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Study of the Effects of Reduced Diesel Fuel Sulfur Content on Engine Wear

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by

Edwin A. Frame
Ruben A. Alvarez
Norman R. Sefer

Southwest Research Institute
6220 Culebra Road
San Antonio, Texas 78284

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EPA Project Officer: Craig A. Harvey

Prepared for

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FOREWORD

This project was conducted for the U.S. Environmental Protection Agency by the Division of Fuels and Lubricants Research, Southwest Research Institute. The project was to complete Task 4 as authorized by Work Assignment B-1 under Contract 68-03-3353. Work was initiated September 2, 1986, and completed in June 1987. It was identified within Southwest Research Institute as Project 08-1193-001. The EPA Project Officer was Mr. Craig A. Harvey, and the Branch Technical Representative was Mr. Timothy Sprik, both of the Emission Control Technology Division, Ann Arbor, Michigan. The SwRI project team included Mr. Edwin A. Frame, Mr. Ruben A. Alvarez, and Ms. Margaret B. Millikin. Mr. Norman R. Sefer was project manager and was involved in the initial technical and fiscal planning.

ABSTRACT

The study evaluated wear in heavy-duty highway-type engines for reduction of sulfur content of diesel fuel in the range of 0.50 weight percent to 0.05 weight percent. A literature review found that wear rates generally were reduced by decreasing fuel sulfur content. The amount of wear reduction was affected as much by operating temperature and engine load as by sulfur in the fuel. Low operating temperatures showed more wear at high sulfur levels and, therefore, more benefit for low sulfur fuels. Increasing engine load caused higher wear rates independent of sulfur content. Lubricant alkalinity (Total Base Number) is effective in controlling corrosive wear at high sulfur levels and reduces the potential wear benefit from low sulfur diesel fuel. Lubricating oil analyses from fleets operating on diesel fuel with less than 0.05 weight percent sulfur were compared with previous data when average sulfur content was 0.35 weight percent. Overall, a significant reduction in engine wear occurred in most engine types as measured by iron content of used oil. Most of the reduction can be attributed to the low sulfur fuel, with minor contributions from changes in the lubricating oils.

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SUMMARY

The effect of diesel fuel sulfur content on wear in heavy-duty highway diesel engines was studied in a two-phase approach. In the first phase, a literature review investigated the role of sulfur content in engine wear as affected by engine operating conditions and lubricating oil quality. Information was also obtained from diesel engine manufacturers. In the second phase, data were obtained from four fleets in Southern California operating on diesel fuel containing less than 0.05 weight percent sulfur. Sulfur content of diesel fuel was controlled at that level by regulation effective January 1, 1985, in the South Coast Air Basin which includes Los Angeles, Orange, Riverside, and San Bernardino Counties. Diesel fuel and used lubricating oil analyses before and after the change were compared in a statistical evaluation.

Fuel sulfur content effects on corrosive engine wear were reported extensively in the literature. Data obtained with modern engines and lubricants were the most applicable, particularly in the 0.50 to 0.05 weight percent sulfur range. The main findings were:

- Reduction of fuel sulfur content results in less engine wear at some conditions.
- Wear reduction is greater below the normal operating temperature of about 175°F. Therefore, the benefit for low sulfur fuel depends on the amount of time the engine would operate below normal temperatures.
- Higher engine load increases the amount of wear, independent of sulfur content.
- Operating temperature, engine load, and fuel sulfur content appear to be equal in importance as factors in engine wear.
- Lubricating oil alkalinity (Total Base Number) controls engine wear at high sulfur levels and reduces the potential wear benefits from low sulfur fuel.
- Lower sulfur fuel may allow longer oil change intervals by less TBN depletion if other oil contaminants are not controlling oil changes.
- Reduction in engine wear from low sulfur fuel may not extend life if other failure modes are controlling the need for engine overhaul.

Data from one fleet showed that average sulfur content of diesel fuel was 0.35 weight percent in 1984 and 0.03 weight percent in 1985-1986. Other fleets analyzed only lubricating oil. The data showed a significant decrease in iron content in the used oil for most engine types between the 1984 and 1985-1986 periods. Most of the wear reduction can be attributed to the lower sulfur diesel fuel. However, there were changes in the new lubricating oils (TBN alkalinity and zinc anti-wear additive) which could be minor contributors to the reduction in wear metal. Some engines showed no reduction or an increase in iron levels after the change in fuel sulfur content.

1. INTRODUCTION

1.1 Background

A study prepared for EPA by Energy and Resource Consultants, Inc. (ERC) investigated the effect of diesel fuel sulfur content on engine wear.(1)* ERC concluded that a reduction of diesel fuel sulfur content from 0.27 to 0.05 weight percent would result in a 30 to 40 percent reduction in engine wear and therefore a 30 to 40 percent increase in engine life and oil drain interval. These conclusions were based primarily on the results of a study by Tennyson and Parker presented in SAE Paper No. 700892 (2), which was conducted in a two-cycle locomotive engine. However, today's engine oils have additive packages which are better able to handle the corrosive wear from fuel sulfur, and some uncertainty exists in extrapolating the locomotive engine results to on-road diesel operations. A further investigation was initiated into the effects of low-level diesel fuel sulfur content on engine wear.

1.2 Objective

The objective of this work was to determine the overall magnitude of the effect of diesel fuel sulfur content on the wear of heavy-duty diesel engines in on-road service, on engine life, and on oil drain intervals. The range of fuel sulfur levels of interest are from 0.05 weight percent to current U.S. levels (approx. 0.3 weight percent).

1.3 Approach

The approach included the following work areas:

1. A literature review was conducted to develop an understanding of the role of diesel fuel sulfur content in the wear of heavy-duty on-road diesel engines. The effects of engine operating conditions on wear were also investigated, and the effects of engine oil additives and oil alkalinity (TBN) were examined.
2. Major U.S. diesel engine manufacturers were contacted for their recommendations regarding operation on low and high sulfur diesel fuels.
3. As an empirical check on the literature study, diesel fleets which are currently operating on 0.05 weight percent sulfur fuel were contacted to obtain used oil analyses. This effort was concentrated in the Southern

* Underscored numbers in parentheses refer to the list of references at the end of this report.

California area, which has undergone a legislated reduction in diesel fuel sulfur content to 0.05 weight percent maximum. Comparison was made of used oil analyses prior to sulfur reduction with those obtained after the reduction to determine the effect of fuel sulfur reduction on engine wear.

2. LITERATURE REVIEW

2.1 Introduction

In examining the effect of diesel fuel sulfur content on engine wear, it is advantangeous to use a systems approach. Diesel engine wear is a very complex event which includes interactions of the following system variables:

- fuel properties (e.g., sulfur content)
- lubricant properties (e.g., alkalinity content)
- engine design and materials
- engine operating conditions

The literature search was designed to obtain information on 1) fuel sulfur effects, 2) lubricant alkalinity effects, and 3) engine operating conditions on high-speed diesel engine wear. Engine design and materials considerations were beyond the scope of this investigation and were not included in the search.

The following five computerized data bases were searched:

1.	SAE Global Mobility	1968 - 1986
2.	NTIS	1964 - 1986
3.	Compendex	1970 - 1986
4.	Chemical Abstracts	1967 - 1986
5.	DOE Energy	1974 - 1986

In addition, SwRI files on fuel sulfur effects were examined. Overall, a large body of information on fuel sulfur effects in high-speed diesel engines was found. Several publications with data in the fuel sulfur range of interest were found which were not included in the ERC report. In the following sections, a general overview of fuel sulfur effects on high-speed diesel engine wear and deposits is presented for fuels in the range of zero to 2 weight percent sulfur. This brief summary documents the fuel sulfur content/engine wear relationship, and is followed by a detailed discussion of data in the zero to 0.3 weight percent fuel sulfur range. Detailed discussions are also presented for the effects of operating conditions and lubricant alkalinity (TBN) on diesel engine wear.

2.2. Discussion of Literature

2.2.1 General Diesel Fuel Sulfur Effects

One of the early considerations of fuel sulfur effects was presented in Ricardo's 1933 lecture in which he proposed that much cylinder wear was corrosive and related to fuel sulfur content.(3) During the 1940's, several researchers reported on the detrimental effects of sulfur compounds in diesel fuel. Cloud and Blackwood (1943) used both cyclic and steady-state 80-hour engine test procedures in a Detroit Diesel 3-71, Caterpillar single-cylinder, and Hercules 6-cylinder to determine the effects of diesel fuel sulfur content on deposits and wear.(4) They reported that an increase in fuel sulfur from 0.2 to 1.0 weight percent resulted in a two to sixfold increase in measured piston ring wear, and a two to fourfold increase in cylinder bore wear. A 40 to 80 percent increase in ring zone deposits was observed, as well as increased ring sticking. Cloud and Blackwood concluded that fuel sulfur type was relatively unimportant as fuels containing naturally occurring and added sulfur (carbon disulfide and diamyl trisulfide) produced about the same level of engine distress. Increased wear and fouling were also caused by the addition of small amounts of SO_2 to the intake air of a fired engine. Addition of SO_3 to the intake air of a motored engine caused dramatic increases in ring wear and deposits. Finally, they reported that 60 to 90 percent of the fuel sulfur was converted to SO_3 during the combustion process.

In 1947, Moore and Kent determined the effect of fuel sulfur content on single-cylinder diesel engine (Caterpillar) wear by using crankcase used oil iron content as an indication of wear.(5) Fuels containing natural sulfur (0.7 weight percent) and sulfur added as thiophene (0.7 weight percent sulfur) produced a four to fivefold increase in iron wear metals compared to the low sulfur baseline. A fuel with 1.3 percent sulfur present as thiophene gave a sevenfold increase in iron wear metals. They also reported that reducing engine coolant temperature from 160°F (71°C) to 100°F (37°C) caused a fourfold increase in wear when using fuels with no sulfur present.

Also in 1947, Blanc of Caterpillar Tractor Co. reported that experiments in a single-cylinder Caterpillar engine showed that as fuel sulfur content increases, ring and cylinder bore wear (top) and piston deposits increase.(6) When the sulfur content of the fuel is increased above 0.5 percent, the pistons become progressively dirtier, the ring grooves pack with carbon, and the rings become more sluggish. With sulfur content greater than 1.0 percent, stuck rings become common. Blanc reported that distillation range of high sulfur fuels was found to affect deposits somewhat, but not to the extent that fuel sulfur content impacted on deposits.

In 1948, Gadebusch reported that fuel sulfur content alone is not satisfactory for predicting engine deposits. He found that a fuel blend of straight run and catalytically cracked materials which contained 0.6 weight percent sulfur gave more deposits than a straight run fuel with a sulfur content of 1.15 weight percent.(7) Cattaneo and Starkman (1948) reported that ring wear increased threefold in going from zero to 1.0 weight percent fuel sulfur and that basic material in the engine oil significantly reduced the wear.(8) Furstoss (1949) investigated field experience involving small-bore medium-speed diesels using high-sulfur fuel and reported that operation on fuel with greater than 0.5 weight percent sulfur resulted in abnormal upper cylinder and ring wear with increased engine deposits.(9) Also in 1949, Broeze reported that cylinder bore wear increased twofold and ring wear increased threefold when fuel sulfur was increased from 0.08 to 1.5 weight percent.(10) In experiments with a Pyrex window in the combustion chamber, Broeze observed that increased fuel sulfur content caused increased lacquer deposits.

After the excellent research of the 1940's, very little information was published the next 20 years on high-sulfur fuel usage effects in high-speed diesel engines. In 1974 Perry and Anderson of the U.S. Navy reported on the effects of increasing the sulfur content of diesel fuel marine (DFM).(11) They found during 1000-hour tests that in going from 1.0 to 1.3 weight percent fuel sulfur (all naturally occurring), top compression ring wear increased by a factor of 2.5, and more ring sticking occurred in both two- and four-cycle diesel engines.

U.S. Army research on high-sulfur fuel utilization was reported by Lestz, LePera, and Bowen in 1976.(12) Using a cyclic operating procedure in an aluminum block two-cycle diesel engine, they found severe increases in fire ring (1.4 to sixfold) and bore wear (zero to three fold) when comparing reference fuel (0.4 percent sulfur) with fuels containing 0.64 and 1.2 weight percent naturally occurring sulfur. Higher lubricant ash content helped in controlling fire ring and bore wear; however, more ring sticking occurred with the higher ash oil. In this work, greater engine distress was consistently observed with the 0.64 weight percent sulfur fuel than with the 1.2 weight percent fuel. This greater distress led the authors to speculate that other fuel components present such as olefinic compounds, oxygenated compounds, naphthenic acids, and pyrrole nitrogen were contributing to the increased wear.

In 1978, Frame reported that in going from 0.4 to 1.0 weight percent naturally occurring fuel sulfur, fire ring wear increased fourfold and liner scuffing increased five to tenfold in a two-cycle diesel engine.(13) No change in engine deposits accompanied the fuel sulfur increase in this work.

Gergel (1980), reported on modified Cat 1-G2 tests run with fuel containing 1.4 weight percent sulfur, with the additional sulfur added as tertiary butyl disulfide.(14) In these tests, which were run without the standard oil drains, piston top groove deposit filling remained the same while weighted total piston deposit rating (WTD) increased threefold; and top ring wear, as determined by weight loss, increased twenty-four fold when the high sulfur fuel was used. Recent work on fuel sulfur effects has been reported by McGeehan. In 1982 McGeehan found, as Gergel had earlier, that fuel sulfur content has very little effect on high temperatures (200° to 260°C) piston top groove deposits in a single-cylinder supercharged Caterpillar engine.(15) In these experiments, fuel sulfur content was increased by adding tertiary butyl disulfide to the base fuel. Total piston deposits increased overall with the higher sulfur fuel due to increased lower area piston deposits at temperatures of 120° to 190°C. In 1983 McGeehan published results of research covering the effects of fuel sulfur content on diesel engine bore polishing.(16) He found in going from 0.2 to 1.0 percent fuel sulfur, bore polishing increased two to threefold in the Mack T-6 600-hour test, and sixfold in the 200-hour Ford Tornado test. Finally, in 1985 Frame reported a two to threefold increase in used oil iron content when going from zero to 1.0 weight percent fuel sulfur in a single-cylinder 4-cycle diesel engine operated at 180°F coolant out temperature.(17) In this work an unformulated lubricant was used to isolate fuel effects and to eliminate acid neutralization by the lubricant.

In summary, fuel sulfur content has been shown to be directly related to engine wear at all fuel sulfur content levels. While many factors such as operating conditions and lubricant quality impact on engine wear, the effect of fuel sulfur content on engine wear is great. In general, for each additional one percent of fuel sulfur content, (e.g., 0.3 to 1.3 percent sulfur), ring and cylinder bore wear increased approximately eightfold and fourfold, respectively. Also, increased fuel sulfur content generally led to additional piston deposits and often even to ring-sticking. Most of the above references covered fuel sulfur effects which went beyond the range of current EPA interest. In the following section, research results in the fuel sulfur range of EPA interest (0.05 - 0.3 weight percent sulfur) are examined in detail. Diesel fuel sulfur effects in the 0.05 - 0.3 weight percent range are compared with effects in other sulfur ranges of the same magnitude.

2.2.2 Low-Sulfur Diesel Fuel Effects

The literature review revealed several publications which contained engine wear data in the zero to 0.3 weight percent sulfur range. Only data which had at least one actual data point in the zero to 0.3 weight percent sulfur range were considered. Extrapolations of data from higher sulfur ranges were not considered. Each cited result will be analyzed in terms of its applicability to current lubricants and on-road, heavy-duty diesel engines.

Cattaneo and Starkman (1948) reported on the effect of fuel sulfur content on measured ring weight loss, while operating at a coolant temperature of 210°F.(8) Their results are plotted in Figure 1, from which it was calculated that in going from 0.3 to zero weight percent sulfur, ring wear (weight loss) decreased 37 percent. While this wear decease is large on a percentage basis, the absolute ring wear rate at 0.3 weight percent sulfur was below 2 mg/HR. The Cattaneo and Starkman data did not specify the engine type, number of cylinders, speed, or load. In addition, the type and properties of the lubricant used are unknown; however, at best the oil would be 1948 vintage, and not of the quality of current engine oils. Because of the above mentioned unknowns, applicability of these results to current diesel engine wear is questionable. It is interesting to note that the wear curve appears to be approximately linear over all sulfur ranges up to 1.4 weight percent sulfur.

Moore and Kent (1947) conducted their work in a single-cylinder Caterpillar diesel engine operating at 75 BMEP, 160°F coolant out temperature (COT), and used a formulated, commercial heavy-duty engine oil.(5) As shown in Figure 2, total engine wear in mg/60 HR as determined by used oil analyses decreased by 43 percent in going

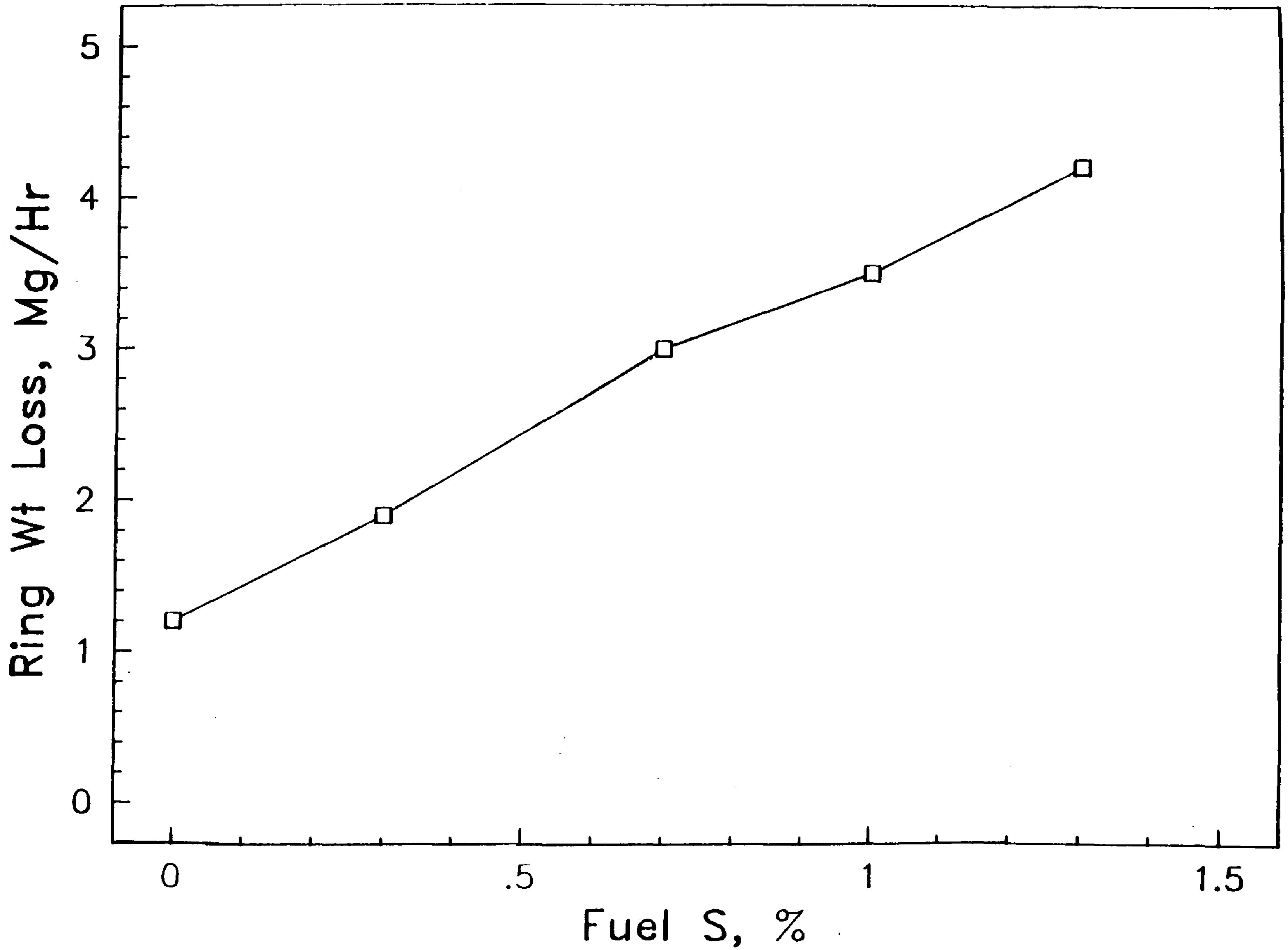

Figure 1. Effect of fuel sulfur content on piston ring wear (10)

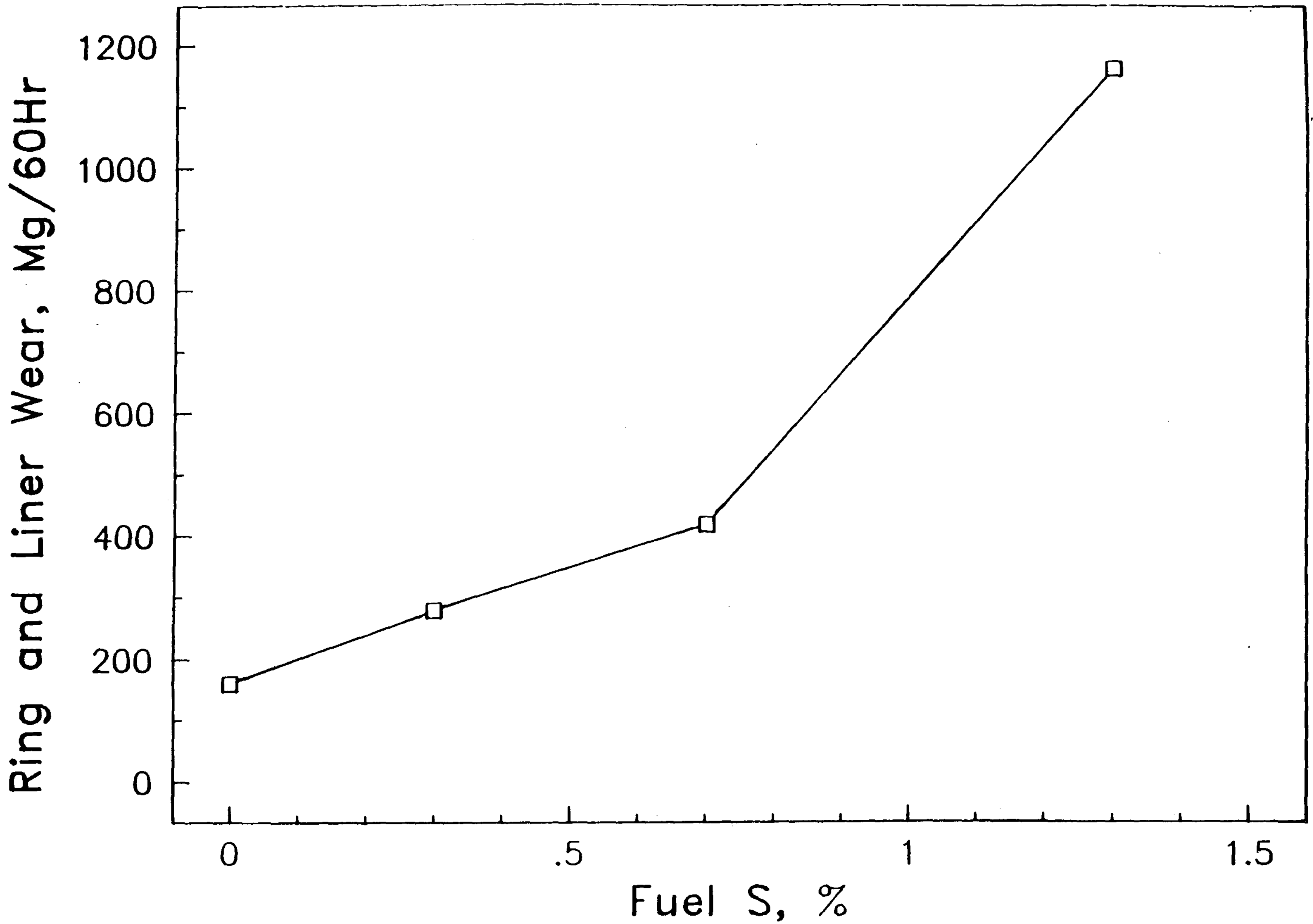

Figure 2. Effect of fuel sulfur content on engine wear (5)

from 0.3 to zero weight percent fuel sulfur. In this work, the wear rate increased above 0.7 weight percent fuel sulfur.

Broeze and Wilson (1949), used a single-cylinder Caterpillar diesel engine operated at 75 BMEP, with a COT of 140°F.(10) Their results show virtually no difference in cylinder bore wear for fuels in the zero to 0.5 weight percent sulfur range as shown in Figure 3. Bore wear started to increase substantially with fuels which contained greater than 1.0 weight percent sulfur. While the lubricant used in this work was not described, the fact remains that no decrease in bore wear was observed from 0.5 to zero weight percent fuel sulfur.

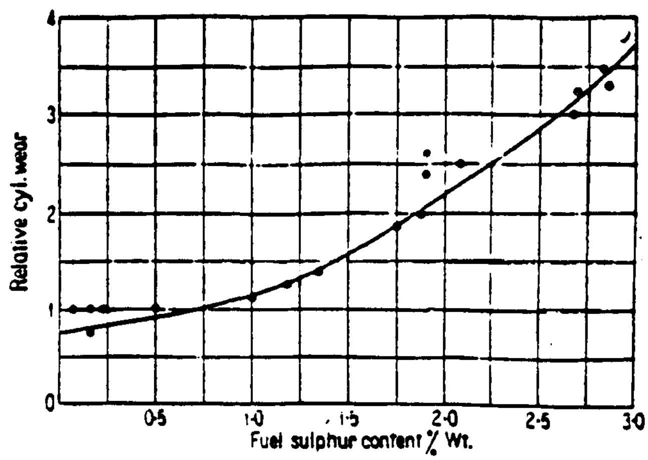

Figure 3. Effect of fuel sulfur on cylinder bore wear (10)

Malyavinskii and Chernov (1958), examined fuel sulfur effects in high-speed Russian diesel engines, using a formulated engine oil.(18) The engine oil met Soviet specification GOST 5304-50. The TBN of the new oil was not stated and how GOST 5304-50 compares to API service classifications is not known. COT was not stated. As shown in Figure 4, a reduction of fuel sulfur from 0.3 to 0.2 weight percent would result in approximately a 10 percent decrease in relative cylinder liner wear as determined by used oil analyses extrapolated to 1000 hours. Figure 5 shows results in a different engine using the same oil fortified with a supplement anti-corrosion additive. In this case a reduction of 5 percent in cylinder liner wear would be expected in going from 0.3 to 0.2 weight percent fuel sulfur.

Pinotti, Hull, and McLaughlin (1949), conducted wear tests in a single-cylinder diesel engine operating at 175°F COT and 150°F oil sump temperature.(19) Top

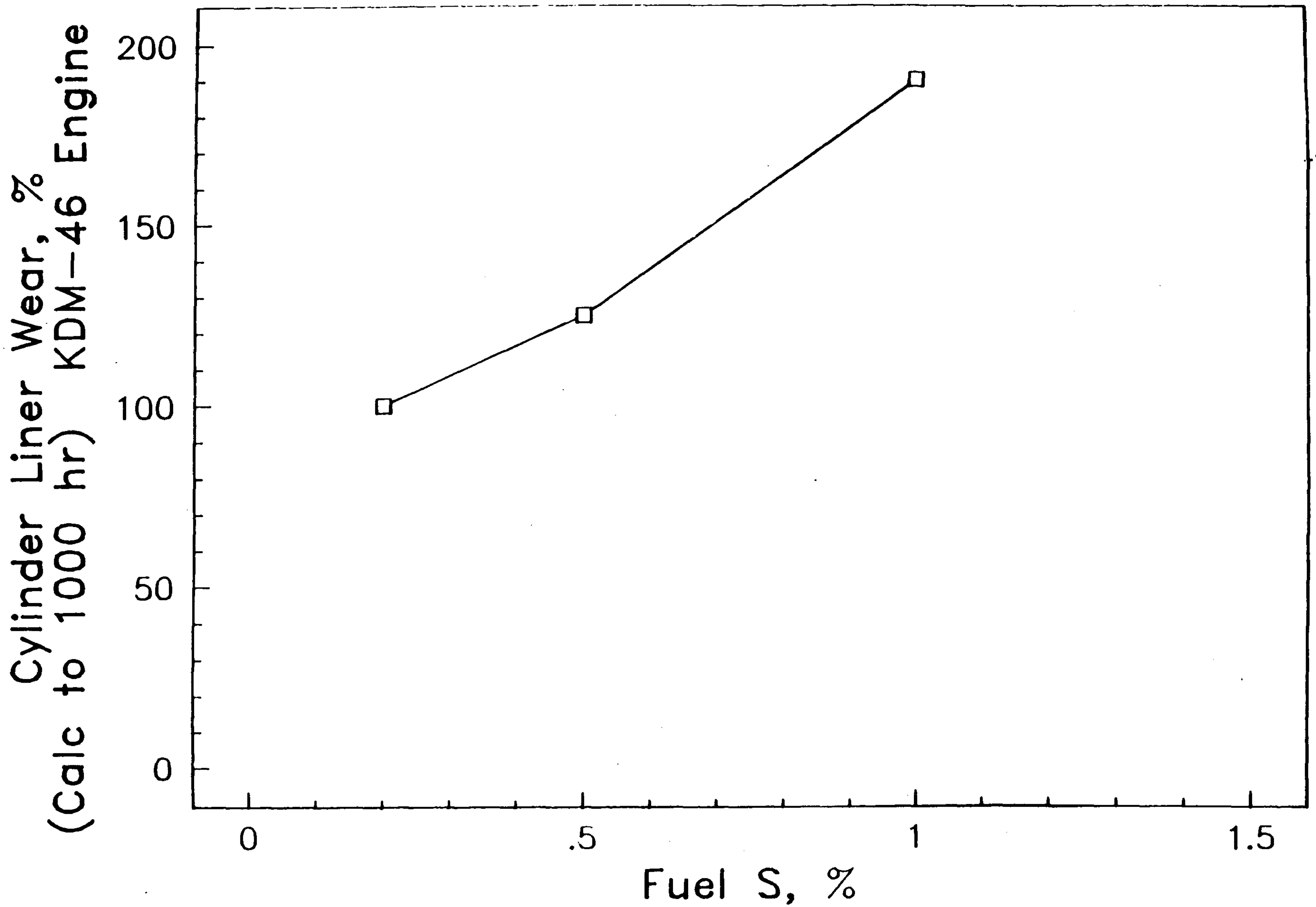

Figure 4. Effect of fuel sulfur content on cylinder liner wear with engine oil 1 (18)

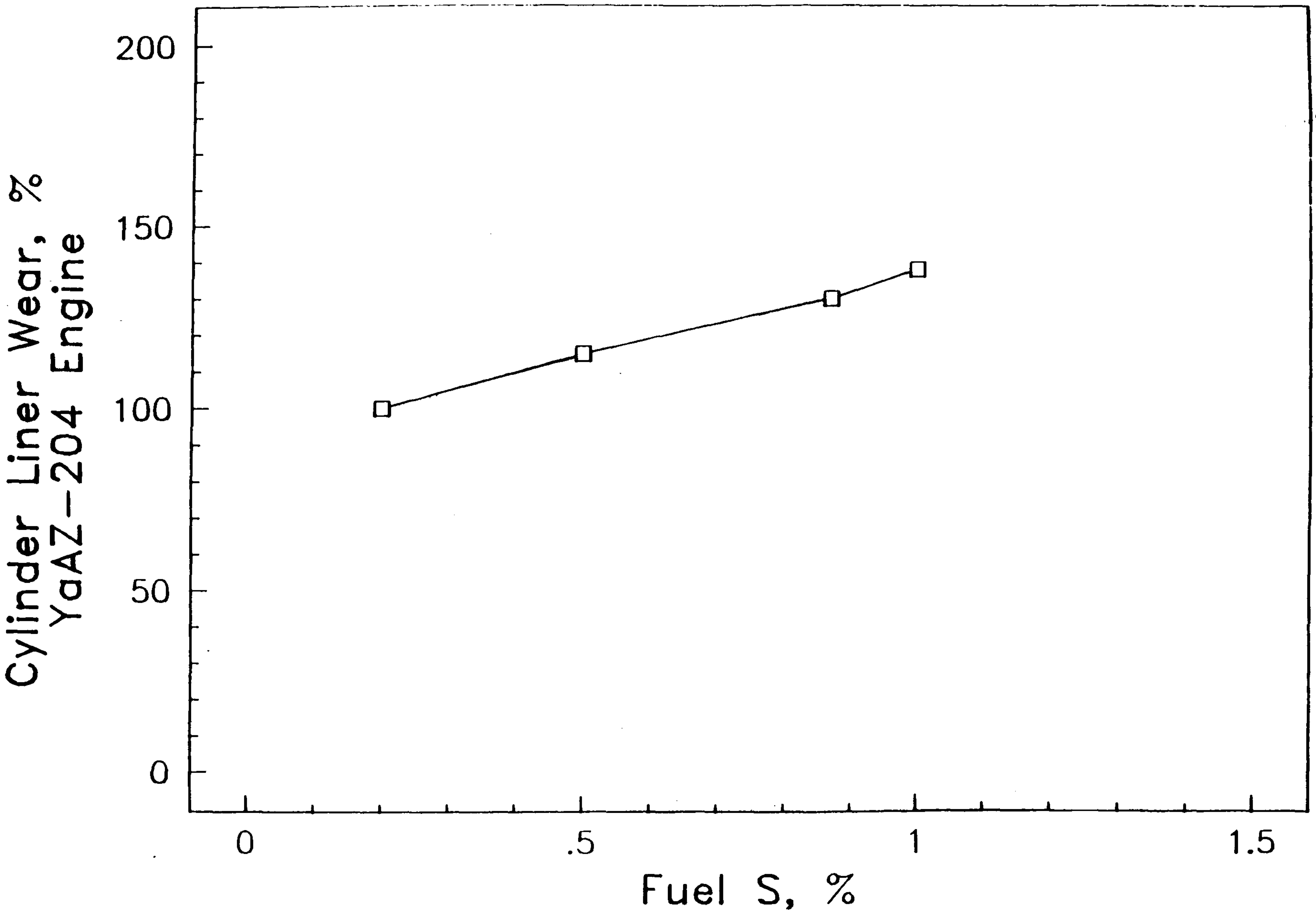

Figure 5. Effect of fuel sulfur content on cylinder liner wear, engine oil 1 with anti-corrosion additive (18)

compression ring wear was monitored by using an irradiated cast-iron ring. In going from 0.3 to 0.05 weight percent fuel sulfur, a 15 percent reduction in ring wear was observed (Figure 6). While the quality of oil used in obtaining Figure 6 data was not stated, the authors did publish results which reveal the relative ring wear performance of 1949 vintage engine oils:

Typical Wear Rates

	Iron Wear Rate, mg per hr.
Uncompounded Oil	1.81
Heavy-Duty Oil Meeting Army Ordnance 2-104B Spec.	1.06
Heavy-Duty Oil Meeting Caterpillar Tractor Series 2 Reqmts.	0.65

Fuel sulfur content used in obtaining these wear rates was not specified. The wear rate for uncompounded oil was similar to that reported by Cattaneo and Starkman (Figure 1) for 0.3 weight percent fuel sulfur.(8) The ring wear reported by Pinotti, et al., was linear over the range investigated. (0.05 - 1.2 weight percent sulfur.)

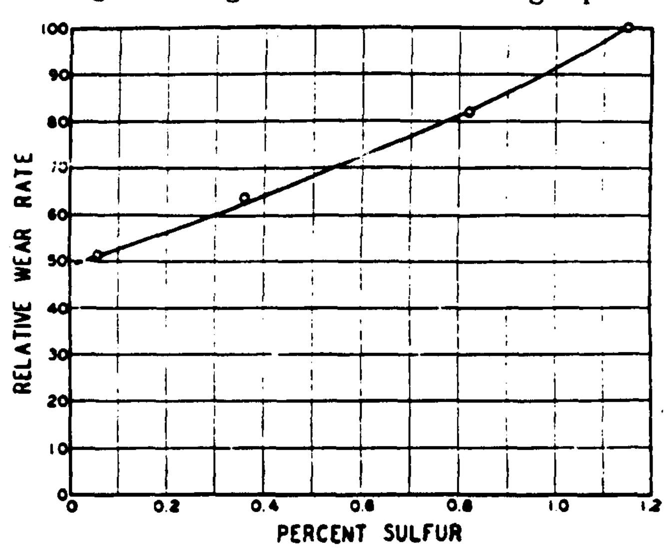

Figure 6. Relation between fuel sulfur content and ring wear, single-cylinder four-cycle engine, 4½-in. bore, 1400 rpm, 150°F oil sump temperature. 800°F exhaust temperature. 175°F jacket temperature.

Mercedes-Benz Truck Company, Inc. has provided EPA with data on fuel sulfur effects in a draft SAE paper.(20) A radionuclide technique was used to determine cylinder liner wear at various fuel sulfur levels and engine operating conditions. Wear tests were conducted in a four-cycle, direct injection, naturally aspirated V-8 diesel engine with one cylinder bore activated. The engine oil met API service classification SE/CC and was 20W-20 viscosity grade. The oil had be to be changed frequently to retain resolution of the measuring method; thus, TBN depletion effect could not be investigated. Wear tests were conducted at fuel sulfur contents of 1.2, 0.26 and 0.05 weight percent.

An empirical wear equation was developed and validated. The calculated wear rates for fuels in the range of zero to 0.5 weight percent sulfur are presented in Figure 7. These diagrams illustrate that a reduction in fuel sulfur level results in a substantial reduction in engine wear at COT below 80°C (176°F). Reduced corrosive wear during conditions typical of cold-start and warm-up was observed. For example, at 50°C (122°F) COT, an 80 percent reduction in cylinder bore wear rate was observed in going from 0.3 to 0.05 weight percent fuel sulfur. By 70°C (158°F), the reduction

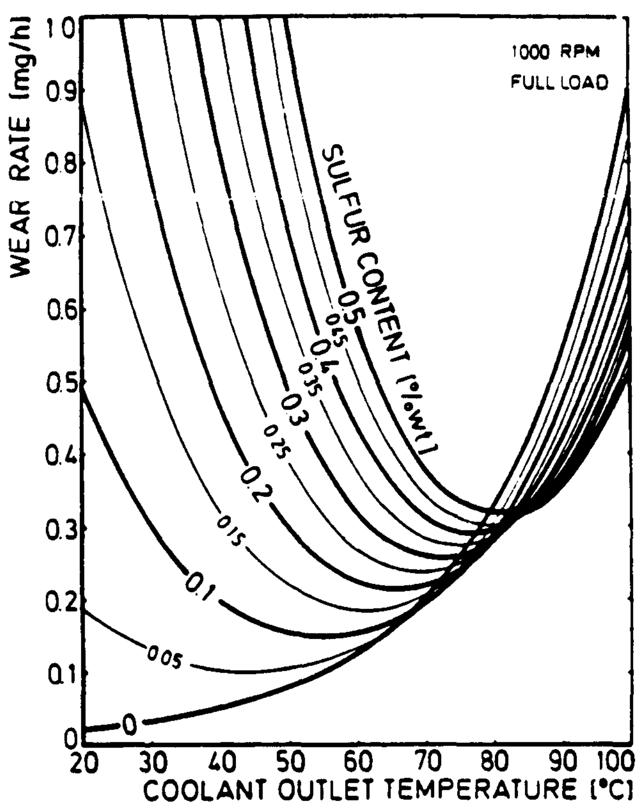

Figure 7. Wear rates with reduced sulfur content

was 28 percent and at approximately 80°C (176°F) the observed wear rate was the same for 0.3 and 0.05 weight percent fuel sulfur. Beyond 80°C (176°F), at higher than normal COT's (>80 to 85°C), fuels with very low sulfur content (0.05 weight percent) could cause a slight increase in wear rate. Of all the data reviewed, the Mercedes-

Benz results appear to be most directly applicable to current U.S. on-road, heavy-duty diesel engines. Still, current diesel engine oils are of slightly higher quality than API classification CC, and the Mercedes-Benz experiments did not include highly loaded turbocharged diesel engines. Both of these factors reduce the applicability of the Mercedes-Benz data to current U.S. conditions. In the following section, the effects of engine operating conditions on diesel engine wear will be discussed, and the overall importance of these effects in relation to fuel sulfur effects will be examined.

4.2.2.3. Operating Condition Effects

The effect of engine operating temperature, generally expressed as coolant out temperature (COT), on diesel engine wear has been extensively documented in the literature. Broeze and Wilson (10) documented an increase in piston ring and cylinder bore wear as COT was lowered, using both high and low sulfur fuels (Figures 8 & 9).

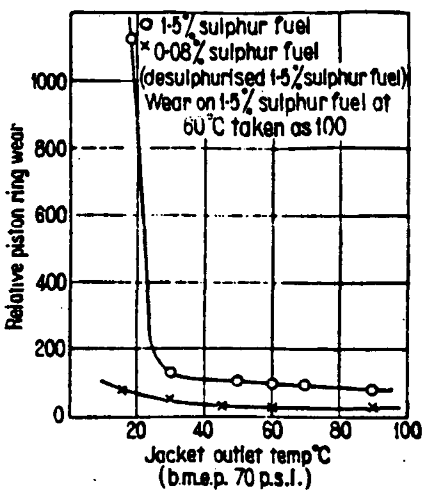

Figure 8. Effect of jacket temperature on piston ring wear with fuels of different sulfur content.

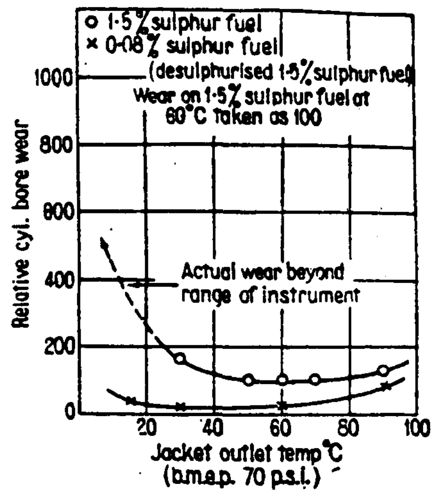

Figure 9. Effect of jacket temperature on bore wear with fuels of different sulfur content.

The observed ring wear increase was very slight for 0.08 weight percent fuel sulfur, and no bore wear increase was observed. Blanc (6) conducted single-cylinder Caterpillar engine tests using 1 weight percent sulfur fuel and observed the following increase in top ring wear at lowered COT:

COT, °F	175	100
Top ring gap increase, IN	0.028	0.045

Pinotti, et al. (19) also showed a substantial increase in iron wear rate at reduced COT (with unknown sulfur content of the fuel):

Jacket Temperature, °F	Load, %	Iron Wear Rate mg per hr
180	100	0.48
125	100	0.83

Nutt, Landen, and Edgar (1955), reported on the effect of engine jacket temperature on piston ring wear.(21) Their results, shown in Figure 10, show wear increasing below 150°F COT.

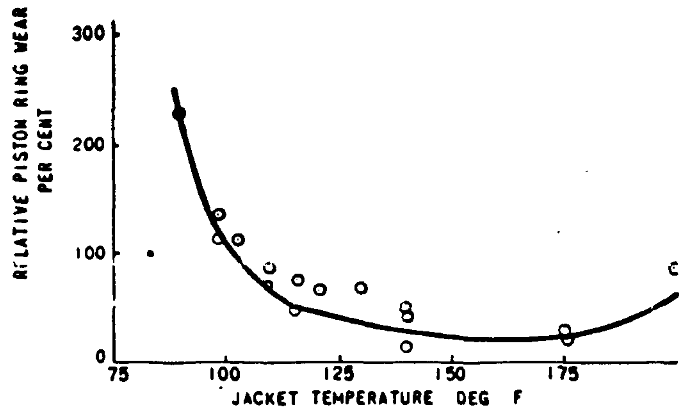

Figure 10. Piston-ring wear related to coolant temperature in a two-stroke diesel engine (unknown fuel S level)

Moore and Kent (1947), reported that when using 0.7 weight percent sulfur fuel (HSF), increasing the jacket temperature from 100 to 160°F decreased engine wear by a factor of nearly 4.5.(5) For a sulfur-free fuel (LSF), the decrease in wear going from 100 to 160°F jacket temperature was slightly less than a factor of 4 (Figure 11). In comparing the actual wear rates, Moore and Kent found the effect of low coolant temperature on the rate of wear was nearly as great as increasing fuel sulfur content by 0.7 weight percent sulfur.

Bolis, Johnson, and Daavetilla (1977) determined the effect of COT on top compression ring chrome face wear rate.(22) A radioactive tracer method was used to determine the ring wear rate of the Cummins VT-903 engine. The results are shown in Figure 12. Somewhat surprisingly, they have shown that ring wear increased with increasing COT, when using fuel with 0.23 weight percent sulfur. The authors offer the following explanation for these results:

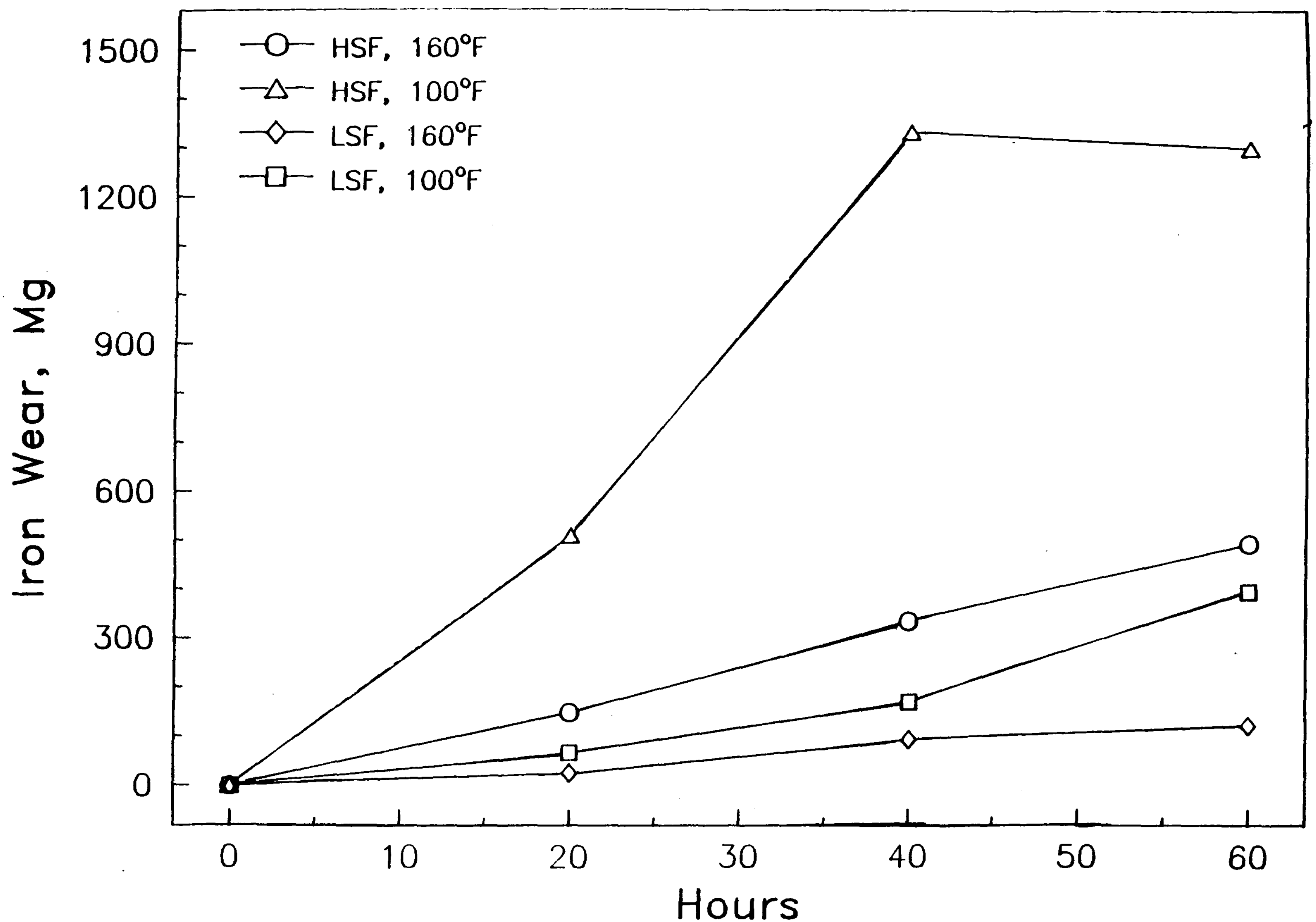

Figure 11. Effect of fuel sulfur content and jacket temperature on engine wear (5)

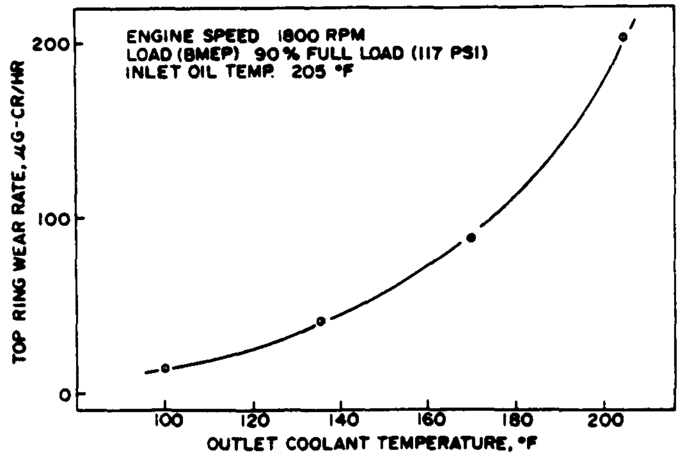

Figure 12. Top compression ring chrome face wear rates for Cummins VT-903, 1800 rpm, 90 percent load 205°F inlet oil temperature. 0.23 weight percent Fuel S.

> "The absence of corrosive wear in our tests indicates that probably some variation in diesel engine design and/or lubricants has shifted the corrosive wear range outside our region. Our engine was a turbocharged, non-aftercooled diesel which would have higher minimum cycle temperatures and pressures than would a similar naturally aspirated diesel. Other design factors may also play an important role in the negligible corrosive wear. It also widely recognized that lubricants have significantly improved in their alkalinity capacity during the past 15 years."

We believe the chrome ring was impervious to corrosive wear under the conditions and durations tested. The Mercedes-Benz data for a nonturbocharged engine (Figure 7) show that for a given fuel sulfur level, bore wear typically increases with decreasing COT below normal operating temperature and increases with increasing COT above normal operating temperature.(20) In general, engine wear can be expected to increase at COT below the normal operating range, with the effect being magnified by increased fuel sulfur content.

The effect of engine load on engine wear has also been documented in the literature. Increased load caused increased top ring wear at various COT as reported by Bolis, et al., and shown in Figure 13.(22) The Mercedes-Benz data (Figure 14) confirm the higher engine wear at increased load (BMEP and peak pressure).(20) At 83°C COT, the Benz data show load to be of greater importance to bore wear than fuel sulfur levels of 0.05 and 0.5 weight percent. Thus, increased engine load causes increased engine wear rate.

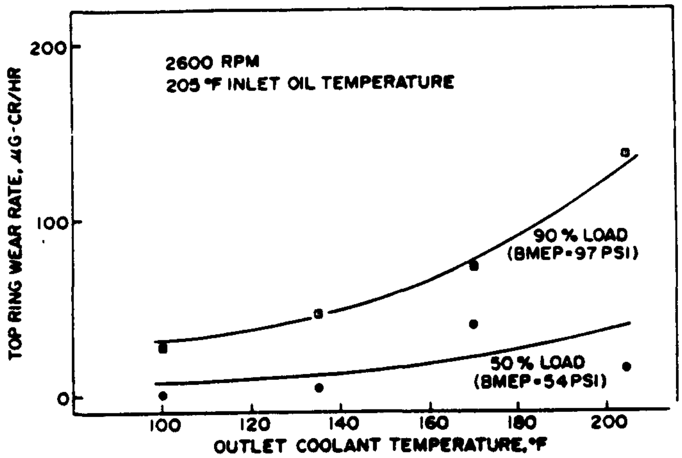

Figure 13. Effect of load on top ring wear rate as a function of outlet coolant temperature

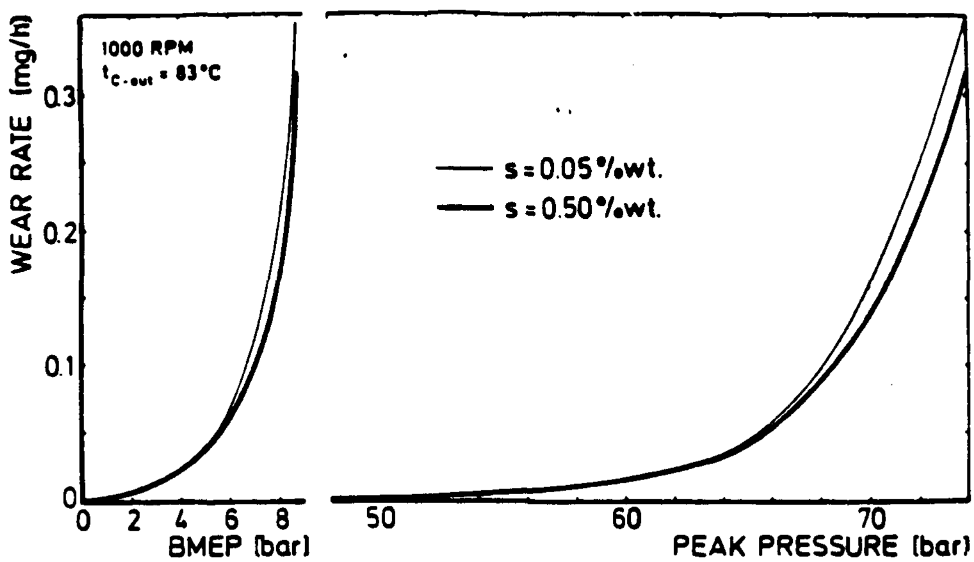

Figure 14. Effect of load (BMEP and peak pressure) on bore wear rate

2.2.4 Lubricant Alkalinity Effects

Lubricant alkalinity as measured by Total Base Number (TBN) expressed as mg KOH/g sample has long been recognized as important in controlling the deleterious corrosive effects of diesel fuel sulfur content. Ellis and Edgar (1953), demonstrated the reduction of low-temperature corrosive wear by using alkaline lube oil additives.(23) Figure 15 illustrates the effect of lubricant alkaline content on ring wear for both a two-stroke and four-stroke diesel engine. Figure 16 from the work of Nutt,

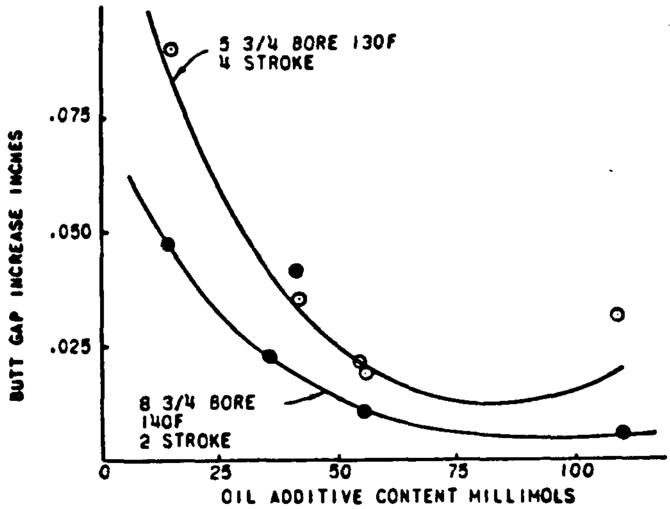

Figure 15. Low-temperature corrosive wear is reduced by use of alkaline lubricating oil additives. These tests were of 480-hr duration at water jacket temperatures of 130 and 140°F as noted.

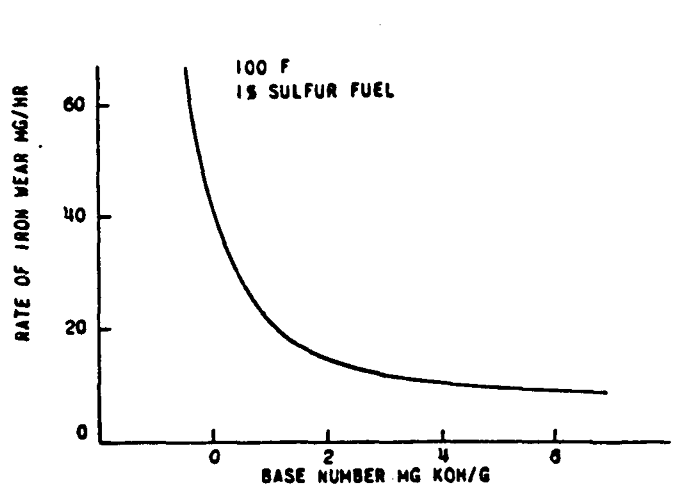

Figure 16. Corrosive wear is reduced through use of alkaline oil (indicated by base number) in a four-stroke diesel engine at full load with a jacket temperature of 100°F.

et al. (1955), also shows the reduction of a low-temperature corrosive wear by using an alkaline oil.(21)

Gergel (1980), presented a discussion of diesel engine oil alkalinity values.(24) The following table lists the approximate TBN level of various diesel engine oils:

Diesel Engine Oil Type	TBN
Universal*	6-10
Generation 3 railroad	10
Generation 4 Railroad	13
Medium Speed Marine	20-30
Cross-Head Marine	50-70

* 1.000 percent total sulfated ash oil meeting API CD, API SF, MIL-L-2104D, MIL-L-46152B.

Gergel also presented a discussion of techniques used to measure TBN. It was concluded that ASTM D 664 measures protective TBN of a used oil, while ASTM D 2896 gives misleading higher values because it measures both protective TBN and the less-protective form of TBN which comes from weak nitrogen bases (ashless dispersants). Figures 17 and 18 illustrate the different used oil TBN values of D 664

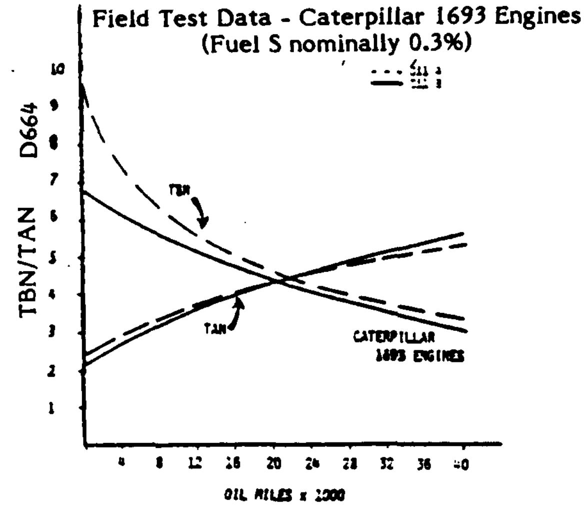

Figure 17. TBN/TAN versus oil miles

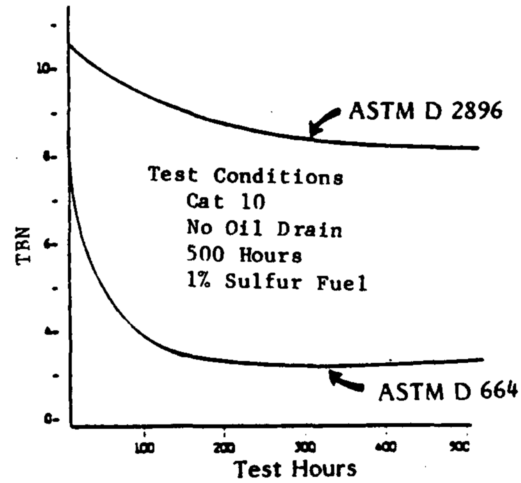

Figure 18. Comparison of ASTM D 664 and ASTM D 2896 TBN Analyses

and D 2896. In summary, the alkalinity value (TBN) of a lubricating oil has been shown to be very important in controlling corrosive engine wear at low temperature operating conditions. Care must be used when discussing new and used oil TBN values because of the differing values produced by ASTM D 664 and D 2896.

2.2.5 Fuel Lubricity Effect

Diesel fuel sulfur content may affect fuel lubricity according to work of Wei and Spikes.(25) A high frequency reciprocating machine was used to simulate the lubricity of diesel fuels in fuel injection pumps. Model sulfur compounds were added to a high-wear severely hydrotreated fuel as shown in the following table:

Wear Test Results Using Sulfur-Containing Model Compounds

Test Fluid	S from Added Compound Wt%	Wear Scar Diameter (mm)
Fuel 13*	0	0.35
Fuel 13 + cyclopentyl sulphide	0.01 (100 ppm)	0.38
Fuel 13 + benzyl mercaptan	0.01	0.40
Fuel 13 + dibenzyl disulphide	0.01	0.35
Fuel 13 + dibenzyl disulphide	1	0.49
Fuel 13 + n-dodecylsulphide	1	0.39

* Fuel 13 is high wear, severely hydrotreated fuel.

The authors concluded that all sulfur compounds tested were pro-wear to some extent and generally gave increased wear at higher concentrations. This effect should be further investigated to determine if the reduction of diesel fuel sulfur from 0.3 to 0.05 weight percent would benefit diesel injection pump wear.

2.3 Comments on SAE Paper 700892

The original work plan included a review of SAE Paper 700892 by Tennyson and Parker (2), to determine the applicability of its results to current on-road, heavy-duty diesel engine operation during this project. After review comments were received from other sources, EPA requested no further review of the paper.(26)

2.4 Engine Manufacturers

Six major engine manufacturers were contacted for in-house information which they could make available concerning fuel sulfur effects in the range of 0.05 to 0.3 weight percent. Only two of the manufacturers were helpful; Caterpillar provided a brochure (27) on fuel sulfur effects and Mercedes-Benz Truck Co. provided a very useful draft SAE paper (20) which was referenced in previous sections. Gergel (1980) published the Table 1 on engine builder recommendations relative to fuel sulfur content.(24) Based on the information in Table 1, the usual efforts to control fuel sulfur effects are: 1) more frequent oil changes, 2) specifying new oil minimum TBN, 3) specifying a used oil minimum TBN. In conclusion, all manufacturers tend to regard TBN depletion as an important parameter.

The following information was obtained from representatives of Detroit Diesel Allison (DDA) during a telephone conversation, and is presented with their consent.(39) This information was received too late to be integrated into the literature study, and written reference for the data has not been released by DDA.

Engine wear studies were conducted at three fuel sulfur levels (0.05, 0.26, 0.95 weight percent). Engine chrome ring wear was determined using a ring irradiation technique and measuring wear debris in the used oil. Details of the wear tests are presented in the following summary:

Engine type	Four-cycle turbocharged diesel
Operating conditions	1200 RPM max torque
	1800 RPM rated horsepower

Table 1. Attitude of Diesel Engine Builders Relative to Sulfur Content of Diesel Fuel

Engine Builder	Country	Position on Diesel Fuel Sulfur Content
Caterpillar (28)	U.S.A.	A. Drain Interval Reduction % Fuel Sulfur — Drain Interval <0.4 — Normal 0.4-1.0 — 50% Normal >1.0 — 25% Normal B. Standard Drain Interval 1. For fuels up to 1.5% sulfur 2. Oil quality a. API CD b. TBN - 20 times % sulfur c. Unknown fuel sulfur Area — TBN U.S.A. — 10 Canada — 10 All others — 20 3. ASTM D 2896 for TBN 4. Oil drain at 50% initial TBN 5. Use wear metal analyses (chromium & iron) or drain indication)
Cummins (29)	U.S.A.	1. Fuel sulfur is recommended not to exceed 1.0 mass percent 2. Emergency specifications allow fuel to contain 2.0% mass sulfur. High TBN oils and shorter drain intervals to be used. No specific TBN or drain period specified. 3. Oils of same TBN may not give same performance.
Daimler-Benz (30)	Germany	Reduce drain interval by 50% if fuel sulfur exceeds 0.5%.
Detroit Diesel (31,32)	U.S.A.	1. Use fuel below 0.5% sulfur for most satisfactory performance 2. Reduce drain interval when fuel is above 0.5% sulfur (No details given). 3. Applicable for two- and four-cycle engines.
Deutz (33)	Germany	Fuel Sulfur — Drain Interval, Km (CC/SE, CD/SE) <0.5% — 10,000, 15,000 >0.5% — 5,000, 10,000
International Harvester (34)	U.S.A.	Drain Interval Reduction Fuel Sulfur — Drain Interval <0.5% — Normal 0.5 - 1.0 — 50% Normal >1.0% — 25% Normal
MACK	U.S.A.	No published Position
M.A.N. (35)	Germany	If high sulfur fuel is used, change oil when TBN falls to 20% new oil value. TBN test method not specified.
Mercedes-Benz (36)	Brazil	1. TBN retention as determined by in-house test is important 2. About 10 TBN minimum
Volvo (37)	Sweden	1. 0.55 maximum fuel sulfur 2. TBN of used oil must remain above 50% new oil value by ASTM D 2896 or not less than 1.0 by ASTM D 664.

Coolant out, °F	184
Oil type	API CD, 15W-40, 8 TBN

DDA found a 75 percent decrease in chrome ring wear when going from 0.26 to 0.05 weight percent fuel sulfur content while operating at 184°F COT and 1200 RPM max torque mode. At 1800 RPM, a lesser wear decrease was observed, however, it fell within test repeatability range. DDA did not feel that these results could be extrapolated to engine life at this time.

The DDA results are somewhat in conflict with the Mercedes-Benz data (20), in that a substantial wear reduction was observed while operating at normal engine temperature. Differences in the M-B and DDA test parameters included:

	DDA	M-B
Wear location	ring	liner
Turbocharged	yes	no
Oil quality	CD	CC
Oil viscosity	15W-40	20W-20

Any or all of the above factors could account for the difference in results. This comparison further exemplifies the complexity of the interrelationships of diesel engine wear variables. The DDA data are most interesting and EPA should remain in contact with DDA to obtain any additional data which can be made available.

3. FLEET DATA ON ENGINE OIL ANALYSES

On January 1, 1985, the sulfur content in diesel fuel was reduced by regulation to 0.05 weight percent maximum throughout the South Coast Air Basin, namely Los Angeles, Orange, Riverside, and San Bernardino Counties in California. This change provided an opportunity to gather fleet data indicating whether or not lower sulfur diesel fuel may result in a reduction in engine wear and an increase in engine life and oil change interval. Data on diesel fuel and used engine oil analyses were sought from fleets operating in the area before and after sulfur content was changed. This section describes the data obtained from four fleets, and the statistical analyses of the data.

3.1 Initial Contact With Fleets

To investigate the effects of low sulfur content in diesel fuel as it relates to engine wear, several fleet operators in the South Coast Air Basin area were asked to participate in the EPA study by providing fuel and used oil analyses. In addition, oil analysis laboratories were contacted to provide other possible data sources for the study. The objectives of the study were explained and several requirements were outlined to establish whether available data could be used in the study.

The following items were deemed necessary for a fleet to be a candidate for the study:

1. Fleets must have been participating in a scheduled used oil analysis program during 1984 and 1985, i.e., before and after the effective date of fuel sulfur regulation on January 1, 1985.
2. Used oil analysis data could be made available on magnetic tape in compatible format for the computer system at SwRI. Due to time constraints, it was not feasible to manipulate and compare the data manually.

Number and Type of Contacts

Eight bus fleets, ten truck fleets, four municipal refuse collection truck fleets, and seven oil analysis laboratories were contacted. The following fleet operators were willing to release data, and did so in time for use in the study:

1. Southern California Rapid Transit District
2. Chandler Truck Fleet
3. Suppose-U-Drive Fleet (Rental Truck Fleet)
4. Laidlaw School Bus Fleet

The diesel fuel and lubricating oil analyses for all four fleets were performed in the laboratories of Analysts, Inc., which provided the data used in the study.

3.2 Southern California Rapid Transit District Fleet

The Southern California Rapid Transit District (SCRTD) is located in Los Angeles, California, and provides urban transit and suburban service in the county of

Los Angeles. It has approximately 2,500 transit buses powered by Cummins, Detroit Diesel, and MAN engines. SCRTD has a comprehensive and organized fuel and engine oil monitoring program in which sampling and analyses are done on a scheduled basis.

Data Obtained

Permission was granted by SCRTD to obtain the diesel fuel and used oil analyses data from Analysts, Inc., an analytical laboratory with corporate headquarters located in Rolling Hills Estate, California. The data obtained consisted of a listing of diesel fuel samples with sulfur content, and magnetic computer tape containing used oil analysis results for 1984, 1985, and about 10 months of 1986.

Sulfur Content Data

There were a total of 870 diesel fuel samples analyzed for sulfur content in 1984, 1985 and 1986. After a thorough check, thirty samples were deleted due to duplications and other errors. The data were entered into the SwRI computer system, and statistical analyses were performed on 191 samples identified as tank farm (refinery) samples and 649 as tank trailer (delivery truck) samples.

Oil Analysis Data

The magnetic tape with the oil analysis data contained a total of 29,949 records for 1984, 1985 and 1986. A sample listing of the raw data was produced to identify the variables in the data base. A listing of the different engine types and frequencies of observations for each year was produced and analyzed in order to understand the data and delete entries where a specific engine type could not be identified. Over 80 percent of the deletions were due to errors in engine-type identification. Nine variables were selected as most likely to be affected by high or low sulfur content in the fuel. In order to eliminate questionable data, limits were established on six variables where aberrations had been noted in the raw data. Observations were deleted where any of the following conditions existed:

1. Zinc (Zn) was less than 500 ppm, indicating erroneous data.
2. Iron (Fe), copper (Cu), and lead (Pb) were 0 ppm simultaneously, which would indicate missing data.
3. Iron, copper, and lead were 998 ppm, indicating an erroneous reading or an actual reading exceeding the limits of the spectrometer.

4. Fuel dilution (FDIL) was more than 9 volume percent. Excessive fuel dilution could affect wear rate or metal analyses.
5. Oil miles were less than 1,000 or more than 30,000, indicating analyses on unused oil or possible errors in recording data.

The following adjustments were made to the data base:

Year	Original Records	Deleted Records	Records Analyzed
1984	2940	282	2658
1985	12780	3142	9638
1986	14229	3717	10512

Frequency distribution plots showing wear elements versus oil miles by engine type and year group were developed. No general pattern could be observed at 1-9,000, 9-15,000, 15-21,000, or 21-30,000 oil mile intervals. Means and standard deviations were calculated using the same parameters as with the frequency distribution plots. No major differences or consistent trends were observed with the variables selected when compared for the same year at the various oil mile intervals. An example of the data for various ranges of oil miles is given in Table 2. Iron content in the lubricating oil shows a consistent increase with oil miles for only the DDV71 engine in 1984. Other engines show upward and downward trends. Also the trends from 1984 to 1985-86 did not show the same effect at different oil miles. Based on these observations, the oil miles data were combined into a single average for each year. The selection of variables to be analyzed was reduced to oil-miles, iron, and total base number (TBN).

Statistical Analysis

The objective of the data analysis was to compare diesel fuel and engine oil analyses, determining if significant differences occurred between 1984 and 1985, and between 1984 and 1986. The method used to compare the means of the variables was the multiple comparison means test. Specifically, J.W. Tukey (40) derived a test designed for pair-wise comparisons based on the studentized range that can use equal or unequal sample sizes. This multiple comparison of means test is called the Tukey test or the "honestly significant difference" (HSD) test. The 95 percent level of confidence was chosen for this study, which may be stated as the 5 percent level of significance.

Table 2. Average Iron Concentration, ppm, for Southern California Rapid Transit District Fleet

Oil Miles x 10^3	1-9	9-15	15-21	21-30
1984				
CUV903	53.5	55.5	65.1	65.3
DDV71	86.0	94.3	99.8	102.2
DDV92	81.7	84.3	76.5	--
MAN866	75.0	272.0 (1 Sample)	--	--
1985				
CUV903	50.7	56.7	72.8	65.8
DDV71	60.8	70.8	53.4	42.2
DDV92	49.4	54.2	--	--
MAN866	104.4	547.3 (3 Samples)	--	--
1986				
CUV093	43.7	35.0	65.5	83.4
DDV71	65.7	68.0	51.6	41.2
DDV92	52.2	49.1	--	--
MAN866	95.9	--	--	--

1. Fuel Sulfur Content - Table 3 shows the results of the comparison test of fuel sulfur content between 1984 and 1985 or 1986. There was a 91 percent decrease in sulfur content in the tank farm samples while the tank trailer samples show a decrease of 94 percent between 1984 and 1985-1986. The combined pool of all samples decreased from 0.35 weight percent sulfur in 1984 to 0.03 weight percent in 1985, and 0.02 weight percent in 1986. Figures 19 and 20 illustrate the information contained in Table 3.
2. Fleet Summary of Oil Analysis Variables - Table 4 and Figures 21-23 present the SCRTD fleet summary of oil-miles, iron (Fe) ppm, and total base number (TBN). There was no significant difference in oil-miles between the three years. However, there was an average 30 percent reduction in the iron content between 1984 and 1985 - 1986. There was a significant difference in used oil TBN of 1.4 between 1984 and 1985, and 1.6 between 1984 and 1986. New oil TBN levels, according to SCRTD records, were 5.4 for 1984, 7.4 for 1985, and 6.1 for 1986. Although there was marked increase in the used oil TBN in 1985 and 1986, it corresponds with the higher TBN's in the new oils used by SCRTD during these years

Table 3. Comparison of Fuel Sulfur Content For Southern California Rapid Transit District Fleet

Sample Type	Year	No.	Sulfur, M% Mean	Significant Difference*	Standard Deviation
Tank Farm	1984	49	0.35		0.09
	1985	98	0.03	S	0.03
	1986	44	0.02	S	0.01
Tank Trailers	1984	26	0.34		0.13
	1985	582	0.03	S	0.04
	1986	41	0.01	S	0.05
Combined	1984	75	0.35		0.11
	1985	680	0.03	S	0.03
	1986	85	0.02	S	0.03

* In comparison of mean values for 1985 and 1986 with 1984 at the 95 percent confidence level;
S means Significant Difference
NS means No Significant Difference

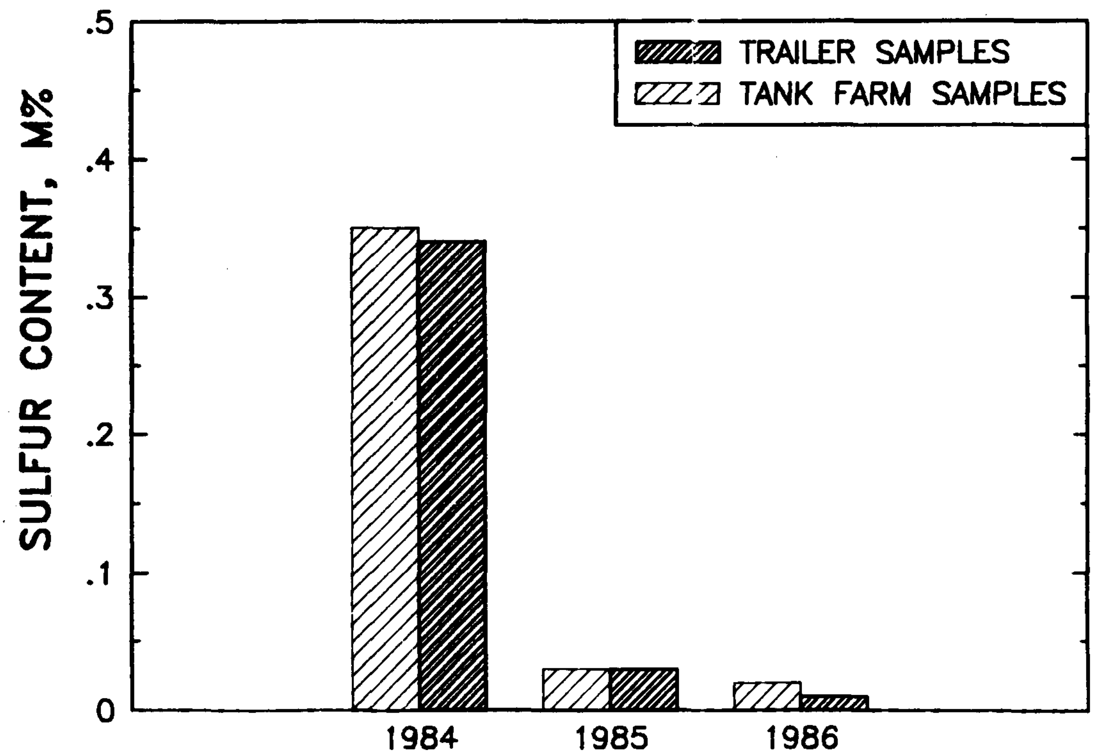

Figure 19. SCRTD fleet, sulfur content of diesel fuel, trailer and tank samples

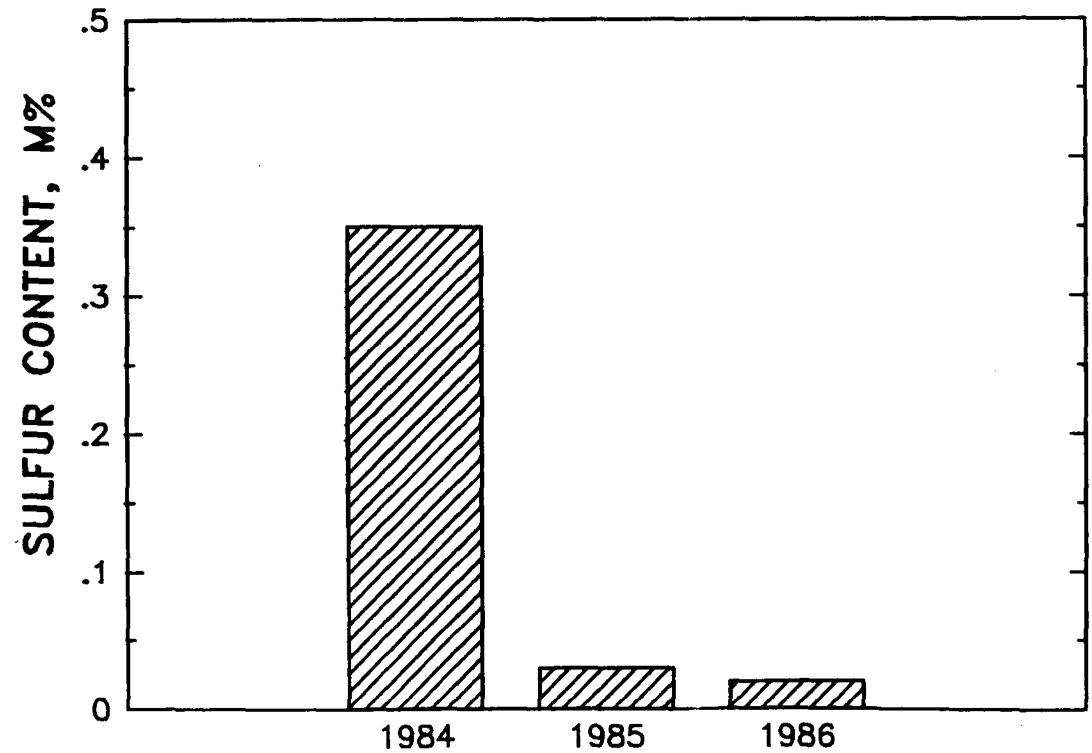

Figure 20. SCRTD fleet, sulfur content of diesel fuel, annual average

Table 4. Comparison of Selected Data For Southern California Rapid Transit District Fleet

Variable	Year	No.	Mean	Significant Difference*	Standard Deviation
Oil Miles	1984	2658	6531.2		3877.1
	1985	9638	6734.5	NS	4099.6
	1986	10512	6424.8	NS	3859.4
Iron, ppm	1984	2658	85.5		53.6
	1985	9638	57.8	S	49.8
	1986	10512	58.8	S	44.6
Total Base No.	1984	2658	4.4		1.0
	1985	9638	5.8	S	0.8
	1986	10512	6.0	S	0.7

* See Table 3.

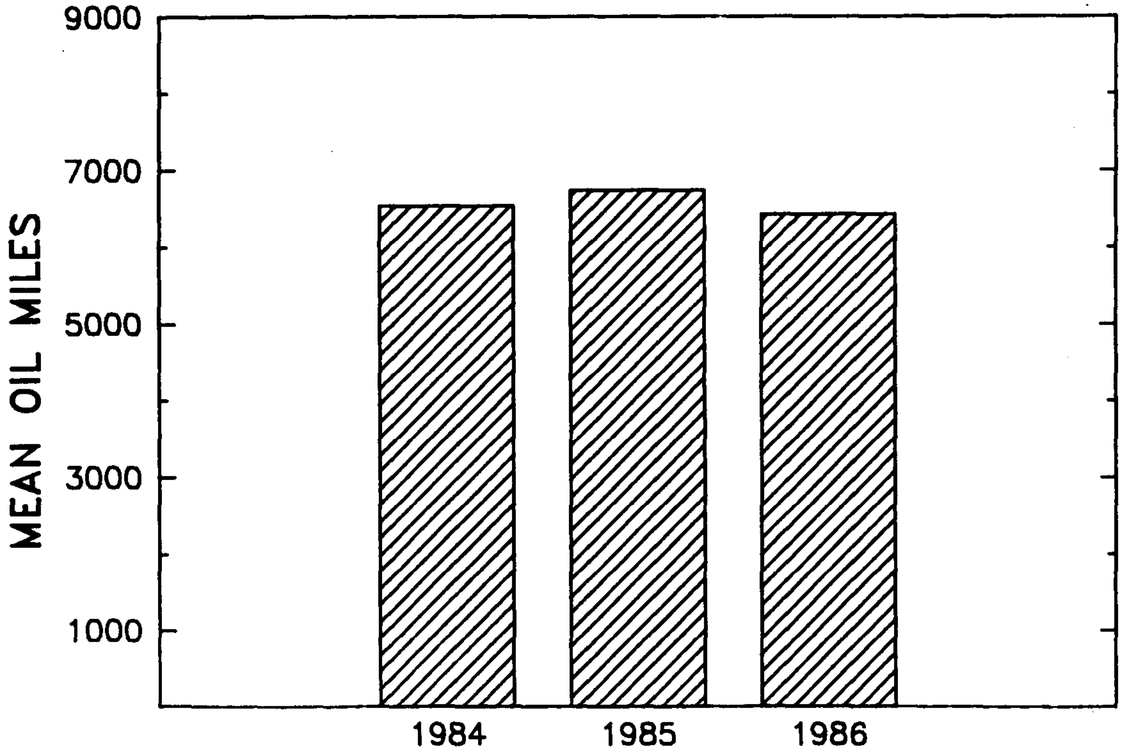

Figure 21. SCRTD fleet, average oil miles

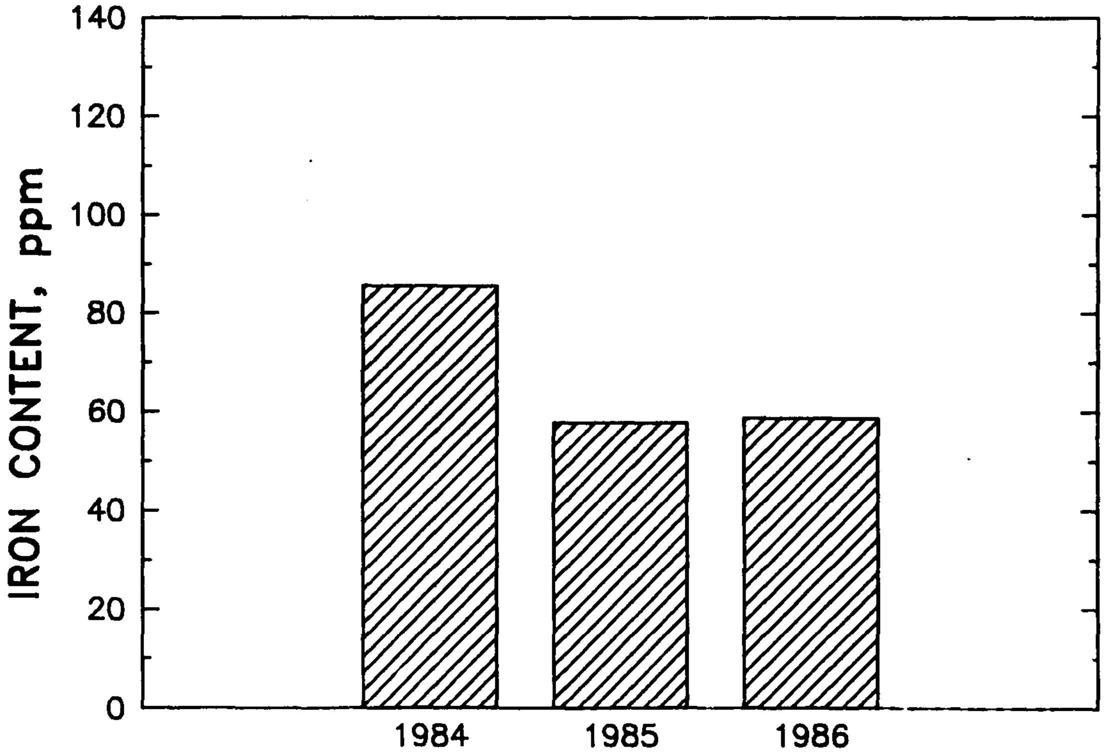

Figure 22. SCRTD fleet, average iron content of lubricating oil

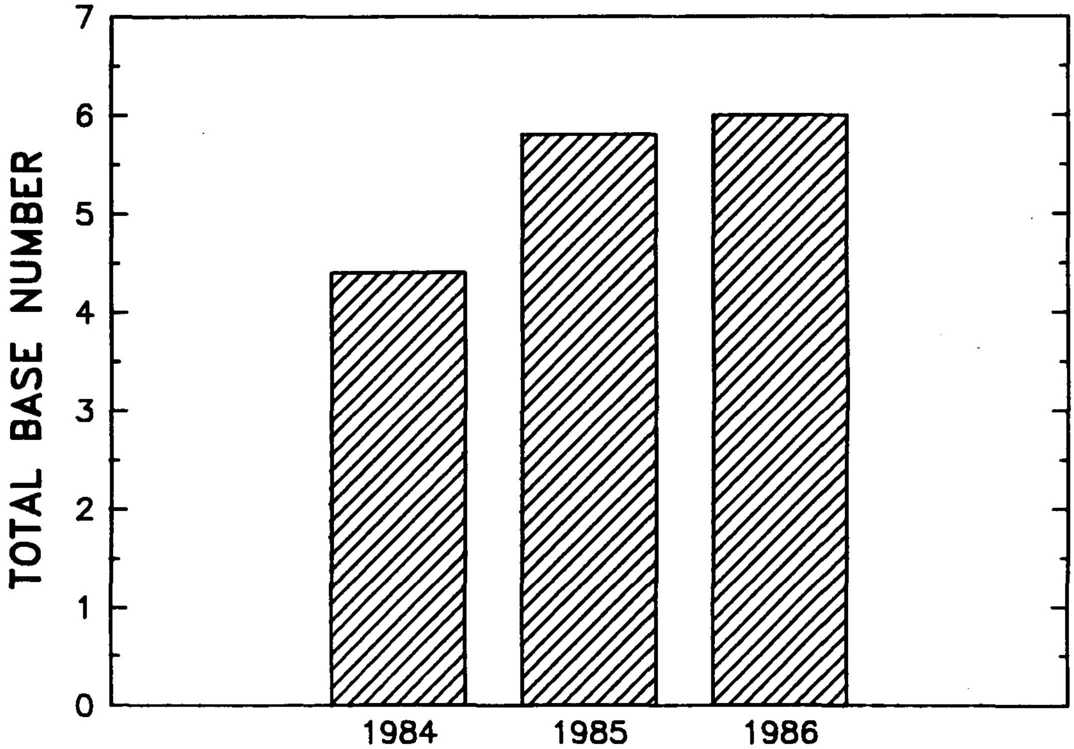

Figure 23. SCRTD fleet, average total base number of lubricating oil

(7.4 and 6.1). Therefore, it is not valid to compare used oil TBN's from year to year because the new oil TBN levels are different. Another approach was to examine the alkalinity depletion for each year, and determine if low sulfur fuel resulted in the expected increase in alkalinity retention. As shown below, no consistent trend is evident in the used oil alkalinity retention:

Year	New Oil, Typical	Used Oil, Average	TBN Depletion
1984	5.4	4.4	1.0
1985	7.4	5.8	1.6
1986	6.1	6.0	0.1

3. Comparison Analyses by Engine Type - Table 5 and Figures 24-35 show the comparison results on the four engine types identified in the SCRTD data. All engines exhibited increased alkalinity levels for 1985 and 1986; therefore, the observation noted for this variable in Table 4 applies.

Table 5. Comparison of Selected Data for Southern California Rapid Transit District Fleet By Engine Type

Variable	Year	No.	Mean	Significant Difference*	Standard Deviation
CUV903 ENGINES					
Oil Miles	1984	87	8841.3		4781.0
	1985	73	6284.9	S	2509.7
	1986	15	6160.0	S	2277.7
Iron, ppm	1984	87	55.5		40.1
	1985	73	51.6	NS	36.7
	1986	15	42.5	NS	32.9
Total Base No.	1984	87	4.1		0.9
	1985	73	5.1	S	0.9
	1986	15	5.4	S	0.6
DDV71 ENGINES					
Oil Miles	1984	2054	6545.7		3915.7
	1985	5111	7198.5	S	4316.3
	1986	4836	6888.2	S	4021.7
Iron, ppm	1984	2054	82.1		65.7
	1985	5111	63.6	S	44.7
	1986	4836	66.2	S	46.3
Total Base No.	1984	2054	4.5		1.0
	1985	5111	5.7	S	0.9
	1986	4836	6.0	S	0.8
DDV92 ENGINES					
Oil Miles	1984	458	6165.3		3567.6
	1985	4387	6222.7	NS	3803.7
	1986	5551	6070.0	NS	3697.2
Iron, ppm	1984	458	82.1		65.7
	1985	4387	50.1	S	50.7
	1986	5551	51.6	S	40.6
Total Base No.	1984	458	4.5		1.0
	1985	4387	6.0	S	0.6
	1986	5551	6.0	S	0.5
MAN866 ENGINES					
Oil Miles	1984	59	5459.3		1221.0
	1985	67	5332.3	NS	2641.1
	1986	110	3993.6	S	563.2
Iron, ppm	1984	59	78.3		51.3
	1985	67	130.9	S	153.3
	1986	110	95.9	NS	79.3
Total Base No.	1984	59	1.9		1.8
	1985	67	4.3	S	1.3
	1986	110	5.2	S	1.4

* See Table 3.

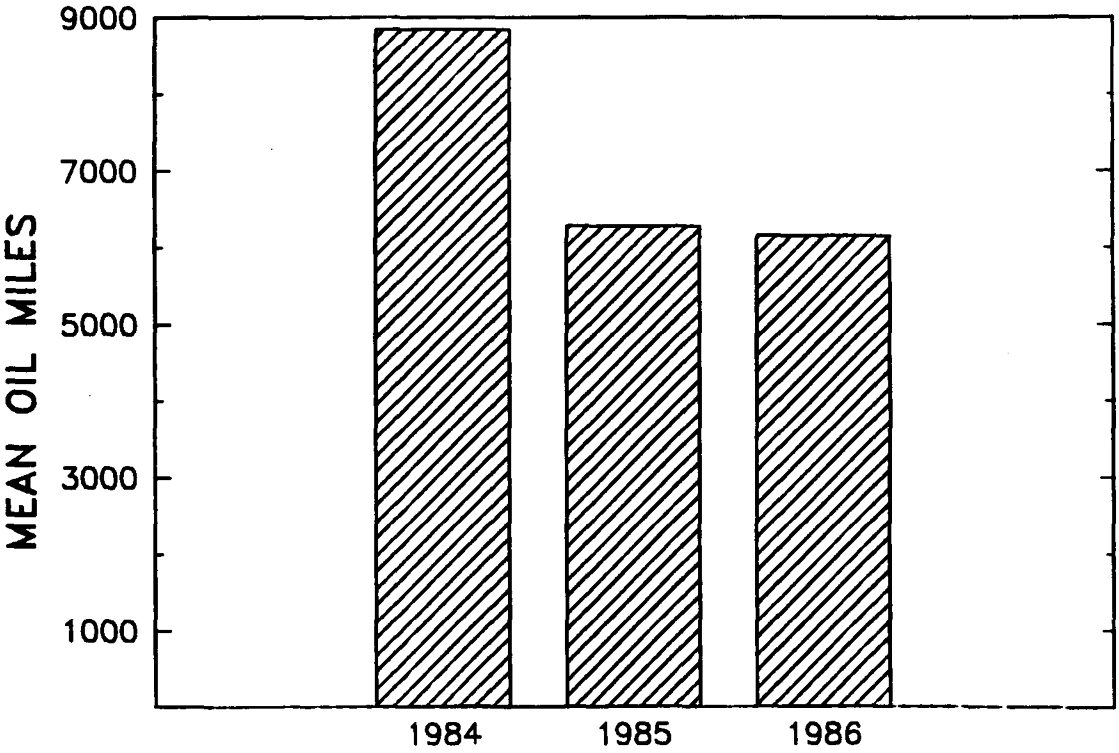

Figure 24. SCRTD fleet, average oil miles (CUV903 engine)

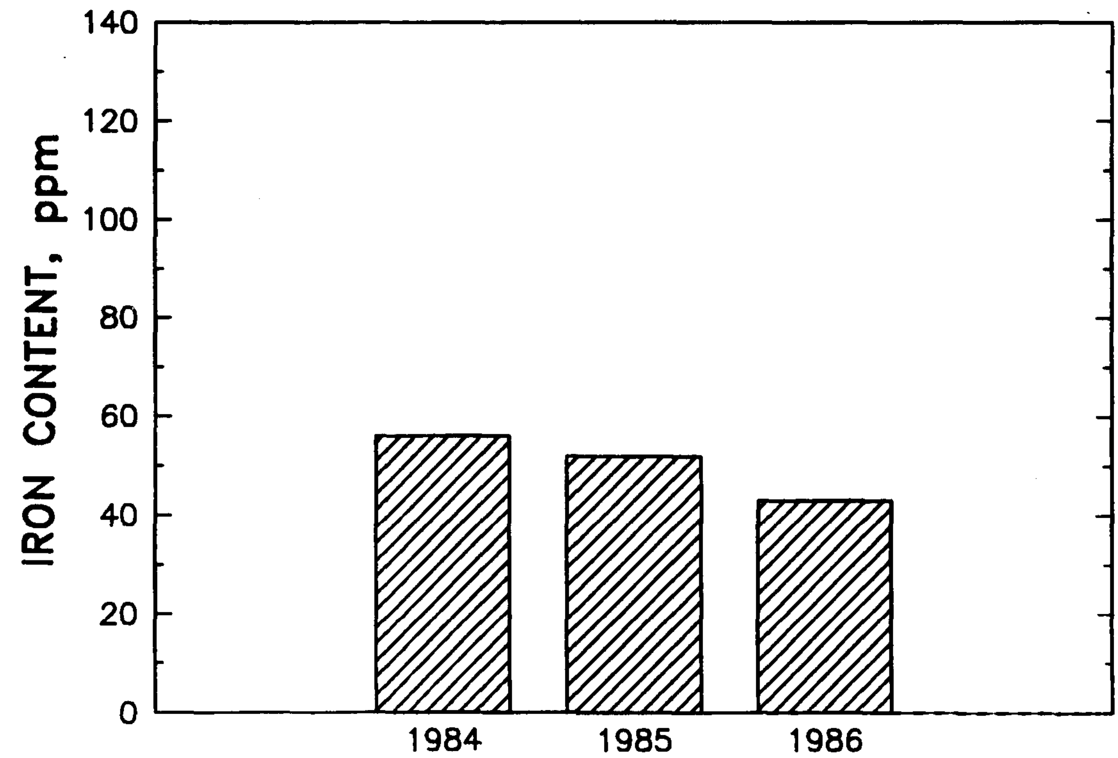

Figure 25. SCRTD fleet, average iron content of lubricating oil (CUV903 engine)

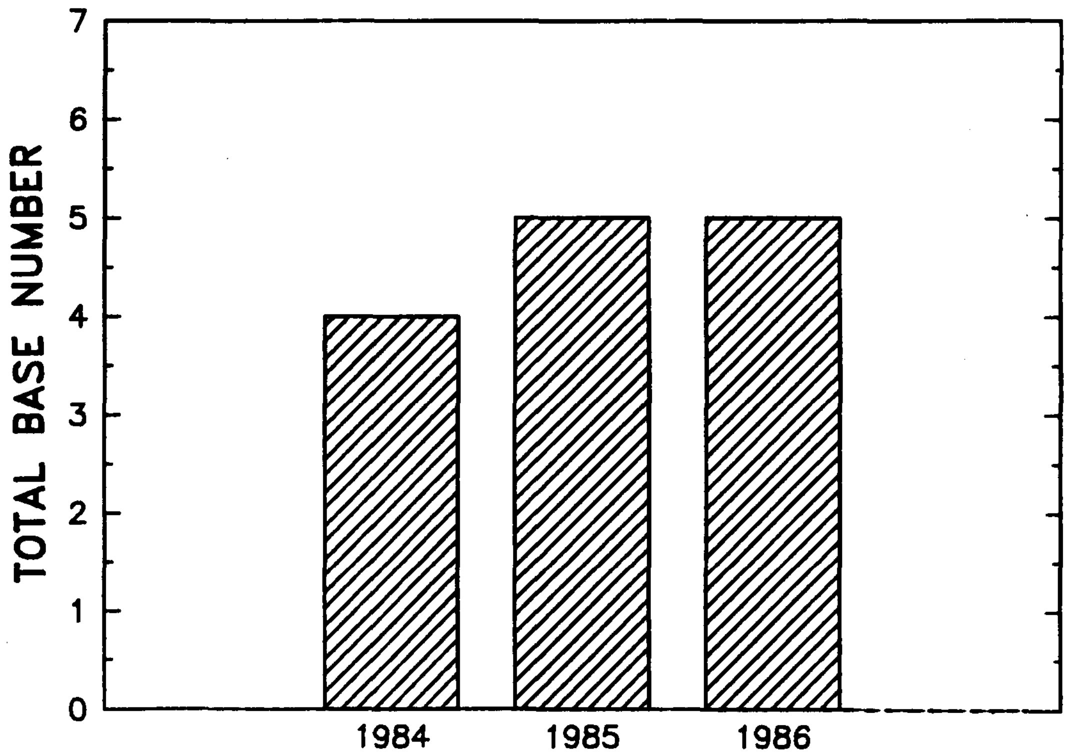

Figure 26. SCRTD fleet, average total base number of lubricating oil (CUV903 engine)

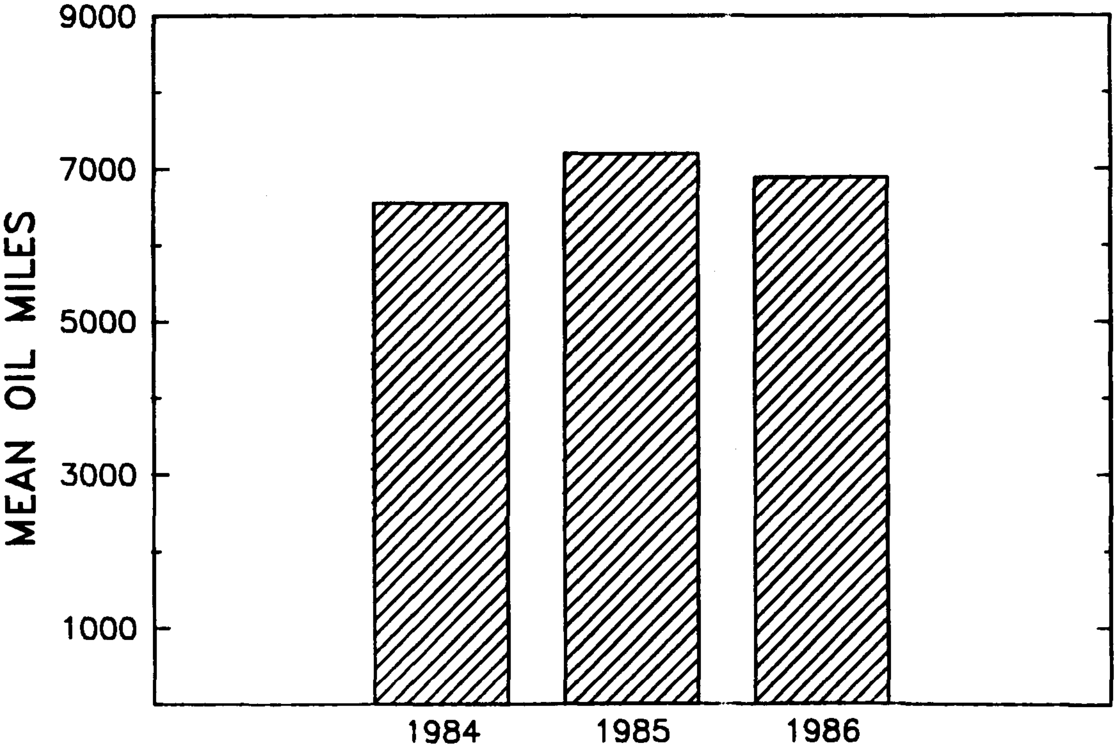

Figure 27. SCRTD fleet, average oil miles of lubricating oil (DDV71 engine)

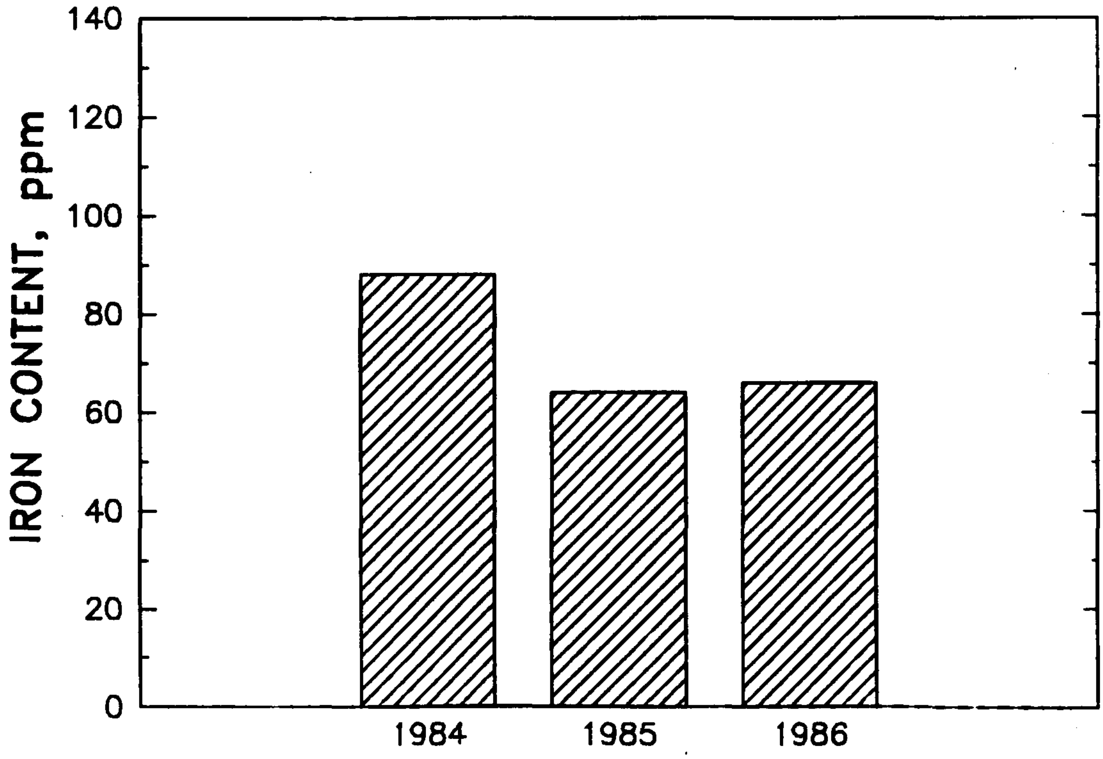

Figure 28. SCRTD fleet, average iron content of lubricating oil (DDV71 engine)

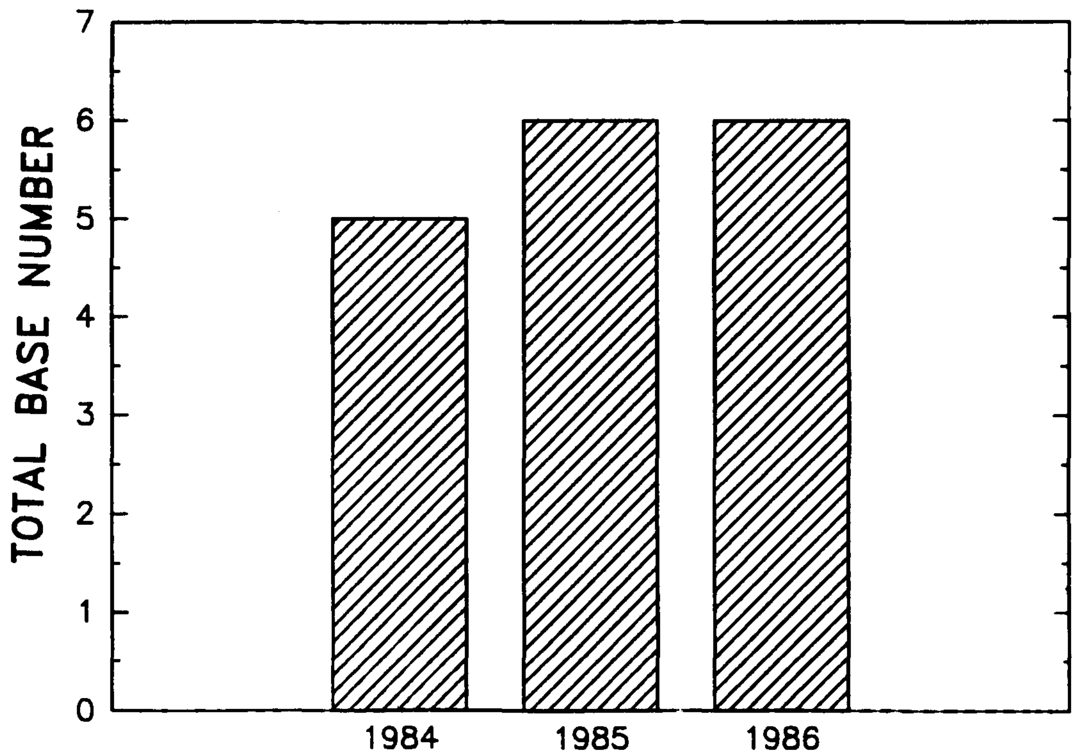

Figure 29. SCRTD fleet, average total base number of lubricating oil (DDV71 engine)

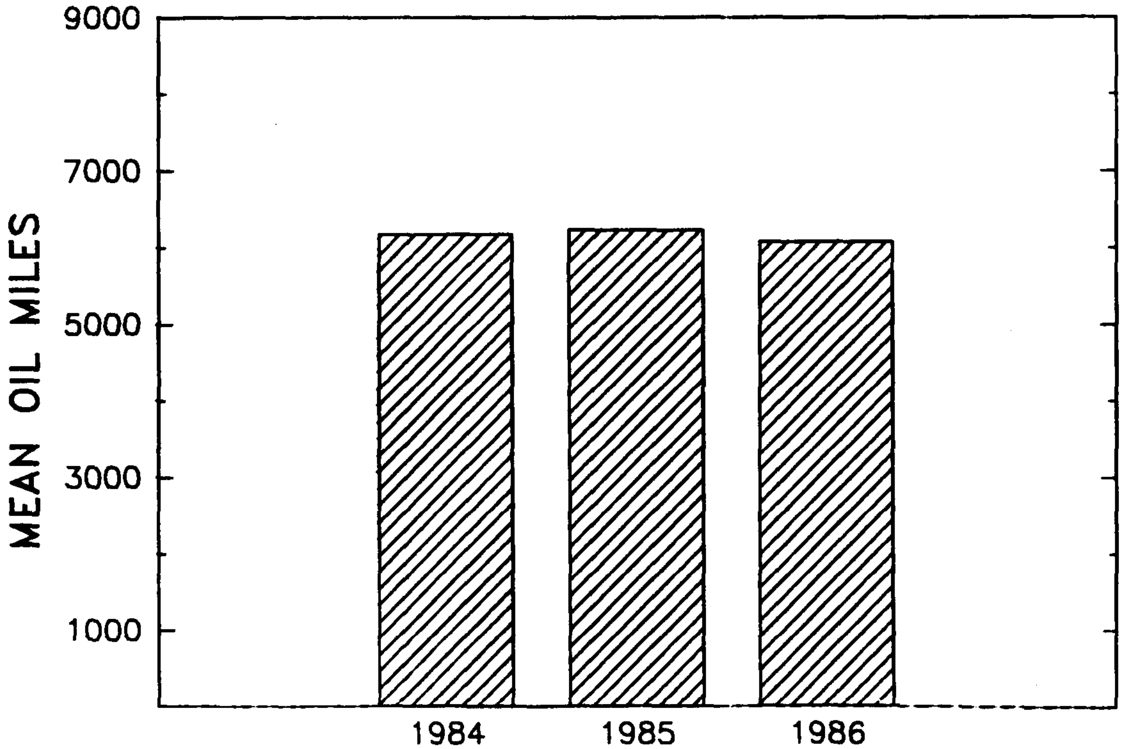

Figure 30. SCRTD fleet, average oil miles (DDV92 engine)

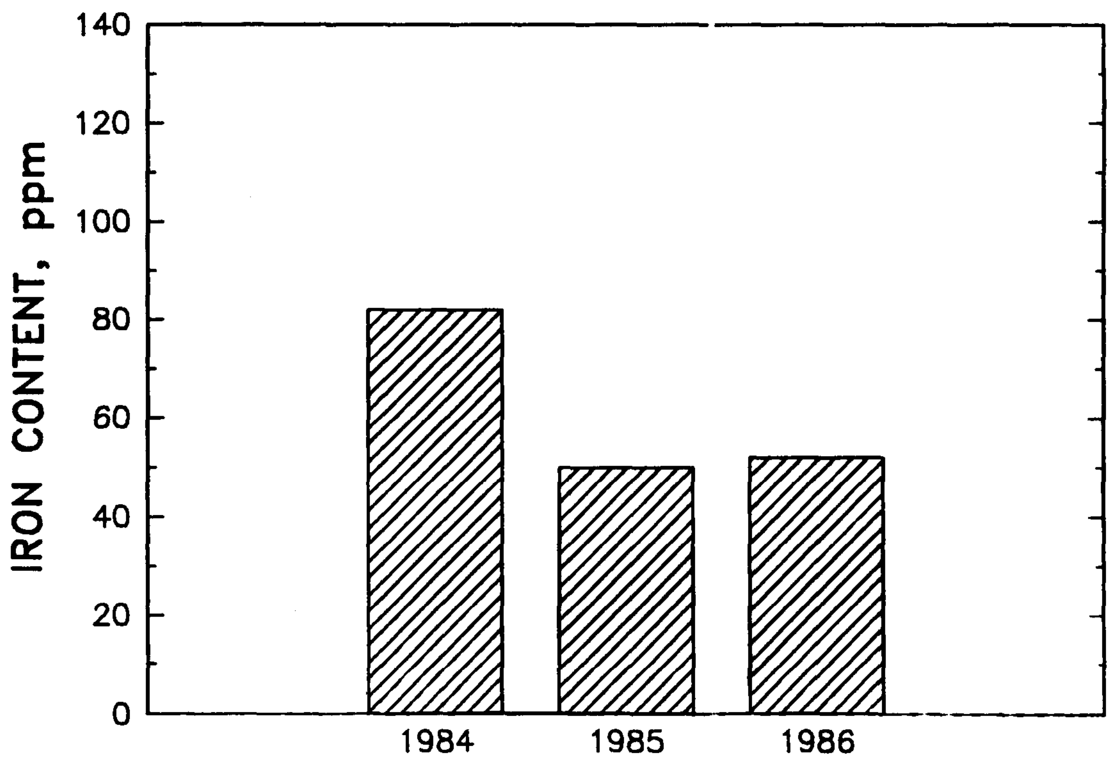

Figure 31. SCRTD fleet, average iron content of lubricating oil (DDV92 engine)

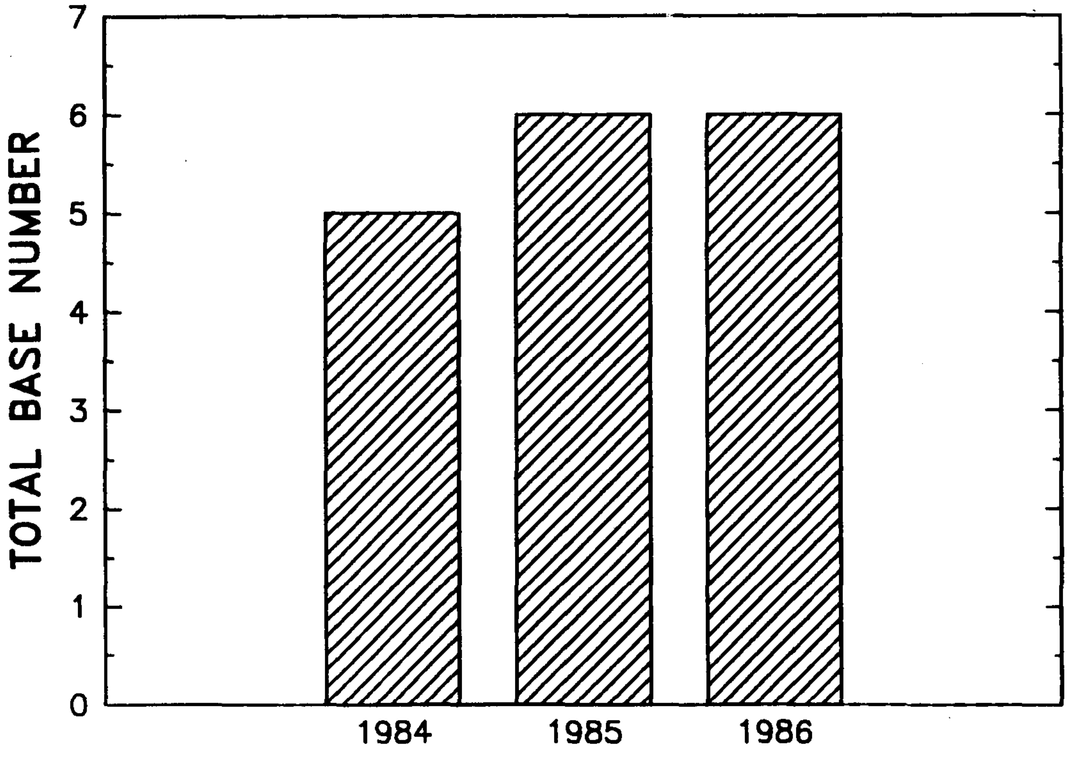

Figure 32. SCRTD fleet, average total base number of lubricating oil (DDV92 engine)

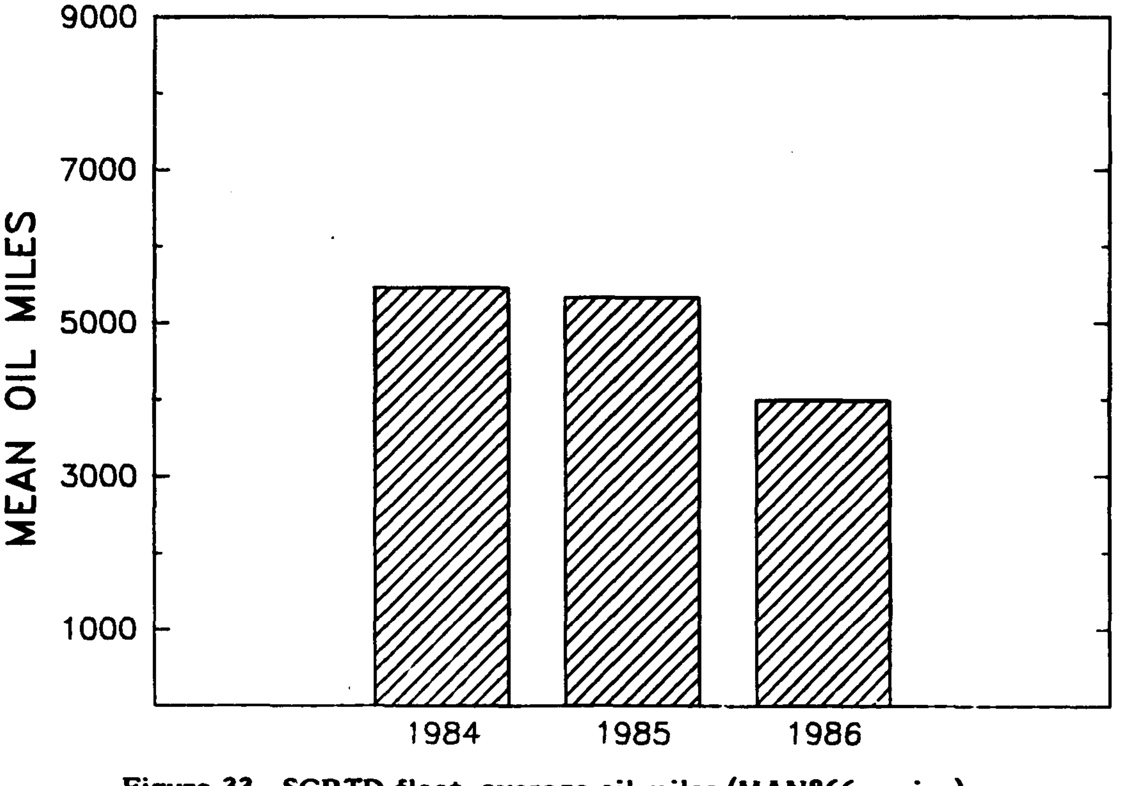

Figure 33. SCRTD fleet, average oil miles (MAN866 engine)

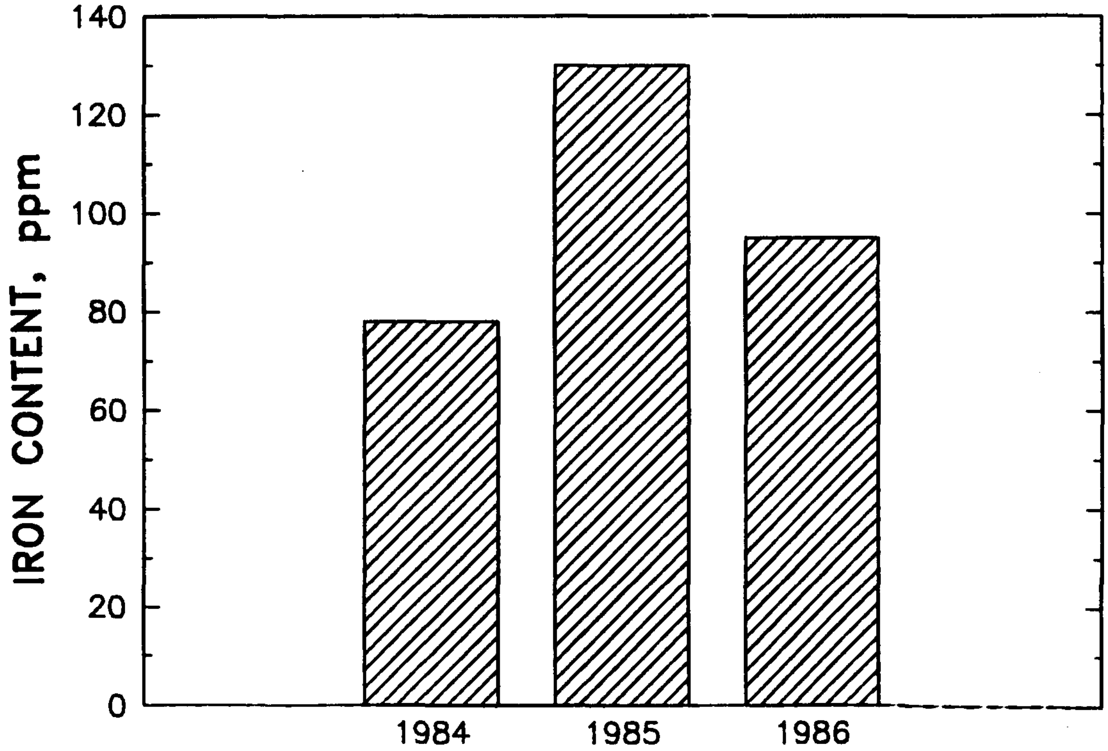

Figure 34. SCRTD fleet, average iron content of lubricating oil (MAN866 engine)

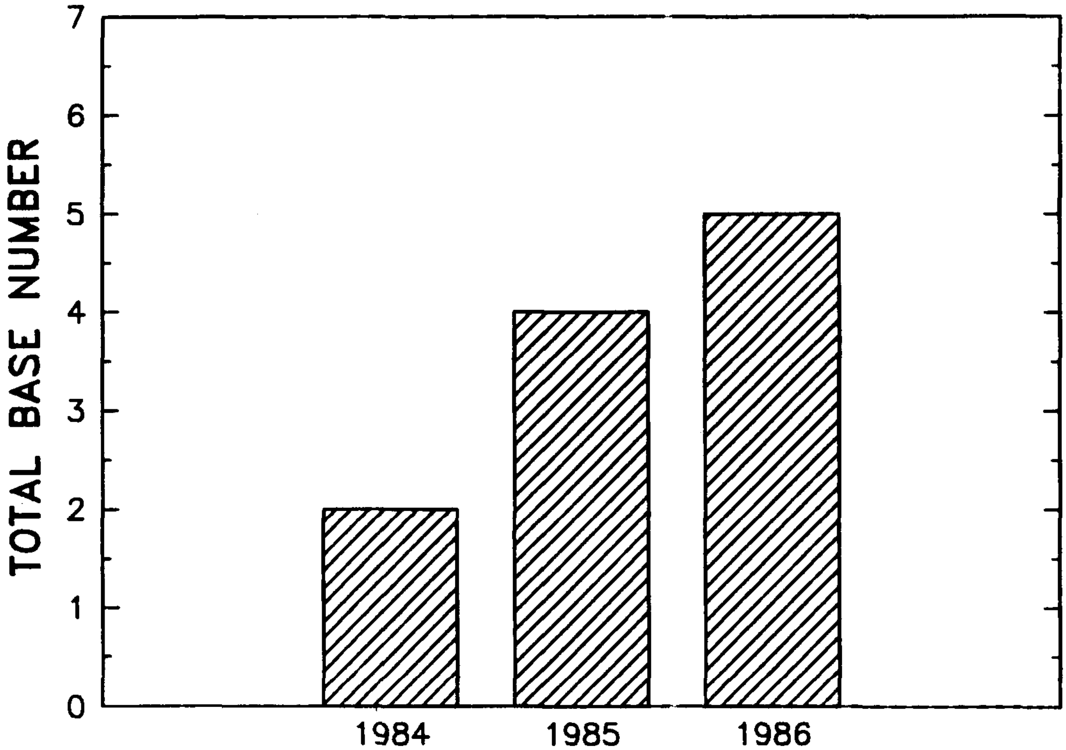

Figure 35. SCRTD fleet, average total base number of lubricating oil (MAN866 engine)

a. CUV903 Engines - There was a 30 percent decrease (significant) in the oil mile averages between 1984 and 1985, 1986. Correspondingly, although not statistically significant, the iron ppm decreased from 56 ppm in 1984 to 52 ppm in 1985 and 43 ppm in 1986.

b. DDV71 Engines - Here we see a significant increase in oil-miles between 1984 and 1985, 1986. The iron ppm; however, decreased significantly by 20 percent; therefore, the decrease in engine wear as indicated by used oil iron content could be attributed to the low sulfur content in the fuel.

c. DDV92 Engines - There was no significant difference in the oil-mile mean for the three year period, however, the iron content exhibits a sharp decrease from 82 ppm in 1984 to 50 ppm in 1985, 1986. This translates to a 38 percent difference. The low sulfur content in the fuel appears to have contributed to this reduction.

d. MAN866 Engines - There was no significant difference in the oil-miles between 1984 and 1985; however, there was a 27 percent decrease between 1985 and 1986. It would be expected that the iron ppm would decrease relative to the oil miles; instead, there is a sharp increase of 45 percent between 1984 and 1985, 1986. It should be noted that samples for these engines were less than 1 percent of the total data base. Very few engines contributed data; therefore, if one or two engines in the group were behaving aberrantly, the analysis as a whole would be affected. The very large standard deviation for the iron content as shown in Table 5 supports this observation.

3.3 Chandler, Suppose-U-Drive (Rental Trucks) and Laidlaw School Bus Fleets

1. The Chandler Palos Verdes Sand & Gravel Company is located in Lomita, California. The fleet consists of 55 gravel trucks powered by Caterpillar, Cummins, Detroit Diesel and Mack engines, and is on a scheduled used oil analysis program. The fleet operates exclusively in the basin area.

2. Suppose-U-Drive Truck Rental Company is located in Glendale, California. There are 152 diesel powered rental trucks of different configurations and sizes. The principal engine types identified are Cummins, Detroit Diesel, Duetz, GMC, and International Harvester. The fleet, for

the most part, operates in the basin area; however, there are a few rental trucks that are used out of the area.

3. The Laidlaw Transit, Inc. with locations in Los Angeles, Van Nuys, 29 Palms, and Palm Springs, California, operates and maintains a total of 190 school buses powered by Cummins and Detroit Diesel engines. Only the vehicles operated in the Los Angeles and Van Nuys area were considered for the study.

Data Obtained

The data on these fleets, provided by Analysts, Inc. laboratory, consisted of a magnetic tape containing used oil analysis for 1984, 1985, and 1986. Fuel sulfur content analyses were not available for any of the fleets. Therefore, it was assumed that these fleets experienced a decrease in fuel sulfur content to 0.05 weight percent max in 1985.

Oil Analyses Data

The magnetic tape contained a total of 2,152 records. The data were separated by fleets and listings produced to identify the variables in the data base. It was found that TBN data were not reported for any of the fleets. Oil mile entries were missing from the Laidlaw fleet; therefore, the oil mile variable was not used for comparison on this fleet. The data were prepared for analyses in the same manner as the SCRTD data. The variable zinc (Zn) was selected for comparison due to a noticeable increase between 1984 and 1985, 1986 in the Chandler and Rental Truck Fleet.

Statistical Analysis

The objectives and methods employed were the same as for the SCRTD fleet. Data on fuel sulfur content were not available for these fleets; therefore, the assumption was made that based on geographic location, sulfur content change was similar to that observed by SCRTD.

1. Chandler Fleet Summary of Oil Analysis Variables - Table 6, Figures 36-38, present the summary of oil miles, iron (Fe) ppm, and zinc (Zn) ppm. There was no significant difference in the average oil miles between 1984 and 1985, 1986. Iron content decreased from 50 ppm in 1984 to 49 ppm in

Table 6. Comparison of Selected Data for Chandler Truck Fleet

Variable	Year	No.	Mean	Significant Difference*	Standard Deviation
Oil Miles	1984	33	3993.9		2721.2
	1985	275	3775.6	NS	2734.5
	1986	455	3412.0	NS	3112.7
Iron, ppm	1984	33	50.1		30.8
	1985	275	48.6	NS	48.6
	1986	455	44.7	NS	43.4
Zinc, ppm	1984	33	1183.0		217.7
	1985	275	1818.6	S	221.4
	1986	455	1940.6	S	161.8

* See Table 3.

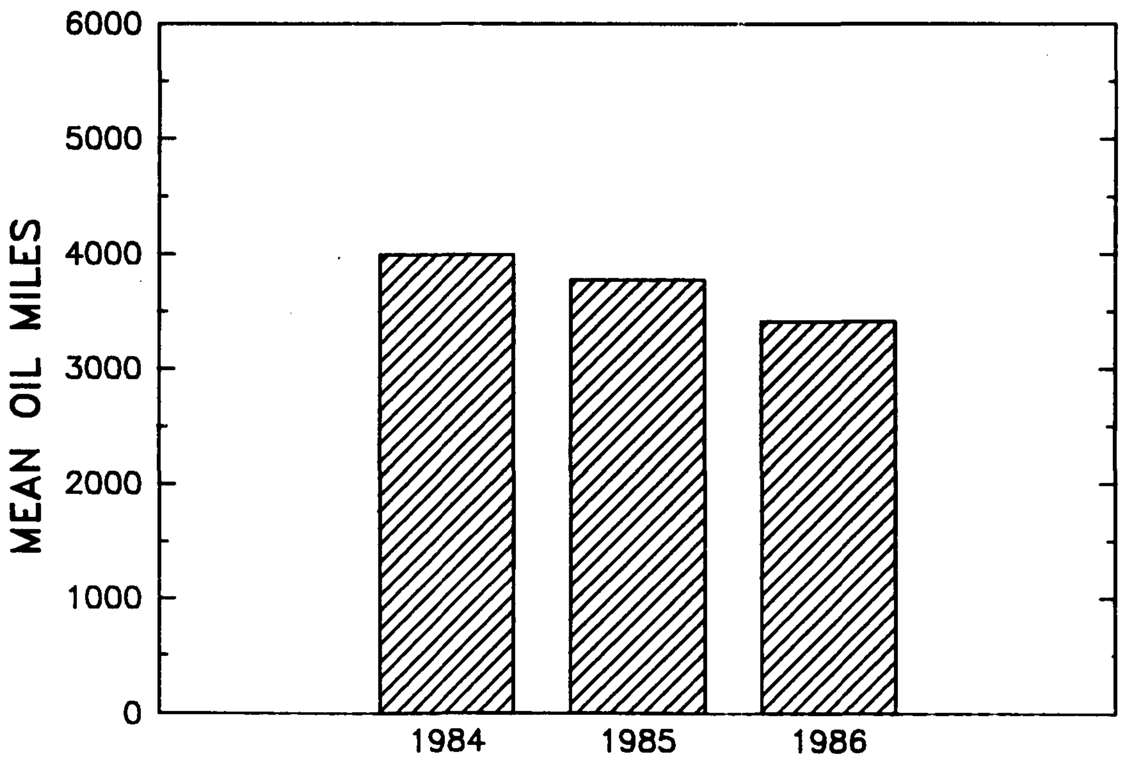

Figure 36. Chandler truck fleet, average oil miles

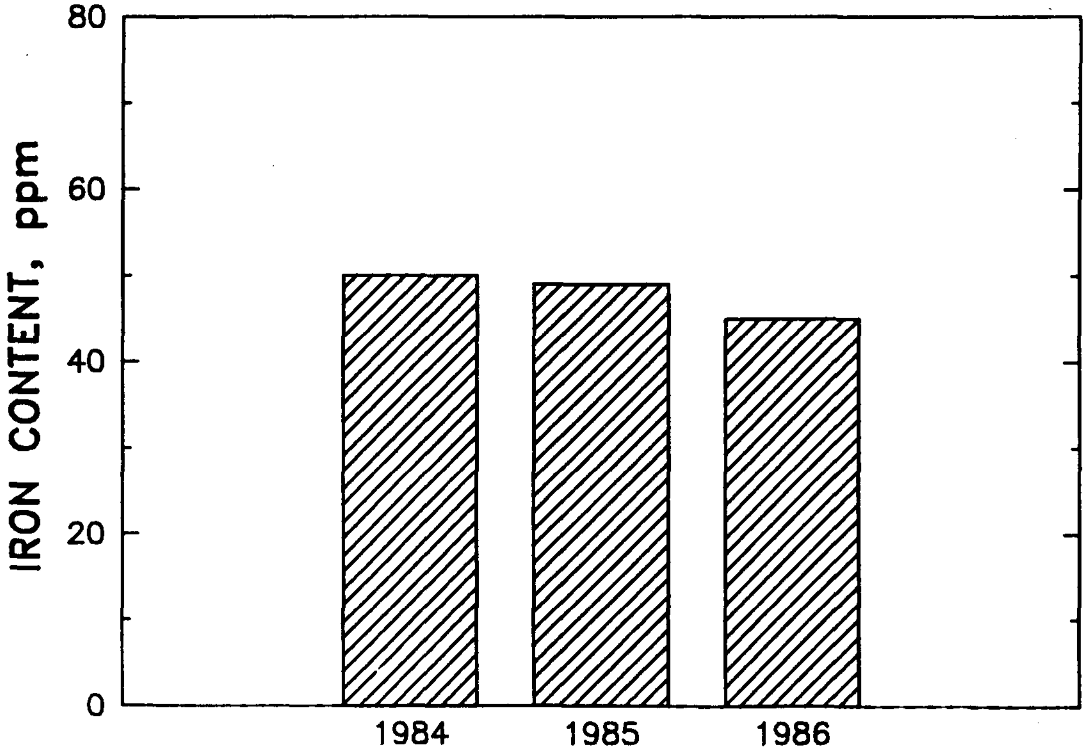

Figure 37. Chandler truck fleet, average iron content of lubricating oil

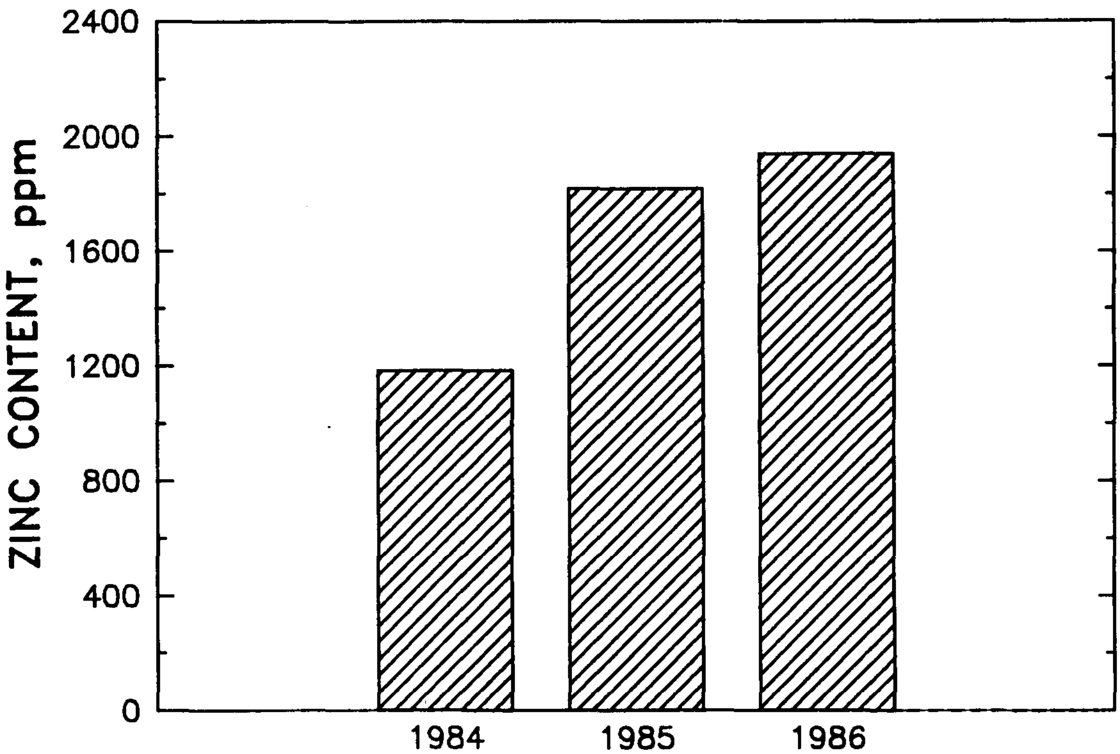

Figure 38. Chandler truck fleet, average zinc content of lubricating oil

1985 and finally to 45 ppm in 1986. However, these differences were not statistically significant. It is noteworthy to mention that the new oil zinc content was significantly different (59 percent higher) between 1984 and 1985, 1986. This indicates that different engine oils were used in 1984 and 1985-1986. The increase in zinc content was found to be consistent in all of the analyses. Therefore, because of the anti-wear properties of zinc oil additives, any reduction in used oil iron content could be caused in part by the increase in lubricant zinc level.(41)

2. Comparison Analysis by Engine Type - Table 7, Figures 39 through 50 present the comparison analyses for the different engine types powering the Chandler truck fleet. The 1984 data were not available for the Mack engines. Means and standard deviations are included for 1985 and 1986.

   a. Caterpillar Engine - There was a significant difference in the mean oil miles between 1984 and 1985-1986. The iron content for 1985 and 1986 decreased by 11 percent, an expected occurrence but not relative to the 54 percent decrease in oil-miles. The small sample size for 1985 possibly played a part in the results.

   b. Cummins Engine - There was no significant difference in the average oil-mile variable for 1984, 1985, and 1986; however, used oil iron content increased by 97 percent. It appears that the comparison was biased by the sample size for 1984.

   c. Detroit Diesel Engines - There was no statistical difference in the oil-miles mean or the used oil iron content between the three years. There was, however, a significant increase in oil zinc content between 1984 and 1985-1986. The increase in zinc could result in less used oil iron content. Overall the expected decrease in used oil iron content was not observed.

   d. Mack Engines - No data were available for 1984 for comparison to be made; however, there was a proportionate decrease in the oil-mile mean and the average iron ppm between 1985 and 1986.

3. Rental Truck Fleet Summary of Oil Analysis Variables - Table 8, Figures 51 through 54 present the results of 1984, 1985 and 1986 comparison analyses of used oil variable means. There were no significant differences

Table 7. Comparison of Selected Data for Chandler Truck Fleet by Engine Type

Variable	Year	No.	Mean	Significant Difference*	Standard Deviation
CATERPILLAR ENGINES					
Oil Miles	1984	6	2966.6		1069.1
	1985	54	1671.9	S	1285.9
	1986	82	1038.6	S	943.4
Iron, ppm	1984	6	72.9		24.9
	1985	54	78.2	NS	70.4
	1986	82	50.4	NS	38.5
Zinc, ppm	1984	6	1160.0		207.6
	1985	54	1794.8	S	237.1
	1986	82	1919.7	S	158.1
CUMMINS ENGINES					
Oil Miles	1984	5	5160.0		1424.0
	1985	74	4584.1	NS	2603.0
	1986	138	4404.3	NS	3202.4
Iron, ppm	1984	5	9.8		3.4
	1985	74	17.2	NS	7.6
	1986	138	21.6	S	14.5
Zinc, ppm	1984	5	1240.0		191.1
	1985	74	1808.2	S	176.0
	1986	138	1923.1	S	185.4
DETROIT DIESEL ENGINES					
Oil Miles	1984	22	4009.0		3162.2
	1985	119	4589.9	NS	2921.8
	1986	185	4251.8	NS	3262.9
Iron, ppm	1984	22	53.2		27.6
	1985	119	55.5	NS	44.7
	1986	185	62.3	NS	54.8
Zinc, ppm	1984	22	1176.3		232.4
	1985	119	1829.9	S	245.9
	1986	185	1957.4	S	147.5
MACK ENGINES					
Oil Miles	1984	0	0		0
	1985	28	2235.7		991.8
	1986	50	1458.0		749.9
Iron, ppm	1984	0	0		0
	1985	28	45.2		26.8
	1986	50	34.4		19.3
Zinc, ppm	1984	0	0		0
	1985	28	1844.2		191.3
	1986	50	1960.8		143.2

* See Table 3.

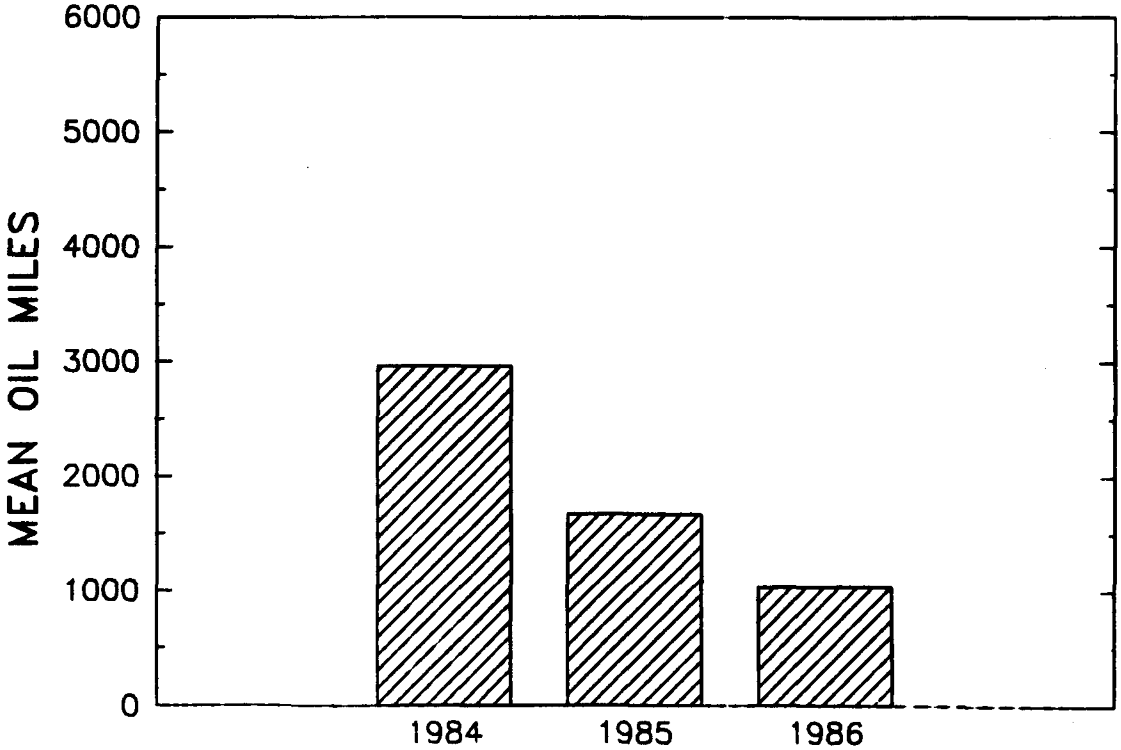

Figure 39. Chandler truck fleet, average oil miles (Caterpillar engine)

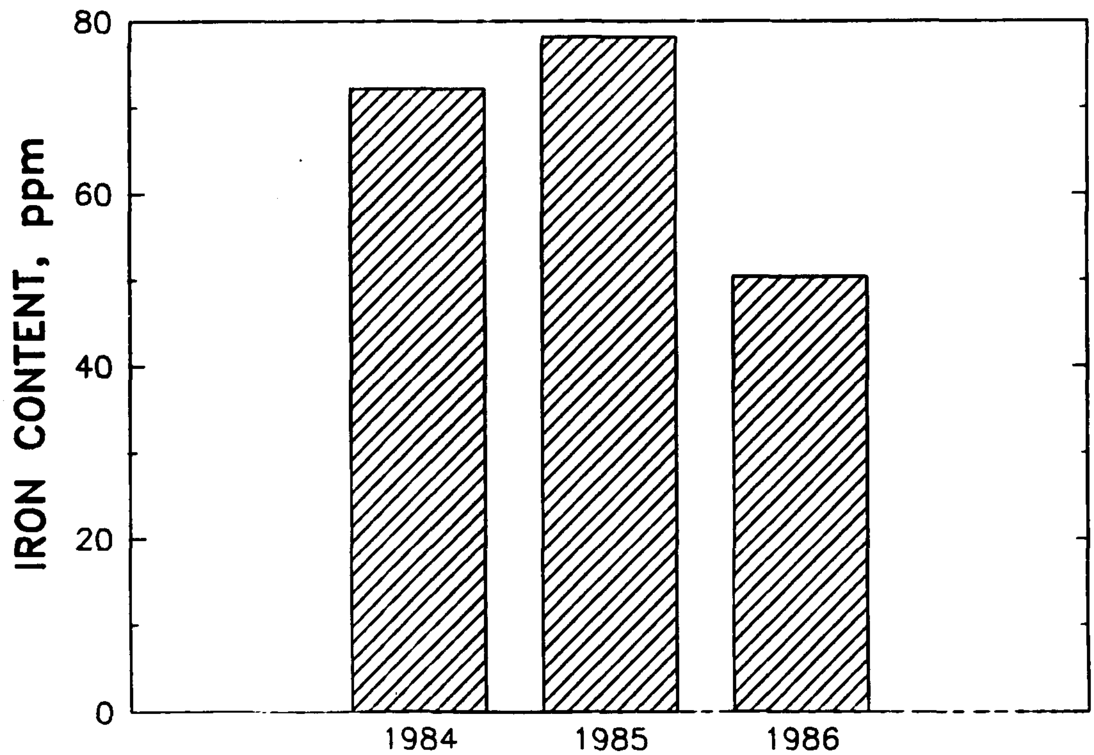

Figure 40. Chandler truck fleet, average iron content of lubricating oil (Caterpillar engine)

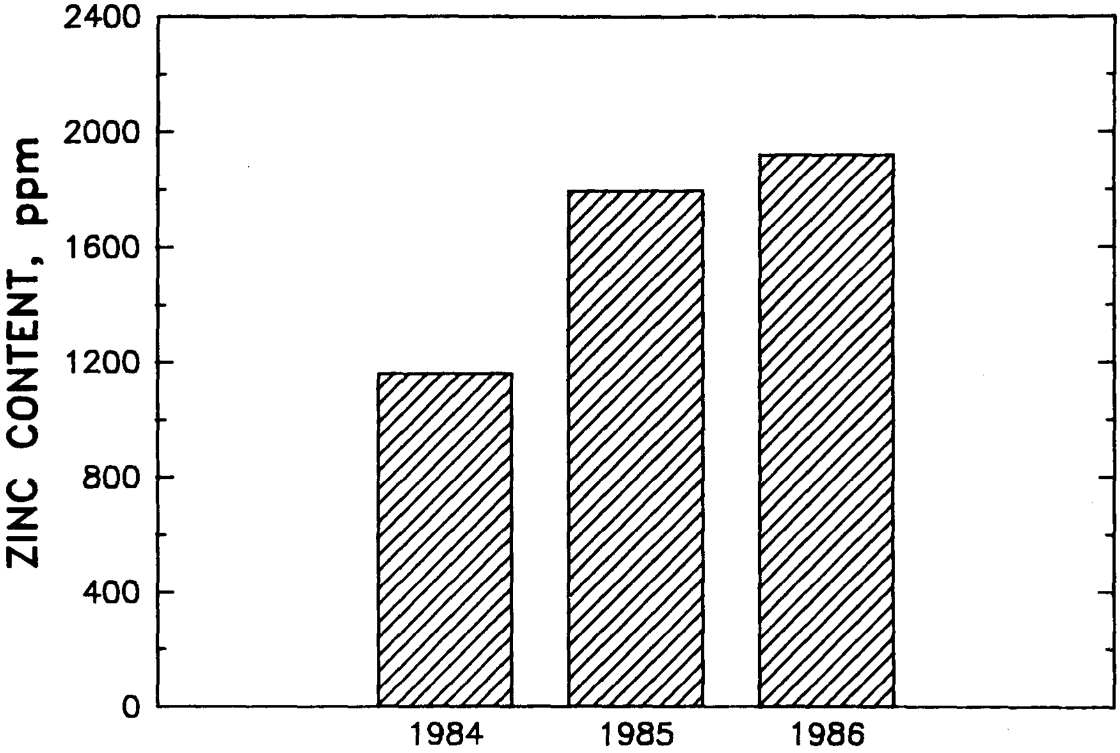

Figure 41. Chandler truck fleet, average zinc content of lubricating oil (Caterpillar engine)

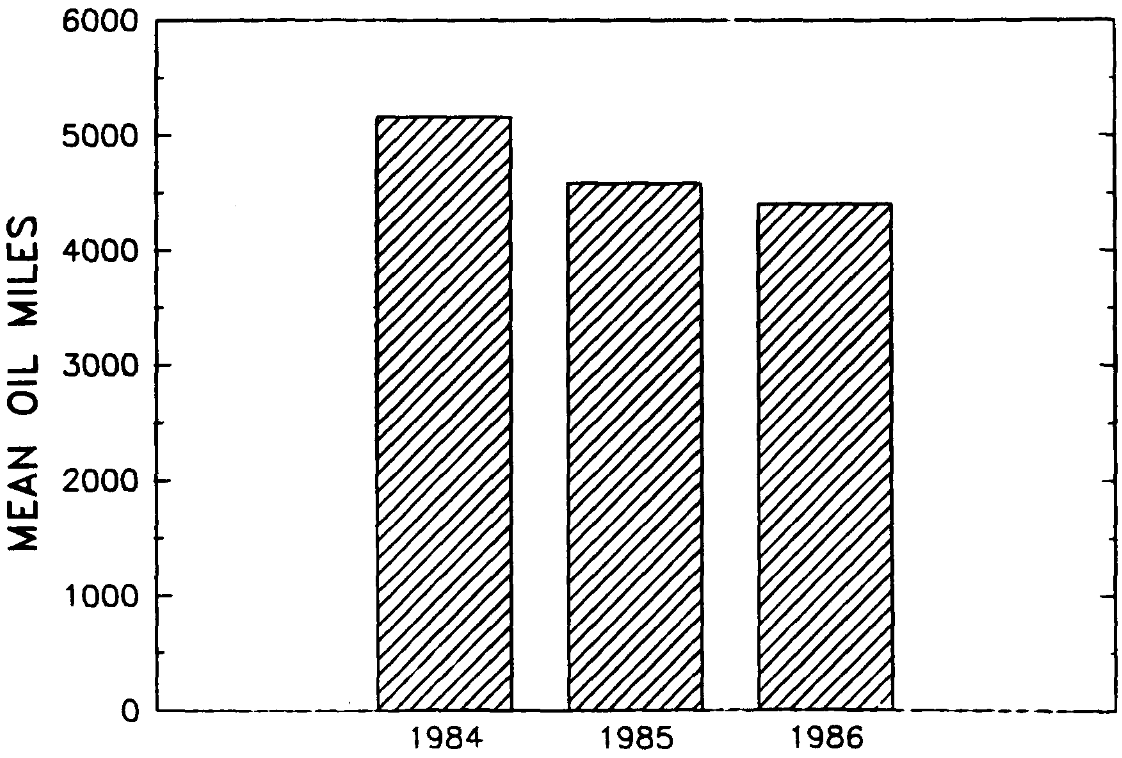

Figure 42. Chandler truck fleet, average oil miles (Cummins engine)

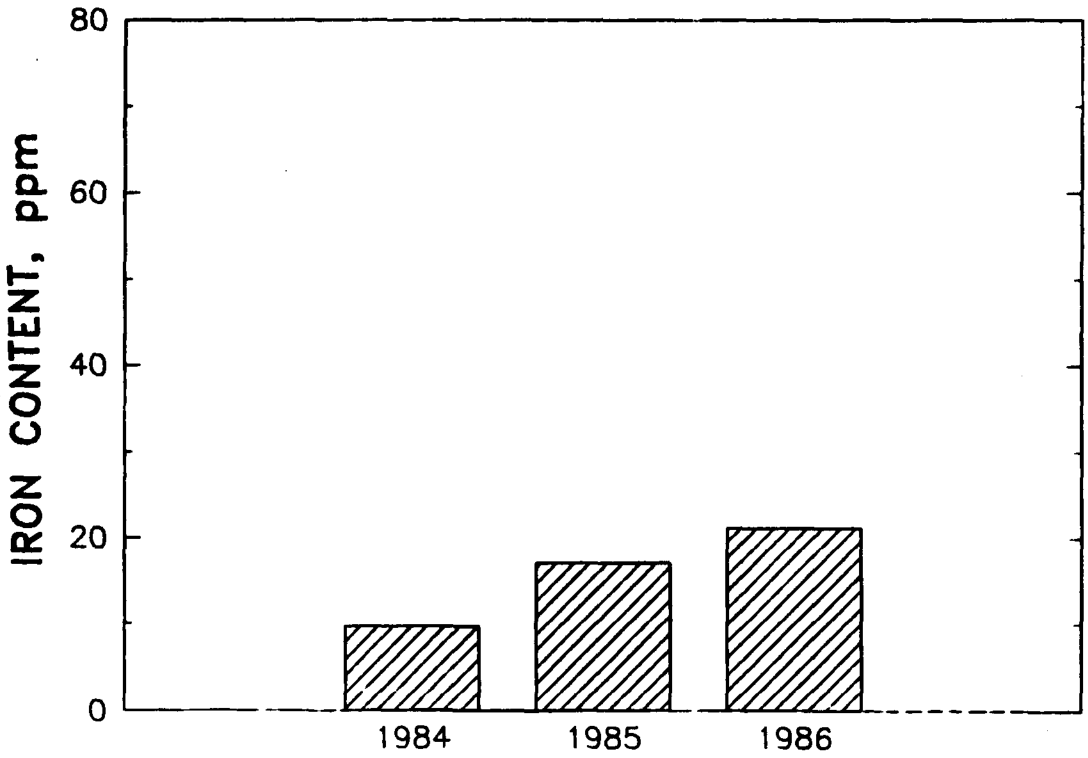

Figure 43. Chandler truck fleet, average iron content of lubricating oil (Cummins engine)

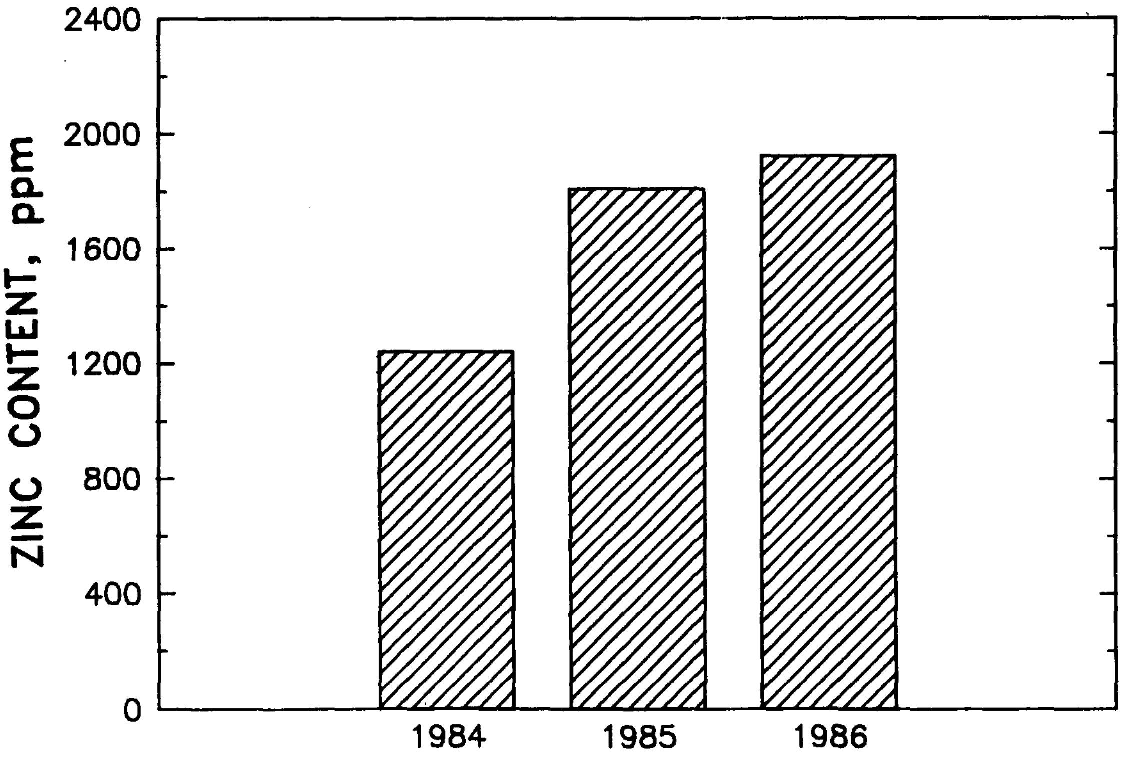

Figure 44. Chandler truck fleet, average zinc content of lubricating oil (Cummins engine)

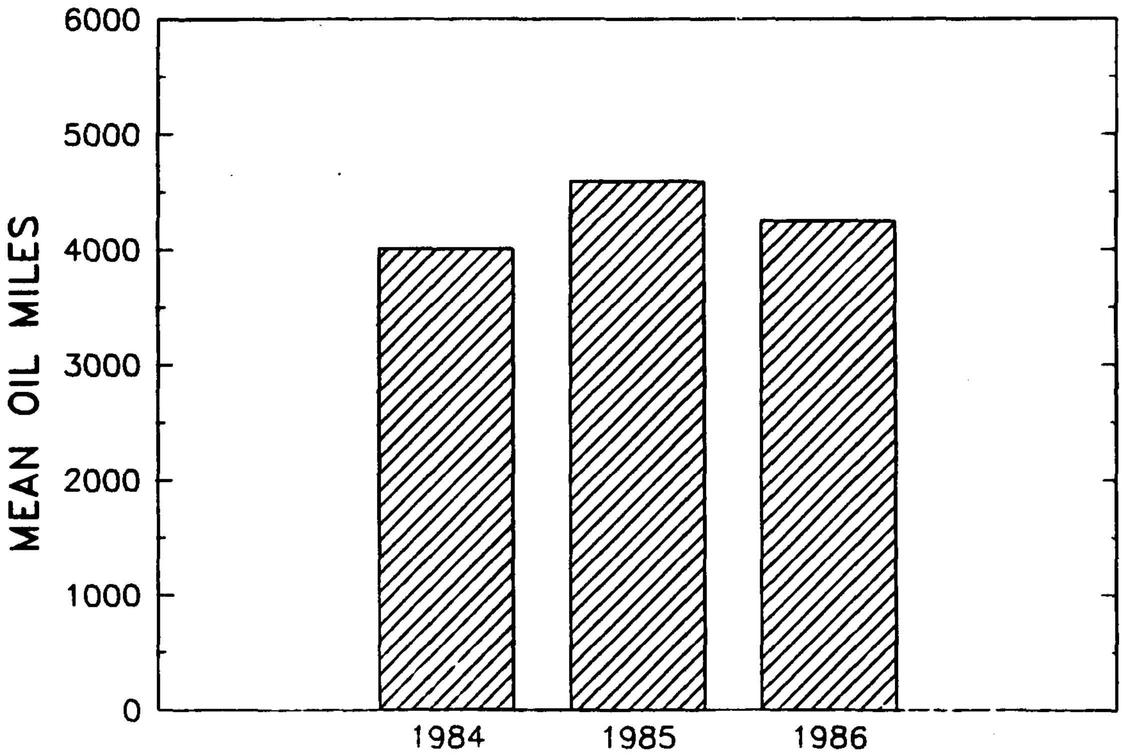

Figure 45. Chandler truck fleet, average oil miles (Detroit Diesel engine)

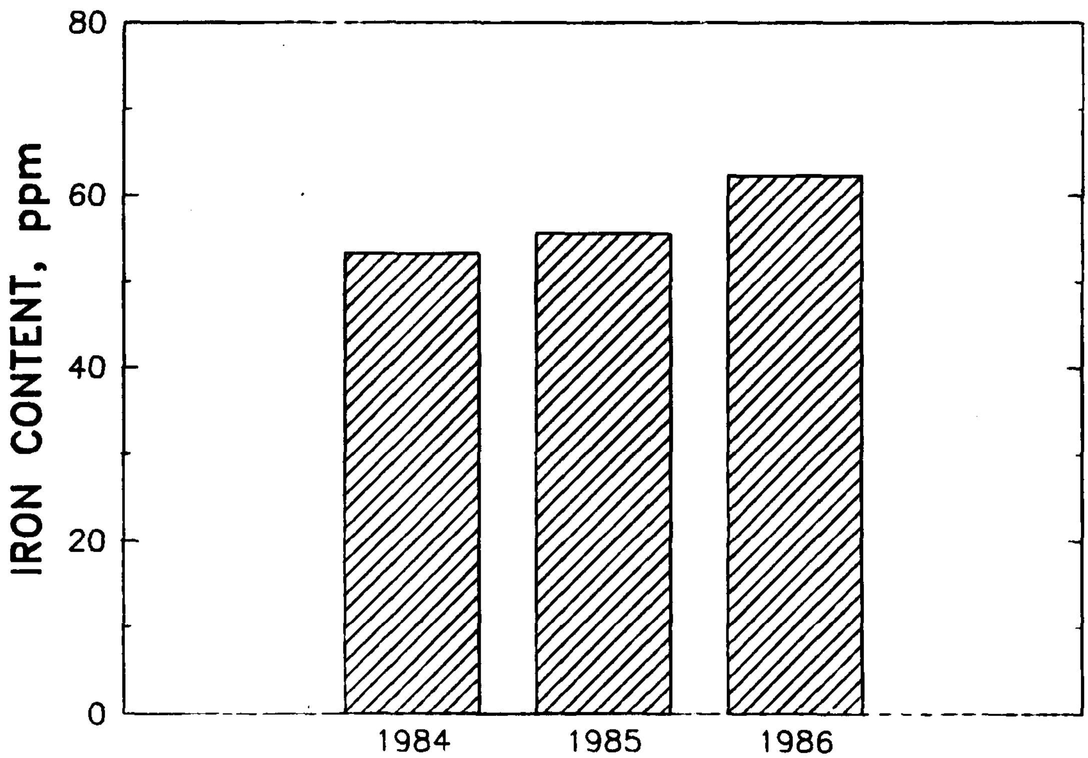

Figure 46. Chandler truck fleet, average iron content of lubricating oil (Detroit Diesel engine)

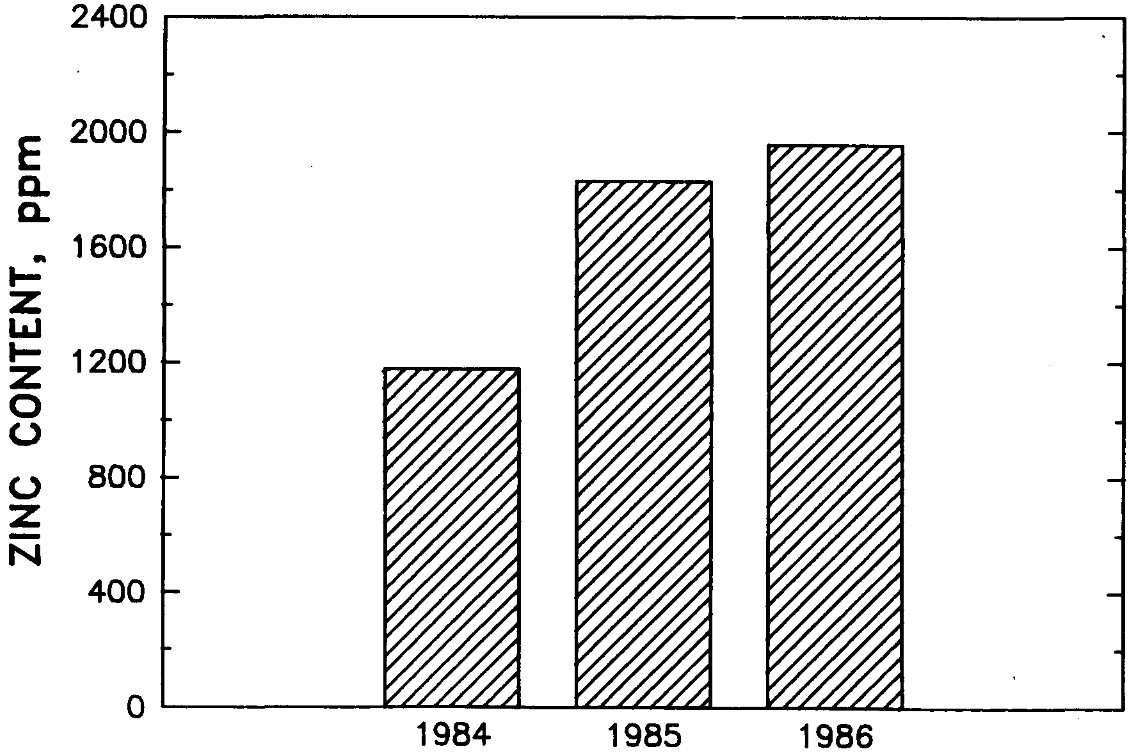

Figure 47. Chandler truck fleet, average zinc content of lubricating oil (Detroit Diesel engine)

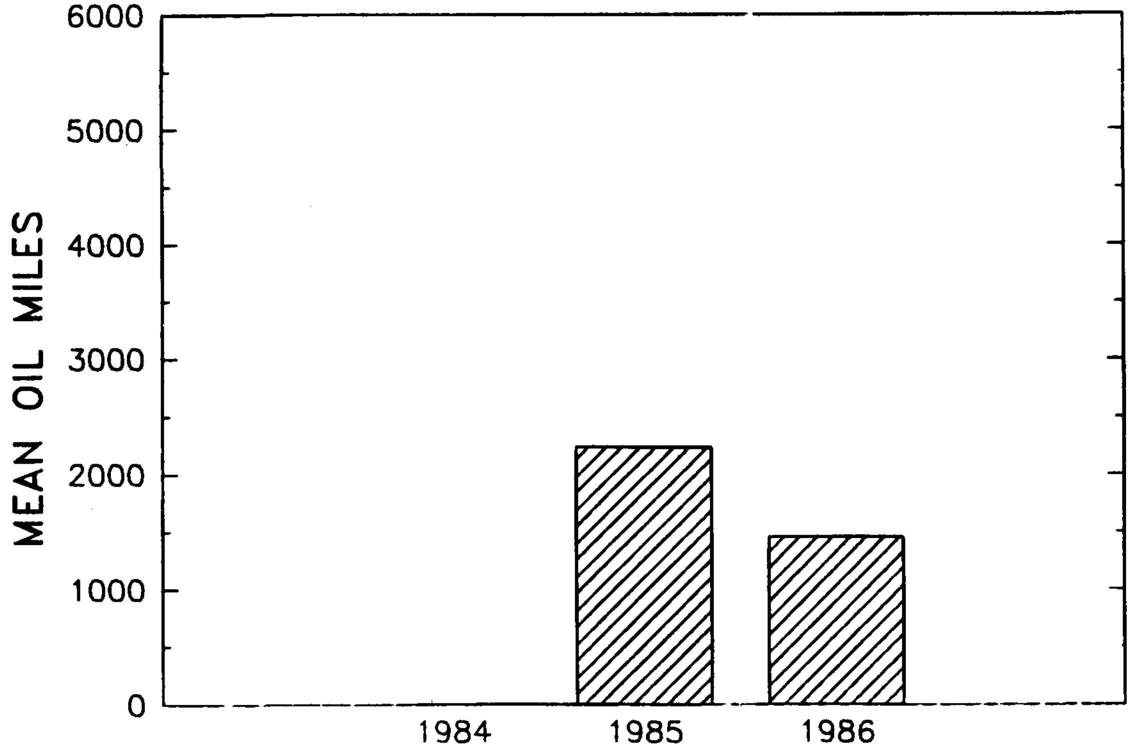

Figure 48. Chandler truck fleet, average oil miles (Mack engine)

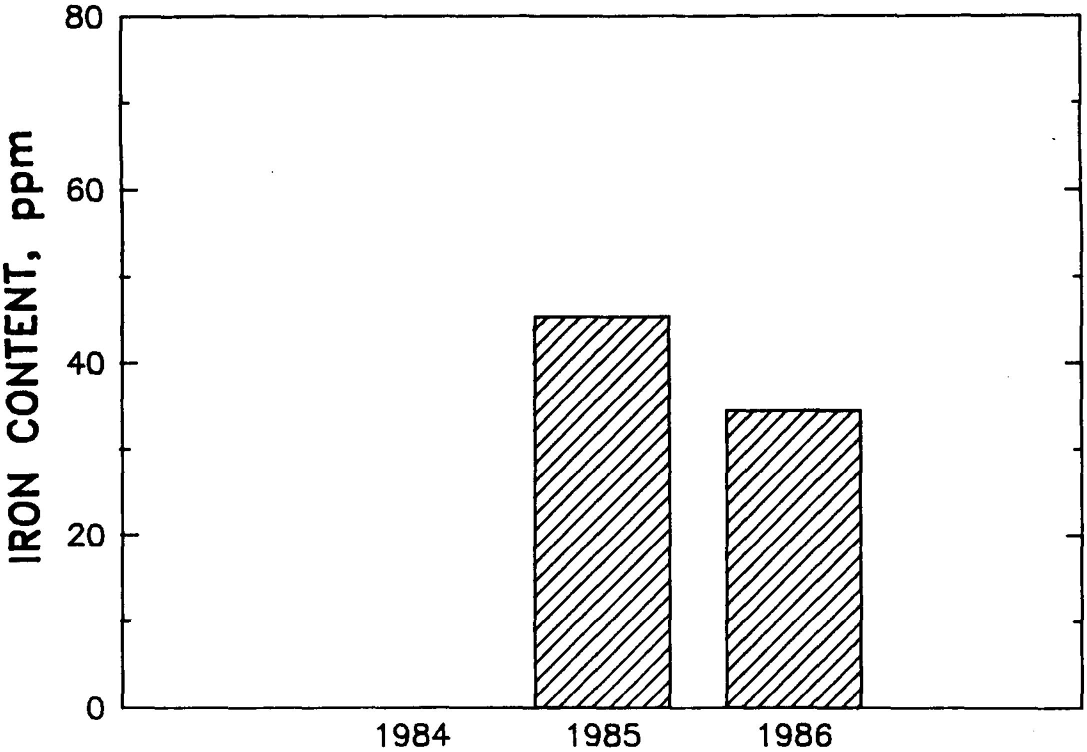

Figure 49. Chandler truck fleet, average iron content of lubricating oil (Mack engine)

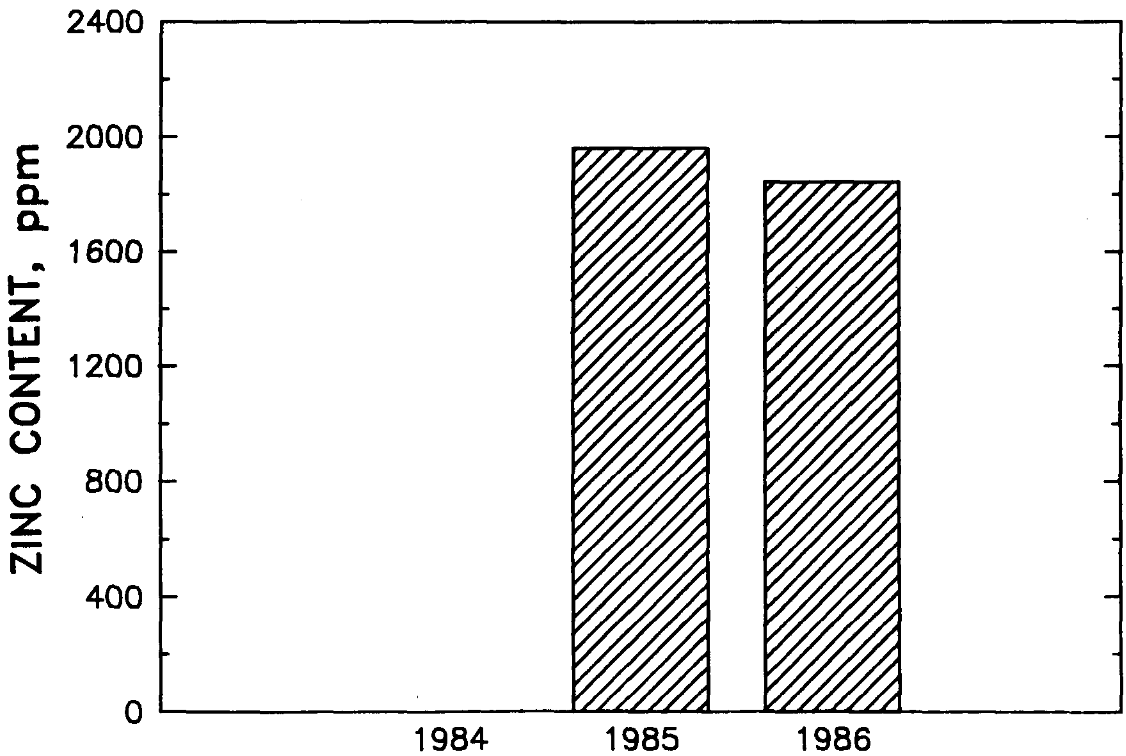

Figure 50. Chandler truck fleet, average zinc content of lubricating oil (Mack engine)

Table 8. Comparison of Selected Data for Rental Truck Fleet

Variable	Year	No.	Mean	Significant Difference*	Standard Deviation
Oil Miles	1984	264	7808.0		3019.5
	1985	329	7514.6	NS	3036.4
	1986	384	8307.8	NS	3591.5
Iron, ppm	1984	264	74.4		44.7
	1985	329	57.3	S	31.2
	1986	384	53.7	S	38.1
Zinc, ppm	1984	264	1410.9		299.2
	1985	329	1674.1	S	263.8
	1986	384	1818.4	S	290.6

* See Table 3.

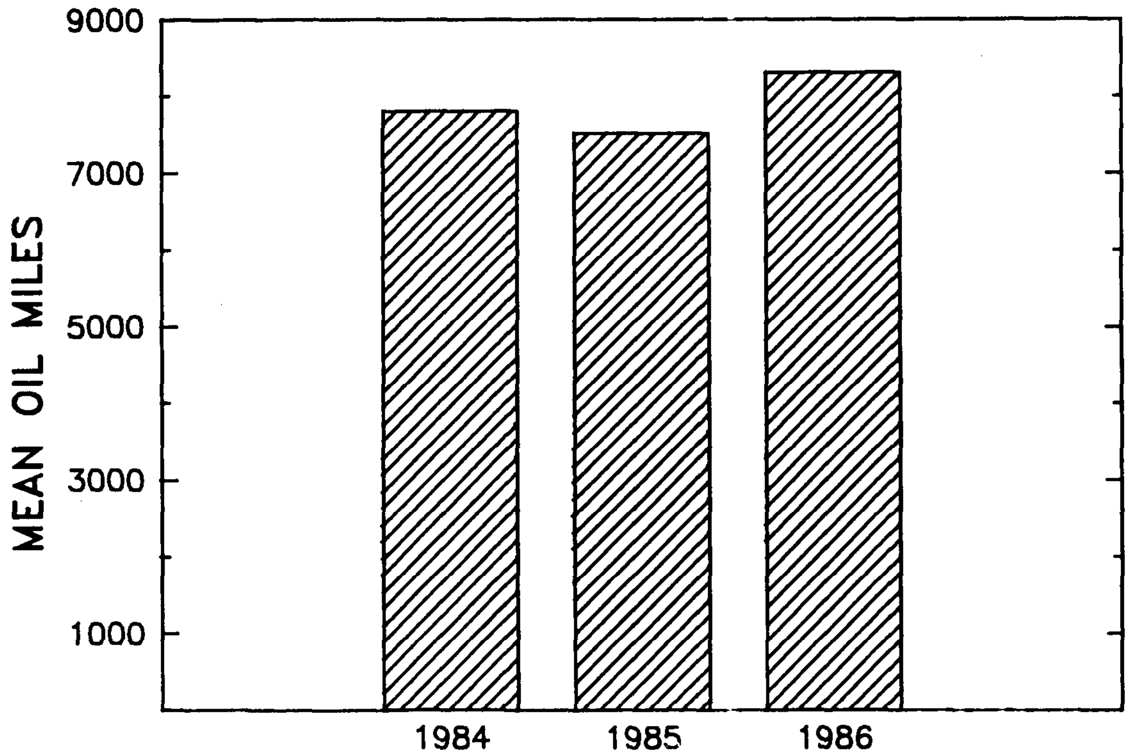

Figure 51. Rental truck fleet, average oil miles

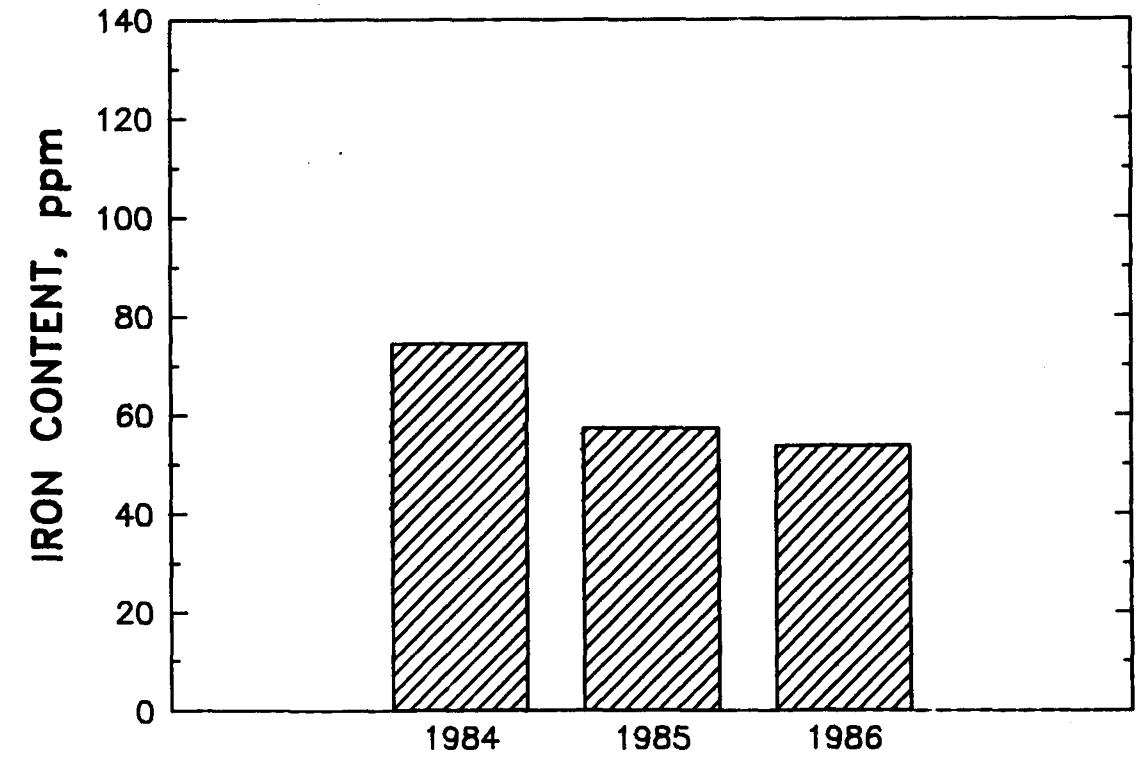

Figure 52. Rental truck fleet, average iron content of lubricating oil

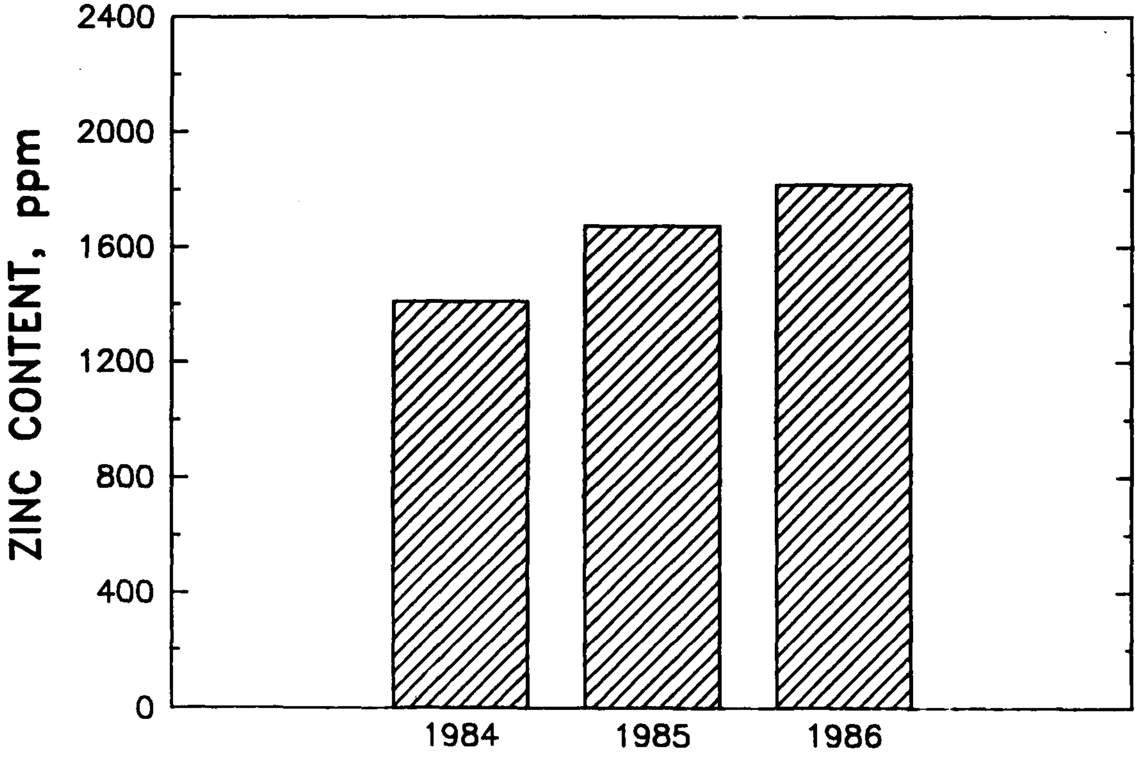

Figure 53. Rental truck fleet, average zinc content of lubricating oil

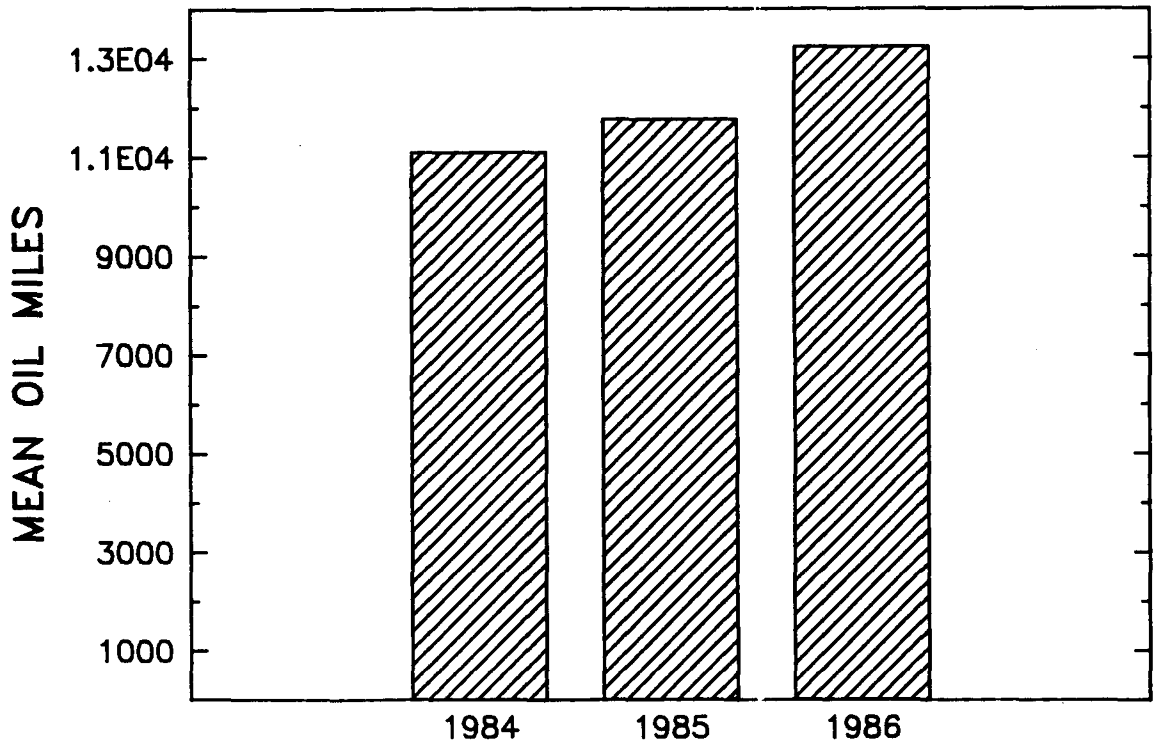

Figure 54. Rental truck fleet, average oil miles (Cummins engine)

between the oil-miles for 1984 and 1985-1986. There can be seen, however, a significant decrease of iron ppm. Normally the iron content would be expected to remain relatively constant given the closeness in the oil-mile means. Instead, we see a 25 percent decrease between 1984 and 1985-1986. The increase in zinc content from the anti-wear additive may have had a minor effect on the iron reduction; however, the low sulfur fuel appears to have significantly contributed to the decrease in iron content.

4. Comparison Analyses by Engine Type - Table 9, Figures 55 through 71, show the comparison analyses for the engine groups in the Rental truck fleet. The zinc variable shows an increase of approximately 25 percent thoughout the engine groups. Due to the anti-wear properties of zinc oil additives, it can be reasoned that zinc may have had an effect in the reduction of iron ppm in addition to the low sulfur fuel.(41)

Table 9. Comparison of Selected Data for Rental Truck Fleet by Engine Type

Variable	Year	No.	Mean	Significant Difference*	Standard Deviation
CUMMINS ENGINES					
Oil Miles	1984	38	11110.3		3194.4
	1985	34	11769.4	NS	3199.2
	1986	51	13235.8	S	4314.5
Iron, ppm	1984	38	34.8		18.3
	1985	34	32.5	NS	18.0
	1986	51	37.3	NS	21.1
Zinc, ppm	1984	38	1347.3		257.9
	1985	34	1567.6	S	204.8
	1986	51	1806.4	S	152.7
DETROIT DIESEL ENGINES					
Oil Miles	1984	126	7973.0		2753.9
	1985	162	7602.3	NS	2565.7
	1986	200	8408.5	NS	2711.5
Iron, ppm	1984	126	85.3		47.7
	1985	162	62.9	S	33.2
	1986	200	56.4	S	24.2
Zinc, ppm	1984	126	1363.9		274.5
	1985	162	1653.6	S	302.6
	1986	200	1756.4	S	299.7
DUETZ ENGINES					
Oil Miles	1984	8	7633.7		1507.2
	1985	16	8462.0	NS	4196.0
	1986	20	7494.0	NS	3634.0
Iron, ppm	1984	8	128.3		35.0
	1985	16	82.3	NS	30.9
	1986	20	102.1	NS	120.3
Zinc, ppm	1984	8	1932.5		603.4
	1985	16	1948.1	NS	245.6
	1986	20	2217.7	NS	473.1
GMC ENGINES					
Oil Miles	1984	2	7038.5		126.5
	1985	2	6994.5	NS	747.4
	1986	4	5777.5	NS	865.7
Iron, ppm	1984	2	31.0		2.8
	1985	2	18.0	NS	8.4
	1986	4	8.7	S	2.7
Zinc, ppm	1984	2	1115.0		77.8
	1985	2	1615.0	S	134.3
	1986	4	1635.0	S	49.3
INTERNATIONAL HARVESTER ENGINES					
Oil Miles	1984	90	6211.7		2140.8
	1985	114	5982.4	NS	2018.5
	1986	108	5978.7	NS	2003.4
Iron, ppm	1984	90	72.0		36.4
	1985	114	53.8	S	26.1
	1986	108	49.3	S	25.8
Zinc, ppm	1984	90	1463.8		261.4
	1985	114	1700.1	S	186.9
	1986	108	1862.2	S	185.7

* See Table 3.

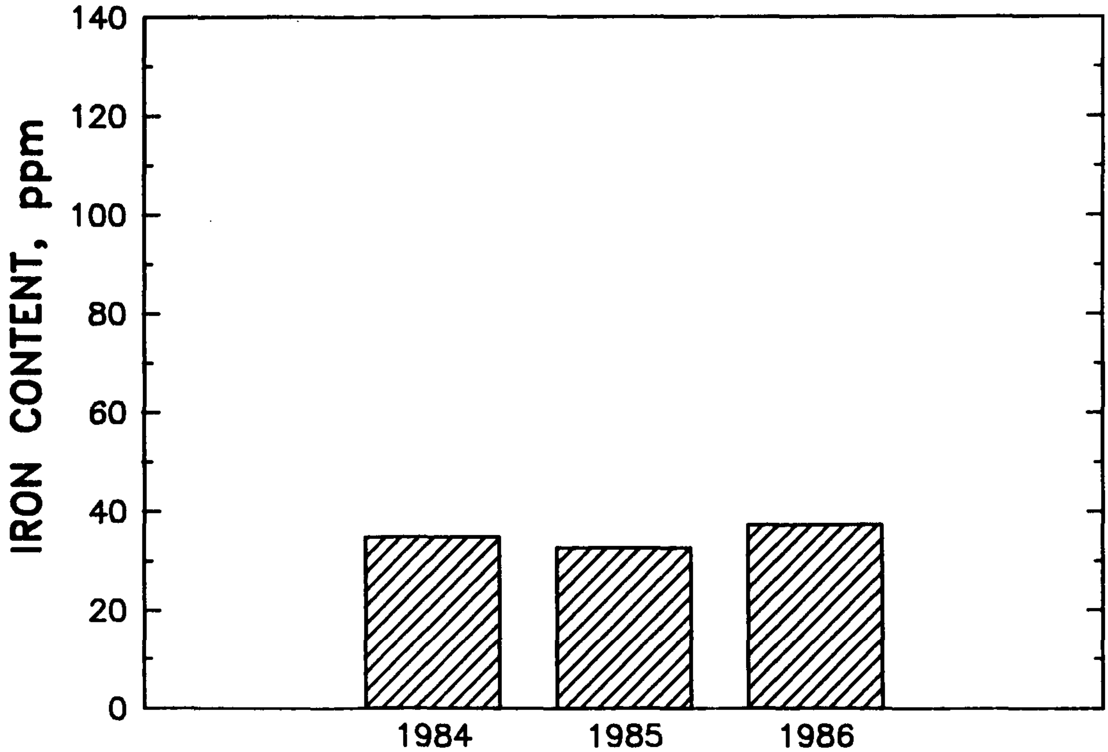

Figure 55. Rental truck fleet, average iron content of lubricating oil (Cummins engine)

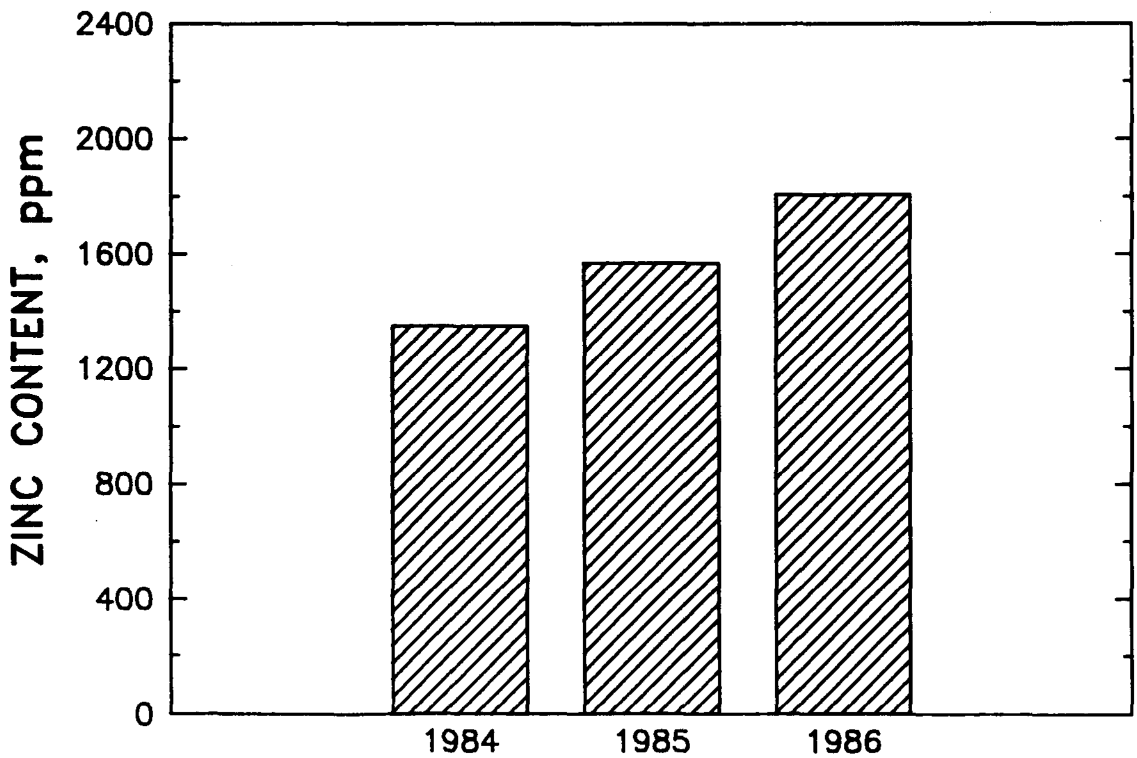

Figure 56. Rental truck fleet, average zinc content of lubricating oil (Cummins engine)

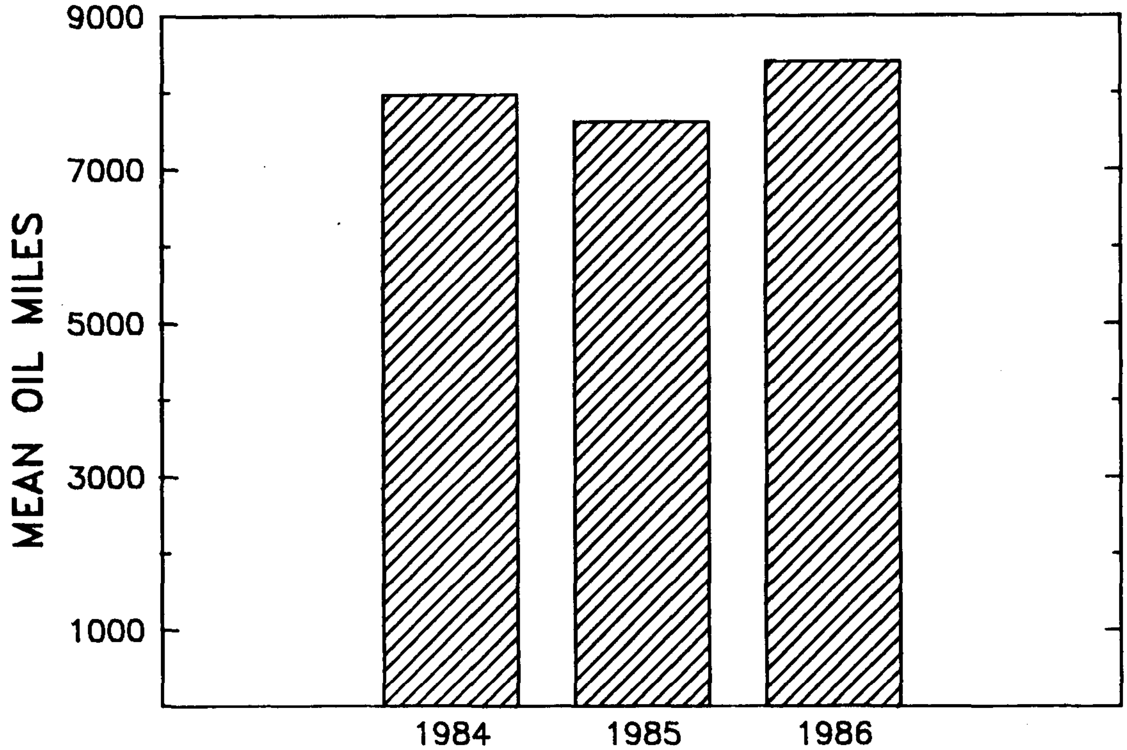

Figure 57. Rental truck fleet, average oil miles (Detroit Diesel engine)

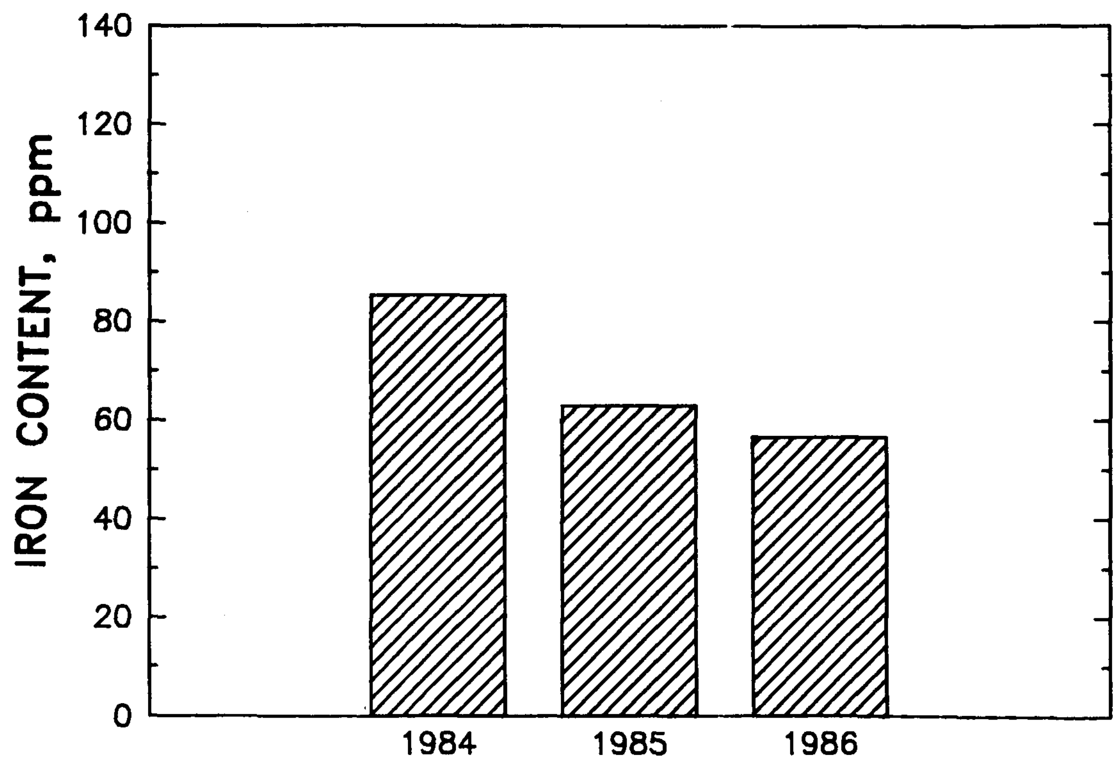

Figure 58. Rental truck fleet, average iron content of lubricating oil (Detroit Diesel engine)

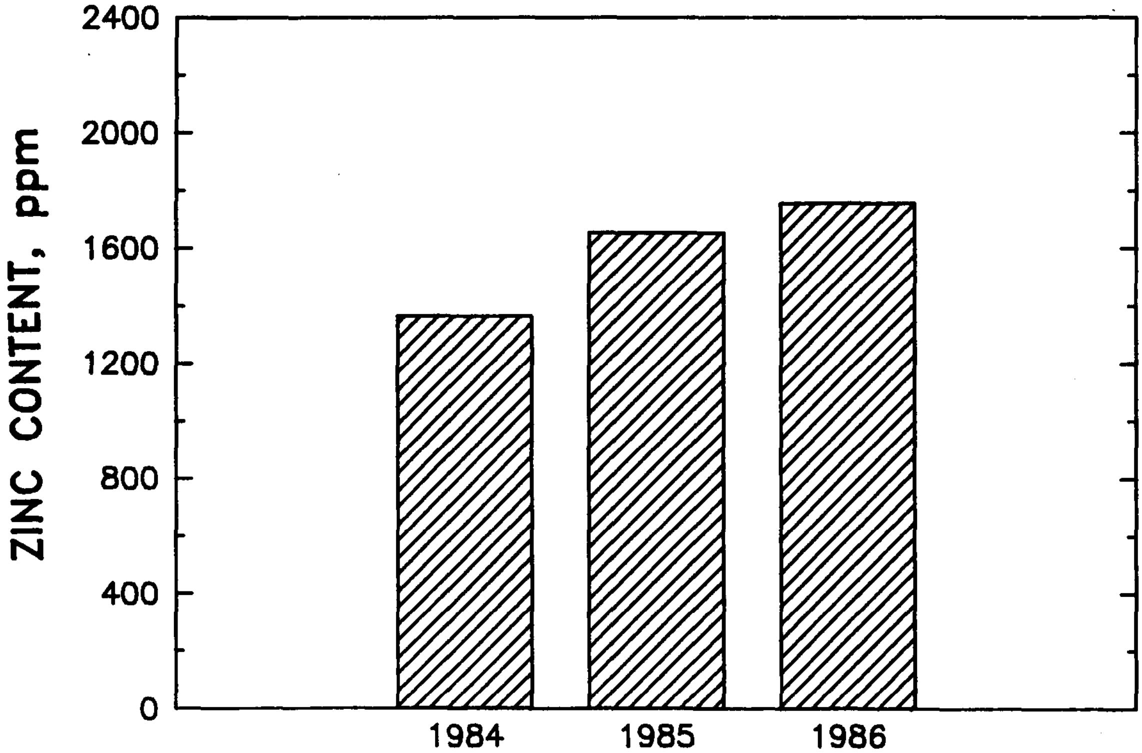

Figure 59. Rental truck fleet, average zinc content of lubricating oil (Detroit Diesel engine)

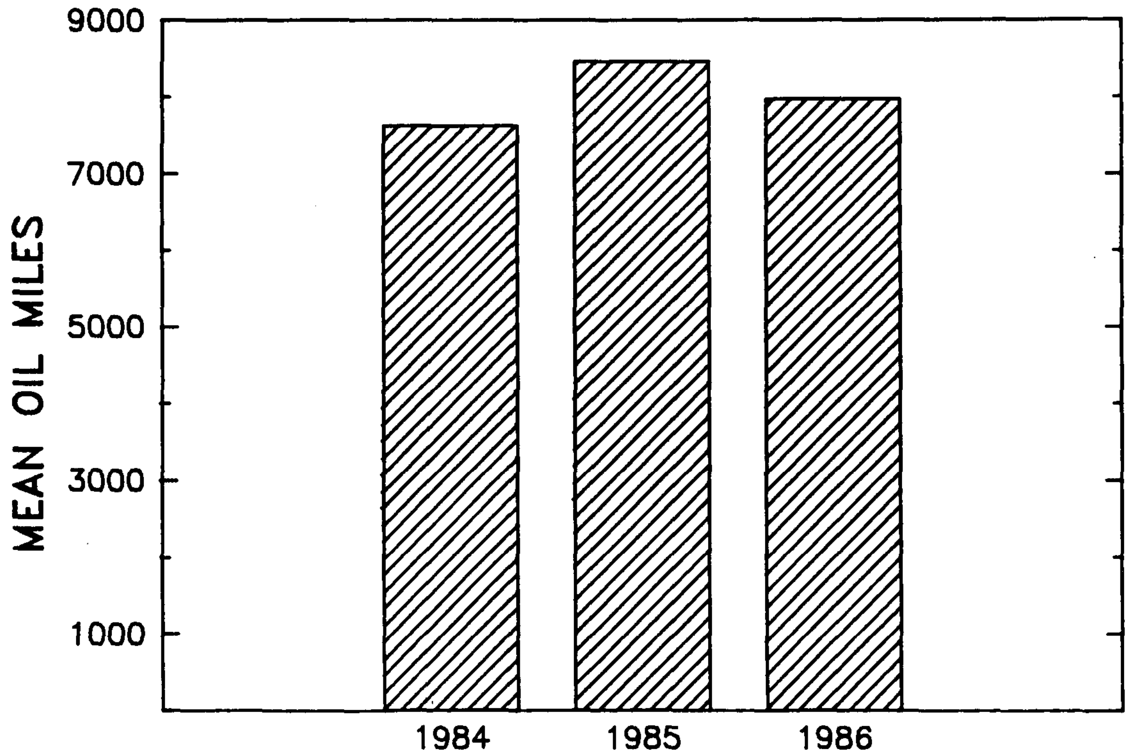

Figure 60. Rental truck fleet, average oil miles (Deutz engine)

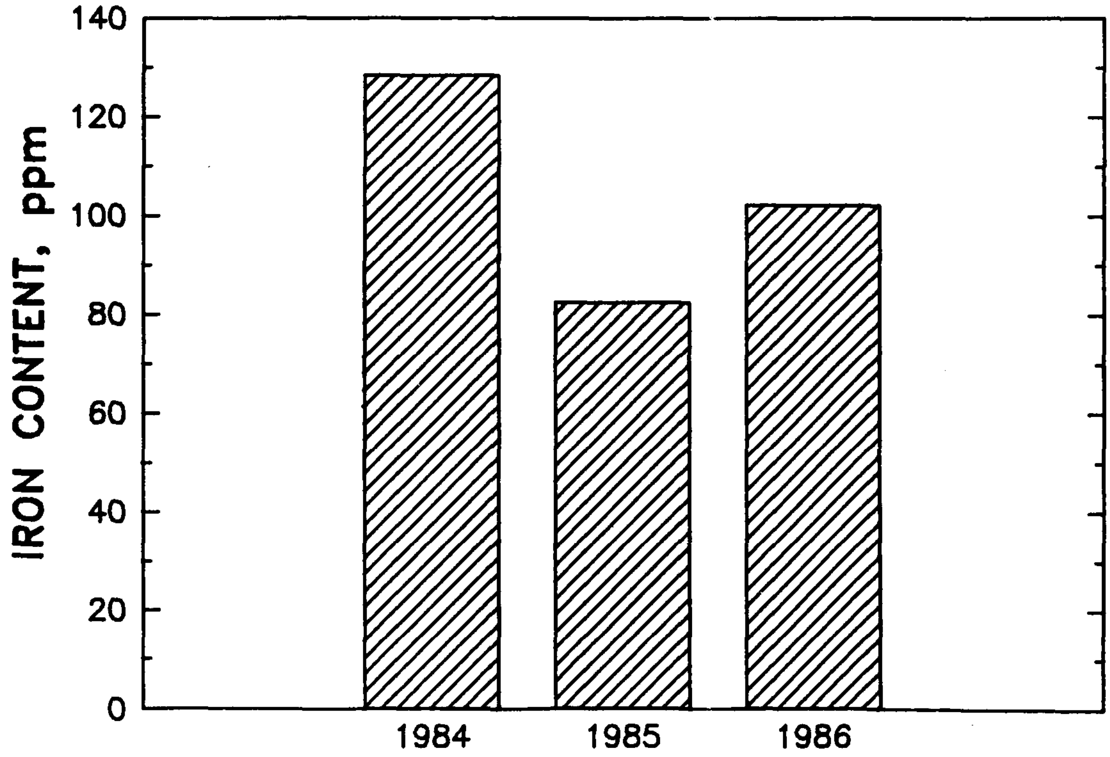

Figure 61. Rental truck fleet, average iron content of lubricating oil (Deutz engine)

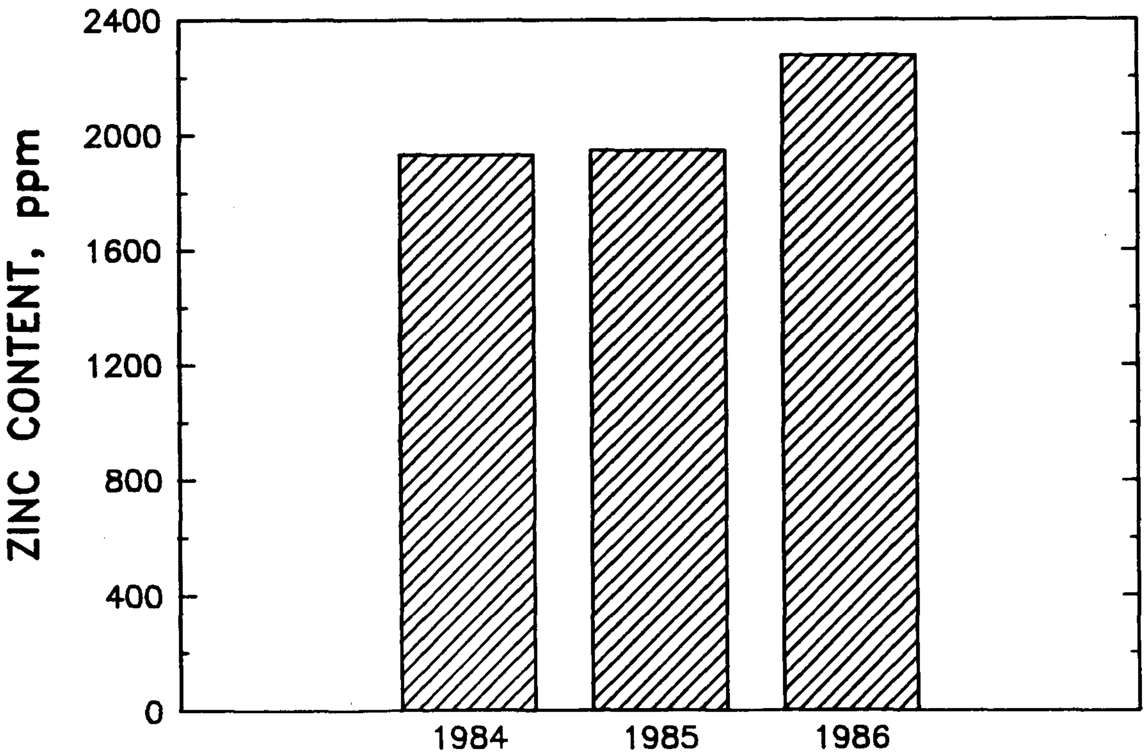

Figure 62. Rental truck fleet, average zinc content of lubricating oil (Deutz engine)

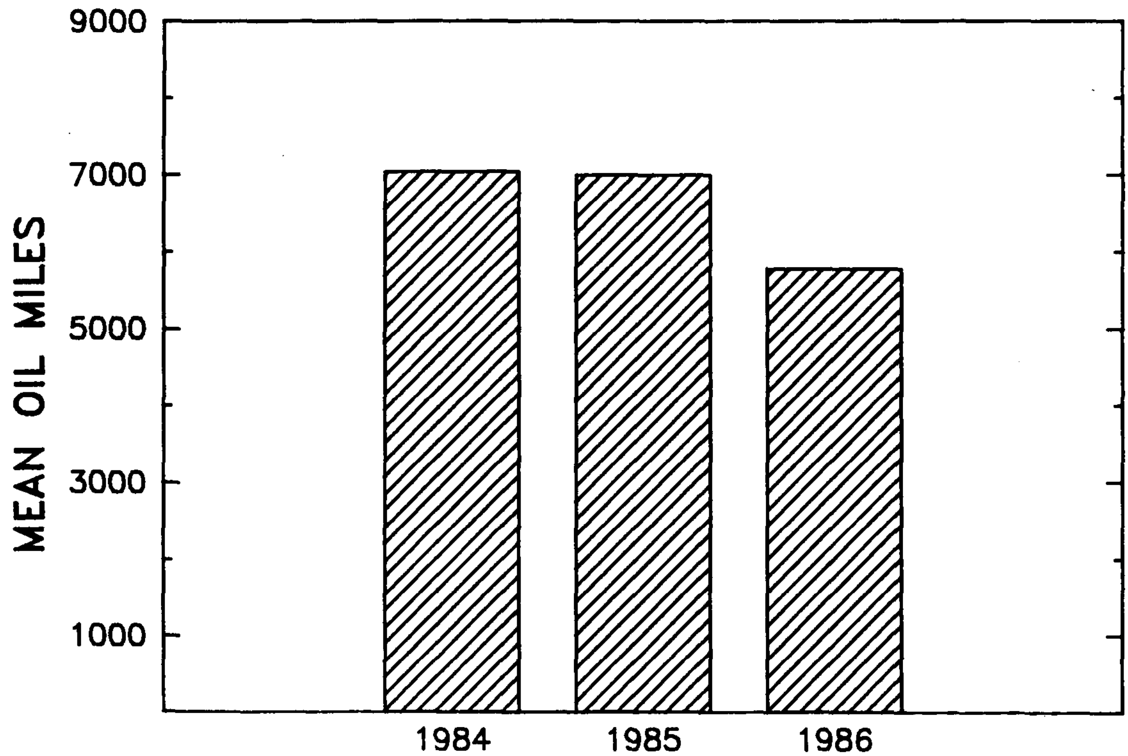

Figure 63. Rental truck fleet, average oil miles (GMC engine)

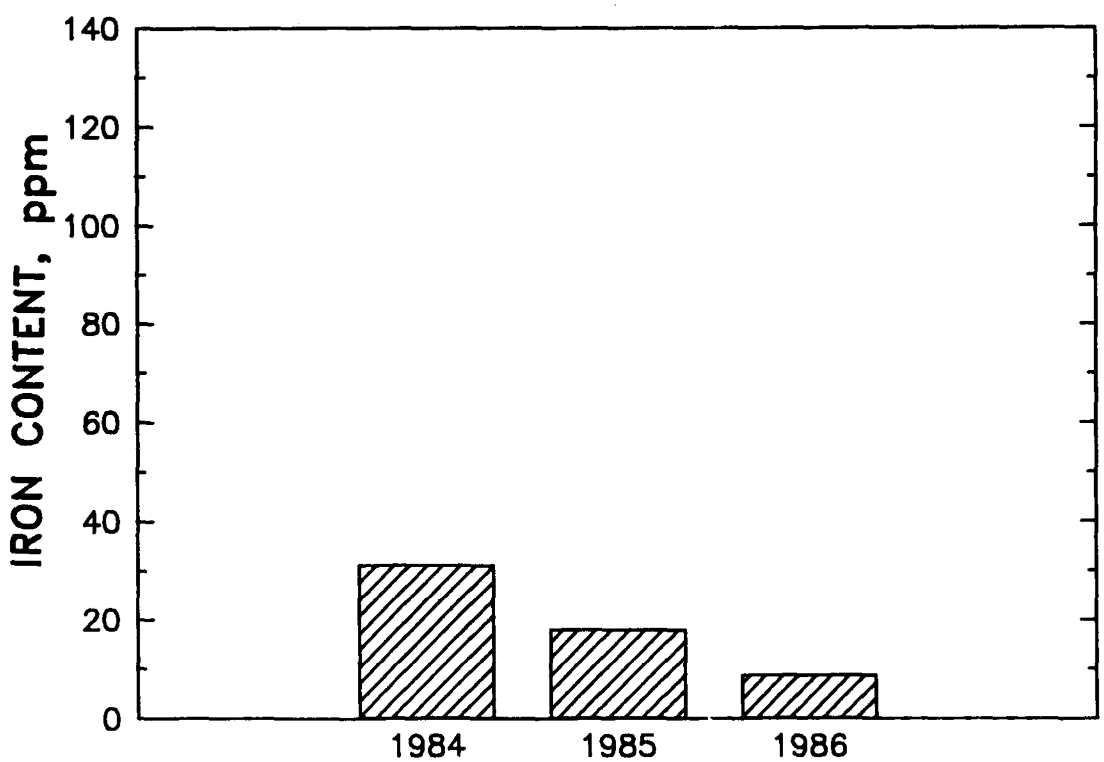

Figure 64. Rental truck fleet, average iron content of lubricating oil (GMC engine)

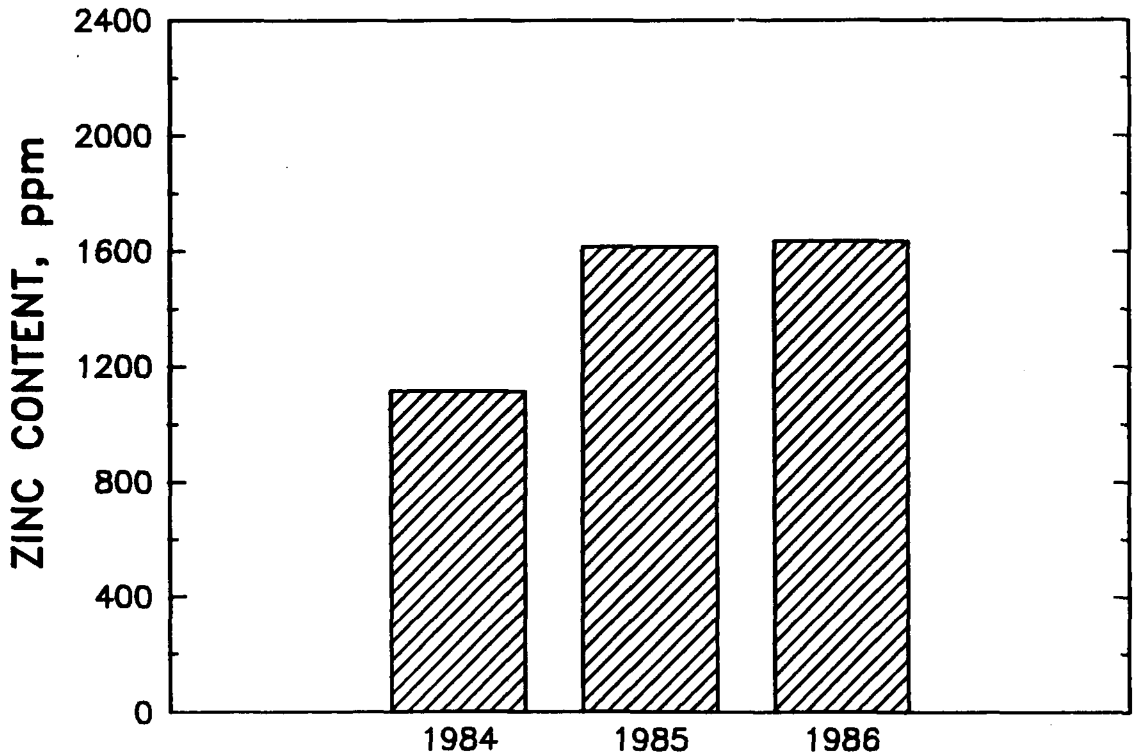

Figure 65. Rental truck fleet, average zinc content of lubricating oil (GMC engine)

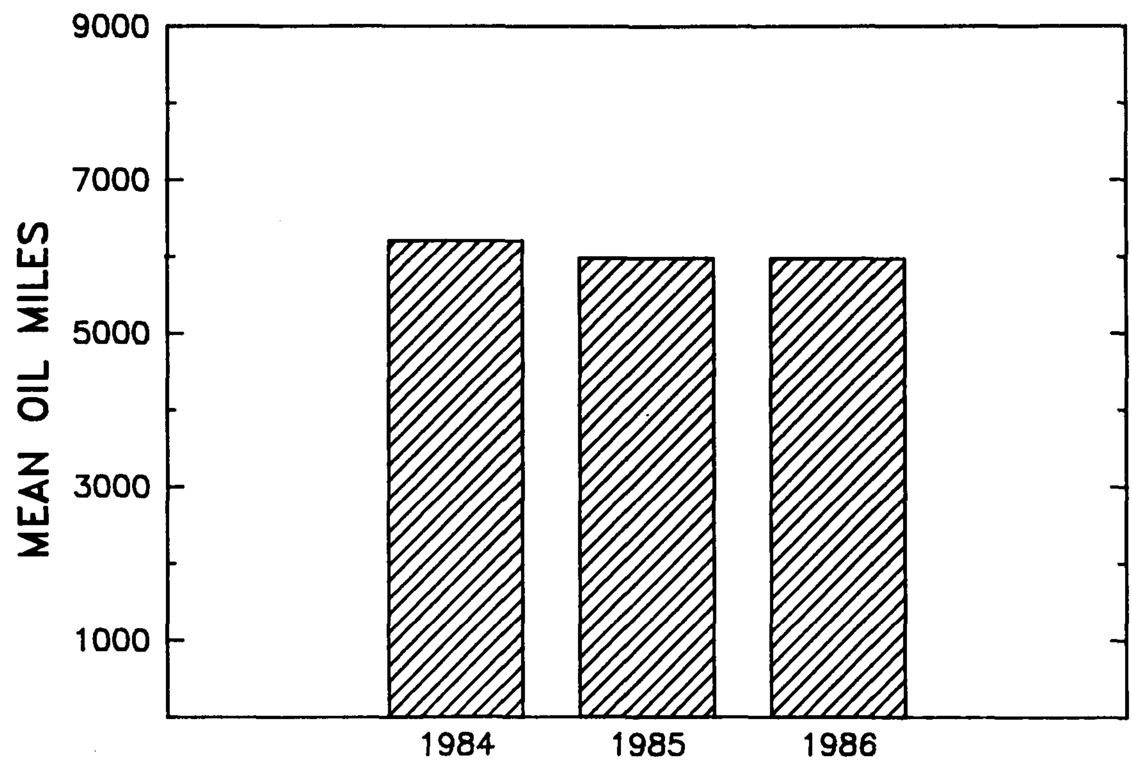

Figure 66. Rental truck fleet, average oil miles (Inter-Harvester engine)

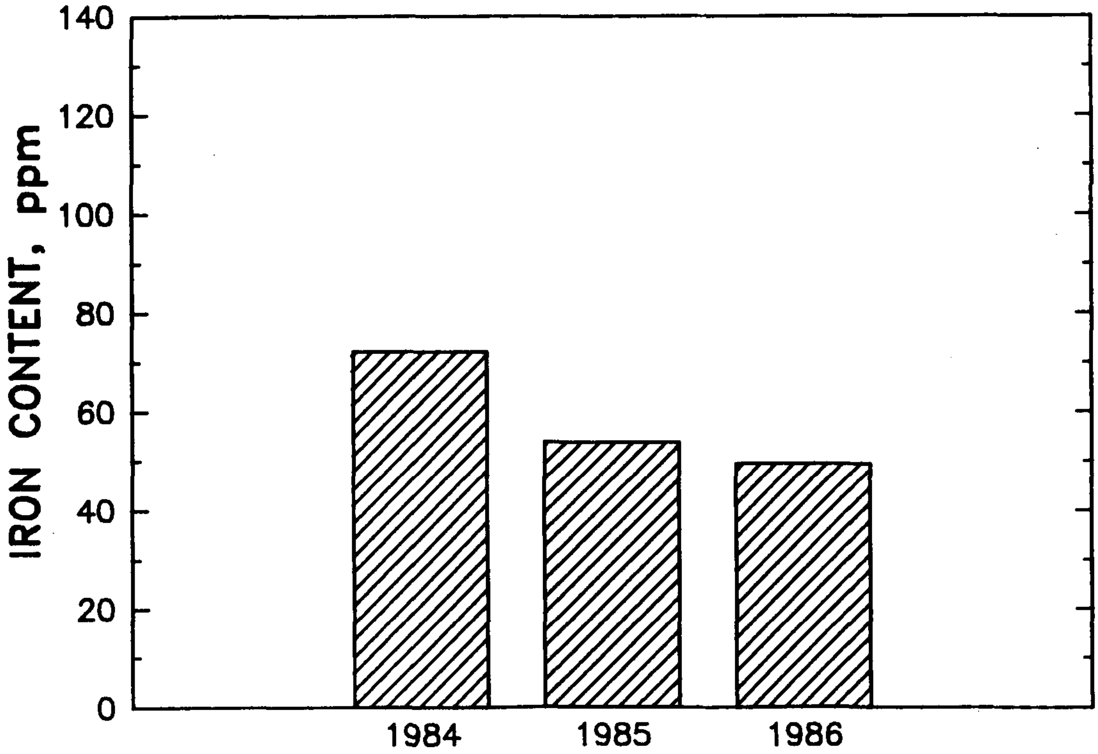

Figure 67. Rental truck fleet, average iron content of lubricating oil (Inter-Harvester engine)

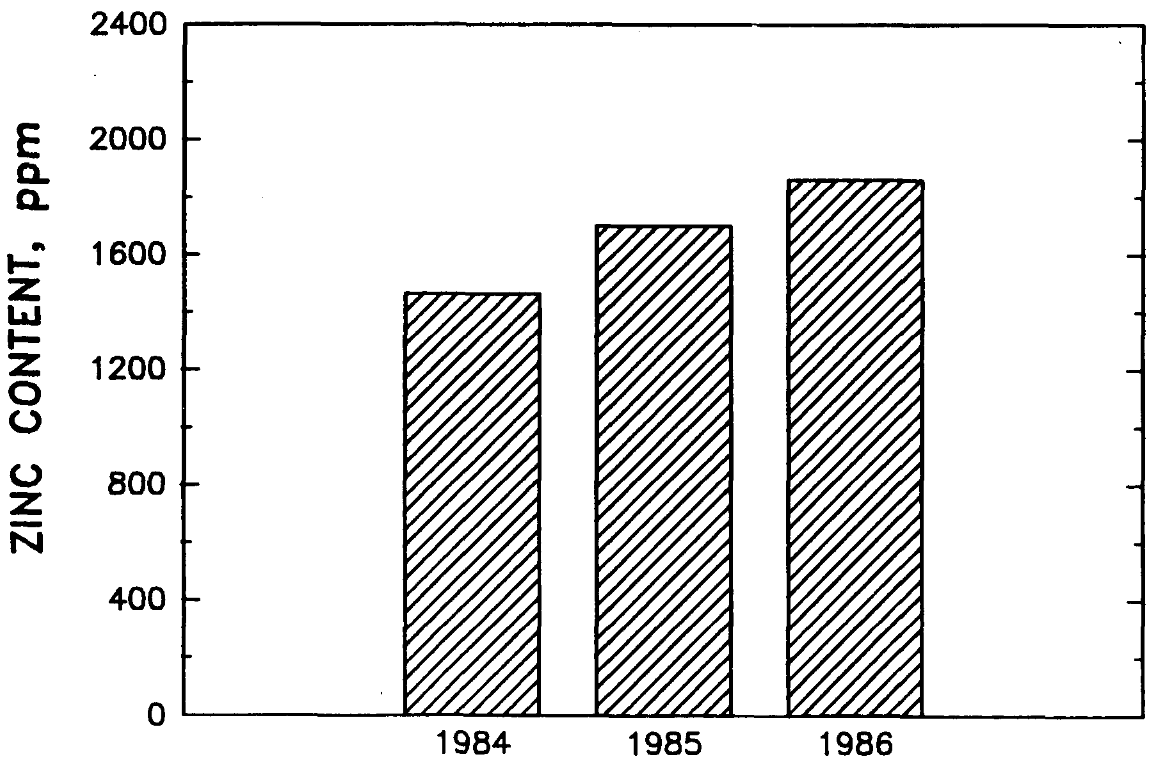

Figure 68. Rental truck fleet, average zinc content of lubricating oil (Inter-Harvester engine)

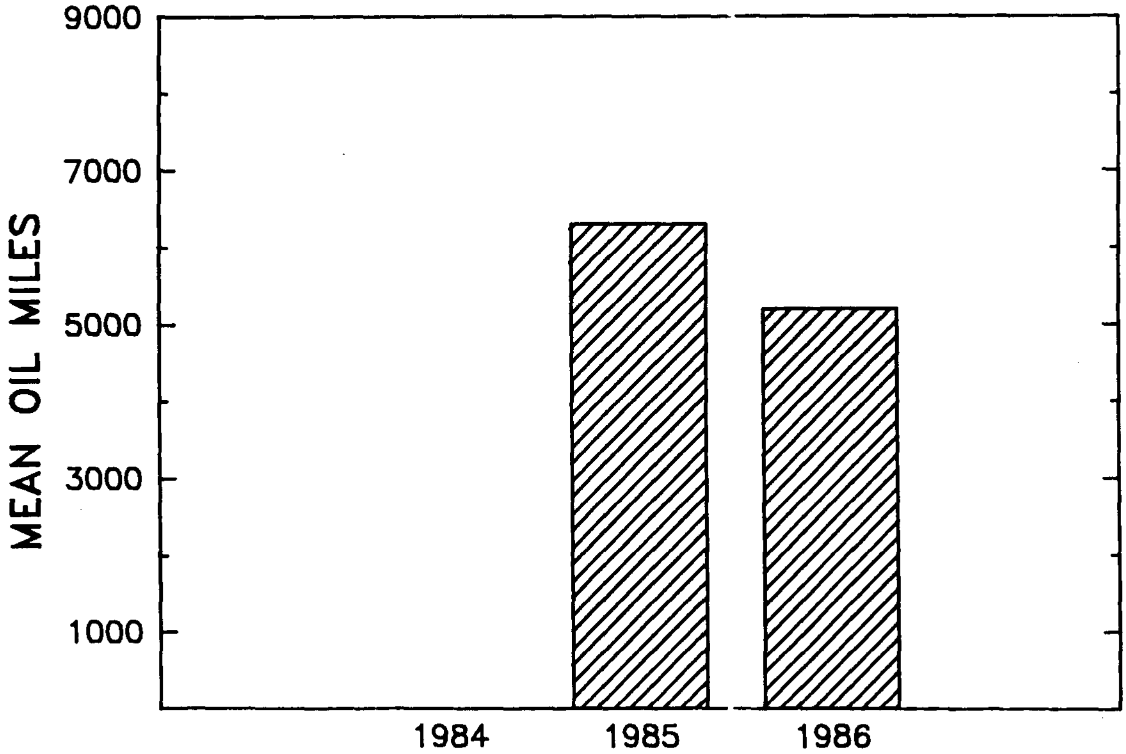

Figure 69. Rental truck fleet, average oil miles (Caterpillar engine)

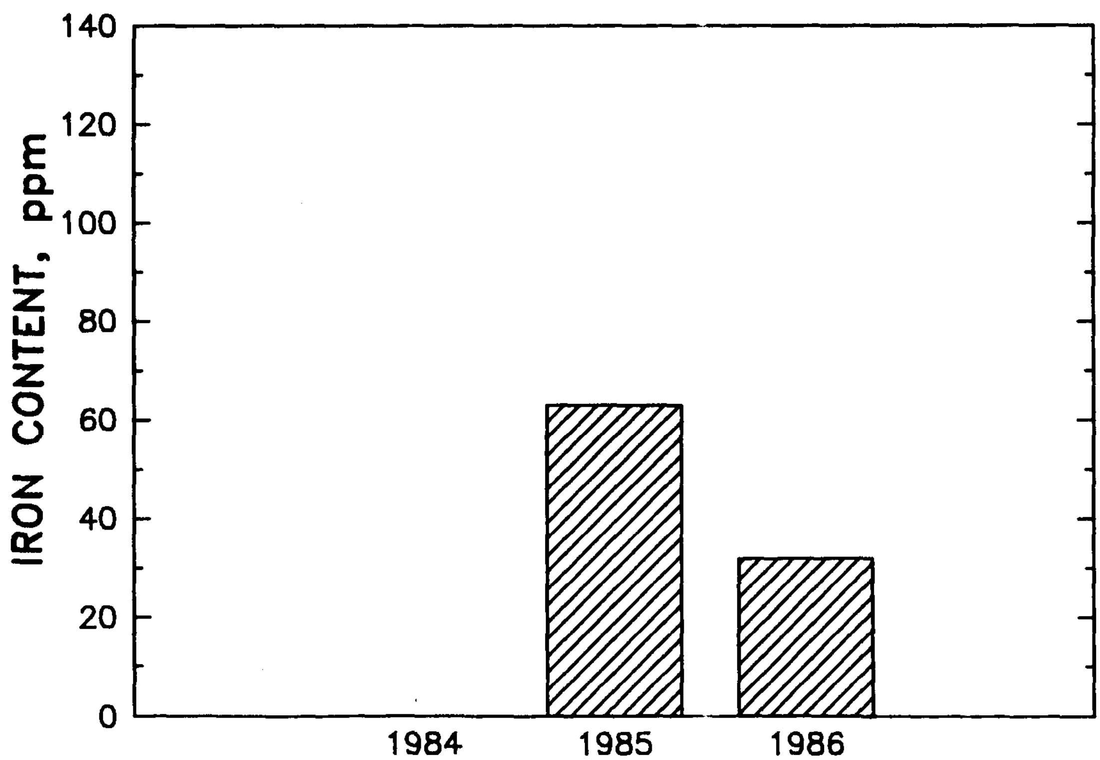

Figure 70. Rental truck fleet, average iron content of lubricating oil (Caterpillar engine)

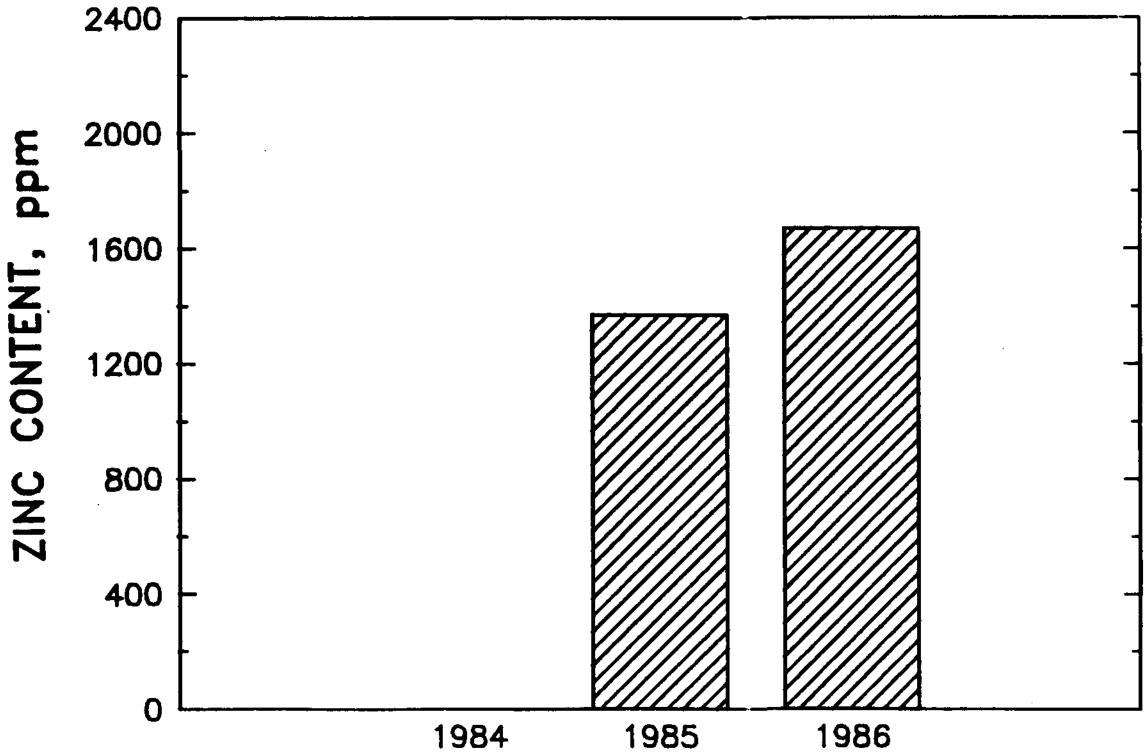

Figure 71. Rental truck fleet, average zinc content of lubricating oil (Caterpillar engine)

a. Cummins Engines - There was a slight (nonsignificant) increase in oil-miles between 1984 and 1985. There was, however, a significant increase in oil-miles in 1986. The used oil iron content was statistically the same for all three years. The iron content increased from 33 ppm in 1985 to 37 ppm in 1986. This coincides with the 12 percent increase in oil-miles for the same period. The level of zinc increased by 25 percent between 1984 and 1985-1986, which could be impacting the wear. For 1986, the increased oil miles would be expected to increase used oil iron content, while low sulfur fuel and higher oil zinc content would be expected to decrease iron. Overall, no clear effect could be determined.

b. Detroit Diesel Engines - There was no significant difference in oil-mile means between 1984, 1985, and 1986. Iron content was reduced from 85 ppm in 1984 to 63 in 1985 to 56 in 1986. The increase in oil zinc concentration may account in part for the 30 percent reduction in iron wear. Low sulfur fuel appears to have had a considerable effect in reducing iron wear.

c. Deutz Engines - There were no statistically significant differences in the three variables (oil-miles, iron, zinc) of concern.

d. GMC Engines - The oil-mile means were not significantly different. The iron content shows a 56 percent reduction, while the zinc level increased by 45 percent. The very small number of samples probably invalidates the comparison results.

e. International Harvester Engines - Although not statistically significantly, there was a 4 percent decrease in oil-mile means between 1984 and 1985-1986. For the same period, iron content shows a 28 percent decrease from 72 ppm in 1984 to 54 in 1985 to 49 in 1986. The sample sizes were approximately even for the three years compared. Although part of the reduction in iron concentration can be attributed to the 22 percent increase in zinc content, low sulfur fuel appears to be related to the decrease.

5. Laidlaw School Bus Fleet Summary of Oil Analyses - Table 10, and Figures 72 through 77 present the fleet summary and engine group analyses. The Laidlaw fleet did not report oil-mile readings with the data; therefore, averages were not calculated. Due to the relationship between oil-miles and iron wear, it was not possible to make an assessment of the results. The data are included as a matter of information.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions From Literature Review

Throughout the literature, fuel sulfur content has been related to corrosive diesel engine wear. A summary of the effects of decreasing the fuel sulfur content from 0.3 to 0.05 weight percent is presented in Table 11. The data from Mercedes-Benz (20) are the most relevant to current lubricants and engines. Extrapolation of earlier results (8, 10, 18, 19) would seem to be tenuous because they were obtained with older oil formulations quite different from the improved lubricants which are available today. The results presented in Table 11 are conflicting. Broeze and Wilson (10) found no reduction in wear below 0.5 weight percent sulfur, even though they were operating at a relatively cool jacket temperature of 140°F and using a lower quality 1949 vintage lubricant. M-B found great reductions in wear for low sulfur fuels

Table 10. Comparison of Selected Data For Laidlaw School Bus Fleet (Total Fleet)

Variable	Year	No.	Mean	Significant Difference*	Standard Deviation
Oil Miles	1984	58	DATA		
	1985	92		NOT	
	1986	123			AVAILABLE
Iron	1984	58	31.8		20.2
	1985	92	27.3	NS	17.3
	1986	123	49.5	S	57.9
Zinc	1984	58	1367.2		109.7
	1985	92	1349.1	NS	113.2
	1986	123	1350.3	NS	78.8
CUMMINS ENGINES					
Oil Miles	1984	25	DATA		
	1985	45		NOT	
	1986	60			AVAILABLE
Iron	1984	25	32.9		20.6
	1985	45	25.4	NS	19.1
	1986	60	41.4	S	30.4
Zinc	1984	25	1382.0		120.1
	1985	45	1332.0	NS	109.2
	1986	60	1345.8	NS	80.3
DETROIT DIESEL ENGINES					
Oil Miles	1984	33	DATA		
	1985	47		NOT	
	1986	63			AVAILABLE
Iron	1984	33	31.0		20.2
	1985	47	29.1	NS	15.3
	1986	63	57.4	S	74.7
Zinc	1984	33	1356.0		101.7
	1985	47	1364.8	NS	115.8
	1986	63	1354.6	NS	77.7

* See Table 3.

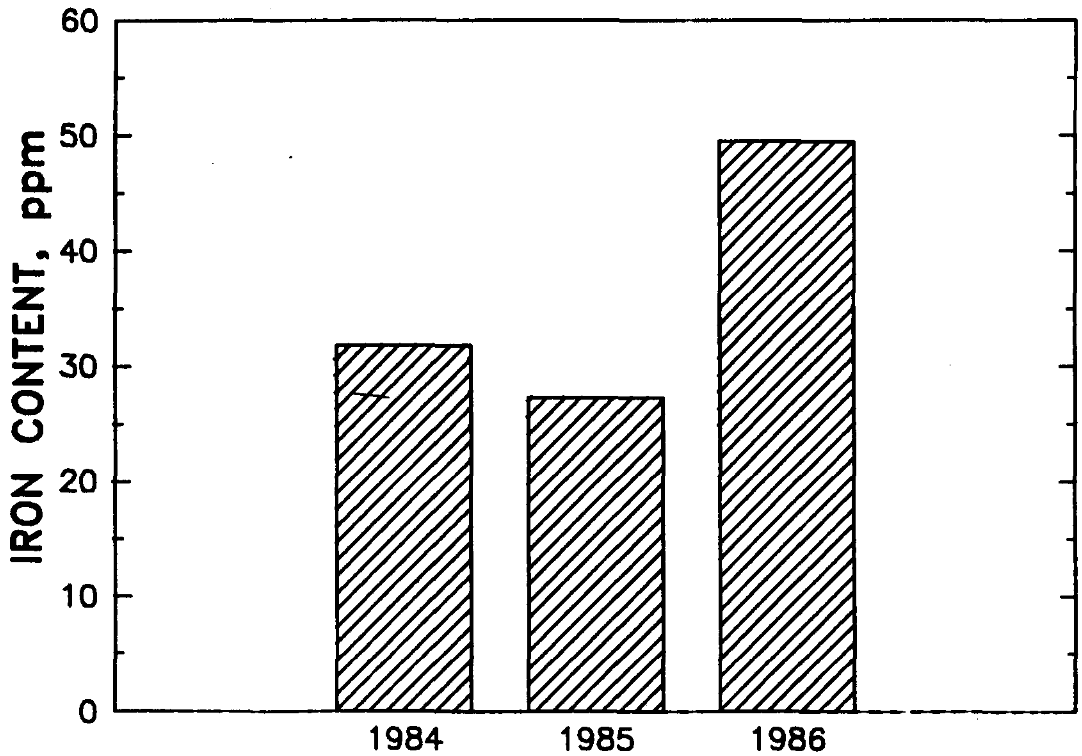

Figure 72. Laidlaw school bus fleet, average iron content of lubricating oil

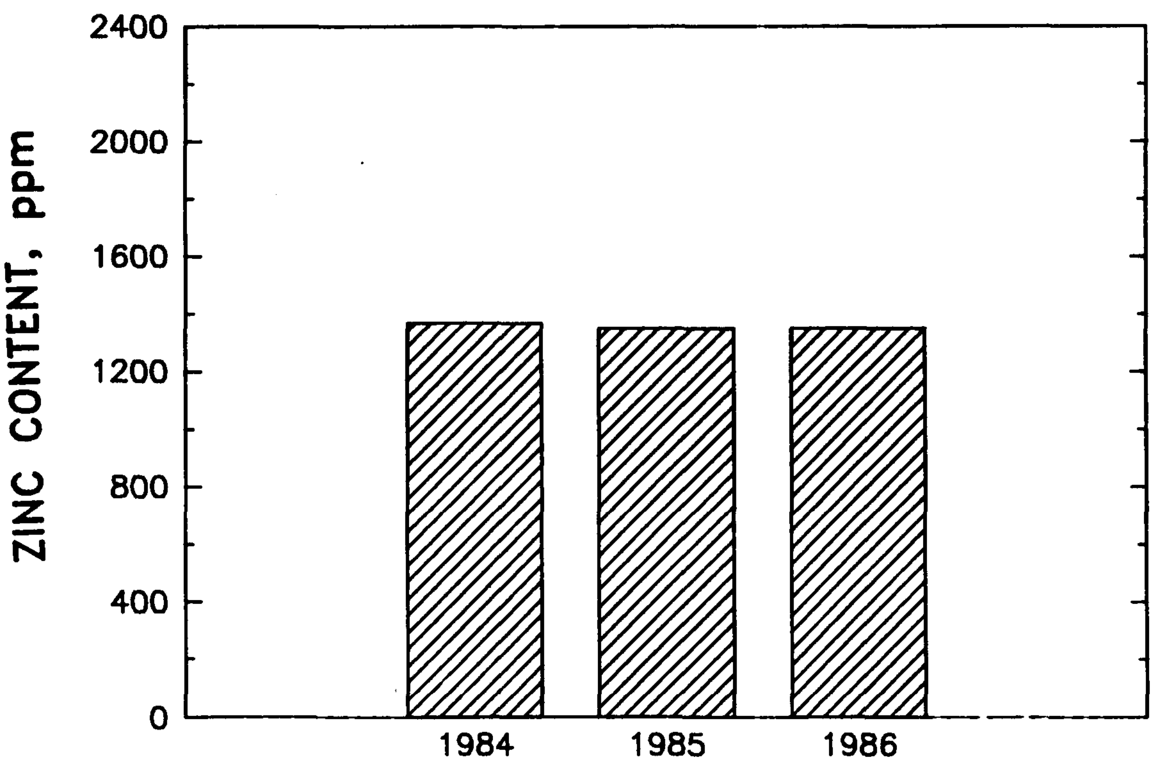

Figure 73. Laidlaw school bus fleet, average zinc content of lubricating oil

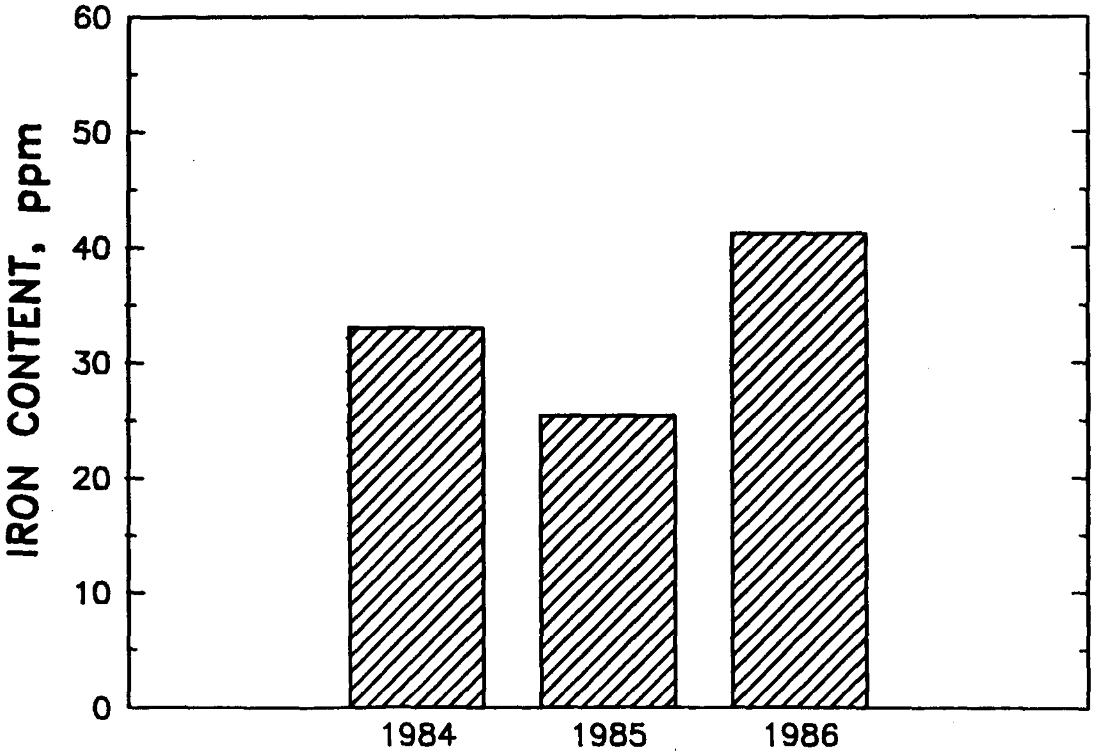

Figure 74. Laidlaw school bus fleet, average iron content of lubricating oil (Cummins engine)

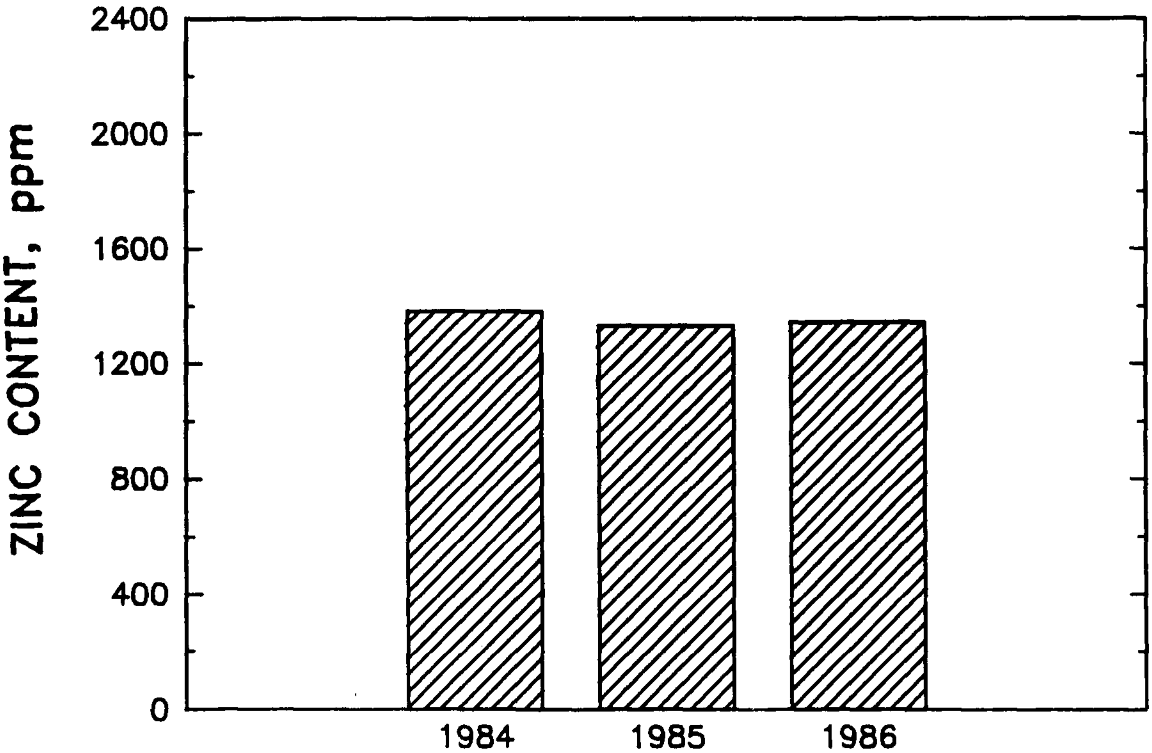

Figure 75. Laidlaw school bus fleet, average zinc content of lubricating oil (Cummins engine)

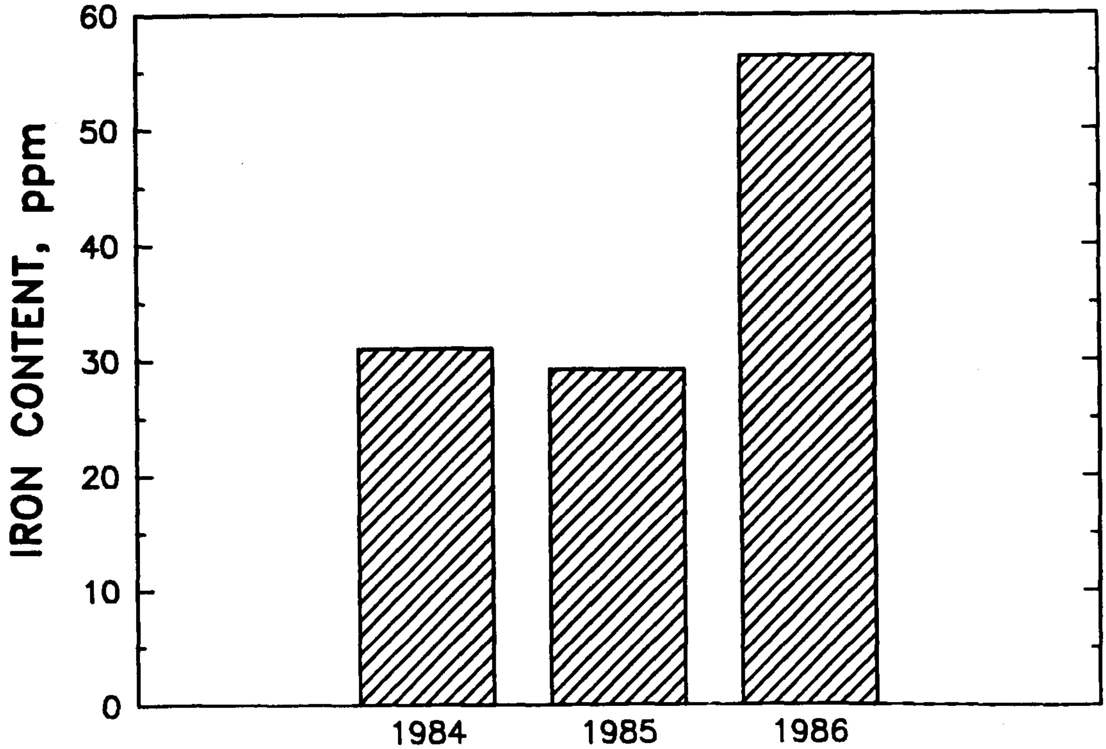

Figure 76. Laidlaw school bus fleet, average iron content of lubricating oil (Detroit Diesel engine)

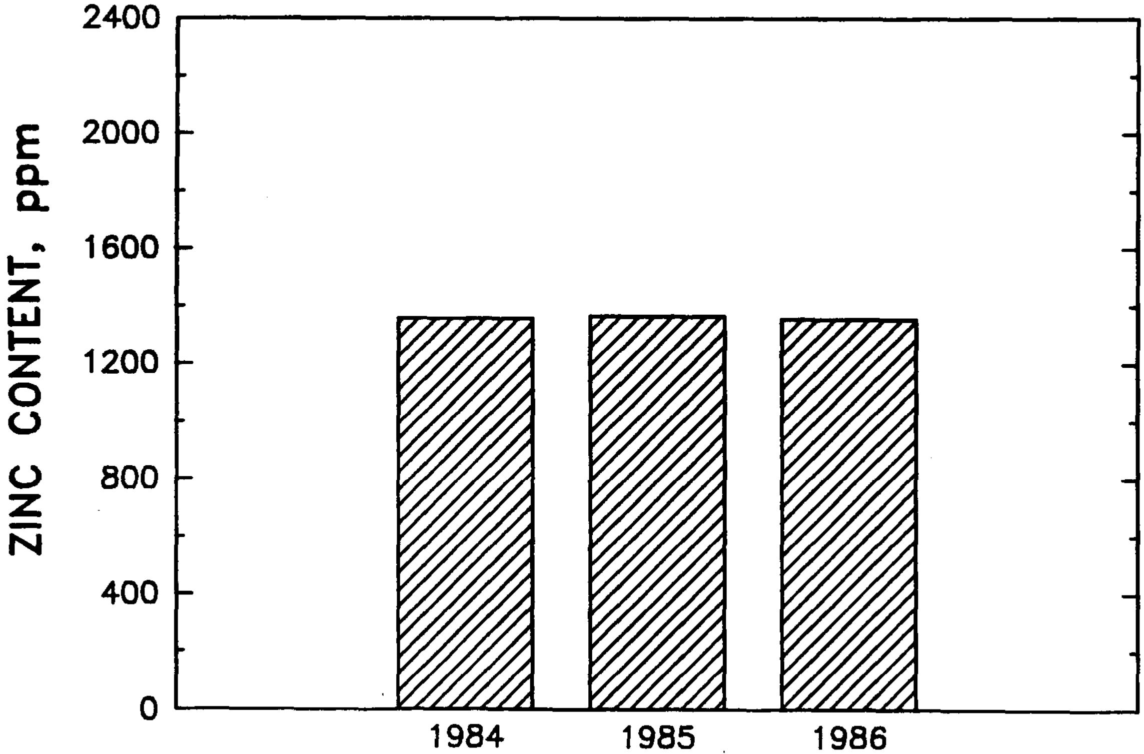

Figure 77. Laidlaw school bus fleet, average zinc content of lubricating oil (Detroit Diesel engine)

Table 11. Summary of Fuel Sulfur Effects

Reference	(Moore & Kent)	(Cattano & Starkman)	(Broeze & Wilson)	(Malyavinski & Chernov)	(Pinotti, Hull, McLaughlin)	(Rosow M-B)
Number	5	8	10	18	19	20
Fuel S Reduction (0.3 to 0.05 weight percent) Effects						
COT, °F	160	210	140	NS*	175	122/158/176
Wear						
Bore wear Reduction	x	x	None	10% (0.3 to 0.2%S)	x	80%/28%/0
Ring Wear Reduction	x	37% (1.2 mg/HR @ 0.05% S)	x	x	15%	x
Total Engine Wear Reduction	43%	x	x	x	x	x
Comments on Applicability to Current Engines and Lubricants						
Limitations	1947, HD Commercial oil	Unknown Lube 1948 vintage	Unknown Lube 1949	Formulated Oil 1958 Russian Engines	1949 Oil Formulation	SE/CC Oil Non-turbo-charged Engines

* Not Stated.

operating below 175°F COT. The Mercedes-Benz data and others reveal the extreme importance of operating temperature (COT), when examining fuel sulfur effects. The amount of benefit from wear reduction when operating on fuels with 0.05 weight percent sulfur would appear to be directly related to the accumulated amount of time the engine operated at COT below 175°F. This time would vary depending on the type of duty cycle involved. For example, on-road line haul diesel engines experience less accumulated cold start and warmup time than engines used for in-city delivery service with frequent stops. Mercedes-Benz data also indicate a possible wear increase for low sulfur fuels at higher than normal COT. Overall, a single figure cannot be extrapolated from the literature for reduction of engine wear when operating on 0.05 weight percent sulfur diesel fuel, due to the strong temperature dependence of the engine wear/fuel sulfur relationships. Other factors and effects such as TBN and engine load also have important impact on the wear/fuel sulfur relationships.

Other effects investigated were oil alkalinity (TBN) level and engine load. Oil TBN level is very important in controlling corrosive engine wear. Operation on 0.05 weight percent sulfur fuel could allow longer oil drain intervals because of reduced TBN depletion. No data were found which could be used to extrapolate and quantify the expected increase oil of alkalinity retention when using 0.05 weight percent sulfur fuel.

As engine load increases, engine wear can be expected to increase as shown in Figure 14.(20) At the normal operating temperature point (175° - 180°F) where there was no effect of fuel sulfur content on wear, (according to Mercedes-Benz) the effect of engine load on wear was fairly substantial.

Overall, operating temperature, load, and fuel sulfur content appear to be of equal importance when discussing diesel engine wear. The complexity and interrelationship of fuel sulfur content, operating temperature, engine load and lubricant alkalinity on diesel engine wear prevent making simple generalizations regarding the effects of any one of these variables. Care must also be used in extrapolating changes in used oil iron content, measured ring wear, and/or cylinder wear to expected engine life. As stated in API comments to EPA (38), the primary reasons for engine overhaul when using today's commercial diesel fuel (0.3 weight percent sulfur average) are:

- Loss of oil control because of
  - bore polishing resulting from excessive top land piston deposits which remove lubrication from the cylinder walls
  - piston ring scuffing resulting from over-fueling, overheating or lack of oil
  - broken piston rings resulting from deformation of aluminum piston grooves or overuse of Jacobs brakes
- Mechanical failures
  - bearing failures due to fatigue or oil contamination
  - camshaft failures due to manufacturing quality control problems
  - injector failures causing over-fueling, piston burning, and/or ring scuffing

These reasons for engine rebuild do not appear to be directly related to corrosive ring and liner wear.

The following is quoted from the API comments:

> "Information available in the literature (SAE Papers Nos. 831721 and 821216), indicates that it is not piston ring or liner wear that determines when engines are overhauled, but a variety of other problems. The most important of these problems is loss of oil control, as indicated by the MVMA survey. This loss of oil control is generally caused by bore polishing, ring scuffing, or broken rings. Bore polishing occurs when excessive deposits of hard carbonaceous material in the top ring land abrasively remove the the crosshatch pattern on the liner. Piston ring scuffing results from over-fueling, overheating, or lack of oil. Broken piston rings are caused by the deformation of the aluminum piston grooves or overuse of Jacobs brakes."(38)

Thus, the expected reduction in engine wear from reducing fuel sulfur content to less than 0.05 weight percent may not extend engine life (time to overhaul), due to the relative importance of other engine failure modes.

4.2 Conclusions From Fleet Data

From the results of the statistical analyses, it was concluded that there was a significant decrease in used oil iron content for several engine types between 1984 and 1985-1986. Anomalies existed in several comparisons of engine types. However, small sample sizes probably had an effect on the results. Based on the fleet summaries and individual engine comparisons, specifically the DDV71 and DDV92 (SCRTD) and Cummins, Detroit Diesel and International Harvester (Rental Truck Fleet), a consistent reduction in used oil iron content occurred as a result of lower sulfur content in the diesel fuel and other changes such as oil zinc content and new oil TBN. We cannot extrapolate the reduction in used oil iron content to increased engine life. In addition to the fuel sulfur reduction between 1984 and 1985, other variables which can affect engine wear were changing. Oils with different total base number were used for each year at SCRTD. The lowest average TBN in 1984 did not go below the minimum levels recommended by engine builders for mandated oil changes (Table 1, page 22) where wear rate would be affected by low TBN. Also, the oil zinc content was significantly higher in 1985 and 1986 for oils used by the Rental Truck Fleet. It appears that the zinc increase (approximately 28 percent) was not a major contributor to the decrease in wear metal content, because the lower zinc content oil used in 1984 was still in a typical range for diesel engine oils and should have provided adequate wear protection.

It is, therefore, concluded that the reduction in diesel fuel sulfur content had an effect in reducing engine wear for some, but not all of the engine types and fleets examined.

4.3 Recommendations

Since neither the literature survey nor the fleet data completely defined the effect of low sulfur fuel on diesel engine life, additional research is needed. The following recommendations are offered for consideration.

EPA should continue to monitor fleet operation on low sulfur diesel fuel. By tracking new engines which enter a fleet operating on low sulfur fuel, and eventually disassembling and measuring the wear of representative engines, a determination of low fuel sulfur content on engine life can be made. Oil drain interval extension could be determined at the same time.

Another possibility is to conduct well-defined engine dynamometer durability tests using low sulfur fuel. While very costly, engine dynamometer tests allow control of variables such as engine load, COT, and oil TBN so that the fuel sulfur effects can be isolated and quantitatively determined. Engine manufacturers have procedures for extrapolating engine life from durability tests. Conduct of durability tests using low sulfur fuel could provide the needed engine life extrapolation. Engine manufacturers should be encouraged to use fuel with a maximum of 0.05 weight percent sulfur for endurance testing.

The possible fuel lubricity effect of fuel sulfur components should be investigated using bench wear tests such as the BOCLE or Cameron-Plint rig. Results should determine if the low sulfur fuel will show a benefit or detriment in this area.

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16. ABSTRACT

The study evaluated wear in heavy-duty highway-type engines for reduction of sulfur content of diesel fuel in the range of 0.50 weight percent to 0.05 weight percent. A literature review found that wear rates generally were reduced by decreasing fuel sulfur content. The amount of wear reduction was affected as much by operating temperature and engine load as by sulfur in the fuel. Low operating temperatures showed more wear at high sulfur levels and, therefore, more benefit for low sulfur fuels. Increasing engine load caused higher wear rates independent of sulfur content. Lubricant alkalinity (Total Base Number) is effective in controlling corrosive wear at high sulfur levels and reduces the potential wear benefit from low sulfur diesel fuel. Lubricating oil analyses from fleets operating on diesel fuel with less than 0.05 weight percent sulfur were compared with previous data when average sulfur content was 0.35 weight percent. Overall, a significant reduction in engine wear occurred in most engine types as measured by iron content of used oil. Most of the reduction can be attributed to the low sulfur fuel, with minor contributions from changes in the lubricating oils.

17. KEY WORDS AND DOCUMENT ANALYSIS

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