, and Steve Sawyer of the Mine Safety and Health Administration (MSHA) for providing the diesel exhaust emissions data used in this report.

We also wish to thank Mr. Joseph Burkart, Environmental Protection Agency; Mr. Richard Holmquist, American Mining Congress; Mr. Allan Nagel, MSHA; and Mr. William Crouse, National Institute for Occupational Safety and Health, who provided technical guidance in the preparation of this manuscript. The manuscript was patiently and very ably typed by Ruby Watson.

INTRODUCTION

The use of diesel powered equipment in underground mines is of great concern to the National Institute for Occupational Safety and Health (NIOSH), the Mine Safety and Health Administration (MSHA), and the mining industry. NIOSH is concerned about the possible health effects of diesel emissions, particularly combined with other mine chemicals such as coal dust. NIOSH has examined the health effects resulting from exposure to a combination of dust and diesel exhaust emissions in noncoal mines, and is currently studying the health effects of diesel exhaust emissions in coal mines. There are serious concerns about possible synergistic effects of respirable coal dust particles and diesel exhaust emissions.

In a letter of June 7, 1976, NIOSH advised MSHA against further introduction of diesel powered equipment into underground coal mines until current health studies on the effects of diesel emissions were completed.[1]

The mining industry has shown strong interest in the health aspects of diesel powered equipment. The American Mining Congress (AMC), which represents the industry, sponsored a study of the health effects of diesel exhaust emissions. The study was performed by Environmental Health Associates (EHA) and included an analysis of the Rockette Report, a study of coal mine mortality. In this study, EHA stated that the United Mine Workers of American (UMWA) Denver District, "which accounts for 95 percent of all dieselized coal mines in the United States, had the lowest risk ot death from all causes (SMR.80), all cancers (SMR.70), and cardiovascular disease (SMR.70)" and "the second lowest risk of death (of all UMWA) for respiratory cancer (SMR.60), third lowest for digestive cancer (SMR.73), and second highest for emphysema (SMR 1.90)."[2]

Much more work needs to be done to determine the health risks of diesel powered equipment in underground mines. Meanwhile, research is underway to control the emissions from diesels. This report is a first step in a continuing effort to control diesel exhaust emissions. This report presents and evaluates emissions data for diesel engines used in underground mines in the United States. The emissions data were collected by MSHA, formerly the MESA, at the MSHA Testing and Certification Center in Bruceton, Pennsylvania. The data were collected during the period 1974 through 1977. MSHA uses the data in certifying engines for use in underground mines and in determining mine ventilation requirements for various types of diesel engines.

The MSHA data have been evaluated by the NIOSH Control Technology Research Branch. The data include the following pollutants: nitrogen oxide (NO), carbon monoxide (CO), and carbon dioxide (CO_2). Exhaust emissions in the tailpipe were collected prior to installation of any emission control devices. Diesel exhaust emissions following the installation of control devices are not discussed in this report.

This report examines only indirect injection (prechamber) combustion diesel engines (IDI). This is logical since it was pointed out in the NIOSH/Morgantown Diesel Workshop in September 1977, that IDI diesel engines produced lower NO, CO, and hydrocarbon (HC) emissions compared to direct injection diesel engines.[3]

THE USE OF DIESEL ENGINES IN UNDERGROUND MINES

Diesel powered equipment has found use in underground mines because of its mobility, high thermal efficiency, and potential for low exhaust emissions. The diesel engine is relatively clean if it is properly designed, adjusted, and maintained. One of the major reasons diesel engines are used in mines is the low volatility of diesel fuel.[4,5,6]

Other advantages of the diesel are: (1) rapid refueling; (2) long periods between refueling; (3) high specific energy storage of fuel, i.e., a lot of energy (diesel fuels) can be stored in a small volume; (4) numerous power levels; and (5) the possibility of various methods of power transmission.[7]

Some disadvantages of diesels used underground are: (1) exhaust emissions; (2) high ventilation needed to cool and clean air; (3) hot engine surface; (4) flameproofing required in gassy mines; and (5) noise.[7]

The primary type of diesel powered equipment used in underground mines are load haul-dump vehicles (LHD), front-end loaders, jumbo drills, roof drills, diesel shuttle trucks, supply vehicles, personnel cars, and small jeeps. Power outputs for most diesels underground range from 60 to 200 horsepower.[8,9,10]

Underground mines employing diesel engines fall into two broad categories: noncoal mines and gassy noncoal mines. Diesel engines are certified for use in noncoal mines by MSHA under Title 31, Part 32, of the Federal Register, Schedule 24. This regulation states, "the exhaust gas, after dilution with air, shall contain no more than 0.5-percent by volume of carbon dioxide, 100 ppm by volume of carbon monoxide, and 25 ppm by volume of oxides of nitrogen (as equivalent NO_2)" and "within the rated power output range, the undiluted exhaust gas of the engine shall contain not more than 0.25-percent by volume of carbon monoxide."[11]

Diesels used in the second type of mine (gassy noncoal mine) are regulated under Title 30, Part 36 of the Federal Register, Schedule 31. (The term noncoal mine is a misnomer since diesel engines tested under Schedule 31 are used in coal mines as well as gassy noncoal mines. MSHA might consider a different term than "gassy noncoal mines" when referring to Schedule 31-type mines.) Schedule 31 requires that "the concentration of exhaust gases diluted by air shall not exceed 0.25-percent by volume of carbon dioxide, 50 ppm by volume of carbon monoxide, and 12.5 ppm by volume of oxides of nitrogen (as equivalent NO_2)" and "the undiluted exhaust gas shall contain not more than 0.30-percent by volume of carbon monoxide, and 0.20-percent by volume of oxides of nitrogen (as equivalent NO_2) under any conditions of engine operation when the intake air mixture contains 1.5 + 0.1 percent by volume of Pittsburgh natural gas."[12] British regulations require that diesel locomotives used in underground mines emit no more than 0.2-percent by volume of carbon monoxide and 0.1-percent by volume of oxides of nitrogen.[13]

DIESEL ENGINE COMBUSTION SYSTEMS AND EXHAUST EMISSIONS

DIESEL COMBUSTION

The diesel engine air, which is neither throttled nor restricted, is pulled into the engine cylinders which compress the air. Then diesel fuel under high pressure is injected and the air/fuel mixture ignites spontaneously in the high temperature/pressure conditions in the cylinder. With the diesel engine, the power output is dependent only on fuel rate.[4]

The diesel engine differs greatly from the spark ignition (SI) gasoline engine where the fuel-to-air mixture is fired by a spark plug. Furthermore, the SI engine output depends not only on fuel rate, but also on the amount of air intake.[4]

There are two basic diesel combustion systems: the direct injection and the indirect injection or prechamber engine. In the direct injection engine, fuel is injected directly into the main chamber or cylinder through orifices. The fuel mixes with the air in the cylinder, vaporizes, and burns. With the indirect injection engine, fuel and a small amount of air, enters the prechamber and begins to burn. This air/fuel mixture then enters the main chamber where combustion is completed.[4]

Diesel engines that take ambient air into the combustion zone are called naturally aspirated. There are both direct injection and indirect injection naturally aspirated engines. The amount of air to the diesel engine can be increased by the use of a turbocharger, which consists of an exhaust-driven turbine in turn driving a compressor. The turbocharger forces a greater amount of air into the system and allows increased power output for the same size engine. Because of the additional heat generated from a turbocharged engine, an aftercooler may have to be added to dissipate the heat.[4]

DIESEL EXHAUST EMISSIONS

Diesel engines produce approximately 200 cubic feet of exhaust from 1 pound of fuel. Exhaust emissions are primarily CO_2, CO, NO_x, water vapor, and free nitrogen. Other exhaust pollutants include HC, particulates, SO_2 and odor. The CO_2 produced is directly proportional to the amount of fuel burned in the diesel engine and cannot be reduced by emission control devices. Therefore, ventilation is the only way to lower CO_2 emissions to acceptable levels in mines. CO, HC, odor, and NO_x from diesel engines can be reduced through the use of control devices. CO, HC, and odor are reduced by catalytic converters and fuel injection refinements. CO emissions also can be reduced by derating diesel engines. NO_x can be reduced by exhaust gas recirculation (EGR), fuel injection modification (including retarded timing and increased fuel rate), and water injection. Particulates are controlled by turbocharging, power limitation, and a catalytic scrubber/water scrubber combination. Proper maintenance is also critical in controlling particulates.

SO_2 in the exhaust is proportional to the sulfur content of the fuel, and thus is controlled by minimizing the amount of sulfur in the fuel.[4,5,10,14,15] The use of any specific control technique for reducing one pollutant can result in the increase of other pollutants. For example, EGR reduces NO_x emissions, but increases CO and unburnt hydrocarbons.[14]

Measurement of diesel exhaust emissions is normally performed in the laboratory using an engine dynomometer. The dynomometer controls engine speed and loading. Fuel usage, airflow to the engine, and intake and exhaust temperatures and pressures are also recorded. Techniques for measuring diesel exhaust pollutants are found in the following publications: (1) Bascom, R. C. and G. C. Hass, A Status Report on the Development of the 1973 Diesel Engine Emissions Standards, Nat. Soc. of Automotive Engrs., Los Angeles, August 24-27, 1970, SAE Paper 700671, 15 pp; and (2) Control of Air Pollution, from New Motor Vehicles and New Vehicle Engines, Vol. 37, No. 221, November 15, 1972, pp. 24250-320.[14]

Upon collecting diesel emissions data for various speeds and loads, the emissions' levels are quantified using a duty cycle. The duty cycle permits an emissions' map for each pollutant to be condensed into a single number. An emissions' map of NO is shown in Figure 1.[16]

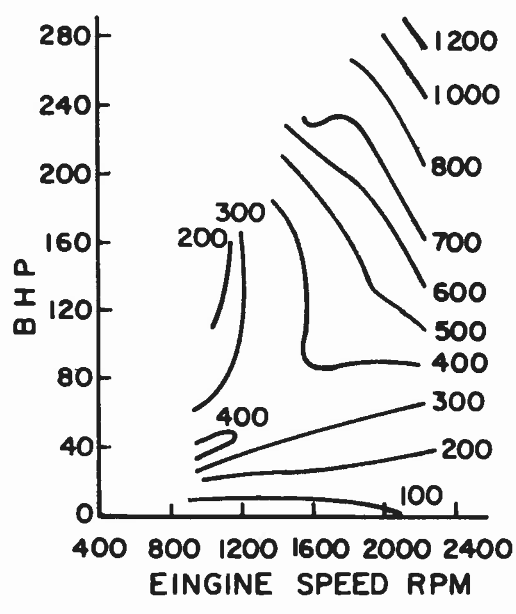

Figure 1. Nitric oxide (NO) emissions map in (gm/hr).

Reproduced from Boescher, R. E. and D. F. Webster, "Precombustion Chamber Diesel Emissions--A Progress Report," Pres. Society of Automotive Engineers, Vancover, BC, Aug. 16-19, 1971, SAE Paper 710672, 13 pp.[16]

Diesel exhaust emissions data can be presented as either emissions flow rate (grams per hour) or brake specific emissions rate (grams per brake horsepower hour). The latter is simply the emissions flow rate divided by brake horsepower to obtain the brake specific emissions rate. This report predominantly uses brake specific emissions rate (grams per brake horsepower hour).

STUDY METHODOLOGY FOR THE ANALYSIS OF MSHA DIESEL EXHAUST EMISSIONS DATA

This report analyzes exhaust emissions data for diesel engines. The emissions data were collected by MSHA and analyzed by NIOSH. The eight engines are indirect injection (prechamber) engines: six naturally aspirated (NA) and two turbocharged aftercooled (TA). The eight engines include two 4-cylinder, four 6-cylinder, one 8-cylinder, and one 12-cylinder engine.

Data for the eight diesel engines, along with the emissions data (in grams/-brake horsepower hour) are shown in the Appendix. Each diesel engine is designated by an identification number such as B-4 or D-8TA1. The first character of the identification number is a code letter for the engine manufacturer. The second character(s) is the number of engine cylinders. Additional letters such as TA indicate turbocharged aftercooled and G indicates tests performed in a methane atmosphere. G1 indicates tests performed in 1-percent methane atmosphere.

All of the engines were tested in a methane-free atmosphere except the F-4, which was tested in both a methane atmosphere and a methane-free atmosphere. F-4 emissions data obtained in the methane atmosphere are indicated by F-4G1.

The diesel engines were run on a dynamometer through a duty cycle consisting of a minimum of nine static operating points, with up to eight additional points in some cases. The nine basic operating points are rated speed with 25-, 50-, 75-, and 100-percent power increments, peak load with the same power increments, and idle. (Emissions data at idle were not available for this report). The engines were brought to temperature equilibrium before exhaust emissions were sampled.

Additional data collected include fuel rate and intake air rate (from vacuum pressure measurements), which are used to calculate the fuel-to-air ratio. Operating parameters recorded include engine speed, torque, horsepower, and percent load. Atmospheric parameters recorded include dry bulb temperatures, barometric pressure, dew point, and humidity (grains of H_2O/pound of dry air). Atmospheric conditions of dry bulb temperature, humidity, and barometric pressure while testing each engine are given in Table 1.

The general procedures for testing diesel engines in nongassy (0-percent methane) atmospheres are found under Schedule 24, Title 30, Part 32. For gassy atmospheres (1- to 1.5-percent methane), they are found under Schedule 31, Title 30, Part 36.[11, 12]

Diesel engines tested in this study were equipped with air cleaner, flame arrestors, exhaust cooling, and exhaust systems. The emissions data are for raw exhaust collected prior to any control devices. Diesel exhaust was analyzed for NO, CO, and CO_2. Exhaust NO_2 emissions, which account for an estimated 1- to 2-percent of the oxides of nitrogen, were not measured.[17]

Table 1. Test conditions of humidity, temperature and pressure.

Engine Identification	Humidity (grains H_2O/ lb dry air)	Intake Air Temperature (^oF)	Barometric Pressure (inches)
A-6	36--40	45--67	28.82--28.87
B-6	38--42	67--80	29.08--29.18
E-6	32	60--66	29.32--29.39
E-6TA	48--70	67--86	29.17--29.60
B-4	21	64--73	29.30--29.32
F-4	27--30	64--77	29.25--29.29
F-4G1	26	79--82	29.22
D-8TA1	37--46	77--85	29.15--29.38
A-12	64--74	59--71	29.16--29.98
Range for all engines	21--74	45--86	28.82--29.98

STUDY METHODOLOGY FOR THE ANALYSIS OF MSHA DIESEL EXHAUST EMISSIONS DATA

This report analyzes exhaust emissions data for diesel engines. The emissions data were collected by MSHA and analyzed by NIOSH. The eight engines are indirect injection (prechamber) engines: six naturally aspirated (NA) and two turbocharged aftercooled (TA). The eight engines include two 4-cylinder, four 6-cylinder, one 8-cylinder, and one 12-cylinder engine.

Data for the eight diesel engines, along with the emissions data (in grams/-brake horsepower hour) are shown in the Appendix. Each diesel engine is designated by an identification number such as B-4 or D-8TA1. The first character of the identification number is a code letter for the engine manufacturer. The second character(s) is the number of engine cylinders. Additional letters such as TA indicate turbocharged aftercooled and G indicates tests performed in a methane atmosphere. G1 indicates tests performed in 1-percent methane atmosphere.

All of the engines were tested in a methane-free atmosphere except the F-4, which was tested in both a methane atmosphere and a methane-free atmosphere. F-4 emissions data obtained in the methane atmosphere are indicated by F-4G1.

The diesel engines were run on a dynamometer through a duty cycle consisting of a minimum of nine static operating points, with up to eight additional points in some cases. The nine basic operating points are rated speed with 25-, 50-, 75-, and 100-percent power increments, peak load with the same power increments, and idle. (Emissions data at idle were not available for this report). The engines were brought to temperature equilibrium before exhaust emissions were sampled.

Additional data collected include fuel rate and intake air rate (from vacuum pressure measurements), which are used to calculate the fuel-to-air ratio. Operating parameters recorded include engine speed, torque, horsepower, and percent load. Atmospheric parameters recorded include dry bulb temperatures, barometric pressure, dew point, and humidity (grains of H_2O/pound of dry air). Atmospheric conditions of dry bulb temperature, humidity, and barometric pressure while testing each engine are given in Table 1.

The general procedures for testing diesel engines in nongassy (0-percent methane) atmospheres are found under Schedule 24, Title 30, Part 32. For gassy atmospheres (1- to 1.5-percent methane), they are found under Schedule 31, Title 30, Part 36.[11, 12]

Diesel engines tested in this study were equipped with air cleaner, flame arrestors, exhaust cooling, and exhaust systems. The emissions data are for raw exhaust collected prior to any control devices. Diesel exhaust was analyzed for NO, CO, and CO_2. Exhaust NO_2 emissions, which account for an estimated 1- to 2-percent of the oxides of nitrogen, were not measured.[17]

Table 1. Test conditions of humidity, temperature and pressure.

Engine Identification	Humidity (grains H_2O/ lb dry air)	Intake Air Temperature (^oF)	Barometric Pressure (inches)
A-6	36--40	45--67	28.82--28.87
B-6	38--42	67--80	29.08--29.18
E-6	32	60--66	29.32--29.39
E-6TA	48--70	67--86	29.17--29.60
B-4	21	64--73	29.30--29.32
F-4	27--30	64--77	29.25--29.29
F-4G1	26	79--82	29.22
D-8TA1	37--46	77--85	29.15--29.38
A-12	64--74	59--71	29.16--29.98
Range for all engines	21--74	45--86	28.82--29.98

EVALUATION OF DIESEL EXHAUST EMISSIONS

AVERAGE DIESEL EXHAUST EMISSIONS FOR NO, CO_2, AND CO

The exhaust emission data for eight indirect injection (IDI) diesel engines are shown in Table 2. The pollutants include NO, CO_2, and CO in units of grams per brake horsepower hour (gm/bhphr). The emission data were obtained by averaging emissions for segments 3, 6, 9, and 10 of the Federal EPA 13-mode cycle for heavy-duty diesel engines. Modes 3, 6, 9, and 10, plus 1 idle mode of the 13-mode cycle, were recommended as the duty cycle for diesel equipment used in underground mines by the Emissions Control Technology Work Group at the NIOSH/Morgantown Diesel Workshop (September 1977). This duty cycle should be used until specific information on underground diesel equipment duty cycles is available.[3] (Emissions data for the idle mode were not available and are not included).

Table 2. Diesel engine exhaust emissions.*

Engine	Cylinder	Type	NO (gm/bhphr)	CO_2 (gm/bhphr)	CO (gm/bhphr)
B-4	4	NA	4.2	600	1.6
F-4	4	NA	5.8	750	1.7
F-4G1	4	NA	4.5	690	7.6
B-6	6	NA	4.2	640	1.9
A-6	6	NA	3.8	670	1.5
E-6	6	NA	5.6	812	2.4
E-6TA	6	TA	5.4	580	0.8
D-8TA1	8	TA	6.0	--	--
A-12	12	NA	4.6	700	2.3

*Based on Modes 3, 6, 9, and 10 of the Federal EPA heavy-duty diesel engine 13-mode cycle.

Nitric oxide emissions ranged from 3.8 to 6.0 gm/bhphr. Lowest emissions were from the 6-cylinder NA/IDI engine (A-6). Highest NO emissions were produced by the 8-cylinder TA/IDI engine (D-8TA1). The number of engine cylinders had little effect on emission levels. NO emissions for the 4-, 6-, 8-, and 12-

cylinder engines averaged 5.2, 4.8, 6.0, and 4.5 gm/bhphr, respectively. Comparing NA/IDI engines and the TA/IDI engines shows NO emissions slightly higher for the TA/IDI engines than for NA/IDI. NO emissions from NA engines averaged 4.8 gm/bhphr compared to 5.7 gm/bhphr from the TA engines.

All engines previously discussed were tested in a methane-free atmosphere. However, the 4-cylinder NA/IDI engine (F-4) was also tested in a 1-percent methane atmosphere. The F-4 engine is designated as F-4G1 when tested in the methane atmosphere. The data show reduced NO emissions in the methane atmosphere (Table 2). F-4 engine emissions averaged 5.8 gm/bhphr in the methane-free atmosphere compared to 4.5 gm/bhphr in the 1-percent methane atmosphere.

CO_2 exhaust emissions, as shown in Table 2, ranged from 580 to 812 gm/bhphr. CO_2 emissions averaged 704 gm/bhphr from the NA engines and 580 gm/bhphr from the TA engines. Average CO_2 emissions from the TA engines were 21-percent lower than from the NA engines. The methane atmosphere slightly reduced CO_2 emissions. In the 1-percent methane atmosphere, the F-4 engine produced 690 gm/bhphr of CO_2 compared to 750 gm/bhphr in the zero-methane atmosphere.

CO emissions, as shown in Table 2, ranged from 0.8 to 2.4 gm/bhphr for the seven engines tested in the zero-methane atmosphere. CO emissions from the TA engine (E-6TA) were much lower than CO emissions from any of the NA diesel engines. CO emissions from the E-6TA engine were half those of the A-6 engine, which emitted the least CO of the NA engines. CO emissions from NA engines averaged 2.0 gm/bhphr or about 2-1/2 times the CO emissions of 0.8 gm/bhphr from the TA engine. The data also indicated the number of engine cylinders had a small effect on CO emissions. The NA 4-, 6-, and 12-cylinder engine CO emissions averaged 1.6, 1.9, and 2.3 gm/bhphr, respectively, in the methane-free atmosphere. In the case of the F-4 engine, CO emissions in the 1-percent methane atmosphere were four-and-one-half times CO emissions in the zero-methane atmosphere.

NO EMISSIONS AT PEAK TORQUE AND RATED SPEED

Table 3 summarizes NO emissions (gm/bhphr) for peak torque; rated load and speed; and the average of segments 3, 6, 9, and 10 of the EPA 13-mode cycle. The data show that average NO emissions (averaged over segments 3, 6, 9, and 10 of the 13-mode cycle) were higher than NO emissions for either peak torque or rated load and speed. These data point out that averaging NO emissions over four segments of the EPA cycle appears to be a more conservative approach than using either peak torque or rated load and speed to regulate NO emissions from diesels.

The data also indicate there is little difference between peak torque NO emissions and rated load/speed NO emissions for NA engines. Data for one of the two TA engines, E-6TA, show NO emissions were significantly higher (35-percent) at rated load/speed than at peak torque. However, NO emissions at peak torque and rated load/speed were the same for the other TA engines (D-8TA1).

Further examination of Table 3 shows that if diesel engines are ranked from highest to lowest on the basis of NO emissions (gm/bhphr), the engines will be ranked almost the same whether the criteria is peak torque, the rated load/speed, or the average over four segments of the EPA 13-mode cycle. For example, the engine, D-8TA1, produced the highest NO emissions at peak torque when averaged over segments of the EPA cycle, and produced the second highest NO emissions at the rated load/speed.

Table 3. Diesel exhaust NO emissions (gm/bhphr).

Engine	Average Modes 3, 6, 9, and 10	Peak Torque	Rated Load and Speed
B-4	4.2	2.5	2.5
F-4	5.8	3.7	3.9
F-4G1*	4.5	3.4	4.1
A-6	3.8	3.3	3.6
B-6	4.2	2.4	2.6
E-6	5.6	2.9	3.0
E-6TA	5.4	3.7	5.0
D-8TA1	6.0	4.6	4.8
A-12	4.6	3.3	3.8

*Operated in 1-percent methane atmosphere

The data in Table 3 also show the TA engines produced higher NO emissions than the NA engines. This is true whether based on peak torque, rated load/speed, or averaged over segments of the EPA cycle.

At rated load/speed, NO emissions ranged from 4.8 to 5.0 gm/bhphr from the TA engines and 2.1 to 4.1 gm/bhphr from the NA engines. Looking only at the 6-cylinder engines (A-6, B-6, E-6, and E-6TA) at rated load/speed, NO emissions from the TA engine (E-6TA) were higher than from the three NA engines. Table 3 also shows the NO emissions from the F-4 engine in the methane-free atmosphere and the 1-percent methane atmosphere. At peak torque and at rated speed/load, NO emission levels for the F-4 engine were about the same in the methane-free and the 1-percent methane atmosphere; however, averages over the four segments of EPA cycle, NO emissions were significantly lower in the 1-percent methane atmosphere than in the methane-free atmosphere.

Table 4 presents the NO mass emissions rate (gm/hr) for eight diesel engines. The turbocharged engines produced considerably more NO (gm/hr) emissions than the naturally aspirated engines. The 8-cylinder TA engine produced twice as much NO than the 12-cylinder NA engine, and the 6-cylinder TA engine produced much higher NO than any of the three 6-cylinder NA engines.

The NO mass emissions rate at rated speed/load is generally higher than the NO mass emissions rate at peak torque or averaged over four segments of the EPA cycle. It is clear from the data that the NO emissions rate depends largely on the size of the engine or number of cylinders, i.e., power output. Without considering power output, it is very difficult to compare emissions' levels for various engines. For this reason, diesel engines are normally compared on the basis of emissions per unit of power output and are reported in units of gm/bhphr.

Table 4. Diesel exhaust NO emissions (gm/hr).

Engine	Average Models* 3, 6, 9, and 10	Peak Torque	Rated Load and Speed
B-4NA	137	159	173
F-4NA	323	344	387
F-4G1NA	311	297	458
A-6NA	317**	394	486
B-6NA	199	185	270
E-6NA	419	388	422
E-6TA	762	822	1,320
D-8TA1	1,660	1,730	2,300
A-12NA	636	653	998

* From 13-mode EPA cycle.
**50-percent load intermediate speed value substituted for 25-percent load intermediate value which is missing.

EFFECT OF ENGINE SPEED, LOAD, FUEL/AIR RATIO, AND HORSEPOWER ON NO AND CO EMISSIONS

Speed and Load

Figure 2 shows NO emissions from three diesel engines: 4-cylinder NA-IDI engine (B-4), 6-cylinder NA-IDI engine (B-6), and 6-cylinder TA-IDI engine (E-6TA). The emissions data were obtained at speeds and loads corresponding to segments 3, 6, 9, and 10 of the EPA 13-mode cycle. At 25-percent load and intermediate speed (segment 3), there was little difference in NO emission levels among the three engines. In the other three modes, the data show the NO emissions from the two NA engines were significantly less than from the TA engine.

Figure 2 also shows the relative importance of each of the four modes in determining an average NO emission number, as found in Tables 2 and 3. For the NA engines, NO emissions at a 25-percent load are much higher than for the three segments with NO emission levels progressively decreasing as load increases from 50- to 100-percent. In the case of the TA engine, NO emissions are almost the same for 25-percent load-intermediate speed, 50-percent load-rated speed, and 75-percent load-rated speed. At 100-percent load-intermediate speed, the NO emissions are significantly less than in the other three modes.

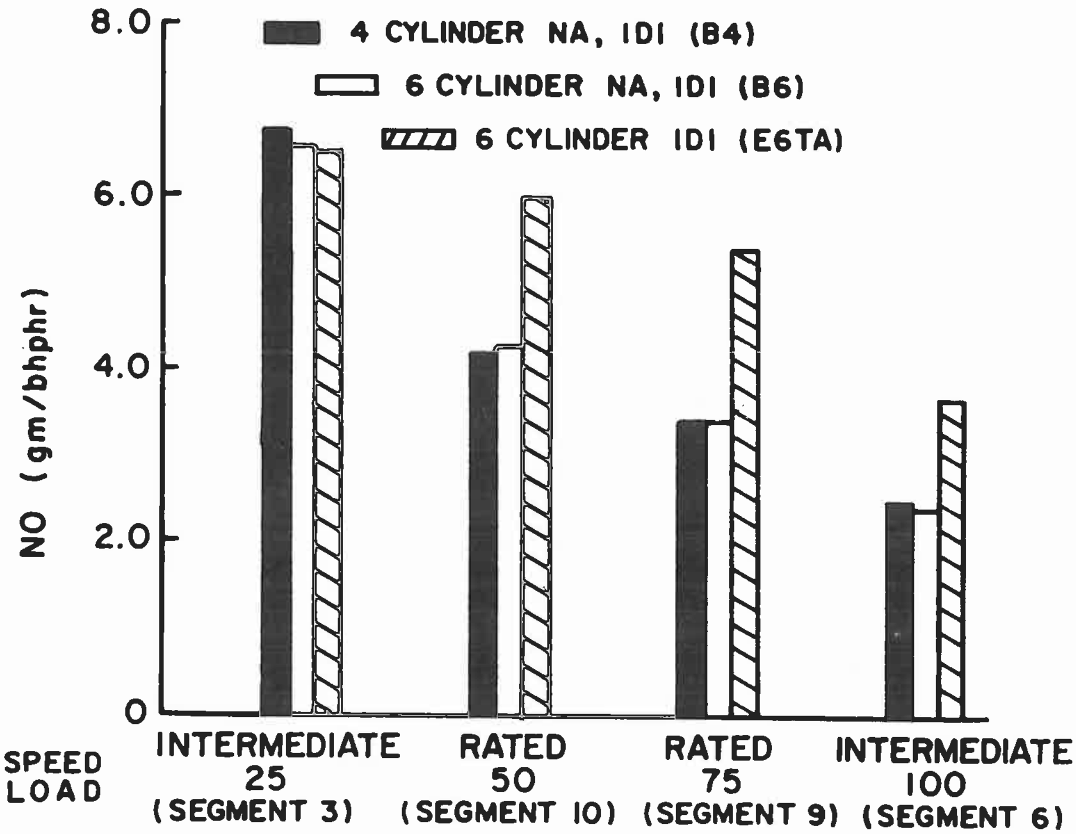

Figure 2. Nitric oxide emissions versus speed and load (four segments of 13-mode cycle).

The effect of engine speed on NO emissions (gm/bhphr) is shown in Figures 3 and 4. Figure 3 shows NO emissions from the NA-IDI engine (B-4). At 50-, 75-, and 100-percent loads, engine speed had little effect on NO levels. However, at 25-percent emission loads, NO decreased slightly with increasing engine speed.

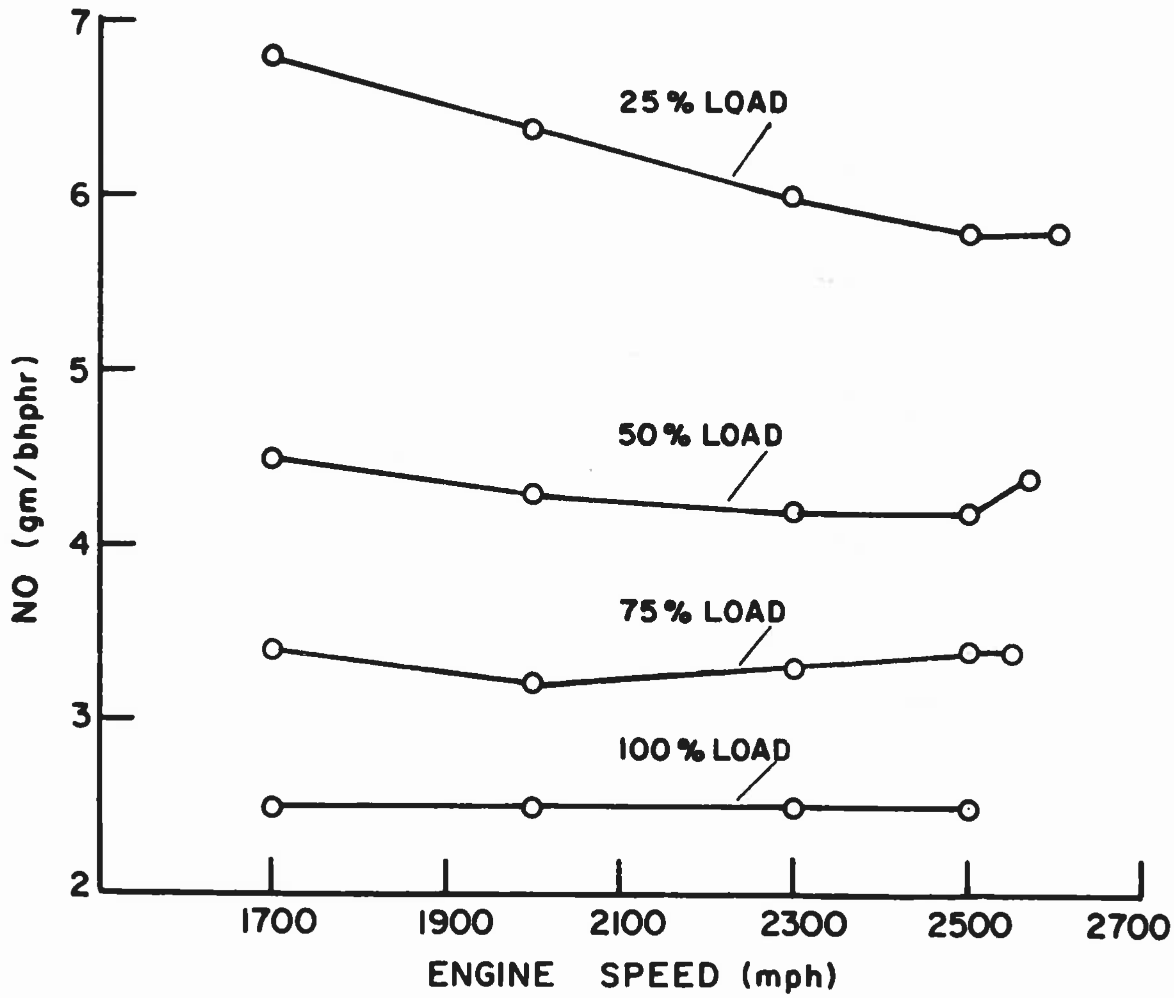

Figure 3. NO emissions versus speed and load (NA engine).

Figure 4 shows NO emissions (gm/bhphr) from the TA-IDI engine (E-6TA). NO emissions were affected by engine speed at all loads. At loads of 50-, 75-, and 100-percent, NO emissions were about 50-percent higher at the rated speed (2,200 rpm) than at the intermediate speed (1,600 rpm). At 25-percent load the NO levels were only slightly greater at higher speed. The data in Figure 3 indicate that the B-4 NA engine can be operated between intermediate and rated speed without affecting the NO emissions. On the other hand, Figure 4 shows that TA engine E-6TA should be operated closer to intermediate speeds to minimize NO emissions.

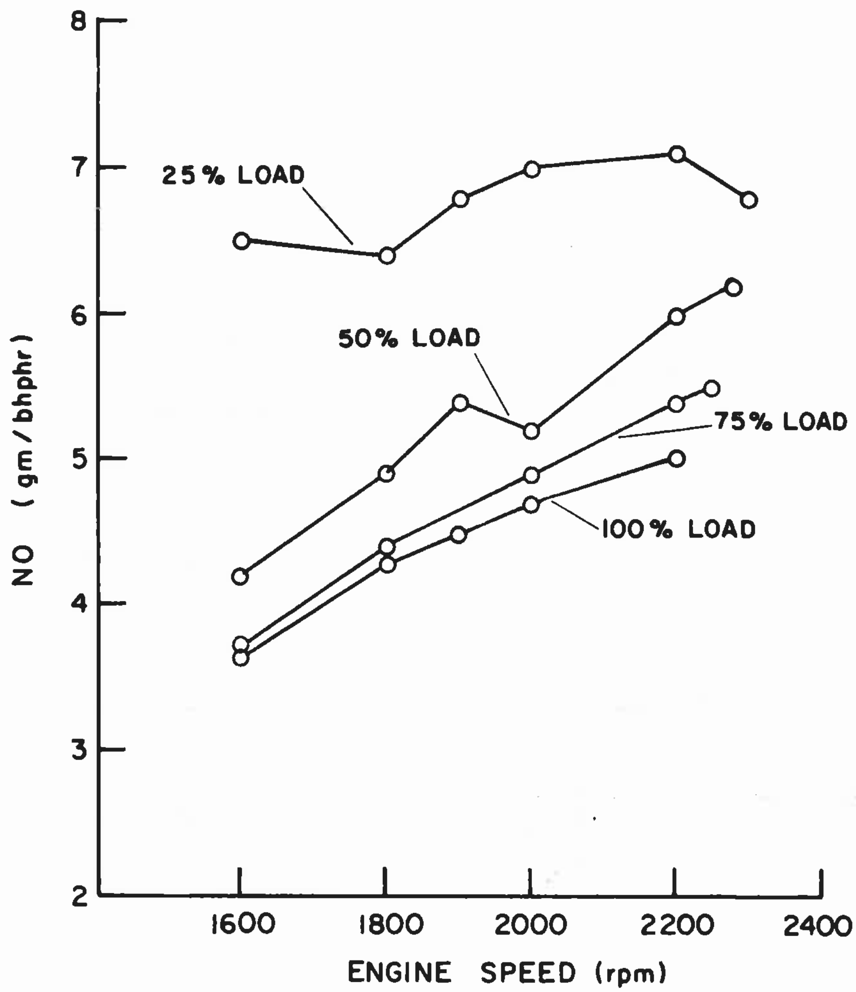

Figure 4. NO emissions versus speed and load (TA engine).

CO emissions for three diesel engines, B-4, B-6, and E-6TA, are shown in Figure 5. CO emissions are highest at 25-percent load intermediate speed and decrease with increasing load. CO emissions from the TA engines are significantly less than emissions from the two NA engines at 25-, 50-, and 75-percent loads. At 100-percent load, there is little difference in CO emissions between the NA engines and the TA diesel engines.

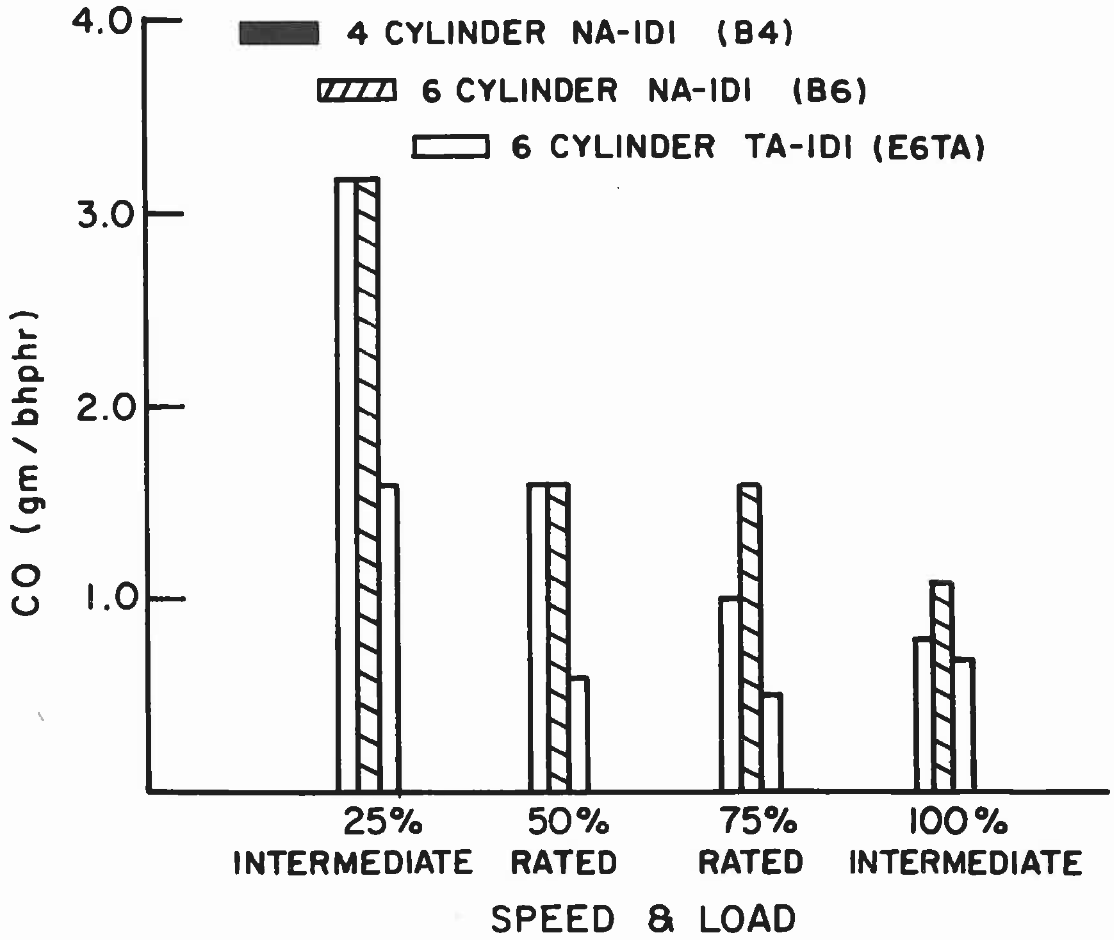

Figure 5. CO emissions versus speed and load (4 segments of 13-mode cycle).

CO emissions versus engine speed for a NA-IDI engine (B-4) is shown in Figure 6. CO emissions from the B-4 engine were not affected by engine speed except at 100-percent load. Here, CO levels jumped slightly as engine speed increased from 2,000 to 2,300 rpm. The data also show that CO emissions (gm/bhphr) are halved as load is increased from 25- to 50-percent and increasing the load from 50- to 100-percent further reduces CO emissions. For mine application, the data indicate it is better to select the smallest practical diesel engine and operate it at higher loadings where CO emissions per unit of power are less.

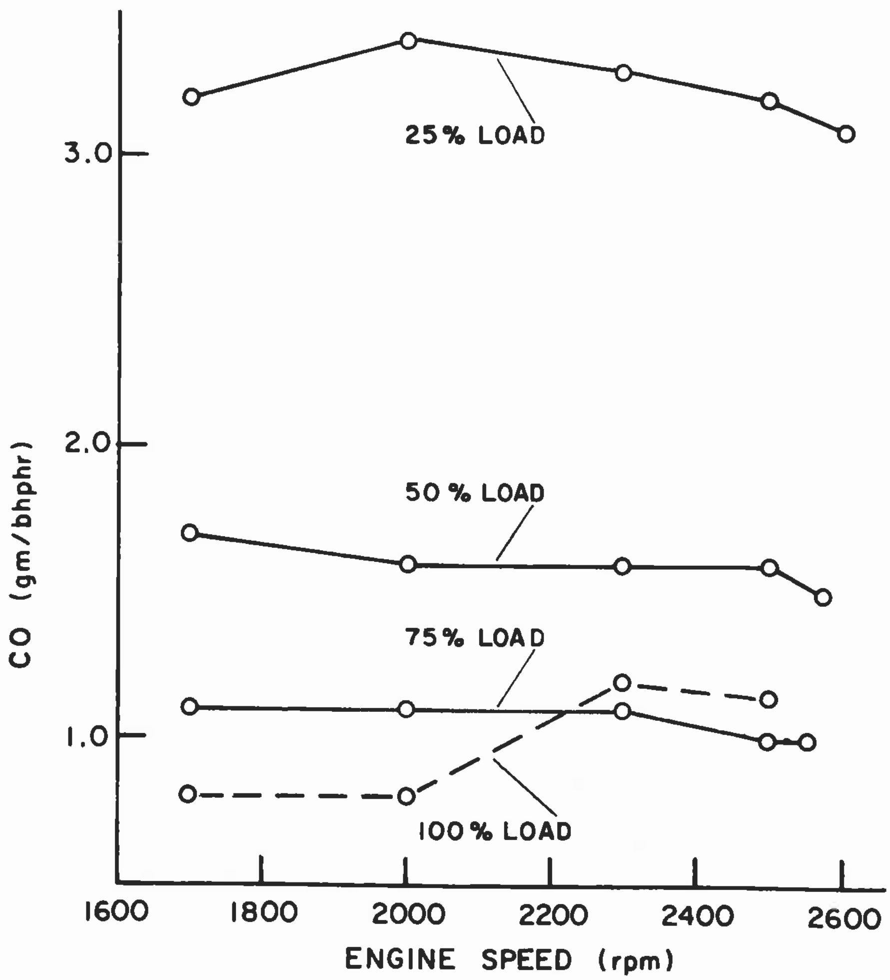

Figure 6. CO emissions versus speed and load (NA engine).

FUEL/AIR RATIO

Figure 7 shows the dependence of exhaust NO emissions on air/fuel (F/A) ratio for three IDI diesel engines, a 4-cylinder NA-IDI (B-4) engine, a 6-cylinder NA-IDI (E-6) engine, and a 6-cylinder TA-IDI engine (E-6TA). NO levels for all three engines decrease with increasing F/A ratios. The data indicate that additional air (oxygen) at lower F/A ratios (.04) results in higher NO emissions. The nearly identical slopes of the curves in the typical operating ranges show the naturally aspirated and turbocharged aftercooled engines are similarly affected by F/A ratio.

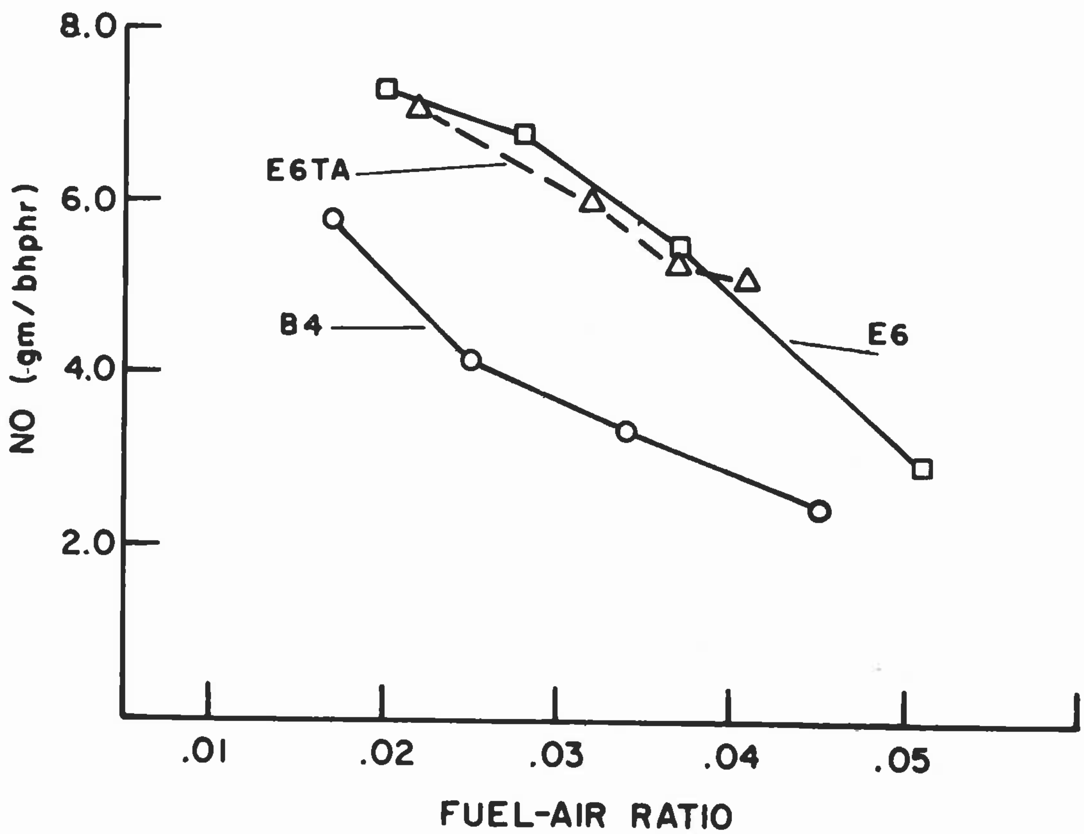

Figure 7 NO emissions (gm/bhphr) versus F/A ratio.

NO emissions are examined on a mass emission basis (i.e, gm/hr) in Figure 8. The NA engines B-4 and E-6 produced highest NO mass emissions (gm/hr) at F/A ratios between .030 and .045. The turbocharged aftercooled engine E-6TA produced very high NO emissions (gm/hr) at F/A ratios from .032 to .041 (there are no data for F/A ratios greater than .041). In terms of mass emission rate, the NA 6-cylinder diesel (E-6) produced lower NO emissions than the 6-cylinder TA engine (E-6TA). However, when the mass emission rates in Figure 8 are divided by power output, the NO emissions from these two engines are nearly identical (as shown in Figure 7).

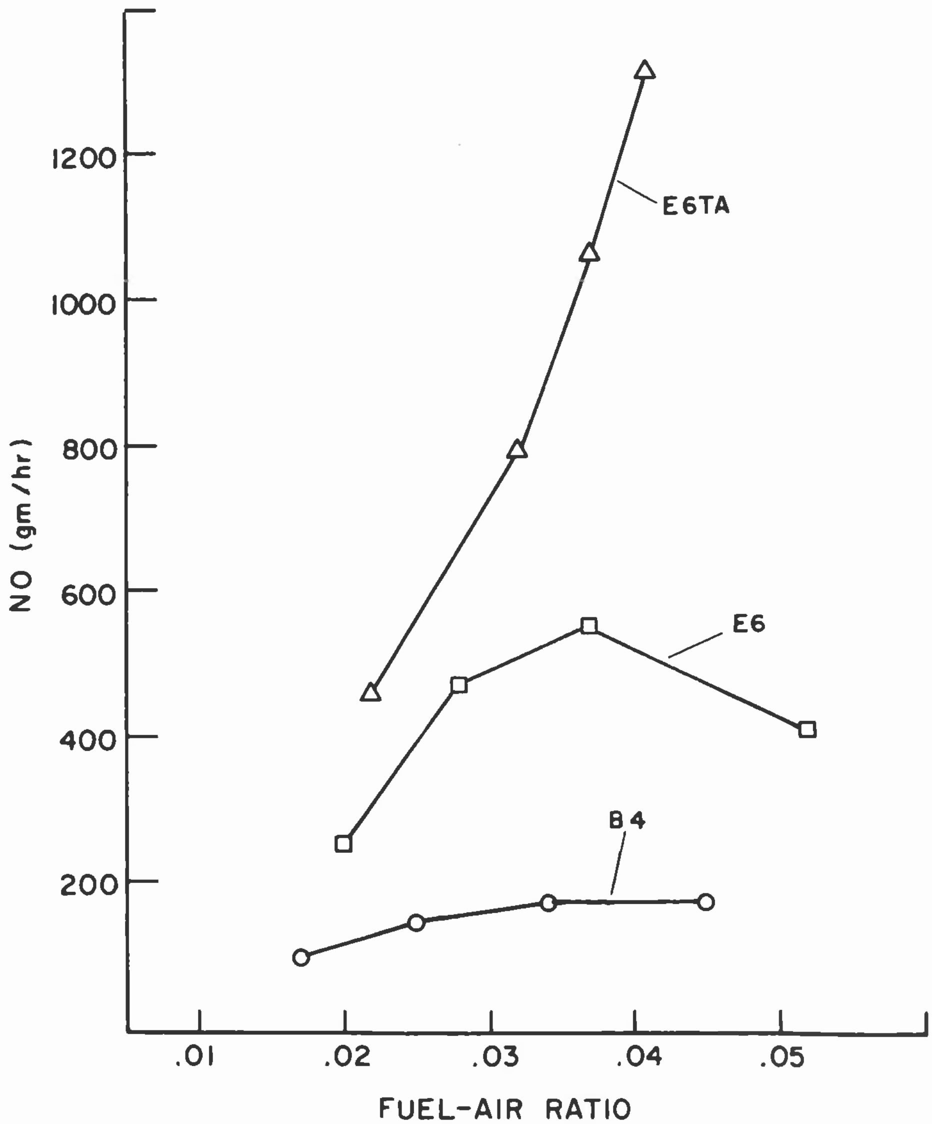

Figure 8. NO emissions (gm/hr) versus F/A ratio.

The 8-cylinder TA-IDI engine (D-8TA1) NO mass emissions rate (gm/hr) for a range of F/A ratios is shown in Figure 9. NO mass emissions increase significantly as the F/A ratio increases from 0.024 to 0.037. Figure 9 also shows that higher engine speed increases the NO mass emissions from the D-8TA1 engine. For example, at the F/A ratio of .034, the NO mass emissions rate was 1,450 gm/hr at 1,800 rpm and 1,900 gm/hr at 2,100 rpm, an increase of approximately 30-percent.

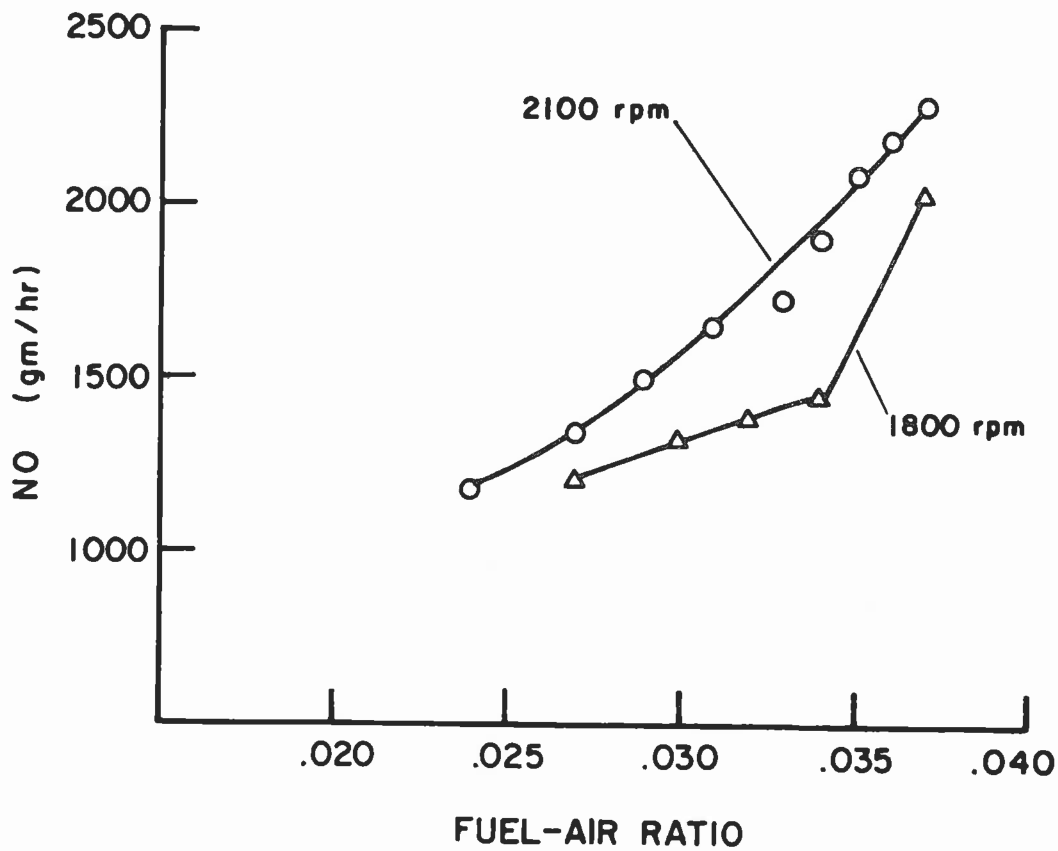

Figure 9. NO emissions versus F/A ratio and engine speed.

The effect of F/A ratio on the CO emissions (gm/bhphr) from three diesel engines, B-4, E-6, and E-6TA, is shown in Figure 10. CO emissions from all three engines were lowest at F/A ratios between 0.032 and 0.045. The data also show one TA engine (E-6TA) produced significantly lower CO emissions than the two NA engines. CO emissions from the E-6TA were half the CO emissions for NA engines in the F/A range of 0.032 to 0.045.

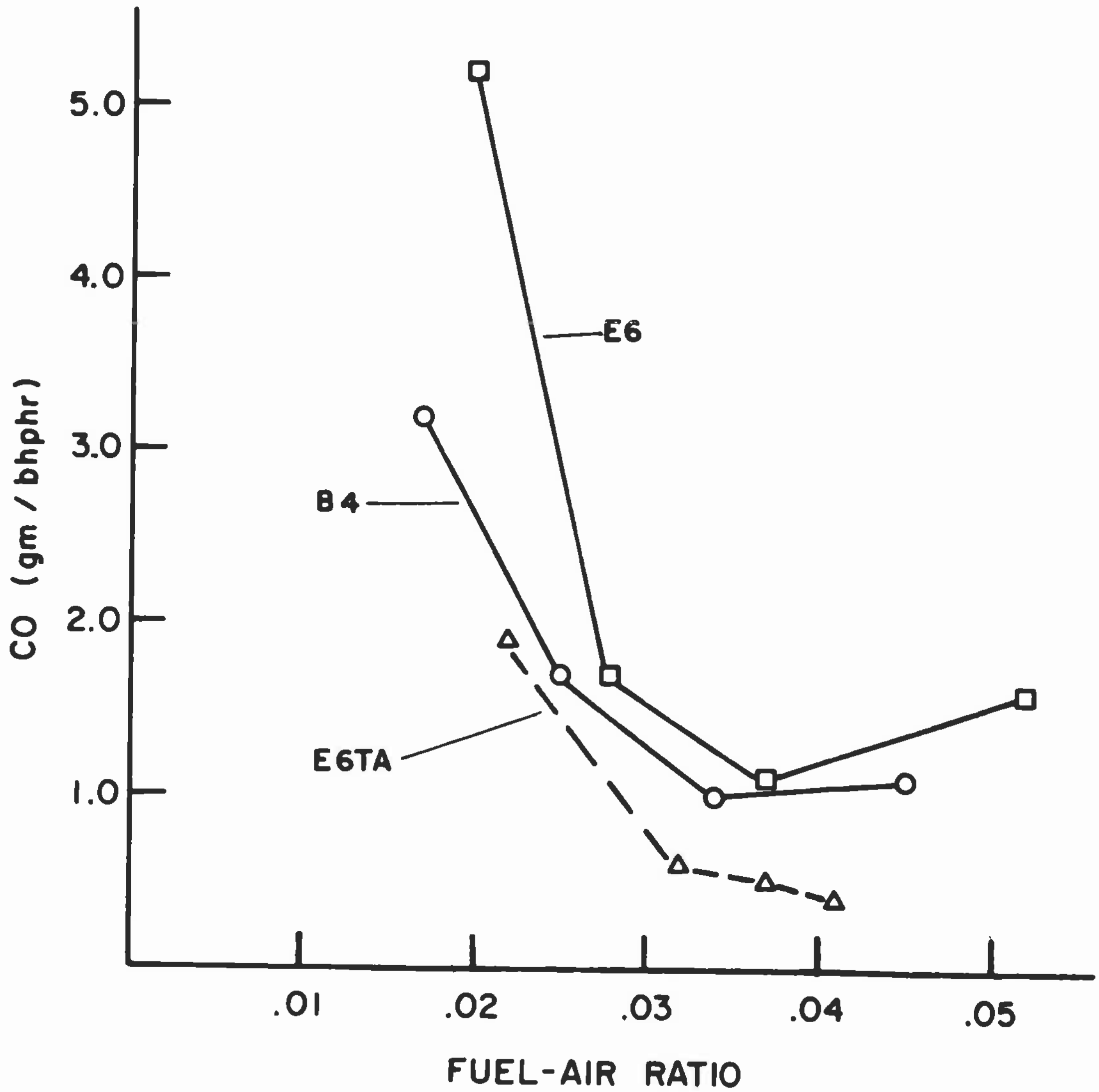

Figure 10. CO emissions (gm/bhphr) versus F/A ratio.

Figure 11 shows CO mass emissions rate (gm/hr) for the above three engines. The minimum CO mass emissions occurred at F/A ratios from 0.028 to 0.037. CO mass emissions for the E-6 and E-6TA engines increased with F/A ratios below 0.028 or above 0.037. The B-4 engine CO mass emissions increased at F/A ratios above 0.037 but did not increase at F/A ratios less than 0.028. It is not clear why decreasing the F/A ratio below 0.028 affected CO emissions from the E-6 and E-6TA engines, but not the B-4 engine.

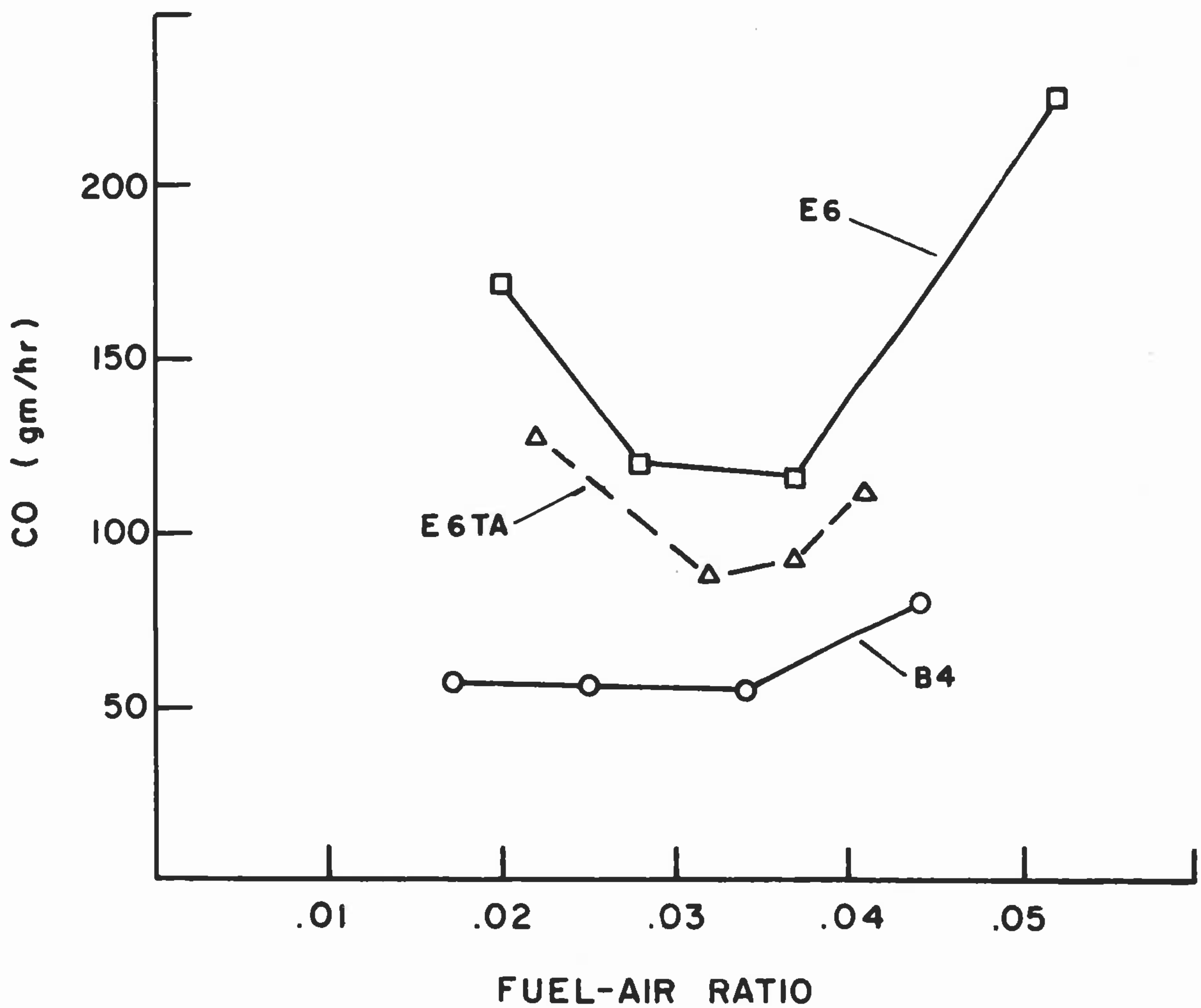

Figure 11. CO emissions (gm/hr) versus F/A ratio.

CORRELATION OF HORSEPOWER, F/A RATIO, AND FUEL RATE

The horsepower and F/A ratio show a direct correlation as illustrated in Figures 12 and 13. Figure 12 presents the relationship between horsepower and F/A ratio for a 4-cylinder NA-IDI engine (B-4) and a 6-cylinder NA-IDI engine (A-6). The data in Figure 12 were obtained at engine speeds ranging from 1,700 to 2,594 rpm for engine B-4, and from 1,900 to 2,409 rpm for engine A-6. The relationship of horsepower to F/A ratio is essentially linear. There is some scatter at high F/A ratios above 0.04 in which engine speed has a more pronounced effect on the relationship of horsepower and F/A ratio.

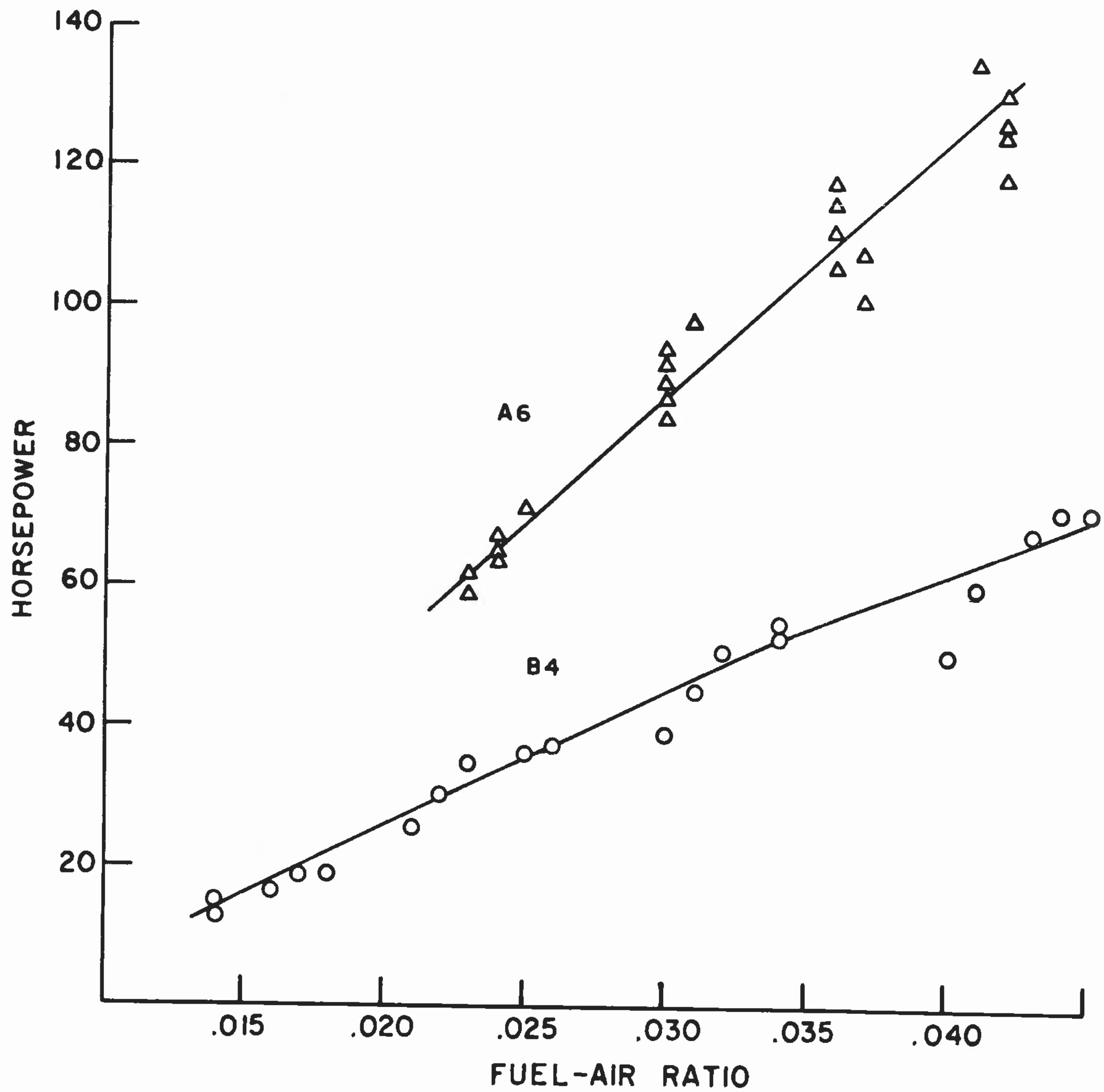

Figure 12. Horsepower versus F/A ratio.

In Figure 13, horsepower is plotted against the F/A ratio for an 8-cylinder TA-IDI engine (D-8TA1). The data are presented for two engine speeds, 1,800 rpm and 2,100 rpm. The data show that, at the same F/A ratios, higher engine speed results in higher horsepower. For example, at the F/A ratio of 0.030, the horsepower is 35-percent higher at an engine speed of 2,100 rpm than at 1,800 rpm.

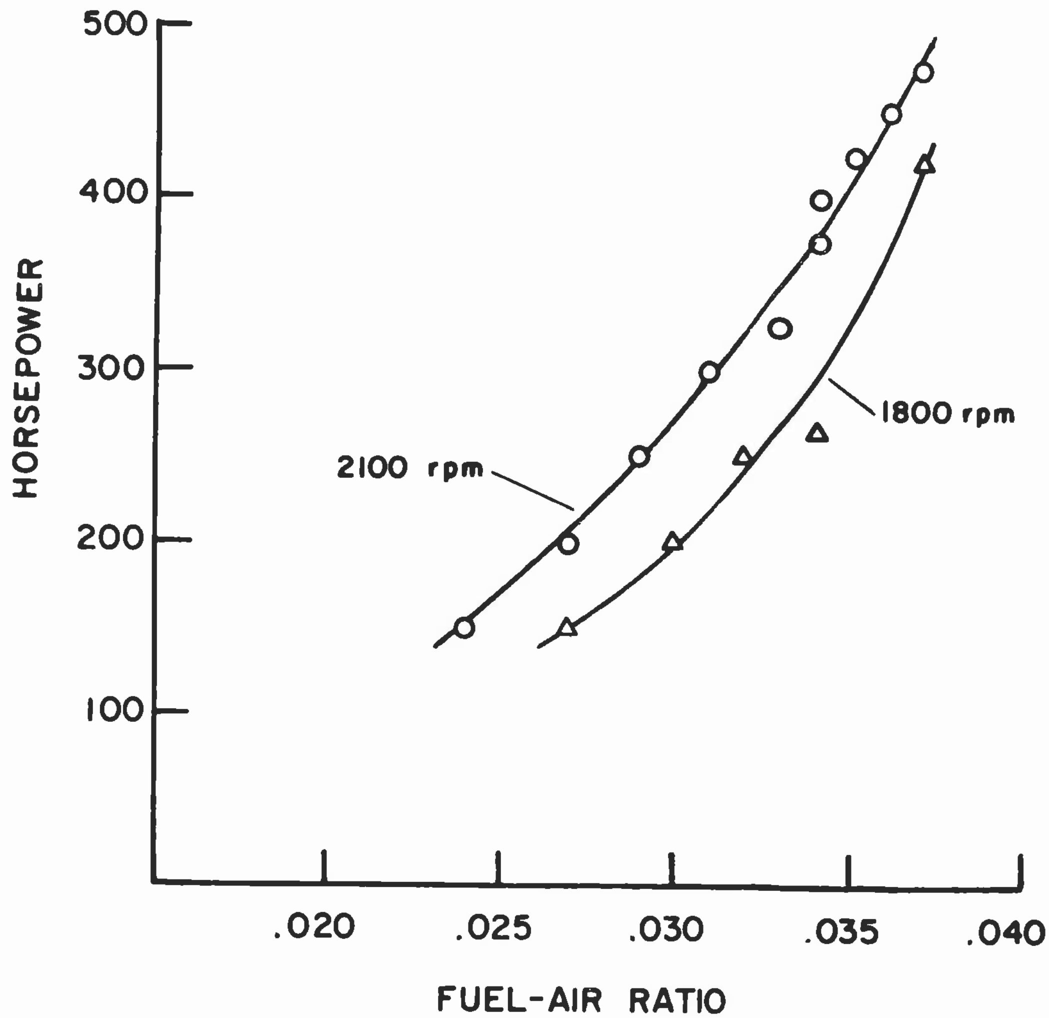

Figure 13. Horsepower versus F/A ratio and engine speed.

Figure 14 relates horsepower to fuel rate (pounds/hour) for three diesel engines. For the 6-cylinder NA-IDI engine (E-6), the relationship of fuel rate to horsepower is linear up to 75-percent load (102 hp). Above this load, the fuel rate per unit of horsepower increased. The relationship of fuel rate to horsepower is also linear up to 50-percent load for the 6-cylinder NA-IDI engine (A-6). Above this, the fuel rate per unit of horsepower increases. The E-6TA engine has a slightly higher fuel rate per unit of horsepower at loads 50-percent and above than at loads of 25-percent.

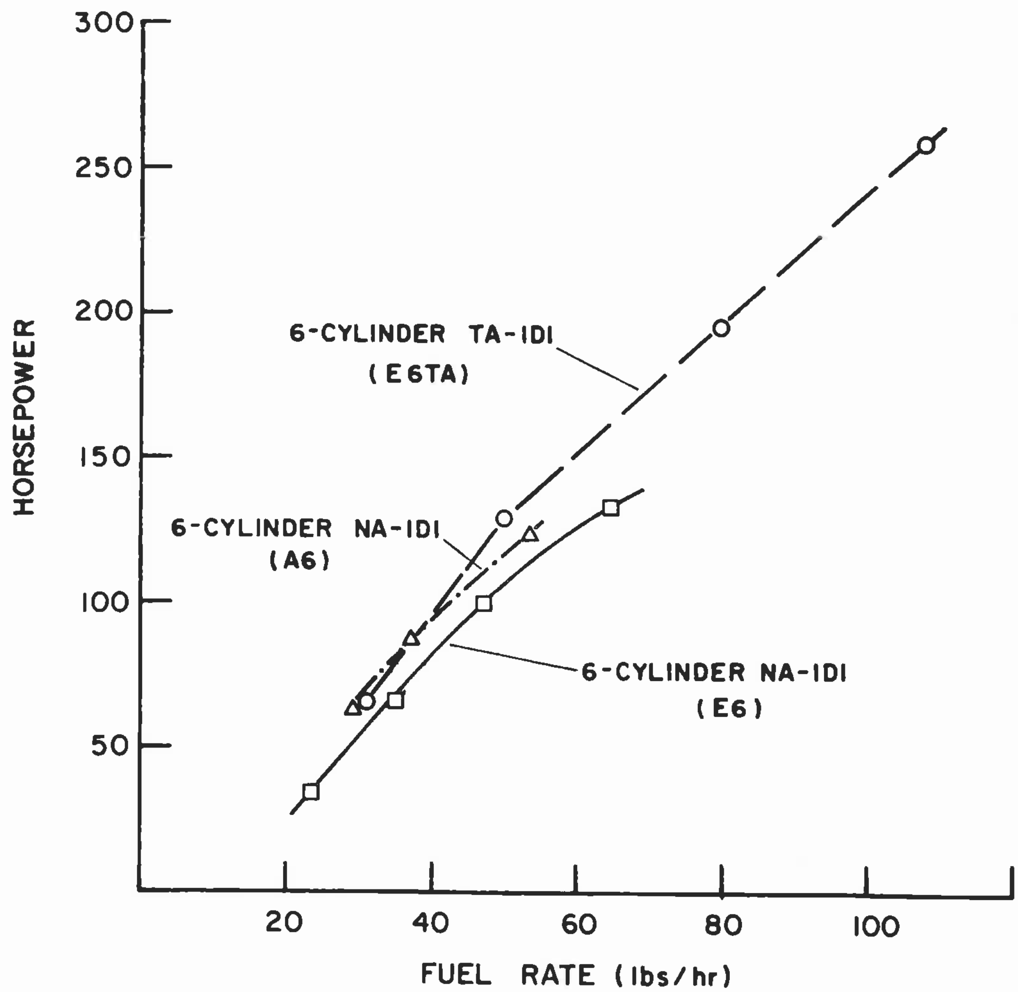

Figure 14. Horsepower versus fuel rate (at 2,000 rpm).

Figure 14 also indicates the relative energy efficiency of these three diesel engines. The E-6 engine uses slightly more fuel per unit of power than the other two engines. It appears that fuel efficiency for the three engines is not affected by the type of air intake system, i.e., by whether it is a NA or TA engine.

EFFECT OF HORSEPOWER ON EMISSION LEVELS

NO emissions (gm/bhphr) from three diesel engines operating at 2,000 rpm are shown in Figure 15. The three engines are a 4-cylinder NA-IDI engine (B-4), a 6-cylinder NA-IDI engine (B-6), and a 6-cylinder TA-IDI engine (E-6TA). The effect of horsepower on the two naturally aspirated engines is clear. Increasing horsepower results in a significant decrease in NO emissions per unit of power. This would indicate it is preferable to use the smallest engine for each particular application so the engine would operate in a higher power range where NO emissions would be lower. The data in Figure 15 also show the 4-cylinder engine produces lower emissions than the 6-cylinder for the same horsepower. For example, at 40 horsepower, NO emissions were 3.6 and 4.7 gm/bhphr for the 4-cylinder and 6-cylinder NA engines, respectively. The 6-cylinder TA engine (E-6TA) produced significantly higher NO emissions at the same horsepower than either of the two NA engines. The data also show that the E-6TA engine NO emissions (gm/bhphr) were constant at loads above 50-percent, unlike the NA engines where NO emissions decreased as loads increased from 50- to 100-percent. If NO emissions become the principal criterion in determining the suitability of diesel engines in mines, NA engines appear to have an advantage over TA engines.

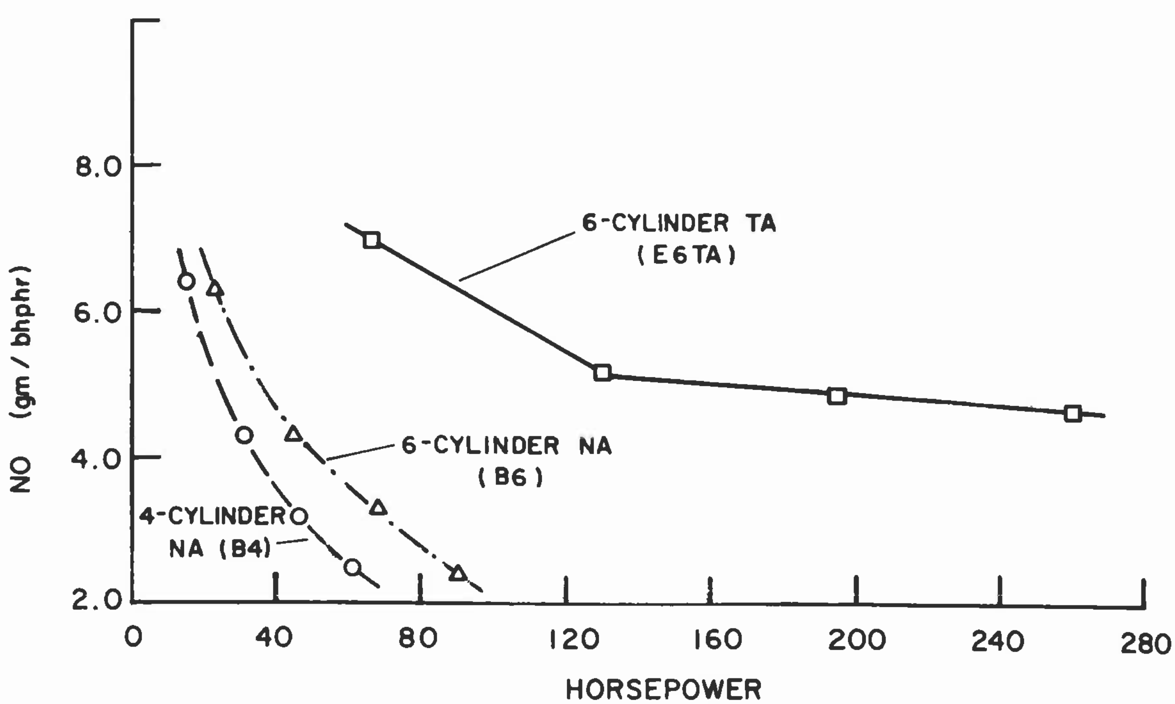

Figure 15. NO emissions versus horsepower (at 2,000 rpm).

CO emissions from the three diesel engines B-4, B-6, and E-6TA are shown in Figure 16. CO emissions (gm/bhphr) are much higher at low load (and horsepower) than at high load (and horsepower), particularly in the case of the two NA engines. CO emissions from the two NA engines, B4 and B6, are halved as the power is doubled 25- to 50-percent load. Comparing the two engines shows the 4-cylinder engine (B-4) produced lower CO emissions than the 6-cylinder engine (B-6). As noted previously, the B-4 engine also produced lower NO emissions than the B-6 engine. Exhaust CO emissions (gm/bhphr) from the TA diesel engine E-6TA greatly decreases (70-percent) as the power increased from 66 to 130 horsepower and the load from 25- to 50-percent. CO emissions (gm/bhphr) were constant as loadings increased from 50- to 100-percent.

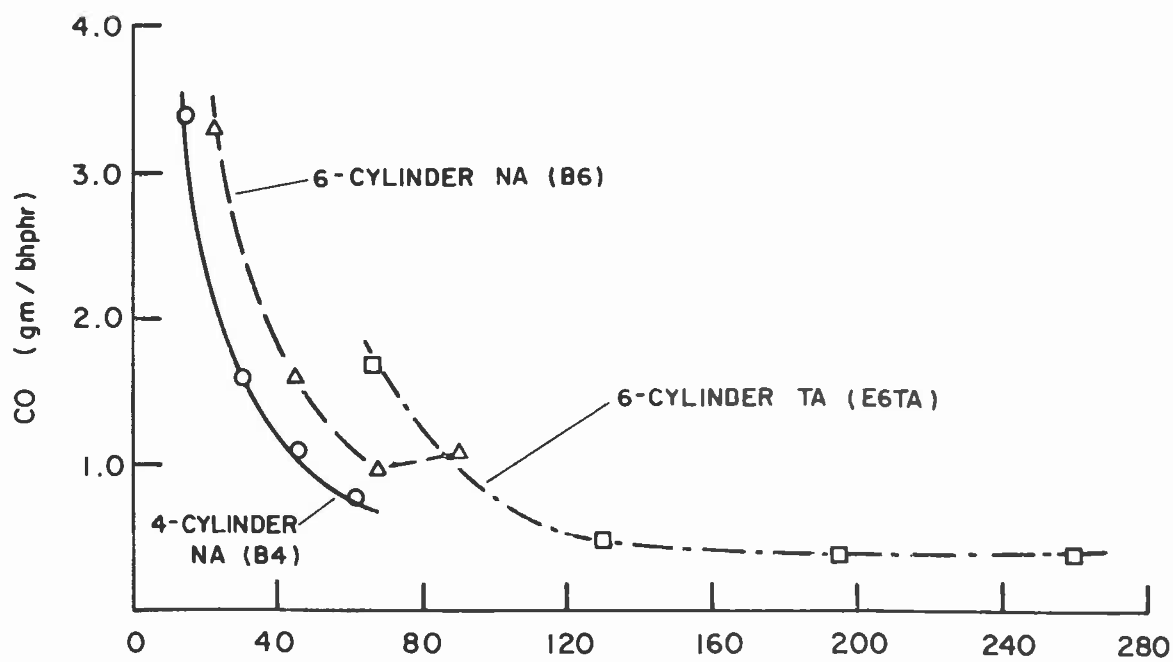

Figure 16. CO emissions versus horsepower (at 2,000 rpm).

EMISSIONS IN A METHANE ATMOSPHERE

NO emissions data for a 4-cylinder NA-IDI diesel engine (F-4) in the methane and methane-free atmospheres are shown in Figure 17. The data were collected at an engine speed of 2,000 rpm. The 1-percent methane atmosphere significantly affected the NO emissions (gm/bhphr) at low-to-medium power (25 to 50 horsepower). For example, at 27 horsepower (25-percent load), NO emissions in the 1-percent methane atmosphere were half NO emissions in the methane-free atmosphere. As horsepower increased, the methane atmosphere had less effect on NO levels. At 100-percent load, NO emissions in the methane and methane-free atmospheres were identical. The methane atmosphere could possibly affect ventilation requirements for underground mines using diesels. For instance, if a diesel were operated largely in a low/medium power range, and NO were the critical emission, the methane atmosphere would lessen NO emissions and might possibly lessen the amount of ventilation required.

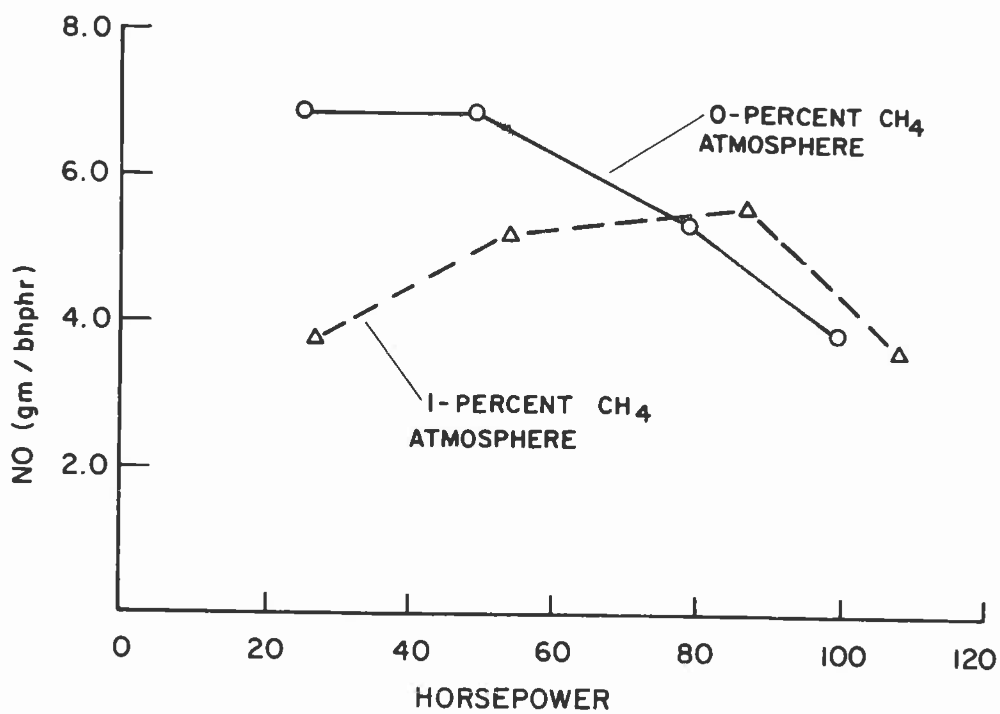

Figure 17. NO emissions versus horsepower with and without CH_4 atmosphere (at 2,000 rpm).

The effect of the methane atmosphere on carbon monoxide (CO) emissions from a 4-cylinder NA-IDI (F-4) diesel engine is presented in Figure 18. It shows the dramatic increase in CO emissions resulting from the 1-percent concentration of methane. With full power, the CO concentration in the methane atmosphere was two-and-one-half times the CO concentration in the methane-free environment. At low/medium power, CO emissions were even higher in the methane atmosphere. For example, at 25-percent load (27 hp), CO emissions were about six-times higher in the 1-percent methane atmosphere than in the methane-free atmosphere; and at 50-percent load (54 hp), CO emissions were five-times higher in 1-percent methane than in the methane-free atmosphere.

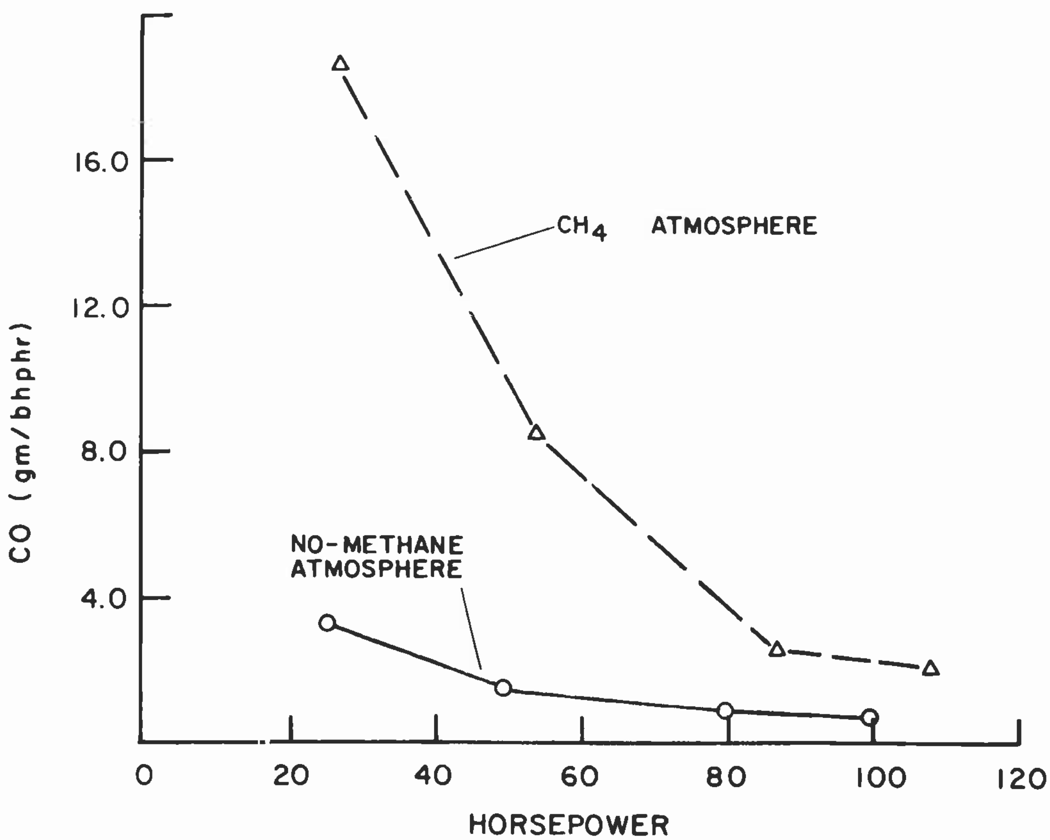

Figure 18. CO emissions versus horsepower with and without CH_4 atmosphere (at 2,000 rpm).

The diesel emissions data were collected in humidities ranging from 21 to 74 grains of H_2O per pound of dry air (gr H_2O/lb dry air). Studies have shown that NO exhaust emissions are affected by the humidity and several correction factors have been developed to correct of humidity. In one study sponsored by the Coordinating Research Council (CRC), a correction factor, K, was developed to adjust NO emissions data for humidity.[18] This factor is calculated using the following equation:

$$K = \frac{1}{1 - 0.00336\ (H-75)}$$

where H = the humidity of the inlet air in gr (H_2O)/lb dry air.

At 75 gr (H_2O)/lb dry air, K is equal to 1. Below 75 gr (H_2O)/lb dry air, it is less than 1; and above 75 gr (H_2O)/lb dry air, it is more than 1. Therefore, when the humidity is less than 75 gr (H_2O)/lb dry air, corrected NO emission levels are less than uncorrected NO levels; and above 75 gr (H_2O)/lb dry air, vice versa.

NO emissions data corrected and uncorrected for humidity are shown in Figure 19 and Table 5. The 4-cylinder NA-IDI engine F-4 was tested in an atmospheric humidity of 28 to 30 gr (H_2O)/lb dry air. The "K" value for 28 gr/lb dry air is 0.86. This factor multiplied by 25-percent load NO emissions value of 6.9 gm/bhphr gives a humidity corrected NO emissions value of 5.9 gm/bhphr, as shown in Table 5. The 6-cylinder NA-IDI engine B-6 was tested in an atmospheric humidity from 38 to 40 gr (H_2O)/lb of dry air. The "K" value is 0.89 for a humidity of 38 gr (H_2O)/lb dry air. Data for the B-6 engine are also shown in Table 5.

Table 5. NO Emissions Uncorrected and Corrected for Humidity.

Engine	Speed (rpm)	% Load	Humidity gr (H_2O)/ lb dry air	"K"*	NO "Uncorrected" (gm/bhphr)	NO "Corrected" (gm/bhphr)
F-4	2,000	25	28	.86	6.9	5.9
F-4	2,000	50	30	.87	6.9	6.0
F-4	2,000	80	30	.87	5.4	4.7
F-4	2,000	100	30	.87	3.9	3.4
B-6	2,000	25	38	.89	6.3	5.6
B-6	2,000	50	38	.89	4.3	3.8
B-6	2,000	75	38	.89	3.3	2.9
B-6	2,000	100	40	.89	2.4	2.1

*Ref 18: CRC No. 447. "Effect of Humidity..."

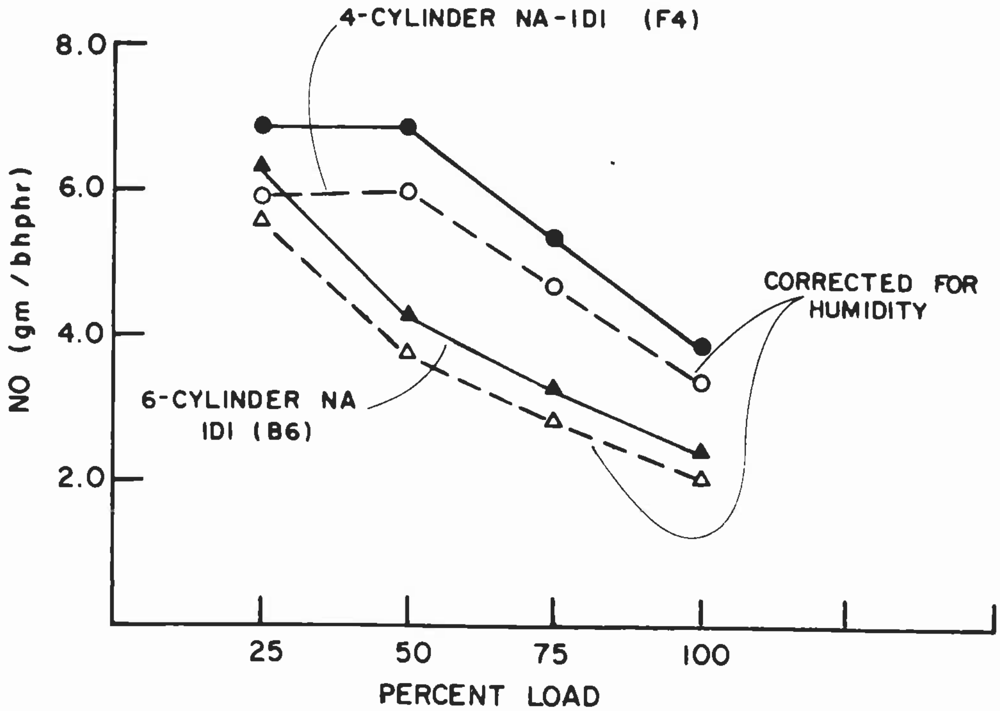

Figure 19. NO emissions versus load and humidity.

CONCLUSIONS

1. Nitric oxide (NO) emissions are higher from turbocharged aftercooled (TA) diesel engines than from naturally aspirated (NA) engines (based on comparison of indirect injection engines). Carbon monoxide (CO) emissions were considerably less from TA engines except at 100-percent load, where CO emissions for both NA and TA engines were the same.

2. The data show that the number of engine cylinders had almost no effect on indirect injection diesel exhaust NO or CO brake specific emissions (i.e., gm/bhphr).

3. Brake specific NO emissions (gm/bhphr) averaged over segments 3, 6, 9, and 10 of the EPA 13-mode cycle, were higher than NO levels at peak torque or at rated load/speed.

4. Brake specific NO emissions (gm/bhphr) decreased with increasing fuel-to-air (F/A) ratio up to a F/A of 0.050. (Data for F/A ratios above 0.050 were not available.) CO emissions were lowest in the range of F/A ratios from 0.032 to 0.045.

5. Both NO and CO (gm/bhphr) emissions decreased considerably as horsepower increased, as would be expected in brake specific terms.

6. A diesel engine, indirect injection--naturally aspirated, produced significantly less NO emissions in the 1-percent methane atmosphere than in the methane-free atmosphere when operated in low-to-medium power range. However, at high power (100-percent load), diesel NO emissions were about the same in the 1-percent methane and the methane-free atmospheres. (At 100-percent load, the engine produced greater horsepower with the methane atmosphere than without it.) CO exhaust emissions increased greatly in the methane atmosphere.

RECOMMENDATIONS

1. Research should be concentrated on the collection and evaluation of emissions data for diesel engines with the control devices attached. The following types of diesel engines with selected exhaust control devices should be tested: (1) direct injection naturally aspirated; (2) direct injection turbocharged-aftercooled; (3) indirect injection naturally aspirated; and (4) indirect injection turbocharged-aftercooled. Although indirect injection engine raw exhaust emissions are generally lower, direct injection engines in combination with certain control devices may produce lower emissions than indirect injection engines with the same control device.

2. The data in this report show that emissions vary even among diesel engines of the same number of cylinders, fuel injection system, and air intake system (e.g., 6-cylinder IDI-NA engines). Therefore, the effective control devices should be tested on several makes of the same engine type.

3. Future studies should include diesel exhaust emissions data with/without control devices at loads from idle to 20-percent. One reviewer noted that NO_2 can be a significant portion of NO_x at idle and low speeds. (Any future studies of emissions at idle speed should note that emissions in gm/bhphr at idle would be infinite, since horsepower at idle is zero.)

4. The duty cycle of underground mine diesels must be assessed to determine the importance of transient conditions on emissions. A study to assess duty cycles sponsored jointly by NIOSH and the U.S. Bureau of Mines is presently underway.

5. This report was confined to gaseous emissions; however, future work should concentrate on oxygenates, particulates, and organics adhering to or absorbed on particulates.

6. Information on exhaust emissions for diesels operated at high elevations (3,000 to 10,000 feet) should be obtained. At higher elevations, the stochiometry is different and a greater potential to pollute exists with reduced combustion air.

7. MSHA, when certifying engines for use in underground mines, should consider measuring diesel exhaust emissions following installation of control devices and, thus, include any benefits of the controls in reducing overall ventilation requirements.

REFERENCES

1. Statement of Edward J. Baier, Deputy Director, NIOSH, before the Subcommittee on Energy Research, Development and Demonstration House Committee on Science and Technology, July 27, 1976, p. 8.

2. Health Effects of Diesel Exhaust Emissions Prepared for the American Mining Congress, Environmental Health Associates, Inc., Berkeley, CA, January 25, 1978, pp. 80-1.

3. The Use of Diesel Equipment in Underground Coal Mining, NIOSH, Morgantown, WVA, September 19-23, 1977, p. 110.

4. Johnson, J. H., Diesel Engine Design, Performance, and Emission Characteristics, Proceedings of Symposium on Use of Diesel Powered Equipment in Underground Mining, Pittsburgh, PA, January 30-31, 1973.

5. Hurn, R. W., Diesel Emissions Measurement and Control, Proceedings of Symposium on the Use of Diesel Powered Equipment in Underground Mining, Pittsburgh, PA, January 30-31, 1973.

6. Henderson, R. D., Diesel Technology, Proceedings of Symposium on the Use of Diesel Powered Equipment in Underground Mining, Pittsburgh, PA, January 30-31, 1973.

7. Bristow, N., Trackless Transport for Men and Materials, Mining Technology Clearing House, Nos. 1-3, Staffordshire, England B797Af, May, 1978.

8. Determination of Breathing Zone Concentrations of Contaminants from Emissions from Diesel Powered Vehicles in Underground Mines, U.S. Bureau of Mines (Part II, Contract No. JO 255001), 1974-76.

9. Alcock, K., Duty Cycles and Load Factors of Diesel Powered Vehicles in Underground Mines, American Mining Congress, 1978.

10. Dainty, E. D. and G. K. Brown, Federal Certification and Research Concerning Environmental Aspects of Diesel Powered Machines in Coal Mines, CIM Bulletin, pp. 80-95, November 1974.

11. Title 30, Part 32 (Schedule 24), Federal Register, Vol. 14, No. 67, pp. 184-195, April 8, 1949.

12. Title 30, Part 36 (Schedule 31), Federal Register, Vol. 26, No. 14, January 24, 1961.

13. Higginson, N., Use of Diesel Engines Underground in British Coal Mines, Proceedings of Symposium on the Use of Diesel Powered Equipment in Underground Mining, Pittsburgh, PA, January 30-31, 1973.

14 Alcock, K., Written Comments Submitted After the Symposium, Proceedings of Symposium on the Use of Diesel Powered Equipment in Underground Mining, Pittsburgh, PA, January 30-31, 1973.

15. Marshall, W. F., Emission Control for Diesels Operated Underground: Catalytic Converters, ERDA-BERC, August 1975.

16. Boescher, R. E. and D. F. Webster, Precombustion Chamber Diesel Emissions--A Progress Report, Pres. Soc. of Automotive Engineers, Vancouver, B.C., SAE Paper 710673, 13 pp., August 16-19, 1971.

17. Sharp, F., Personal Communications, MSHA, Bruceton, PA, 1978.

18. Effect of Humidity of Air on Nitric Oxide Formation in Diesel Exhaust, Coordinating Research Council, Inc., No. 447, p. 18, New York, December 1971.

APPENDIX
DIESEL ENGINE TEST DATA

ENGINE B4

TEST NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	AVERAGE
RPM	1700	2500	2500	2544	2570	2594	2500	2500	2500	2300	2300	2300	2300	2000	2000	2000	2000	1700	1700	1700	
PERCENT LOAD	25	100	100	75	50	25	75	50	25	100	75	50	25	100	75	50	25	100	75	50	
FUEL/AIR	.014	.044	.045	.034	.026	.018	.034	.025	.017	.043	.032	.023	.016	.041	.031	.022	.014	.040	.030	.021	
NO (gm/bhphr)	6.8	2.5	2.4	3.4	4.4	5.8	3.4	4.2	5.8	2.5	3.3	4.2	6.0	2.5	3.2	4.3	6.4	2.5	3.4	4.5	4.1
CO_2 (Gm/bhphr)	714	572	573	567	606	782	557	600	770	583	548	569	746	541	541	563	741	547	542	562	610
CO (gm/bhphr)	3.2	1.2	1.1	1.0	1.5	3.1	1.0	1.6	3.2	1.2	1.1	1.6	3.3	.8	1.1	1.6	3.4	.8	1.1	1.7	1.7
TORQUE (100-percent load)		151	151							156				159				159			
HORSEPOWER	12.8	71.8	71.8	54.6	37.3	18.8	53.7	36.2	18.1	68.5	51.3	34.6	17.3	60.7	45.6	30.6	15.0	51.6	38.8	26.0	

ENGINE F4

TEST NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
RPM	2306	2200	2200	2200	2000	2000	2000	2000	1800	1800	1800	1800	
PERCENT LOAD	25	80	50	25	100	80	50	25	100	80	50	25	
FUEL/AIR	.020	.039	.028	.019	.049	.038	.025	.018	.049	.038	.026	.017	
NO (gm/bhphr)	6.6	5.4	6.7	7.0	3.9	5.4	6.9	6.9	3.7	5.2	7.3	7.3	6.0
CO_2 (Gm/bhphr)	1107	690	779	1093	654	656	735	999	622	627	676	928	800
CO (gm/bhphr)	6.5	1.0	1.7	5.1	.8	1.0	1.6	3.3	.8	1.0	1.6	3.2	2.3
TORQUE (100-percent load)					259				272				
HORSEPOWER	27	81	51	25	99	79	49	25	93	74	46	23	

ENGINE E6

TEST NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
RPM	2200	2200	2200	2200	2000	2000	2000	2000	2200	2287	2313	2332	
PERCENT LOAD	100	75	50	25	100	75	50	25	100	100	100	100	
FUEL/AIR	.052	.037	.028	.020	.050	.036	.026	.017	.052	.039	.030	.021	
NO (gm/bhphr)	3.0	5.3	6.8	7.3	2.9	5.2	7.1	7.5	3.0	5.4	6.6	7.3	5.6
CO_2 (Gm/bhphr)	722	714	794	1147	693	666	730	1018	720	752	815	1152	830
CO (gm/bhphr)	1.6	1.1	1.7	5.2	1.2	1.1	1.7	5.1	1.6	1.1	1.7	5.1	2.4
TORQUE (100-percent load)	338				352				338	254	169	85	
HORSEPOWER													

ENGINE B6

TEST NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	AVERAGE
RPM	2500	2550	2575	2584	2500	2500	2500	2300	2300	2300	2300	2000	2000	2000	2000	1700	1700	1700	1700	
PERCENT LOAD	100	75	50	25	75	50	25	100	75	50	25	100	75	50	25	100	75	50	25	
FUEL/AIR	.046	.034	.025	.018	.034	.024	.017	.045	.033	.023	.016	.044	.032	.022	.015	.043	.032	.023	.015	
NO (gm/bhphr)	2.6	3.3	4.4	5.9	3.4	4.3	5.3	2.5	3.2	4.3	5.8	2.4	3.3	4.3	6.3	2.4	3.2	4.7	6.6	4.1
CO_2 (Gm/bhphr)	616	608	658	913	618	646	849	597	574	616	805	568	565	590	769	560	543	572	750	650
CO (gm/bhphr)	1.6	1.6	1.6	3.2	1.6	1.6	3.3	1.2	1.6	1.6	3.2	1.1	1.0	1.6	3.3	1.1	1.0	1.5	3.2	1.9
TORQUE (100-percent load)	217							234				237				238				
HORSEPOWER	103.4	79.4	53.2	27.1	77.9	51.7	26.2	102.0	77.2	51.3	25.9	90.2	67.7	45.1	22.6	77.1	58.0	38.8	19.2	

ENGINE D8TA1

TEST NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	AVG.
RPM	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100	2000	2000	2000	2000	2000	1900	1900	1800	1800	1800	1800	1800	1600	
PERCENT LOAD	100	95	89	84	79	68	63	53	42	32	100	65	54	43	33	100	91	100	63	60	48	36	100	
FUEL/AIR	.037	.036	.035	.034	.034	.033	.031	.029	.027	.024	.038	.033	.031	.028	.025	.038	.036	.037	.034	.032	.030	.027	.038	
NO (gm/bhphr)	4.8	4.9	5.0	5.0	5.1	5.3	5.5	6.0	6.7	7.9	4.7	5.4	5.9	6.7	8.1	4.6	4.8	4.9	5.5	5.5	6.6	7.9	4.6	5.7
CO_2 (Gm/bhphr)						572	592	617	660	713		583	605	641	695				581	588	616	648		620
CO (gm/bhphr)						.5	.6	.6	.7	.8		.5	.6	1.3	1.6				1.0	.5	.6	1.4		0.8
TORQUE (100-percent load)	1187										1208					1216		1225					230	
HORSEPOWER	475	450	425	400	375	325	300	250	200	150	460	300	250	200	150	440	400	420	265	250	200	150	375	

ENGINE E6TA

TEST NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	AVG.
RPM	2200	2200	2200	2200	2000	2000	2000	2000	1900	1900	1900	1900	1800	1800	1800	1800	1600	1600	1600	1600	2250	2282	2301	
PERCENT LOAD	100	75	50	25	100	75	50	25	100	75	50	25	100	75	50	25	100	75	50	25	75	50	25	
FUEL/AIR	.041	.037	.032	.022	.043	.039	.034	.023	.044	.038	.031	.024	.044	.041	.035	.023	.047	.043	.036	.023	.035	.032	.023	
NO (gm/bhphr)	5.0	5.4	6.0	7.1	4.7	4.9	5.2	7.0	4.5	4.7	5.4	6.8	4.3	4.4	4.9	6.4	3.7	3.7	4.2	6.5	5.5	6.2	6.8	5.4
CO_2 (Gm/bhphr)	563	564	587	728	556	540	514	666	543	543	548	651	541	543	543	638	550	562	553	618	578	613	757	590
CO (gm/bhphr)	.4	.5	.6	1.9	.4	.4	.5	1.7	.8	.4	.5	1.7	.4	.4	.5	1.7	.7	.4	.5	1.6	.5	.6	2.0	0.8
TORQUE (100-percent load)	628				684				698				711				730							
HORSEPOWER	263	197	132	66	260	195	130	66	252	189	126	63	244	183	122	61	222	167	111	56	187	135	69	

ENGINE A6

TEST NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	AVG.
RPM	2409	2390	2365	2300	2300	2300	2300	2200	2200	2200	2200	2100	2100	2100	2100	2000	2000	2000	2000	1900	1900	1900	1900	
PERCENT LOAD	100	100	100	100	85	70	50	100	85	70	50	100	85	70	50	100	85	70	50	100	85	70	50	
FUEL/AIR	.025	.031	.036	.041	.036	.030	.024	.042	.036	.030	.024	.042	.037	.030	.024	.042	.036	.030	.023	.042	.037	.030	.023	
NO (gm/bhphr)	4.5	4.0	3.9	3.6	3.8	3.9	4.3	3.4	3.6	3.7	3.8	3.4	3.4	3.6	3.5	3.3	3.5	3.5	3.5	3.3	3.5	3.5	3.6	3.7
CO_2 (Gm/bhphr)	767	674	648	665	642	659	762	638	624	637	709	634	625	651	674	628	611	607	668	606	595	597	658	650
CO (gm/bhphr)	1.8	1.3	1.1	.9	1.1	1.3	1.9	.9	1.0	1.3	1.8	1.3	1.0	1.3	1.7	1.3	1.0	1.2	1.7	1.2	1.0	1.2	1.7	1.3
TORQUE (100-percent load)	154	216	262	307				313				319				327				330				
HORSEPOWER	71	98	118	135	115	94	67	131	111	92	65	127	108	89	64	125	106	87	62	119	101	84	59	

ENGINE A12

TEST NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	AVG.
RPM	2452	2433	2415	2300	2300	2300	2300	2100	2100	2100	2100	1900	1900	1900	1900	1700	1700	1700	1700	1500	1500	1500	1500	
PERCENT LOAD	100	100	100	100	75	50	25	100	75	50	25	100	75	50	25	100	75	50	25	100	75	50	25	
FUEL/AIR	.019	.026	.034	.044	.033	.024	.017	.044	.032	.025	.017	.042	.031	.023	.016	.042	.031	.023	.015	.043	.032	.023	.015	
NO (gm/bhphr)	7.2	5.9	5.0	3.8	4.8	5.3	6.9	3.7	4.4	4.8	5.8	3.7	4.5	4.3	5.5	3.6	4.0	3.9	4.8	3.3	4.3	4.1	5.0	4.7
CO_2 (Gm/bhphr)	1110	775	709	678	688	748	1106	629	636	712	997	605	631	698	940	587	584	633	868	568	565	584	800	730
CO (gm/bhphr)	3.6	1.8	1.2	1.3	1.2	1.8	3.7	.8	1.2	1.8	5.4	.9	1.2	1.8	5.6	.8	1.1	1.7	5.3	1.2	1.1	1.6	5.1	2.2
TORQUE (100-percent load)	151	300	450	599				620				619				649				684				
HORSEPOWER																								

ENGINE F4G1

TEST NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	AVERAGE
RPM	2200	2239	2278	2299	2200	2200	2200	2000	2000	2000	2000	1800	1800	1800	1800	
PERCENT LOAD	100	80	50	25	80	50	25	100	80	50	25	100	80	50	25	
FUEL/AIR	.053	.044	.031	.021	.042	.030	.020	.057	.042	.028	.019	.055	.041	.027	.018	
NO (gm/bhphr)	4.1	5.9	5.5	4.2	5.8	4.8	4.0	3.6	5.6	5.2	3.8	3.4	5.6	5.5	3.9	4.7
CO_2 (Gm/bhphr)	661	669	731	972	633	693	957	646	636	661	858	626	606	622	826	720
CO (gm/bhphr)	1.8	2.2	8.6	20.1	2.7	8.8	20.8	2.1	2.6	8.5	18.7	2.0	2.6	8.3	17.0	8.5
TORQUE (100-percent load)	269							285				298				
HORSEPOWER	113	92	59	30	90	57	28	108	87	54	27	102	82	51	26	

☆ U.S. GOVERNMENT PRINTING OFFICE:1980--657-147/1044

DEPARTMENT OF HEALTH AND HUMAN SERVICES
PUBLIC HEALTH SERVICE
CENTER FOR DISEASE CONTROL
NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH
ROBERT A. TAFT LABORATORIES
4676 COLUMBIA PARKWAY, CINCINNATI, OHIO 45226

DHHS (NIOSH) Publication No. 80-146