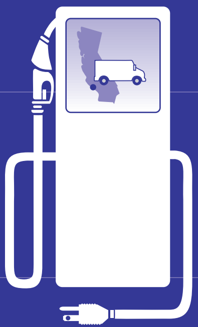

CleanFleet

FINAL REPORT

VOLUME 3

Vehicle Maintenance and Durability

December 1995

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Glossary

ADP = Adaptive digital processor

AFE = Advanced fuel electronic

ARB = Air Resources Board (California)

ATA = American Trucking Associations

CNG = Compressed natural gas

ECU = Electronic control unit

EGR = Exhaust gas recirculation

FFV = Flexible fuel vehicle

Fleet = A unique combination of vehicle manufacturer and type of fuel

GVWR = Gross vehicle weight rating

IAC = Idle air control

LPG = Liquefied petroleum gas

M-85 = Methanol fuel comprised of 85 percent methanol and 15 percent RFG by volume

MAP = Manifold absolute pressure

OEM = Original equipment manufacturer

PM = Preventive maintenance

ppm = Part per million

PRO = Propane gas

RFG = California Phase 2 reformulated gasoline

RO = Repair order

SCE = Southern California Edison

TBN = Total base number

UNL = Unleaded, regular gasoline

VAGIS = Vehicle and Ground Support Equipment Information System

VURR = Vehicle Use and Repair Report

VEHICLE MAINTENANCE
AND DURABILITY

CleanFleet is a demonstration of panel vans operating on five alternative motor fuels in commercial package delivery operations in the South Coast Air Basin of California. The five alternative fuels are propane gas, compressed natural gas (CNG), California Phase 2 reformulated gasoline (RFG), methanol (M-85 with 15 percent RFG), and electricity. Data were gathered on in-use emissions, operations, and fleet economics. This volume of the final report summarizes the maintenance required on these vans from the time they were introduced into the demonstration (April through early November 1992) until the end of the demonstration in September 1994.

The vans were used successfully in FedEx operations; but, to varying degrees, the alternative fuel vehicles required more maintenance than the unleaded gasoline control vehicles. The maintenance required was generally associated with the development state of the fuel-related systems. During the demonstration, no non-preventive maintenance was required on the highly developed fuel-related systems in any of the unleaded gasoline production vehicles used either as controls or as RFG test vehicles. The maintenance problems encountered with the less developed systems used in this demonstration may persist in the short term with vehicles featuring the same or similar systems. This means that fleet operators planning near-term acquisitions of vehicles incorporating such systems should consider the potential for similar problems when (1) selecting vendors and warranty provisions and (2) planning maintenance programs.

Introduction

This volume of the final report summarizes data on the maintenance and durability of 20 CleanFleet vans running on propane gas, 21 vans running on compressed natural gas (CNG), 20 vans running on M-85, two electric vans, 21 vans running on California Phase 2 reformulated gasoline (RFG), and 27 control vans running on regular unleaded gasoline. The period of time covered by this report is from the introduction of the vehicles into the demonstration (April through September 1992) through the end of the demonstration (September 1994). The demonstration was conducted at five FedEx facilities in the Los Angeles area. Each site had one type of alternative fuel van and the associated control vans (i.e., unmodified production versions of the CleanFleet vehicles built to operate on unleaded gasoline) from each manufacturer of the alternative fuel vans.

In general, the vans were used successfully in FedEx operations. To varying degrees, the alternative fuel vehicles required more maintenance than the unleaded gasoline control vehicles, and that maintenance was associated with the state of development of the fuel-related systems. In this regard, it is important to note that, during this demonstration, no non-preventive maintenance actions were required on the highly developed fuel-related systems in any of the gasoline production vehicles used either as controls or as RFG test vehicles. The maintenance problems encountered with the less developed systems used in the demonstration may persist in the short term with vehicles featuring the same or similar developmental systems. Therefore, fleet operators planning near-term acquisitions of vehicles incorporating such systems should consider the potential for similar developmental problems when they (1) select vendors and warranty provisions and (2) plan maintenance programs.

None of the maintenance problems associated with the alternative fuel technologies evaluated in this report are likely to be insolvable in developing these technologies for incorporation into future production vehicles. Their coverage here should, however, help to indicate both the relative state of development of these technologies and the areas warranting attention.

This volume of the findings of the project is divided into five sections following the Introduction: Vehicle Information, Vehicle Maintenance, Oil Consumption and Analysis, Engine Teardown, and Discussion. The Discussion summarizes the results and places them in perspective.

Vehicle Information

Overview

Included in the demonstration were 111 vans powered by liquid and gaseous fuels and electricity. The CleanFleet vans used liquid and gaseous alternative fuel technologies that were available for commercial service in 1992, met FedEx requirements for operations, and were backed by the three manufacturers—Ford, Chrysler, and Chevrolet. Pertinent aspects of the vehicle technologies used with each of the fuels evaluated are described below.

- The propane gas vans from Ford and Chevrolet were gasoline vans modified to operate on propane gas using IMPCO Technologies, Inc. systems. The Ford vans were equipped with IMPCO’s adaptive digital processor (ADP) system. The Chevrolet vans were equipped with the newer generation advanced fuel electronic (AFE) system.

- The Chevrolet CNG vans were gasoline vans modified to operate on CNG using IMPCO’s AFE system. The Ford CNG vans were built especially for the project to operate on CNG. The Dodge CNG vans were among the first production CNG vans.

- The M-85 vans were Ford flexible-fuel vans, operating strictly on M-85.

- The RFG and unleaded control vans were standard, gasoline-powered, production vans.

- The electric vans were G-Vans equipped with either lead-acid or nickel-cadmium batteries.

Table 1 contains selected vehicle and powertrain characteristics of the 111 CleanFleet vehicles. Control vehicles (i.e., vehicles that operated on regular unleaded gasoline) were acquired from each of the three major vehicle manufacturers who manufactured or modified vehicles to operate on the alternative fuels. It should be noted that, in addition to the engine changes required for operating the engines on the alternative fuels, some non-fuel related engine differences were demonstrated because of the relatively limited pool of engines from which to pick.

The problem of the limited pool from which to pick was severe for the electric vehicle category. Here, only one candidate van approached the various requirements for FedEx operations. This candidate was the G-Van, which featured technology that was neither highly developed nor current. Because there was a strong desire to include a broad spectrum of alternative fuels in the demonstration, it was decided to include the G-Vans, but to treat them as a special, restricted case in both (1) conducting the demonstration and (2) analyzing and reporting the results.

Ideally, all of the engine/vehicle combinations selected would have featured engines/vehicles comparable in size and performance. The 4.9-liter, in-line, 6-cylinder gasoline engine in a full-size Ford Econoline Van is in widespread use by FedEx. The gross vehicle weight rating (GVWR) of this van is 7,200 pounds. The closest General Motors engines available at the start of the demonstration (1992) were a 4.3-liter V6 and a 5.7-liter V8. At that time, a gaseous fuel compatible version of the 8.6:1 compression ratio, 5.7-liter, V8 was available, but a gaseous fuel compatible version of the 4.3-liter V6 was not. Operating a gasoline engine with a given displacement on a single throttle body gaseous fuel system without

Table 1. Selected Powertrain and Vehicle Specifications

Location	Fuel	Manufacturer	Model	Number of Vans	Curb Weight (lbs)	Powertrain(a)	Engine Oil Specifications(b) and Special Engine Materials
Irvine	CNG	Chevrolet	G30	7	5,462	5.7L IMPCO Throttle Body Fuel V8 8.6:1 CR Hp N/A	Chevron DELO 15W40 Hardened Valves and Seats Chrome Compression Rings
		Dodge	B350	7	5,122(c)	5.2L SMPI V8 9.08:1 CR 200 Hp	Chevron DELO 15W40 Hardened Valve Seat Inserts
		Ford	E250	7	5,782	4.9L SMPI In-line 6 Cyl. 11.0:1 CR Hp N/A	Chevron DELO 15W40 Hardened Valve Seat Inserts
Log Angeles	RFG	Chevrolet	G30	7	4,956	4.3L CPI HD V6 8.6:1 CR 155 Hp	Chevron DELO 15W40 Standard Materials
		Dodge	B350	7	4,812	5.2LSMPI V8 9.08:1 CR 230 Hp	Chevron DELO 15W40 Standard Materials
		Ford	E250	7	5,490	4.9L MPI In-line 6 Cyl. 8.8:1 CR 150 Hp	Chevron DELO 15W40 Standard Materials
Rialto	Propane Gas	Chevrolet	G30	7	5,128	5.7L IMPCO Throttle Body Fuel V8 8.6:1 CR Hp N/A	Chevron DELO 15W40 Hardened Valves and Seats Chrome Compression Rings
		Ford	E250	13	5,379	4.9L IMPCO Throttle Body Fuel In-line 6 Cyl. 8.8:1 CR Hp N/A	Chevron DELP 15W40 Hardened Valves Hardened Exhaust Seat Inserts

Table 1. Selected Powertrain and Vehicle Specifications (Continued)

Location	Fuel	Manufacturer	Model	Number of Vans	Curb Weight (lbs)	Powertrain[a]	Engine Oil Specifications[b] and Special Engine Materials
Santa Ana	M-85	Ford	E250[d]	20	5,526	4.9L SMPI In-line 6 Cyl. 8.8:1 CR Hp N/A	Lubrizol MFV 10W30 Hardend Valves and Seats
Culver City	Electric	Conceptor	G-Van	2	7,756	52 Hp DC Traction Motor	
Irvine, Los Angeles, Rialto	Unleaded	Chevrolet	G30	9	4,956	4.3L MPI HD V6 8.6:1 CR 155 Hp	Chevron DELO 15W40 Standard Materials
Irvine, Los Angeles		Dodge	B350	6	4,812	5.2LSMPI In-line 6 Cyl. 8.8:1 CR 150 Hp	Chevron DELO 15W40 Standard Materials
Irvine, Los Angeles, Rialto, Santa Ana		Ford	E250	12	5,490	4.9L MPI In-line 6 Cyl. 8.8:1 CR 150 Hp	Chevron DELO 15W40 Standard Materials

[a] All vehicles were equipped with automatic transmissions except for the electric vehicles, which were built with a transmission/drive train that provided a single gear ratio in both forward and reverse. Abbreviations: CPI = central port fuel injection, CR = compression ratio, DC = direct current, Hp = horsepower, SMPI = sequential multiport fuel injection, HD = heavy duty, N/A = not available.

[b] Oil capacity in all vehicles is six quarts including the amount in the filter. Old filters were replaced at each oil change. Filters are Motorcraft FL-1A (or the AC Delco equivalent).

[c] Weight shown is for Dodge CNG van with fourth tank added.

[d] Ford M-85 vans are flexible fuel vehicles (FFV) that were operated strictly on M-85.

increasing the compression ratio or making other performance enhancements can result in a loss of power of about 20 percent. Therefore, it was decided to use the 155-horsepower, 8.6:1 compression ratio, 4.3-liter V6 for the Chevrolet control vehicles and the larger (but same 8.6:1 compression ratio) 5.7-liter V8 (which is rated at about 190 horsepower on gasoline) as the basic engine for the Chevrolet natural gas and propane gas vehicles.

Dodge's closest available CNG engine was a newly released 5.2-liter V8 option, featuring sequential multi-port fuel injection and a compression ratio of 9.08:1. Ford was able to offer a CNG gas version of their 4.9-liter, in-line, 6-cylinder engine featuring both a higher compression ratio (i.e., 11:1 versus 8.8:1) and multi-port fuel injection. Ford also made available a propane gas prep package engine for the propane vehicles, which was fitted with an IMPCO throttle body fuel injection system.

The electric G-Vans used 52 horsepower DC traction motors and a "transmission" with a single gear ratio in both forward and reverse.

Fuel System Technologies

Propane Gas. The Chevrolet propane gas vans were originally built to operate on gasoline, but featured special V8, 5.7-liter gaseous fuel compatible engines. These vans were subsequently modified to operate on propane using IMPCO's AFE system. This is a microprocessor-based, electronic control unit (ECU), engine management system that controls spark and exhaust gas recirculation (EGR) functions to provide optimum engine performance. AFE's operational functions interacted with the original equipment manufacturer (OEM) vehicle's on-board computer. The AFE strategy allowed the OEM on-board diagnostic routines to remain operational at all times. The compression ratio was not changed in the modifications; it remained at 8.6:1.

A schematic diagram of IMPCO's AFE system is shown in Figure 1. Liquefied petroleum gas (LPG) is drawn from the tank through the fuel filter and lockoff valve to the convertor, where it is changed from a liquid to a gas and the pressure is regulated. The gas moves through the gas mass sensor to the gas ring, and then through the throttle body into the engine.

The Ford propane gas vans featured 4.9-liter, in-line, 6-cylinder LP prep package engines. The vehicles were modified to operate on propane gas using IMPCO's ADP fuel system. The ADP is a stand-alone, alternative fuel system, with an electronic, closed loop feedback controller. The electronic controller features a 16-cell block learn memory that provides stoichiometric fuel mixtures when used in conjunction with IMPCO's air/fuel mixer. The ADP controller is not capable of interacting with the OEM's on-board computer. The compression ratio was not changed in the modification process; it remained at 8.8:1.

A schematic diagram of the ADP system is shown in Figure 2. Liquid propane fuel is drawn from the tank through a fuel filter and lockoff valve to the convertor, where it is changed to a gaseous state and the pressure is regulated. The propane is then drawn through IMPCO's air/fuel mixer and the throttle body into the engine.

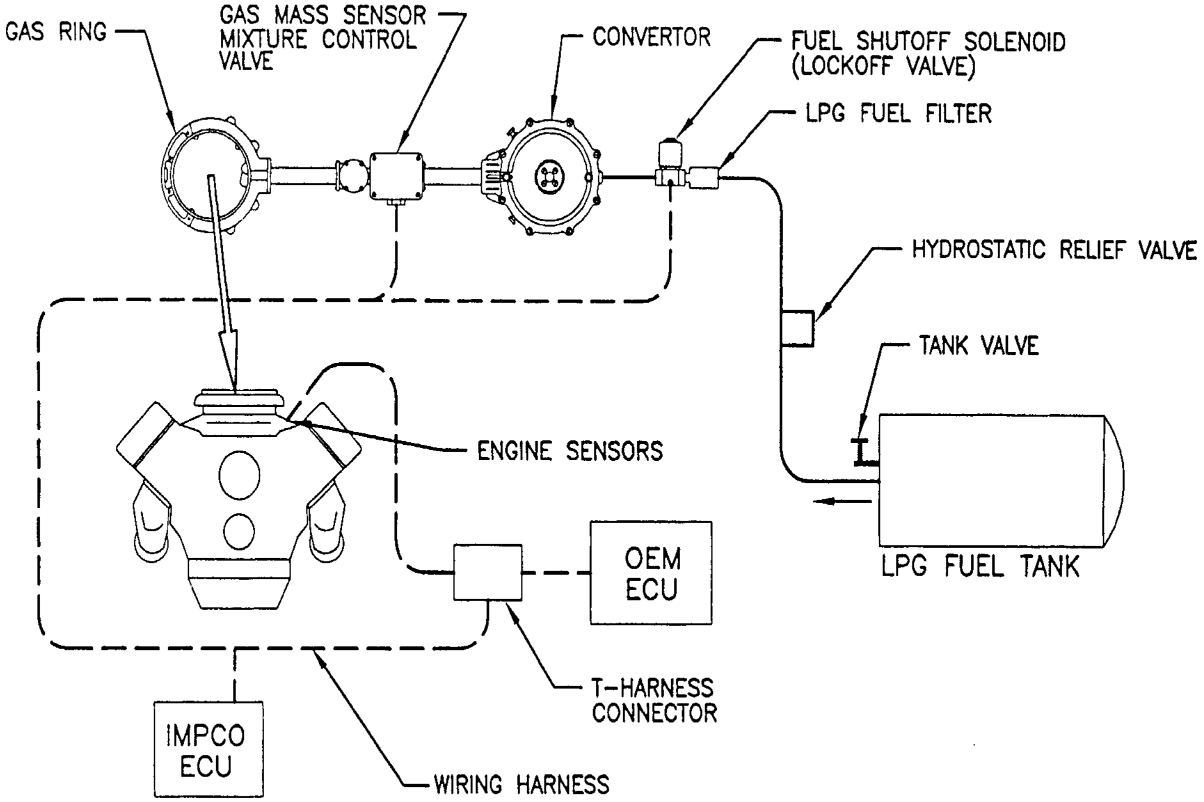


Figure 1. IMPCO's AFE System.

The ADP controllor uses manifold absolute pressure (MAP) and engine speed to control gas pressure within the alternative fuel system. The ADP system also uses oxygen sensor input to update fuel system data stored in the adaptive memory. By using stored stoichiometric mixture data, the ADP can instantly adjust the fuel system to meet the required combustion characteristics. The fuel adjustment function is accomplished by sending a duty cycle signal back from the ADP to the fuel control valve that varies the fuel pressure to the IMPCO feedback mixer. This process will continuously readjust the air/fuel ratio over the entire service life of the vehicle. Block learn memory is also used to compensate for engine wear and degradation.

Compressed Natural Gas. The Chevrolet compressed natural gas vans were built originally to operate on gasoline, but featured V8, 5.7-liter gaseous fuel compatible engines. These vans were subsequently modified to operate on CNG using IMPCO's AFE system. This is a microprocessor-based engine management system that controls spark and EGR functions to provide optimal engine performance. AFE's operational functions interact with the OEM vehicle's on-board computer. The AFE strategy allows the OEM on-board diagnostic routines to remain operational at all times. The compression ratio was not changed during the modification process; it remained at 8.6:1.

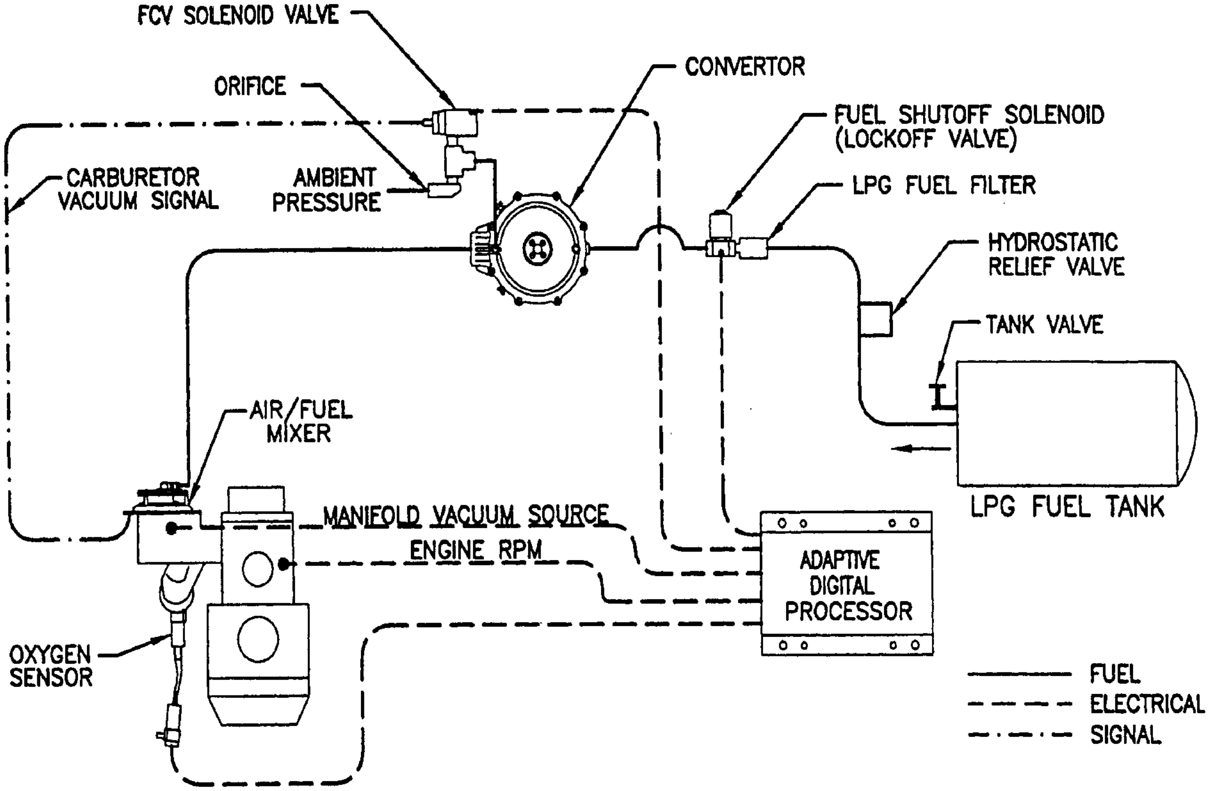


Figure 2. IMPCO's ADP System.

High pressure (up to 3,000 psi) CNG is drawn from the tank through the primary regulator and lockoff valve to the secondary regulator. The gas moves through the gas mass sensor to the gas ring, and then through the throttle body into the engine.

The Dodge vans used in the CleanFleet demonstration were originally manufactured to operate on natural gas. The Dodge CNG vehicles had an unexpectedly short range (80 to 90 miles) in FedEx service. In February and March 1993, one extra fuel tank (i.e., a fourth tank) was installed on each of the seven Dodge vans, giving them a total fuel capacity equivalent to 16 gallons of gasoline. Larger tanks were not installed because vehicle components would have had to be moved to accommodate them. The fourth tanks were installed by NGV Technologies under contract to Southern California Gas Company.

The Ford CNG vehicles were provided ready to operate on natural gas and featured 4.9-liter, in-line, 6-cylinder engines with sequential, multi-port, electronic fuel injection and a compression ratio of 11:1. After receipt, they were modified to allow them to be fueled with the CNG dispenser nozzle used by CleanFleet. The fill fitting orientation on the tank prevented the dispenser nozzle from connecting to the Ford tank; therefore, the fill fittings were changed on all the Ford vehicles.

M-85. In March 1992, 23 Ford vans were delivered to the demonstration site, 20 of which were to be modified by Ford to operate on M-85 and three to be used as control vehicles. The 20 M-85 vans were flexible fuel vehicles (FFV) designed to use methanol-gasoline mixtures ranging from zero to 85 percent methanol. These vans used sequential, multi-port, electronic fuel injection. They were equipped with six fuel injectors plus a seventh “cold-start” injector, which is not needed in the southern California climate.

Electric. Southern California Edison (SCE) provided two early-prototype electric G-Vans (powered by lead-acid batteries) for the demonstration in April 1992, anticipating that the G-Vans would be replaced when new designs became available. These vans were modified for electric propulsion by Conceptor Corporation, a subsidiary of Vehma International, Inc., and began service in Culver City in April 1992. The lead-acid battery pack weighed about 1,140 kilograms, and it was composed of 36 six-volt monoblocks. A Chloride, Inc. charger that provided 35 amperes of direct current was used. Midway through the demonstration, one of the two G-Vans was equipped with nickel-cadmium batteries. The nickel-cadmium battery pack weighed about 850 kilograms, and it was composed of 34 monoblocks. A LaMarche charger with an output of 46 amperes was used.

Maintenance Policies and Practices

All of the engines used in the CleanFleet project were built with conventional wet oil sumps that hold six quarts of oil, including the oil filter. All of the engine sumps, except those running on M-85 fuel, were filled with a mineral-based, 15W40 oil sold under the Chevron DELO name. A Lubrizol MFV 10W30 oil was used in the Ford vehicles operating on M-85 fuel. While the exact additive packages for each oil were not provided by the manufacturers, both appeared to have conventional extreme pressure and antiwear additives based on common zinc and phosphorus compounds. The lubricants also appeared to have additives containing calcium or magnesium that are often associated with detergent and antioxidation additives. The Chevron oil is the standard oil for FedEx fleet vehicles, and the Lubrizol oil was formulated for use in flexible-fuel vehicles. No additive package development was performed specifically for this project.

Fleet vehicles used by FedEx on its routes are generally considered to be in “severe service” as defined by the OEMs. This means the vehicles may be subject to prolonged periods of idling, low-speed operation, or frequent starts and stops. While the manufacturers do not typically prescribe maintenance procedures for fleet vehicles, a maintenance schedule based on the “severe service” guidelines for gasoline-powered passenger vehicles is a good guideline to follow. These guidelines usually recommend oil changes every three months, chassis lubes every other oil change, a coolant change once a year, a transmission filter and fluid change at least every two years, and air filter replacement as needed up to every two years. Actual fleet maintenance schedules were proposed by FedEx and agreed to by the OEMs for warranty purposes.

VEHICLE MAINTENANCE

FedEx maintains a policy for preventive maintenance on its delivery trucks to ensure safe operation of its fleet and to prolong the life of the vehicles. Preventive maintenance is scheduled every 12 weeks (84 days). Engine oil is changed at this time or more frequently if a panel van accumulates more than 6,000 miles during this period. FedEx fleet managers at the district level can implement a schedule more frequent than 84 days if warranted. (Three fleet managers had responsibility for vehicles at the five demonstration sites.) Most panel vans in CleanFleet operations did not accumulate more than 6,000 miles in an 84-day period. Only four CleanFleet vehicles had a more frequent schedule for oil changes. These were vans that operated on long routes in the eastern portion of the South Coast Air Basin. These vans had an eight-week interval between oil changes. Three propane gas vans and one unleaded control van had an eight-week schedule for oil change. The schedule of oil changes for vans operated out of the propane site changed because the vans were rotated among delivery routes for the CleanFleet project. Route characteristics at the other sites were such that modifications of the oil change schedule were not required.

Vehicle Maintenance

Information on the maintenance performed on CleanFleet vehicles is presented in two parts. The approach used to collect maintenance data is described. Then maintenance activities on fuel-related systems and a statistical summary of maintenance activities are provided.

Approach

Information on maintenance activities that appeared to be fuel related was obtained by monitoring FedEx repair order data and through discussions with FedEx mechanics at each of the five participating demonstration sites and representatives from vehicle manufacturers, local vehicle dealers, and third-party vendors (i.e., Southern California Edison, IMPCO, Suburban Propane). Following the narrative description of maintenance activities are statistical summaries of the maintenance data reported by FedEx mechanics, vehicle manufacturers, dealers, and vendors. The procedures used to collect, process, and analyze the CleanFleet maintenance data are discussed below.

Data Collection. Vehicle maintenance data were obtained from

- FedEx vehicle repair orders
- Warranty and maintenance information obtained from vehicle manufacturers, local dealers, and third-party vendors
- Daily Vehicle Use and Repair Reports (VURRs).

FedEx maintains an information system on all repairs to its fleet vehicles. This system is called the **V**ehicle **a**nd **G**round Support Equipment **I**nformation **S**ystem (VAGIS). Maintenance data on all demonstration vehicles were periodically transferred from VAGIS to Battelle in electronic form and placed into the CleanFleet database. The data include date of repair, repair order number, mechanic employee number, party responsible for the repair (vendor or FedEx), reason for the repair (e.g., scheduled, breakdown, driver report), type of repair, labor performed, parts replaced, and cost of labor and parts. All labor and parts replaced are reported using American Trucking Associations (ATA) codes.

In addition to the information supplied by VAGIS, Battelle also obtained data from local dealers and other organizations who performed certain warranty repairs. Information on manufacturer warranty repairs were received directly from the manufacturers. Two of the three vehicle manufacturers (Chevrolet and Dodge) provided costs on all fuel-related warranty repairs. Maintenance data on the electric vehicles were obtained from Southern California Edison. The data received from FedEx, vehicle manufacturers, local dealers, and vendors were reviewed by Battelle for accuracy and completeness. After reconciling any differences, the data were combined into a single maintenance database containing approximately 6,500 repair orders.

Each time a FedEx employee drove a fleet vehicle, he or she was required to record its use and report any problems on a VURR. Mechanics reviewed the VURRs daily and recorded any maintenance performed.

Battelle received copies of all VURRs to monitor this communication between drivers and mechanics. The data maintained in the CleanFleet database included date of use, vehicle identification number, and a description of problems reported. The data were primarily used to monitor oil consumption as it was reported by couriers during their early morning vehicle check.

Data Processing. Data from FedEx's VAGIS were transmitted to Battelle on a bi-weekly basis during the course of the demonstration. Battelle developed software applications that reduced and stored the VAGIS data in appropriate files for data analysis. A second set of application programs was run against the data to ensure their validity and integrity. Questionable data were flagged and reported, and problems were resolved before the data were included in any reports or statistical analyses.

Repair and maintenance data from vehicle manufacturers, dealers, and vendors were received on hard copy forms and keyed into separate data sets. The data from all sources were merged with the VAGIS data and cross-checked to ensure that only one occurrence of a vehicle repair was retained in the final CleanFleet database. After these data processing steps were completed, several adjustments were made to allocate total costs between labor and parts and to account for certain types of missing data. These adjustments are discussed below.

Some repair orders (ROs) were excluded from the final analysis of the data. These ROs involved issues that Battelle determined were external to the fuel/vehicle system under study. For example, repairs associated with vehicle accidents, installation of additional CNG fuel tanks, vehicle fires, and the introduction of contaminated fuel into the vehicles were eliminated from the database before final analysis. These issues generate repair requirements and costs, but the repairs are not the type that are of direct interest to this study.

Data Analysis and Reporting. Maintenance costs and the frequency of maintenance activities are detailed in a series of six data reports contained in Appendix A. The key results are presented in the "Results" section. These include the number of repair orders per 100 service days (a measure of the overall frequency of repair actions), total maintenance costs, and vehicle availability and utilization.

The six data reports in Appendix A contain detailed information about the maintenance performed for each fleet (unique combinations of fuel type, manufacturer, and demonstration site). Each report aggregates the data at two levels: (1) all maintenance activities performed and (2) maintenance on selected vehicle systems that are more likely to involve problems with the fuels or the fuel delivery technologies. The selected vehicle systems include instruments (ATA system code 003), electrical group (030 - 035), and engine/fuel systems (040 - 048).

The first data report summarizes the preventive maintenance (PM) activities in terms of number of PMs performed, labor hours, labor costs, and parts costs. The next five reports summarize the non-preventive maintenance activities in terms of number of ROs, labor hours, labor costs, parts costs, and total costs. The total number of ROs per fleet is presented along with normalized values based on the number of vehicles, total miles driven, and number of days in service. Similarly, the labor hour and cost parameters are normalized to the number of ROs, miles driven, and number of days in service.

Vehicle availability is generally defined as the percent of normal operation time that a vehicle is available for use, whether or not the vehicle is used. For FedEx, normal operation is generally between the hours of 7:00 AM and 8:00 PM, Monday through Saturday. There are some site-to-site differences in operations times.

Vehicle availability (A) was calculated as

$$A = (T-D)/T,$$

where, for each vehicle, T is the total hours of normal operation between the first and last day the vehicle participated in CleanFleet, excluding time required for CleanFleet emissions testing, and D is the total hours of downtime due to maintenance activities. Periods of time in which a vehicle was available but not used by FedEx are included in T, but not in D. On the other hand, the time a vehicle was waiting to be repaired is included in D.

Downtime (D) was usually calculated by FedEx as part of the normal data processing within VAGIS. When FedEx mechanics prepare ROs, they report the date and time of day when the vehicle is taken out of service and the date and time when the vehicle is returned to service. The VAGIS information management system calculates “downtime” as the amount of operation time that the vehicle is out of service. Note that if the vehicle is taken out of service after 8:00 PM and returned to service before 7:00 AM the next day, the downtime is zero.

However, the VAGIS database did not always contain complete information on out-of-service time for vehicles repaired at vendors. When ROs obtained from VAGIS, vendors, and the OEMs contained duplicate or complementary information about a single maintenance incident, the information was combined by Battelle into a single repair order. This often involved modifying the return-to-service date on the combined repair order. Occasionally, the repairs performed by vendors were not entered into VAGIS by FedEx mechanics. The only information available was the repair order provided by the vendor. Many times these repair orders did not contain complete information about downtime. In particular, the times at which the vehicle went out of service or returned to service were often not available. If the out-of-service date and the return-to-service date were reported, downtime was calculated by assuming that the vehicle was out of service for half of the first day and all the succeeding days. For example, the downtime for a vehicle serviced by a vendor within one day was estimated to be approximately 6.5 hours.

In some cases, especially those involving dealer repairs, the return-to-service date was also missing. A random sample of these repairs was investigated individually, using the vehicle activity data to determine the best estimate of downtime.

Vehicle availability for a fleet was calculated after summing the values of T and D, respectively, for each vehicle. Availability was calculated separately on the fleets of unleaded vans from each manufacturer at each demonstration location. That is, the average availability is calculated for each combination of fuel type, vehicle manufacturer, and location.

Vehicle utilization is defined as the percent of scheduled service days that a vehicle was actually used in delivery service. Vehicle activity data, reported by drivers, were used to calculate utilization. Utilization was calculated by first determining for each van (1) the number of weekdays (Monday through Friday) on which the van was driven (utilized) and (2) the total number of weekdays between the first and last day the van was scheduled to be used. The sum of the days utilized was then divided by the sum of the days scheduled (after subtracting the number of days vehicles were at the California Air Resources Board for emissions testing) to determine the utilization for each fleet. Saturdays and Sundays were excluded from the calculation because FedEx stations are closed on Sunday and because there are differences in Saturday delivery requirements among the five demonstration sites.

Data Adjustments. To present a more complete and accurate picture of the maintenance performed on CleanFleet vehicles, it was necessary to make certain adjustments to the data reported by the various organizations. The adjustments account for the ways in which certain vendors report cost details and FedEx's procedures for reporting warranty costs.

A computer check of the relationship between labor hours and labor costs revealed that, for many of the non-preventive maintenance repairs from vendors, values were missing or inconsistent. Three types of data adjustments had to be made.

(1) The first problem affected labor records from non-preventive maintenance repair orders in which either labor hours or costs were not adequately reported. Adjustments made on individual labor records are discussed below.

   (a) For some labor items, the number of labor hours appeared realistic; but the total cost was shown as $0.01, zero, or missing. In this case, it was assumed that the repair work was being performed under warranty and that the vendor or FedEx mechanic correctly reported the labor hours. The labor costs were re-calculated as the number of labor hours times an average rate of $20 per hour.

   (b) For some labor items, the labor cost was a significant positive number but was not consistent with the number of labor hours reported. For example, a vendor might report several hundred dollars of labor on an item but not report the actual number of hours worked. When entering the information in VAGIS, the FedEx mechanic simply reported one hour of labor. For these types of records, the cost was assumed to be correct; and the labor hours were calculated as the total cost divided by the average labor rate of $20 per hour. This adjustment was made whenever the calculated rate, based on the reported cost and labor hours, fell outside the range of $10 to 35 per hour.

   It should be noted that the average rate of $20 per hour used in (a) and (b) above was approximately the average hourly rate when calculated across all labor records in the detailed record database that did not have either of those types of data problems.

(2) The second type of data adjustment was needed because some vendors reported the total cost for a repair, but did not allocate the costs between labor and parts. The total costs were divided equally between labor and parts. Next, the costs allocated to labor were divided by the average labor rate of $20 per hour to calculate estimated labor hours.

(3) The third type of data adjustment was required in cases where vendors described the work that was accomplished but did not provide any cost information. In those cases, Battelle staff searched the database for other similar repairs to provide an estimate of the labor hours and parts cost involved. Labor costs were calculated using the average rate of $20 per hour.

Results

Results are provided in two parts. First, maintenance on fuel-related systems is described. Then, a statistical summary of maintenance actions is presented.

Description of Fuel-Related Maintenance. Fuel-related maintenance activities are summarized below.

Propane Gas. Twenty CleanFleet vehicles were fueled with propane gas. In May 1992, 13 Ford vans were modified to run on propane gas. Modifications of the seven Chevrolet vans were not completed until October 1992. These vans were not OEM production propane vans, and their maintenance histories should be viewed in that light.

All the CleanFleet propane gas vans had problems with the fuel quantity gauge mounted on the instrument panel. The reading on this gauge depended on a tank-mounted float sensor in the horizontally mounted cylindrical propane tank, which did not have internal baffling to prevent fuel sloshing or errors caused by unlevel ground. However, the drivers did not rely completely on the dash-mounted gauge. They checked a tank-mounted gauge at the start of the day when the vehicle was stopped on level ground. Further, the drivers knew how far they could drive on a tank full of liquefied propane gas (LPG).

Chevrolet. The Chevrolet vans were modified to operate on propane gas by an outside contractor. Upon inspection of these installations, Battelle, FedEx, and IMPCO decided that some of the equipment needed to be removed and installed differently. IMPCO personnel reinstalled the equipment. After the modifications, the propane receptor fittings on the Chevrolet vans had to be reconfigured from a straight head fitting to an angled fitting so that the propane dispensing nozzle at the demonstration site could attach to the vans.

Two Chevrolet propane gas vans were out of service in November 1992 because of rough running and stalling. On one of these vans the idle air control (IAC) grommet blocked the air bypass passage; replacing this grommet solved the problem. The other van had low secondary fuel pressure. Replacing the fuel pressure regulator solved this problem.

Two Chevrolet vans were repaired for surging problems under cold operating conditions in December 1992. This problem was traced to the mixture control valves, which were replaced.

In February 1993, a contaminated oxygen sensor failed in one Chevrolet van. This sensor was replaced; however, the source of the contamination was never positively identified.

The gas mass sensor/mixture control valves in all of the Chevrolet propane gas vehicles were replaced in March 1993. Inspection of the gas mass sensors showed that they all had a manufacturing defect and were not internally grounded as they should have been. They were replaced with gas mass sensors that were properly grounded.

The originally installed control fuses were mounted in an in-line fuse holder near the battery in the Chevrolet vans. After some time in operation, vapors from the battery corroded the fuse and interfered with reliable vehicle operation. These fuses were relocated in a weather-resistant fuse holder near the center of the firewall of the vehicle, which resolved the problem.

In April 1993, a Chevrolet van provided to the California Air Resources Board (ARB) for emissions testing refused to idle correctly. Testing of this vehicle was terminated, and IMPCO was notified. Upon inspection, it was discovered that a vacuum port on the throttle body had not been properly blocked. Blocking this port resolved the problem.

In May 1993, new fuel lockoff valves (with a higher temperature tolerance than the original lockoffs) were installed in all Chevrolet vans. The lockoff is an electrical solenoid operated valve that prevents fuel flow when the vehicle is not running. The original valves installed proved to be temperature sensitive. Once the vehicle reached operating temperature during hot weather and was shut down, the heat-soaked lockoff valves made it impossible to restart the vehicles when the engines were hot. New lockoff valves were installed as a precautionary measure because the Ford vans with the same type of valves had experienced trouble in the summer of 1992. The Chevrolet vans were placed in service after the hot weather in 1992.

In May 1993, it was discovered that the idle speed on the Chevrolet propane vans had dropped. This change was attributed to operating the vehicles. The idle speed of all Chevrolet propane vans was restored to the original setting.

Error code and driveability problems with one Chevrolet van were corrected in May 1993. This van and two others were drawing fuel from the vapor in the fuel tank rather than from the liquid, and their fuel supply lines had to be switched to the correct locations. This change resolved the driveability problems with these vehicles. Also, all propane gas powered vans were checked for proper hookup.

Some components in the circuits of the gas mass flow sensors on the Chevrolet vans could not tolerate the heat during the summer of 1993. These units were redesigned, and new units that were more tolerant of summer temperatures were installed. This change solved the problems.

Primary seats in the regulators delaminated, causing a loss of pressure and preventing proper metering of the fuel. Rubber disks attached to a metal part were detaching from the metal. IMPCO worked with the manufacturer to develop an improved attachment process, and all the seats in the propane gas and IMPCO-equipped natural gas vans were replaced.

A continuing problem was experienced with dirt in the throttle bodies of the Chevrolet propane gas vans using AFE. These vans were operated in a desert-like area, which may have played a role in the problem. However, gasoline-fueled vehicles operated in these conditions do not experience the same degree of problem. The gasoline tends to wash the dirt out of the throttle body, while propane does not. Cleaning the throttle bodies of propane vehicles should be done on a regular basis, i.e., every 10,000 to 12,000 miles.

Because the original IAC grommets between the idle air control valve and the throttle body were not tolerant of the propane fuel, they started to leak after a period of operation. The original grommets were replaced with grommets of a more compatible material.

Deterioration of the gasket between the air cleaner and throttle body appeared to be a durability rather than a fuel compatibility issue. The original gaskets were replaced with more durable parts.

By September 1993, IMPCO had completed a series of maintenance actions on all the Chevrolet propane gas vans because they had been running poorly. In addition, IMPCO used this general maintenance of the vans to introduce technology updates to their equipment. The actions taken were to

- Replace the diaphragm in the pressure regulator with a fluorosilicone diaphragm
- Replace the S4-7 seat in the regulator
- Adjust the idle speed
- Clean the throttle body
- Replace the oxygen sensor
- Update the erasable, programmable read-only memory (EPROM).

In September 1993, a bad ground wire on one Chevrolet electronic control unit board was repaired.

In November 1993, a Chevrolet propane gas vehicle would not start. IMPCO asked FedEx to clear the “block learn,” and use the van for several days before bringing it into IMPCO. IMPCO found a problem on the ECU board and also determined that the block learn strategy had a problem. Repairs were made and the van operated without problems. A second Chevrolet van started displaying the same symptoms and would not function even after the block learn was cleared. Eventually, this was resolved.

A defective gas mass sensor in another Chevrolet propane gas van was replaced in November 1993.

The block learn fuse of a different Chevrolet propane gas van was pulled daily to keep the van in operation in January 1994. This was another AFE software problem that was subsequently resolved by IMPCO.

In January 1994, a bent primary pressure regulator diaphragm with a small accumulation of oil in the regulator was found in one of the Chevrolet propane gas vans. This van was in for repair for 35 days.

In February 1994, a Chevrolet propane gas van was removed from service for poor performance. A check of the fuel system showed that no liquid was being drawn from the tank because the lines were incorrectly connected. This problem had been noted in some vans in May of 1993 and all the vans were checked at that time to make sure that the fuel system connections were correct. Apparently the inspection was inadequate.

All Chevrolet propane gas vans were serviced between July and September 1994 to tune up the vehicles and to install updated fuel lockoff valves, an updated EPROM, and a more durable tank-mounted fuel gauge.

Ford. In August 1992, faulty fuel lockoffs were replaced in the Ford vehicles. The lockoff is an electrical solenoid operated valve that prevents fuel flow when the vehicle is not running. The original valves proved to be temperature sensitive. Once the vehicles reached operating temperature during hot weather and were shut down, the heat-soaked lockoff valves made it impossible to restart the vehicles when the engines were hot. These valves were replaced by less temperature-sensitive ones, which resolved the problem.

A problem with the “check engine” light in some of the Ford propane gas vehicles was discovered in September 1992. The van’s OEM computer was receiving false signals indicating that a problem existed with the emission control system. The OEM microprocessors were still programmed as if the vehicles were operating on gasoline. To correct the fault, IMPCO manufactured a device (an ADP diagnostic box) to intercept the faulty signal and pass an acceptable signal on to the OEM computer. This device was installed in all Ford vans by July 1993.

In February 1993, the primary diaphragm in the fuel regulator was replaced in a Ford van. In March 1993, the diaphragm was replaced in two more Ford vans. The diaphragm was replaced in a fourth Ford van in May 1993. The diaphragms of all the Ford vans were replaced with fluorosilicone diaphragms in June 1993. The problem was traced to a material incompatibility between the original diaphragm material and the propane fuel. This change resolved the problem.

Delaminated primary seats in the regulators caused a loss of pressure in the regulator and prevented proper metering of the fuel. These seats consist of rubber disks attached to a metal part, from which the rubber was detaching. IMPCO worked with the manufacturer to develop an improved attachment process, and all of the seats in the propane and IMPCO-equipped natural gas vans were replaced.

In June 1993 an ADP processor on one of the Ford vans had to be replaced. It was commanding a very rich mixture, preventing the van from passing the emissions test. After replacement of the processor, the carbon monoxide level dropped from over 5 percent to less than 0.05 percent.

The tachometer signal for the ADP was too weak for reliable vehicle operation. In July 1993, the location from which that signal was taken was changed to provide the ADP with a stronger signal, which resolved the problem.

Temperature-sensitive fuel-control valves on the Ford vans were replaced in July 1993 with less temperature-sensitive and more durable units.

The “check engine” light illuminated on a regular basis in late 1993 through February 1994 on several Ford propane gas vans. This problem first arose in September 1992. IMPCO developed a diagnostic box to intercept the faulty signal and pass an acceptable signal on to the OEM computer. This device was installed in all Ford vans by July 1993. The strategy used by this box proved to be incorrect; it seemed to solve the problem for a few months, but the problem resurfaced. New diagnostic boxes, using an updated strategy, were installed during July and August 1994.

In August and September 1994, the hoses used to carry coolant from the cooling system to the regulator to heat the LPG started to deteriorate. These hoses were replaced with better quality hoses. Also, more durable tank-mounted fuel gauges were installed in this same period.

Compressed Natural Gas. There were 21 CNG fueled vehicles in the CleanFleet demonstration. By October 1992, three Ford vans and seven Chevrolet vans were modified to run on CNG. Modifications on two more Ford vans were completed in November 1992. The seven Dodge vans were supplied by Chrysler as production CNG vehicles, generally available to the public as of June 1992.

The CNG vans used fuel quantity gauges that measure the amount of natural gas remaining in the tanks. A pressure transducer measures the pressure in the tanks. This reading is passed to a module that sends a signal to the dash-mounted fuel gauge indicating the amount of fuel remaining. This system did not prove sufficiently reliable for FedEx operations. Several changes were made, including replacing the control modules and transducers with units that are pressure and temperature compensated. However, the fuel gauges still were not reliable.

Chevrolet. Early in the demonstration, two Chevrolet CNG vans were out for a day to fix cold surging problems. Throughout the next several months, problems continued with this fleet of CNG vans. The problem was traced to the block learn mode in the computer. These vehicles were programmed with a default set of engine parameters (e.g., ignition timing), which were changed progressively according to the driving cycle of the vehicle. The changes are supposed to allow better operation of the vehicle. In this case, however, the software degraded vehicle operation the farther the vehicles were driven. Eventually, the vehicles became undriveable and even unstartable. A number of interim fixes were tried to address various problems with the vehicles until the basic problem was identified and correct software was prepared and installed in September 1993.

Significant amounts of compressor oil (generally varying between 30 and 70 milliliters) were found in the Chevrolet regulators. The oil displaced a like volume of fuel in the regulator and caused problems, especially when the vans were driven under load (e.g., hard acceleration or uphill).

The gas mass flow sensor assemblies were replaced on the Chevrolet vans in February 1993 to correct problems with cold starting and poor performance. As in the propane gas vehicles, these gas mass flow sensor assemblies had an internal grounding manufacturing defect. These sensors were replaced with properly manufactured units.

Also, as in the propane gas vehicles, the fuse from the electronic control module was moved and a new sealed in-line fuse holder was installed to prevent fuse corrosion. The idle air control gaskets were also replaced.

Three Chevrolet vans continued to stall during May and June 1993. The oil filter tube was inadvertently rubbing against, and grounding, the body of the gas mass flow sensor. When the flow sensor was remounted or relocated on all the vans, they ran without problems.

As a precaution, the gas mass flow sensors and pressure regulators were replaced on all the Chevrolet natural gas vans. Also, all vans received an EPROM update. This was done because the corresponding propane gas vehicles using these components were having problems.

In February 1994, a van broke down on its delivery route. The engine would crank but not start and there was a strong odor of natural gas under the hood. Another van was removed from service for a surging problem at cruise speed. This van had a defective gas mass flow sensor.

Another van was removed from service in March for poor performance and delivered to IMPCO. The gas mass flow sensor was replaced, and the regulator was remounted so that it would have less chance of retaining compressor oil entering with the CNG during fueling. IMPCO instituted a program to remount all the regulators so they would be less likely to trap oil.

A Chevrolet CNG van was removed from service by IMPCO because the clearance between the tank and frame appeared inadequate. The tank was removed and a new tank installed with increased clearance. Subsequently, all tanks were inspected, with the result that two were removed and replaced due to damage.

In June 1994, two Chevrolet CNG vans were sent to IMPCO with stalling problems. IMPCO serviced the throttle body and adjusted the minimum idle speed on one van, while replacing the gas mass flow sensor, servicing the throttle body, and completely tuning up the other.

In August 1994, a van overheated while returning to the station. The driver was instructed by her manager to try driving it the rest of the way back. Subsequently, a radiator hose ruptured, wetting the ignition system and causing a short. The vehicle was towed in, and inspection showed significant engine damage. A new CNG engine was installed.

Dodge. A Dodge van was out of service for a pressure regulator problem in October 1992. The regulator was replaced, but the reason for its failure is not known.

One Dodge van was at a dealership throughout May 1993. The van was returned to service in June 1993 after several repairs to the fuel system.

Leaks were found in the fuel lines in two Dodge vans in May 1993. The leaks were stopped by properly torquing the fittings.

In June 1993, a revised CNG-calibrated engine computer and a new regulator were installed in a Dodge van that would not idle. These changes resolved this problem.

Pressure gauges were installed at the fuel tanks in six Dodge vans in November 1993. The instrument panel fuel gauges were not accurate and could not be relied upon to correctly reflect the amount of fuel remaining in the tank. The Chevrolet vans already had such fuel tank pressure gauges, and the other Dodge van was out of the station when the gauges were installed. (The pressure gauge was installed on this van in January 1994.)

Obtaining prompt service from the local Dodge dealer was a problem. A Dodge CNG van delivered for service to the dealer was sometimes not looked at for a week or longer. Therefore, these vans probably were less available for service than if they had been given prompt support from the dealer.

One van spent 16 days at the dealer. During this time a regulator and ECU were replaced, but the van continued to run poorly. Finally, replacing two injectors allowed the van to be returned to service. However, this problem resurfaced early in February, necessitating further work.

An idle problem sent a CNG Dodge van to the dealer for 14 days in February. The dealer replaced a pressure regulator and a motor.

A van was returned to the dealer when it began running rough. It appeared that the catalytic convertor was coming apart.

In February, a CNG Dodge van would not accept fuel because of a stuck check valve. Another van was out of service for four days due to a faulty idle speed motor. Upon its return to service, it ran a half day and had to be towed to the dealer.

A CNG Dodge van was out of service for 8 days due to a stalling problem in traffic. The dealer cleaned the throttle body and cleared the computer memory and returned the van to service.

Ford. In November 1992, one Ford CNG van experienced rough running and misfiring, with the "check engine" lighted. Even after a processor was replaced in December 1992, this vehicle ran roughly and remained out of service throughout the month. In January 1993, compressor oil was found in the pressure regulator of one of the vans, which was the cause of the rough running and misfiring. Problems with fuel injectors were also traced to compressor oil. The injector manufacturer, Bosch, indicated that these injectors could be cleaned and returned to service; however, some injectors were replaced before this was known.

After a few months of service, Ford replaced all regulators on all natural gas vehicles. Some regulators had been manufactured incorrectly without internal sintered metal filters. However, no attempt was made to determine which regulators lacked these filters; all regulators were replaced.

In April 1993, one Ford van developed a leak in a fuel tank solenoid valve. This leak occurred inside the FedEx building, which had been equipped with flammable gas detectors. The alarm did not sound, but the building was evacuated. After review of the sensor records, it was discovered that, at the time the building was evacuated, the level of gas in the building was less than 10 percent of the lower explosion limit. Because the alarm threshold is set at 20 percent of the lower explosive limit, the alarm would not have been expected to sound in this instance. The van responsible was identified and pushed outside, allowing the building to be reoccupied. The solenoid valve was replaced and sent to the manufacturer, where internal corrosion was discovered. This valve was redesigned and new valves stocked to replace future failures.

Three Ford vans would not take a full fueling in June 1993, and another Ford van exhibited the problem in August 1993. A manual lockdown on the fuel tank solenoid may have been the cause. When the lockdown is screwed in, a nylon insert broke loose and blocked the passage. This went undetected when the lockdown was unscrewed. The short-term fix was to remove and replace the existing manual lockdown if it was suspected of causing a problem.

Fuel tank pressure gauges were installed in six Ford vans in November 1993. The instrument panel fuel gauges were inaccurate and did not reliably reflect the amount of fuel remaining in the tank. The Chevrolet vans already had such fuel tank pressure gauges, and the seventh Ford was out of the station when the gauges were installed.

In February, a minor leak occurred in one of the CNG fuel lines, necessitating replacement of the line.

A CNG Ford van was sent to the dealer in early March for engine misfiring. The dealer discovered worn plugs and replaced them with platinum-tipped spark plugs. Ford indicated that the CNG fuel stresses the ignition system much more than gasoline. This condition may cause misfiring or failure to properly ignite the mixture. The condition may go unnoticed in normal operation. Results of emissions testing showed less than a 5 percent decrease in nonmethane hydrocarbons using the platinum spark plugs.

M-85. By April 1992, modification of 13 of the Ford M-85 vans was complete. By October 1992, all M-85 vehicles were in service, with the exception of two Ford vans, one of which was out of service for a fuel leak and the other for fuel pump noise. The fuel leak was traced to an improperly tightened fuel rail, and the noisy fuel pump was replaced even though it seemed to be operating properly.

Two vehicles were pulled from service in November 1992 when they lost power as a result of fuel contamination from a dispenser hose that was incompatible with M-85. The fuel tanks of all M-85 vehicles were cleaned and the fuel filters replaced. After this, the dispenser hose was replaced with one compatible with M-85.

In February 1993, two Ford vans were out of service because of a broken wire in the fuel control modules. This proved to be a manufacturing defect and was resolved by replacing the modules.

In March 1993, five other Ford M-85 vehicles began to have problems with the fuel control modules (FCM), and the modules were replaced. In April 1993, a sixth Ford had problems with the FCM, which was also replaced. In May and June 1993, the fuel control modules were replaced in all the Ford M-85 vans. Inspection revealed that the pickup tubes on the FCM were too long and were rubbing the inside of the tank, which removed the plating. The plating passed through the fuel system, damaging the fuel pump. Fuel control modules with shorter pickup tubes were installed, and the fuel lines and filters were replaced.

Three of the Ford vans had difficulty accepting fuel at full flow rates. Ford suspects that this problem involves the anti-siphon device in the fuel tank filler tube.

Two M-85 vans experienced engine compartment fires in late 1993. These problems were traced to the cold start injector housings. Cold start systems are not required in the Los Angeles climate; therefore, all cold start systems were subsequently removed from these developmental M-85 vehicles.

Injectors and spark plugs were replaced in one van because of a slight misfiring problem.

In January 1994, a defective fuel pump was replaced in one van. This failure did not appear to be related to the use of M-85 fuel or to debris in the fuel system.

Injectors and spark plugs were replaced in an M-85 van in February because of misfiring. A third van experienced the same problem in March. A faulty injector caused this problem; all injectors were replaced.

A defective fuel pump was replaced in an M-85 Ford van in April 1994. No fuel-related problems were evident.

In the fall of 1994, it was decided that only the two M-85 vans scheduled for engine teardown would continue to operate on M-85. The remainder would operate on gasoline. Subsequently, several of the gasoline-fueled vans ran out of fuel on their routes. The M-85 fuel had caused a build-up on the card sender in the fuel tank. The card sender sent a full (or nearly full) signal to the dash-mounted fuel gauge regardless of the amount of fuel in the tank.

Electric. The electric vans with the PbA batteries required maintenance on the battery packs and traction motors, which were replaced on both vehicles. Some of the work on the PbA vans was done to increase their driving range, not because the batteries required maintenance. In contrast, the Ni-Cd van did not require significant maintenance during the time it was demonstrated. Because of the low range of one of the electric vans, the battery pack was replaced by SCE in early June 1992. After a 40.7-mile controlled drive, the battery pack showed a 1/8 charge remaining. (The range potential shown by this SCE driving cycle probably cannot be duplicated in normal FedEx service because the duty cycles used by the two organizations are so different. SCE drives the vehicles on a cycle with controlled accelerations and limited top speeds, which produces a fairly high battery range. This controlled cycle is reasonable for a commuter vehicle, but FedEx vehicles are driven in a more demanding manner necessitated by the need to deliver the maximum number of packages in a minimum amount of time.) This vehicle was returned to FedEx.

At the end of July, the two G-Vans were returned to SCE for repairs. Both were reported to have problems operating in reverse gear. No problem was found. Further investigation revealed that the drivers were treating these vehicles as they would treat gasoline-powered vans, placing the gearshift in reverse without coming to a complete stop. Reverse in the G-Vans is implemented by reversing the traction motors. To avoid overloads on this motor, a safety switch prevents placing the van in reverse while still moving forward. The vans were returned to service in August, and the drivers were given further instruction on how to avoid this problem.

In September 1992, a traction motor and five battery monoblocks were replaced on one van in response to a complaint that the van stalled when turning corners or backing. The vehicle was test driven by SCE and showed a range in excess of 40 miles.

In October 1992, both electric vans were removed from service for installation of new traction motors. On one van, the original traction motor failed a diagnostic with a bad armature reading. The reason for this failure was not identified. The van was returned to service in November 1992. The motor armature isolation resistance of the other van (which had a traction motor change in September) fell short of specified values. The motor was replaced, and the van was returned to service.

Throughout November, both G-Vans experienced problems with low ranges of 20 to 25 miles on a charge. Four bad battery monoblocks were replaced on one van. The Chloride, Inc. charger’s constant overcharging of the batteries (putting energy into the batteries when the battery pack was full) might have contributed to the need to replace the batteries. The van was subjected to an SCE-controlled driving test and showed a range of 40 miles. It was returned to FedEx on December 1, but complaints of low range continued. Five bad battery monoblocks, then the entire battery pack, were replaced, and all the watering blocks were also replaced. Both vans remained out of service during most of December.

In November 1992, the controller-failed signal in one van began to remain continuously illuminated while the vehicle was in operation (normally, the signal goes out a few seconds after the vehicle is started). The controller was returned for repairs. Also, auxiliary 12V power to the inside of the van failed. Upon inspection, extensive corrosion was found on the electrical connectors. These were cleaned, greased, and reassembled.

Both vans were out of service in January and February of 1993. One was returned to service in March 1993 with a new lead-acid battery pack. The second van was kept out of service for conversion to a nickel-cadmium (Ni-Cd) battery. This van resumed service in the middle of November.

In April 1993, the lead-acid battery van was out of service for three weeks (two weeks for service and one week because no trained operator was available). This van operated without problems in May 1993, but was out of service in June because its route was eliminated. In July 1993, the van was assigned to a new route in Century City.

In August 1993, the “fuel gauge” stopped functioning on the lead-acid battery powered van. The van was repaired and returned to service.

In late March 1994, the Ni-Cd battery powered van experienced a problem with the fuse in the controller. The fuse was replaced, and the van was returned to service.

The lead-acid battery powered van was removed from service on April 8, 1994. In a final performance test, this van did very poorly, indicating that the battery pack was in poor shape. The Ni-Cd battery powered van was removed from service on April 11. Its performance test went very well.

RFG. No fuel-related maintenance problems occurred with the RFG-fueled vehicles.

Gasoline Control Vehicles. In February 1994, a Dodge control van was taken to the dealer because it would not start when the engine was hot. The dealer was unable to duplicate the problem. Later testing by an independent driving service also was unable to duplicate the problem.

Statistical Summary of Maintenance Activities. Nearly 6,000 separate maintenance reports or ROs were prepared for the 109 liquid- and gaseous-fueled vehicles that participated in the two-year demonstration. This includes approximately 1,000 PM actions (oil and filter changes and chassis lubrication) and over 200 accidents or incidents that were not related to vehicle performance (e.g., repairs resulting from M-85 fuel contamination). Of the remaining 4,800 non-PM ROs that contain relevant information about the maintainability of the vehicles, slightly more than 1,900 include repairs on the engine/fuel systems (e.g., fuel injector), electrical systems (e.g., ignition control modules), and the instruments (e.g., fuel gauges). These systems, defined by specific ATA codes, are the most likely to be affected by fuel type and fuel-related technologies.

Detailed summaries of the information contained in the 1,000 PM and 4,800 non-PM maintenance reports are presented in Appendix A. Results include various measures of maintenance frequency (ROs per van, ROs per 10,000 miles, and ROs per 100 service days) and costs (labor, parts, and total) associated with all maintenance actions and, separately, for maintenance performed on selected fuel-related vehicle systems. Key results are summarized below.

Frequency of Non-PM Actions. Tables 2a and 2b contain the frequencies of non-PM actions for the various fleets involved in the demonstration, as well as statistical comparisons of the maintenance frequencies observed for the alternative fuel and control (unleaded) vehicles at each demonstration site. Fleets are defined by unique combinations of fuel type, vehicle manufacturer, and demonstration site. Table 2a compares the alternative fuel and control vans in terms of the average number of non-PM ROs per 100 service days, while Table 2b contains similar comparisons for maintenance performed on the selected vehicle systems that are more likely to involve fuel-related components.

Table 2a shows, for example, that the seven Chevrolet CNG vans averaged 441 service days per vehicle and required a total of 367 non-PM repair orders during the two-year demonstration. The rate of 11.9 repairs per 100 service days is 42 percent higher than the rate observed for the three Chevrolet unleaded vans maintained at the same demonstration site. Using a simple Poisson statistical model for the rate of occurrence of maintenance actions, it can be stated with 95 percent confidence that the frequency of maintenance on the Chevrolet CNG vans is between 17 percent and 72 percent higher than the frequency observed for the Chevrolet control vans. Because this interval does not contain the value zero, the difference in rates is said to be statistically meaningful. Maintenance frequencies were also significantly higher, based on the total number of ROs, for the Ford CNG and M-85 vans and Chevrolet propane gas vans when compared to their respective controls. There were no statistically significant differences between the maintenance frequencies of the RFG vans and those for the unleaded control vans from the same manufacturer.

By focusing on the selected (potentially fuel-related) vehicle systems (Table 2b), larger relative differences are observed in the frequency of maintenance activities among the CNG, propane gas, and M-85 vans and their respective controls. The statistically significant differences range from 46 percent higher for the Ford M-85 vans to 183 percent higher for the Ford CNG vans. In addition to the alternative fuel fleets whose total ROs were significantly higher than their controls, the Dodge CNG fleet's rate of repairs on the selected vehicle systems was significantly higher than the rate for Dodge unleaded vans. Again, there were no significant differences between the RFG and control fleets.

Non-PM Costs. Figures 3a and 3b summarize the non-PM costs for all repairs and for repairs associated with selected systems (fuels/engines, electrical, and instruments), respectively. It's important to note that there are significant differences in the reported maintenance costs for the unleaded vans among the four demonstration sites. In particular, the reported total maintenance costs on the unleaded vans at the Irvine and Rialto sites range from $250 to $750 per 100 service days, while the corresponding costs at Los Angeles and Santa Ana are less than $250 per 100 service days. These differences may be attributed to several causes including differences in vehicle duty cycles (e.g., daily mileage, type of route), price differences among vendors and local dealers, variations in vendor service response capabilities, and variations in maintenance practices among FedEx mechanics. While certain non-fuel-related warranty costs are not included in any of these figures, these "missing costs" are expected to be the same for the unleaded and

Table 2a. Relative Differences in the Number of Non-Accident Repair Orders per 100 Service Days Between Alternative Fuel Vans and Unleaded Gasoline Vans

Manufacturer	Fuel	N	Service Days per Vehicle	Total ROs [a]	RO/100 Days	Relative Difference [b]	95% Confidence Interval
Chevrolet	CNG	7	441	367	11.9	42%	(17%, 72%)
	Unleaded	3	573	144	8.4		
Dodge	CNG	7	460	383	11.9	8%	(-10%, 29%)
	Unleaded	3	544	180	11.0		
Ford	CNG	7	455	319	10.0	31%	(8%, 60%)
	Unleaded	3	630	144	7.6		
Chevrolet	RFG	7	608	295	6.9	19%	(-4%, 48%)
	Unleaded	3	660	115	5.8		
Dodge	RFG	7	605	207	4.9	-23%	(-39%, -4%)
	Unleaded	3	607	116	6.4		
Ford	RFG	7	648	241	5.3	-15%	(-31%, 6%)
	Unleaded	3	647	121	6.2		
Chevrolet	Propane Gas	7	432	465	15.4	27%	(7%, 50%)
	Unleaded	3	502	183	12.2		
Ford	Propane Gas	13	522	648	9.6	11%	(-7%, 32%)
	Unleaded	3	572	148	8.6		
Ford	M-85	20	521	649	6.2	41%	(11%, 78%)
	Unleaded	3	595	79	4.4		

[a] ROs = Repair orders.

[b] Relative difference (percent) in RO/100 days compared to unleaded vans from the same manufacturer and maintained at the same FedEx facility.

Table 2b. Relative Differences in the Number of Selected[(a)] Repair Orders per 100 Service Days Between Alternative Fuel Vans and Unleaded Gasoline Vans

Manufacturer	Fuel	N	Service Days per Vehicle	Selected ROs (a)	RO/100 Days	Relative Difference (b)	95% Confidence Interval
Chevrolet	CNG	7	441	183	5.9	183%	(98%, 305%)
	Unleaded	3	573	36	2.1		
Dodge	CNG	7	460	185	5.8	64%	(22%, 121%)
	Unleaded	3	544	57	3.5		
Ford	CNG	7	455	157	4.9	86%	(36%, 156%)
	Unleaded	3	630	50	2.7		
Chevrolet	RFG	7	608	110	2.6	16%	(-18%, 65%)
	Unleaded	3	660	44	2.2		
Dodge	RFG	7	605	75	1.8	1%	(-33%, 52%)
	Unleaded	3	607	32	1.8		
Ford	RFG	7	648	118	2.6	-6%	(-32%, 29%)
	Unleaded	3	647	54	2.8		
Chevrolet	Propane Gas	7	432	164	5.4	54%	(13%, 110%)
	Unleaded	3	502	53	3.5		
Ford	Propane Gas	13	522	254	3.7	21%	(-10%, 63%)
	Unleaded	3	572	53	3.1		
Ford	M-85	20	521	264	2.5	46%	(1%, 112%)
	Unleaded	3	595	31	1.7		

(a) Repair orders involving maintenance on selected vehicle systems such as instruments (ATA system code 003), Electronics (030-035), and Fuel-Engine Group (040-048).

(b) Relative difference (percent) in RO/100 days compared to unleaded vans from the same manufacturer and maintained at the same FedEx facility.

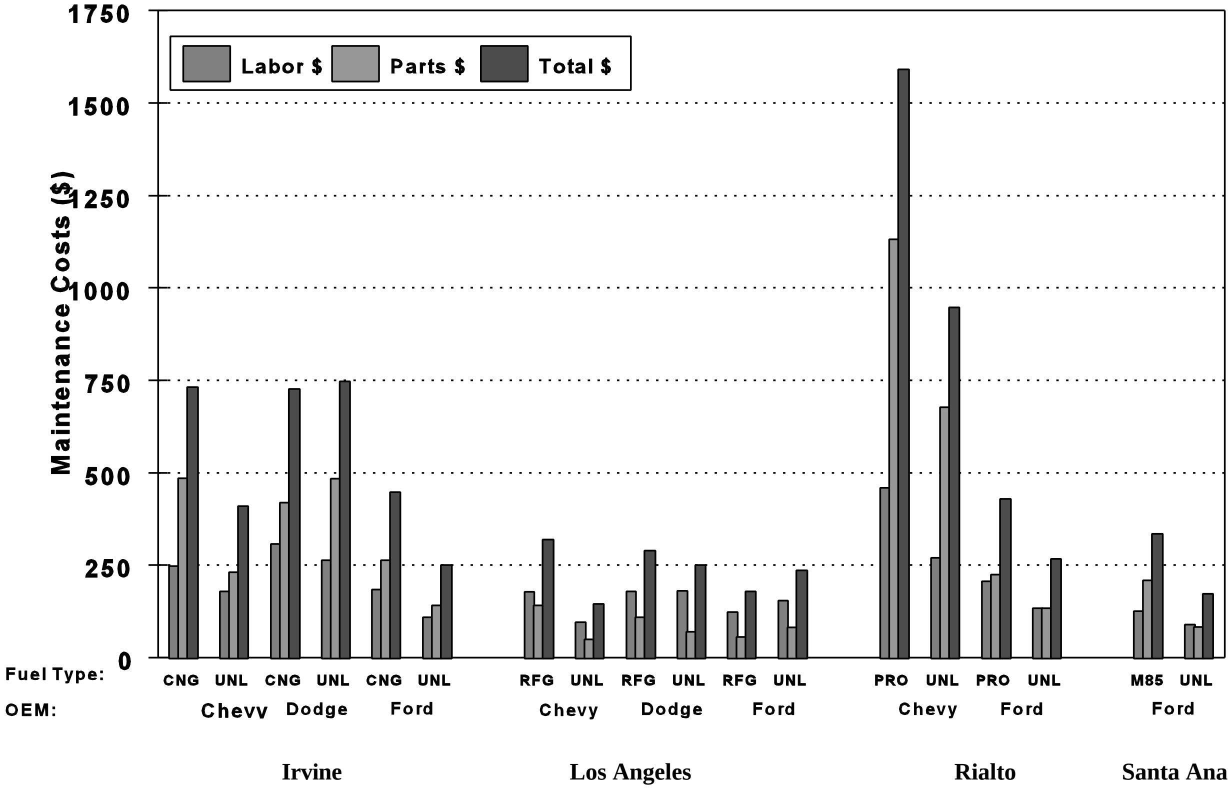


Figure 3a. Non-Preventive Maintenance Summary (All Non-Accident Repairs) Maintenance Costs per 100 Service Days by Location, OEM, and Fuel Type

alternative fuel vans. For the fuel-related warranty repairs, Chevrolet, Dodge, and the fuel system vendors (IMPCO and Suburban Propane) supplied costs to Battelle. Battelle engineers estimated the costs of the fuel-related repairs on the Ford vans. The site-to-site differences in repair costs and the missing non-fuel-related warranty costs are of little consequence as long as only vans from the same manufacturer at the same demonstration site are compared.

Figure 3a shows that, on a site-by-site basis, the total non-preventive maintenance costs for the CNG, propane gas, and M-85 vans were generally 50 to 80 percent higher than the costs for the corresponding control vans. An exception is the comparison between Dodge CNG and unleaded vans at Irvine. A similar comparison, based on the costs of maintenance on selected vehicle systems (fuels/engines, electrical, and instruments), is shown in Figure 3b. On a site-by-site basis, Figure 3b shows that maintenance costs on the potentially fuel-related systems for the CNG, propane gas, and M-85 vans are two to four times the amount for the corresponding control vans. There were no clear differences in maintenance costs between the RFG and unleaded vans.

Availability and Utilization. Nearly all of the delivery vans assigned to a FedEx station are scheduled to be in service between the hours of 7:00 AM and 8:00 PM. Mechanics generally perform maintenance when the vehicles are not in service. Because most FedEx stations usually do not keep

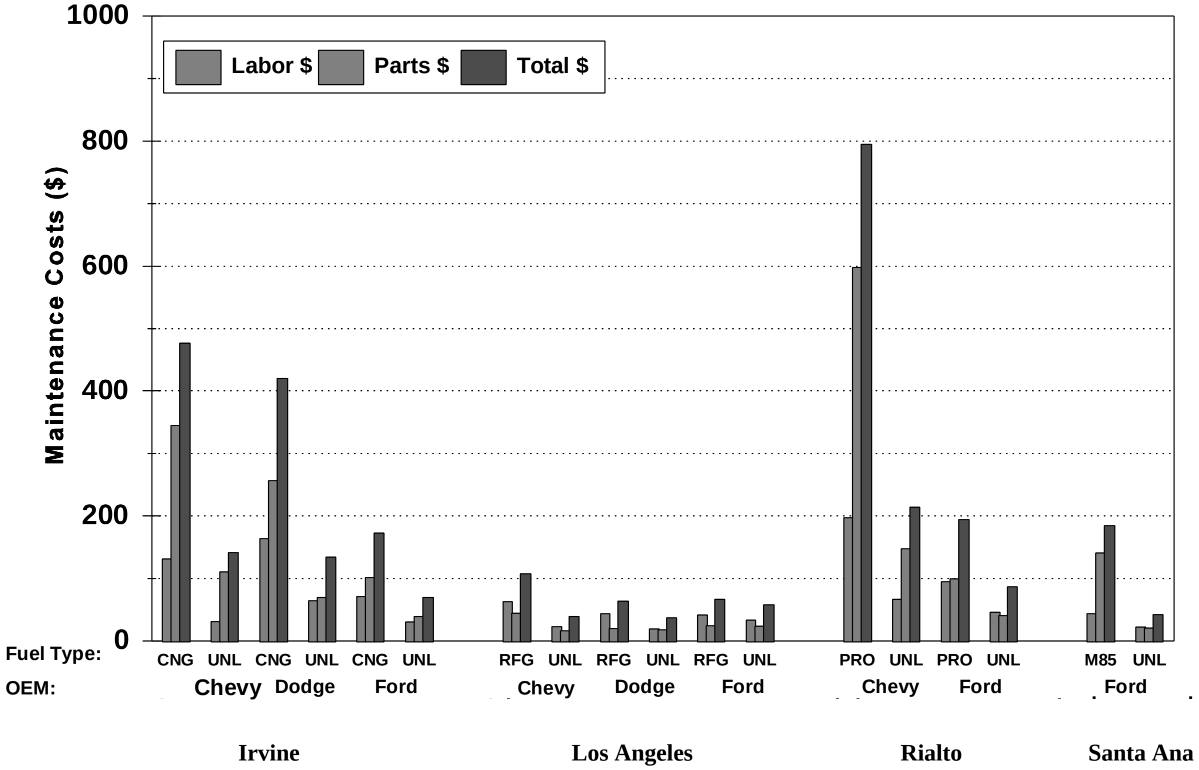


Figure 3b. Non-Preventive Maintenance Summary (Selected ATA Codes) Maintenance Costs per 100 Service Days by Location, OEM, and Fuel Type

"spare" vehicles on hand, all of the CleanFleet vans were scheduled for service five or six days per week except when they were scheduled to be in for emissions testing. (The level of delivery services performed on Saturday varies among the different stations.) Availability, as it pertains to maintenance activities, is defined as the percentage of scheduled service time that the vehicle was available for service. As discussed in the "Approach" section, vehicle availability was calculated using the reported downtime in FedEx maintenance reports and the total scheduled service time during the demonstration period. Total service time was adjusted to account for periods when the vehicles were at the ARB facility for emissions testing. Also, downtime resulting from accidents and certain maintenance "external" to vehicle operation induced maintenance (e.g., M-85 fuel contamination) is not included in the calculation of availability.

Vehicle utilization percentages are also presented. Utilization is the percent of scheduled service days that a vehicle was actually used. The averages presented below were adjusted to account for periods of time when certain vehicles were sent to the ARB for emissions testing. Thus, the results differ slightly from the results presented in the CleanFleet Quarterly Data Reports. (See, for example, Quarterly Data Report No. 8, July 1–September 30, 1994.) Utilization is always less than or equal to availability. The difference between these values represents the percent of scheduled service time that a vehicle is available but not utilized.

VEHICLE MAINTENANCE

Table 3 contains estimates of vehicle availability and vehicle utilization for each fleet of vans. Average availability varied from 88 percent for the Chevrolet propane gas fleet at Rialto to 98 to 99 percent for several fleets of unleaded and RFG vans. The average availability of vans from each alternative fuel fleet was between 4 percent lower and 2 percent higher than the average availability of the unleaded vans at the same location. No consistent pattern was detected.

Utilization varied from 83 percent for the Chevrolet CNG fleet to 97 percent for the Ford unleaded fleets at Irvine and Los Angeles. Generally, utilization was 1 percent to 7 percent lower than availability. Exceptions included the Dodge CNG fleet (9 percent lower) and the Chevrolet CNG fleet (11 percent lower). Under normal fleet operations, one would expect to see a consistent difference between availability and utilization, especially in a package delivery service such as FedEx, which must have a minimum number of vehicles available *at all times*. Comparing the utilization of alternative fuel fleets with that of the corresponding control fleets, the average utilization of RFG, propane gas, and M-85 vans was within 5 percent of the average utilization for the unleaded vans. On the other hand, the utilization of the Chevrolet and Ford CNG vans was 7 to 9 percent lower compared to the corresponding unleaded vans at the same locations. Two possible reasons for these differences are (1) the Irvine station may have had a greater need for vans that could be assigned to longer routes (over 100 miles per day), and (2) there may have been times when "driveability" concerns caused the couriers to choose available unleaded vans even though the CNG vans were not officially out of service for maintenance. Other factors that can affect utilization include the availability of spare vehicles, changes in delivery schedules, employee preferences for certain types of vehicles, and variations in maintenance scheduling practices.

Table 3. Vehicle Availability and Utilization

Location	Fuel	Manufacturer	Average Availability [(a)]	Average Utilization [(b)]
Irvine	CNG	Chevrolet	94	83
		Dodge	93	84
		Ford	94	88
	Unleaded	Chevrolet	95	90
		Dodge	91	87
		Ford	98	97
Los Angeles	RFG	Chevrolet	98	95
		Dodge	98	91
		Ford	98	94
	Unleaded	Chevrolet	99	92
		Dodge	99	96
		Ford	98	97
Rialto	Propane gas	Chevrolet	88	86
		Ford	96	93
	Unleaded	Chevrolet	91	89
		Ford	96	92
Santa Ana	M-85	Ford	97	94
	Unleaded	Ford	99	95

[(a)] Availability is defined as 100 (T-D)/T, where T is the scheduled service time and D is the downtime required for maintenance.

[(b)] Utilization is defined as 100 U/T, where T is the number of scheduled service days and U is the number of days that the vehicle was actually used by FedEx.

Oil Consumption and Analysis

Approach

Each time the oil was changed on a CleanFleet vehicle, the mechanic recorded the date, odometer reading, and oil level on the dipstick. Adding oil between oil changes was also reported and made it possible to account for total oil consumption. A sample of used oil was collected at each oil change and sent to a laboratory for chemical analysis. Through September 1994, data from 918 oil changes and 858 oil analyses were reported.

Data Collection. Data used for assessing oil consumption rates and properties of used oil came from various sources:

- Information on oil changes or additions of oil was reported by FedEx mechanics on special CleanFleet data collection forms. For oil changes, the data included the vehicle identification number, date, odometer reading, dipstick oil level, and oil sample identification number. Samples of used oil are collected at each oil change. If the mechanic added oil between oil changes, he or she recorded the date, odometer reading, and amount of oil added.

- FedEx mechanics are required to report all maintenance activities, including parts and labor for preventive maintenance and additions of oil, in VAGIS. FedEx sent copies of the VAGIS data for all CleanFleet vehicles to Battelle bi-weekly in electronic form.

- As required by the U.S. Department of Transportation, drivers complete a VURR each time they drive a vehicle. The information includes employee number, date of vehicle use, ending odometer reading, and maintenance required. Mechanics review the VURRs each day and respond to the maintenance items. Copies of the VURRs at all participating stations were sent to Battelle on a regular basis. The VURRS were reviewed by Battelle to identify instances when either the driver or mechanic added oil between oil changes.

- Oil samples, collected during each oil change, were shipped to a commercial laboratory for analysis. The oil analysis package included measurements of 12 engine metals, 11 contaminants or additives, and four oil properties. The specific parameters reported and their baseline values in the Lubrizol and Chevron oils are shown in Table 4. The baseline values are averages based on analyses of two samples of unused oil.

Data from all of these sources were combined into a common database to assess data completeness and to identify potential outliers (data that do not fit the usual patterns for oil change frequencies or oil analysis results). Dates and odometer readings from each oil change, oil addition, and oil analysis (reported through the various data collection protocols) were sorted and matched to resolve discrepancies. Because of the redundancy built into the data collection protocols and the consistency in the data reported, it is unlikely that oil changes could have been performed on CleanFleet vehicles and not reported in one

Table 4. Measured Properties of Unused Oil Samples

Category	Parameter	Average Value[a] Chevron DELO 400 15W40[b]	Average Value[a] Lubrizol MFV 10W30[b]
Engine Metals	Iron	2.5	6.5
	Chromium	<1	<1
	Nickel	1.5	1.5
	Aluminum	2.5	<1
	Lead	1.5	2.5
	Copper	1.5	<1
	Tin	<1	<1
	Silver	0.1	<0.1
	Titanium	<1	<1
	Molybdenum	<5	<5
	Antimony	<1	2
	Vanadium	<1	<1
Contaminants	Silicon	2	11
	Sodium	28	9
	Potassium	<10	<10
	Barium	<10	<10
	Water (% vol)	<0.05	<0.05
	Fuel (% vol)	-[c]	-[c]
Additives	Boron	166	5
	Phosphorus	1,055	1,118
	Zinc	1,236	2,200
	Calcium	2,315	43
	Magnesium	57	2,462
Properties	Viscosity(cSt)[d]	15.1	10.9
	TBN (≥ 0)	6.51	8.53
	Oxidation (0-99)	-[c]	-[c]
	Nitration (0-99)	-[c]	-[c]

(a) Properties measured in ppm unless stated otherwise.
(b) Lubrizol MFV oil is used in M-85 vehicles only. Chevron DELO 400 is used in all other vehicles.
(c) Not measured in unused oil samples.
(d) cSt = CentiStokes.

of the sources. Oil analysis results are available from 858 used oil samples collected during 918 oil changes performed on CleanFleet vehicles through September 1994—a 93 percent data completion rate. The data were screened to identify significant outliers. Results from three analyses were excluded because it was suspected that the wrong vehicle numbers were recorded on the oil sample labels.

Oil consumption data included the amount of oil added between oil changes and the amount low, as indicated on the dipstick, prior to an oil change. There were 23 instances of the driver or mechanic reporting adding oil to a CleanFleet vehicle between oil changes and 171 instances of the mechanic reporting that the oil level was low prior to an oil change. As reported, these data indicated low oil consumption rates. The results were discussed with FedEx fleet managers, mechanics, and drivers to assess the completeness of the oil consumption data.

Oil Analysis Procedures. The complete oil analysis package used by the commercial laboratory for the CleanFleet samples consisted of several tests. The test package was broken down into a spectrochemical analysis and several physical property tests. The spectrochemical analysis was conducted to detect certain chemical elements dissolved or suspended in the oil. The analysis detected particles with diameters of 10 µm or smaller. Particles in this size range have an elemental composition that is representative of all the debris in the sump. Furthermore, wear particles with diameters above about 15 µm are typically filtered out of the oil and would not be available for analysis anyway. Thus, used engine oil is not analyzed to determine total engine wear. Instead, the calculated weight of engine metal removed represents only particles with diameters less than 10 µm and is used only for comparative purposes.

Oil viscosity was measured using a method that approximates American Society for Testing Materials (ASTM) standard D445; the exact procedure has been modified to accommodate the automated equipment. The viscosity was reported in units of centistokes at 100 degrees centigrade. The total base number (TBN) was determined by an acid titration process (a modified ASTM 664) and reflected the amount of additional acidic contaminants the oil can neutralize. Oxidation and nitration numbers were both determined using infrared absorption to compare the used oil sample to a new oil baseline. The greater the difference between the infrared light transmitted through the used oil sample compared with the fresh reference oil sample, the higher the oxidation and nitration numbers. These numbers were reported on a scale of 1 to 99; values above 25 usually indicate sufficient oil degradation to warrant an oil change.

Water content was determined qualitatively using a hot plate crackle test. If water was found in the oil, additional testing is done to estimate the percentage. Fuel dilution was determined using gas chromatography techniques in accordance with a modified ASTM 3524 standard.

Table 4 contains the average measured parameters for the base Chevron DELO and Lubrizol MFV oils used by CleanFleet vehicles. For each type of oil, the averages were determined from analyses of two samples of unused oil. The most notable differences in the oils are in the additive packages. The Lubrizol oil, used exclusively in the M-85 vans, contains higher levels of zinc and magnesium; while the Chevron oil, used in all other vehicles, has higher levels of boron and calcium.

Data Modeling and Statistical Analysis Approach. Because of its relevance to assessing overall engine durability, information on metal accumulation in the oil is of primary interest. Modeling is needed to calculate the amount of metal that accumulated in the oil and to make statistical comparisons between the alternative fuel and control vehicles. Graphical and tabular methods were used to characterize the distributions of oil contaminant and additive levels and oil properties at the first and last oil changes. Relationships between oil properties and miles driven between oil changes were investigated further using regression methods. The modeling and statistical approaches used in the analyses of engine metals and oil properties are discussed in Appendix B.

Results

Two types of data were collected: (1) data describing the frequency of oil changes and rates of oil consumption, and (2) results from the analysis of used engine oil. The oil change data were used to compare the frequencies of oil changes among the different fleets. Differences in the oil change frequencies were considered in evaluating the data from the analysis of used oil. The amount of oil consumed (through leaks or combustion exhaust) was determined from reports of adding oil between oil changes and the level of oil recorded just prior to an oil change.

Data from the analysis of used oil samples were used to assess the overall health of the vehicles and to identify individual vehicles that may have been developing engine durability problems. Table 5 lists the various parameters that are measured in the analysis of used oil. It also lists the typical sources of engine metals, potential problems indicated by high levels of contaminants, and information on the importance of the oil properties that are measured. The “generic” or typical sources of engine metals shown in Table 5 are not necessarily potential sources from CleanFleet vehicles. Also, engine parts or sources other than those listed may contribute to the levels of various metals in the oil. Table 5 only lists the typical sources for this class of vehicle. Vehicle manufacturers did not provide specific information on the composition of engine parts used in CleanFleet vehicles.

Oil Change Intervals and Oil Consumption Rates. Table 6 contains summary information on the frequency of oil changes and the amount of oil consumed through leakage or combustion exhaust. The average total miles for each fleet is based on the mileage accumulated as of the last oil change reported prior to September 30, 1994. Between six and ten oil changes were performed on individual vehicles during the two-year demonstration. By fleet, the average ranges from 7.7 to 9.0 oil changes per vehicle.

FedEx schedules preventive maintenance, including oil and filter changes, on its delivery vans every 12 weeks (84 days). Vehicles that accumulate more than 6,000 miles during that period are scheduled sooner. Table 6 shows that the average number of miles between oil changes for individual fleets varied from 2,000 miles for the Chevrolet RFG vans to 4,600 miles for the Ford unleaded vans at Rialto and the Dodge unleaded vans at Irvine. The average number of days between oil changes ranged from 80 to 99. Although the averages at the Los Angeles site exceeded the 84-day limit, all but four of the 241 oil changes at this site were performed within 5,000 miles of the previous oil change.

Oil consumption, as reported by the drivers and mechanics, averaged between zero and 0.9 quarts per 10,000 miles among the various fleets. Discussions with the mechanics and drivers revealed some inconsistencies in reporting oil addition between changes and recording dipstick levels during preventive maintenance. However, based on the data collected at stations known to have reported complete data and the discussions with personnel at each station, it is believed that oil consumption was not a problem for any of the CleanFleet vehicles and average consumption did not exceed one quart per 10,000 miles driven for any of the fleets. Because of the low rates of consumption, statistical comparisons of oil consumption rates are not particularly meaningful.

Table 5. Information Available from the Analysis of Used Oil Samples

Category	Parameter	Type of Information
Engine Metals		**Possible Source of Engine Metals**
	Iron	shafts, cylinder liners, piston rings, valve train (mainly cam lobe and follower)
	Chromium	piston rings
	Nickel	certain kinds of valve and valve guides
	Aluminum	pistons, aluminum bearings or bushings
	Lead	bearing babbitt or bronze bushings
	Copper	bearing babbitt or bronze bushings
	Tin	bearing babbitt or bronze bushings
	Silver	bearing babbitt, solder from cooling system contamination
	Titanium	alloy steel parts
	Molybdenum	piston rings
	Antimony	bearing babbitt
	Vanadium	not applicable
Oil Contaminants		**Problems the Presence of Contaminants Might Indicate**
	Silicon	dirt entering engine
	Sodium	coolant leak
	Potassium	coolant leak
	Water	short duty cycle, engine not reaching operating temperature, coolant leak
	Fuel	engine running rich (or not fully warmed up)
Oil Additives		**Oil Identification**
	Barium Boron Phosphorus Zinc Calcium Magnesium	(Additive levels determined by oil manufacturer.)
Oil Properties		**Importance of Property**
	Viscosity	to maintain hydrodynamic oil films in journal bearings- Normal range: 9.3 to 12.5 (SAE30) and 12.5 to 16.3 (SAE40)
	TBN	alkaline reserve for neutralizing acidic combustion products- Normal range: should always be greater than zero
	Oxidation	measure of lubricant breakdown- Normal range: less than 25 on a scale of 1-99
	Nitration	measure of blow by contamination- Normal range: less than 25 on a scale of 1-99

Table 6. Summary Information on Oil Change Intervals and Oil Consumption Rates

Location	Manufacturer	Fuel	Average Total Miles[a]	Average Number of Oil Changes	Average Miles Between Oil Changes	Average Days Between Oil Changes	Average Oil Consumed per 10,000 Miles[b] (quarts)
Irvine	Chevrolet	CNG	25,900	8.3	3.100	81	0.9
		Unleaded	39,500	9.0	4,400	84	0.4
	Dodge	CNG	20,700	8.4	2,500	82	0.7
		Unleaded	41,300	9.0	4,600	83	0.2
	Ford	CNG	28,200	8.1	3,500	79	0.5
		Unleaded	37,700	9.0	4,200	81	0.5
Los Angeles	Chevrolet	RFG	19,300	7.9	2,500	95	0.3
		Unleaded	15,400	7.7	2,000	99	0.2
	Dodge	RFG	17,900	7.9	2,300	96	0.2
		Unleaded	25,100	8.3	3,000	90	0.0
	Ford	RFG	20,000	8.1	2,500	92	0.1
		Unleaded	18,700	8.7	2,200	89	0.0
Rialto	Chevrolet	Propane gas	33,400	8.4	4,000	80	0.2
		Unleaded	37,900	9.0	4,200	83	0.2
	Ford	Propane gas	37,900	9.1	4,200	81	0.2
		Unleaded	41,300	9.0	4,600	84	0.1
Santa Ana	Ford	M-85	23,200	8.2	2,800	80	0.5
		Unleaded	24,500	9.0	2,700	80	0.1

(a) All values in this table are averages per vehicle.
(b) Includes added oil and amount low at time of oil change.

Figures 4 and 5 show the distribution of miles and days between oil changes by individual fleet. The distributions are presented using box-and-whisker plots. The box indicates the range over which the central 50 percent of the values lie. The median value is indicated by the vertical line inside the box and the minimum and maximum values are represented by the ends of the whiskers. For example, a total of 58 oil changes were performed on the Chevrolet CNG vans. The number of miles between oil changes ranged from 200 to 7,200. Fifty percent of the oil changes were performed at between 2,200 and 3,800 miles, with a median value of 2,900 miles.

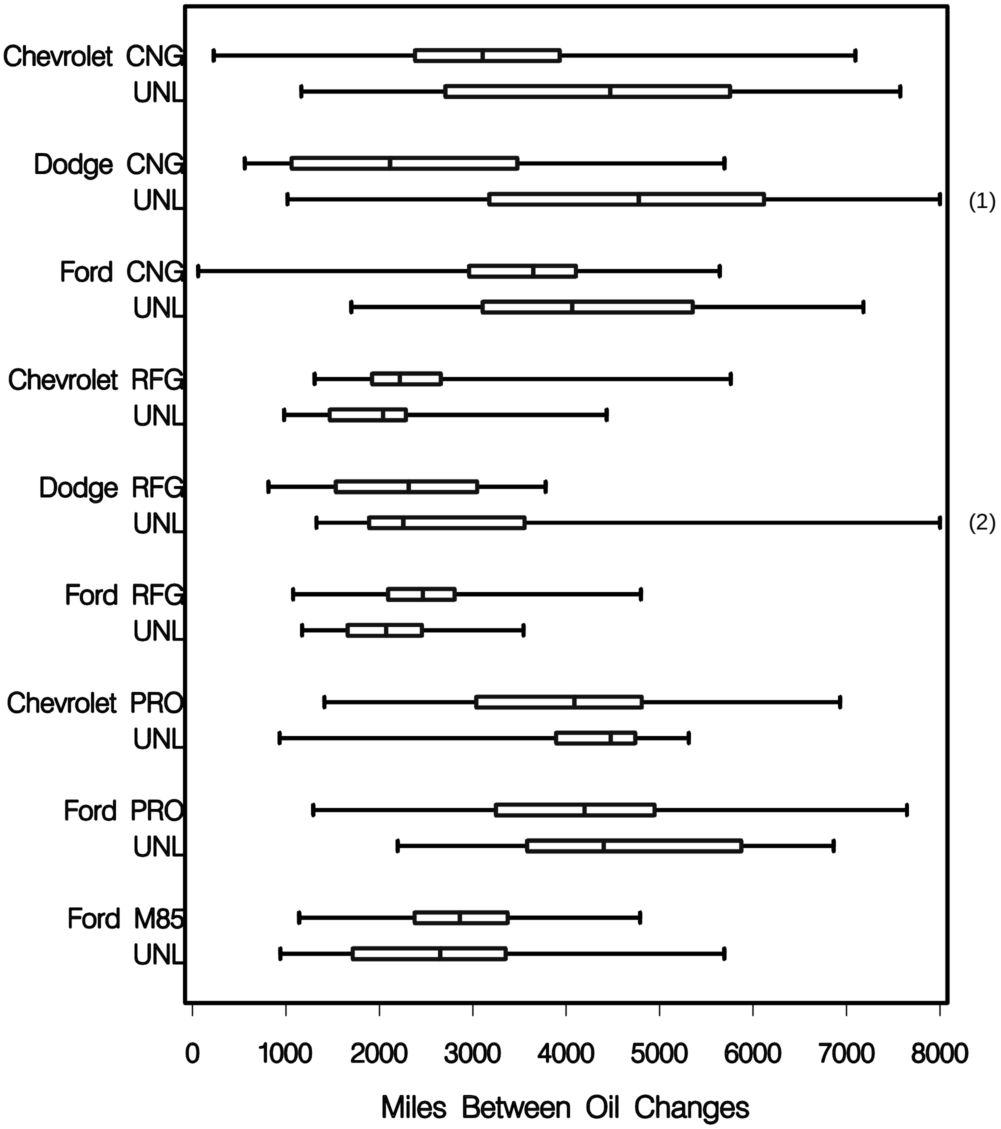
Figures 4 and 5, as well as the averages shown in Table 6, demonstrate that the number of miles between oil changes varied considerably from fleet to fleet. However, the number of days between changes was fairly consistent. This occured because (1) FedEx schedules oil changes based on time rather than miles driven, and (2) there are differences in vehicle duty cycles—specifically, the average length of delivery routes. Site-to-site differences in duty cycles are unavoidable. Rialto has the largest service area and, therefore, the longest delivery routes—approximately 80 miles per day. On the other hand, routes from the Los Angeles station average around 30 miles per day.

Within each site the fleet-to-fleet differences in duty cycles (and, therefore, miles between oil changes) are smaller because the vehicles were randomly assigned to routes, then periodically rotated. The only notable exception is at Irvine where the CNG vans were initially assigned to shorter routes because of concerns over vehicle range. Efforts to improve the comparability of duty cycles between the CNG and unleaded vehicles at this location were discussed in the CleanFleet Quarterly Data Reports. (See, for example, CleanFleet Quarterly Data Report No. 8, July to September 1994.)

The FedEx policy of scheduling oil changes based on time rather than miles is based on their experience at operating a large fleet with significant variations in vehicle duty cycles. They recognize that vehicles driven on the shorter delivery routes require oil changes after fewer miles when compared to vehicles used on long-distance routes. The advantages of this policy are demonstrated in the following section in which the accumulation of metals in the oil is discussed. In short, the number of miles between oil changes had no measurable effect on engine metal wear rates.

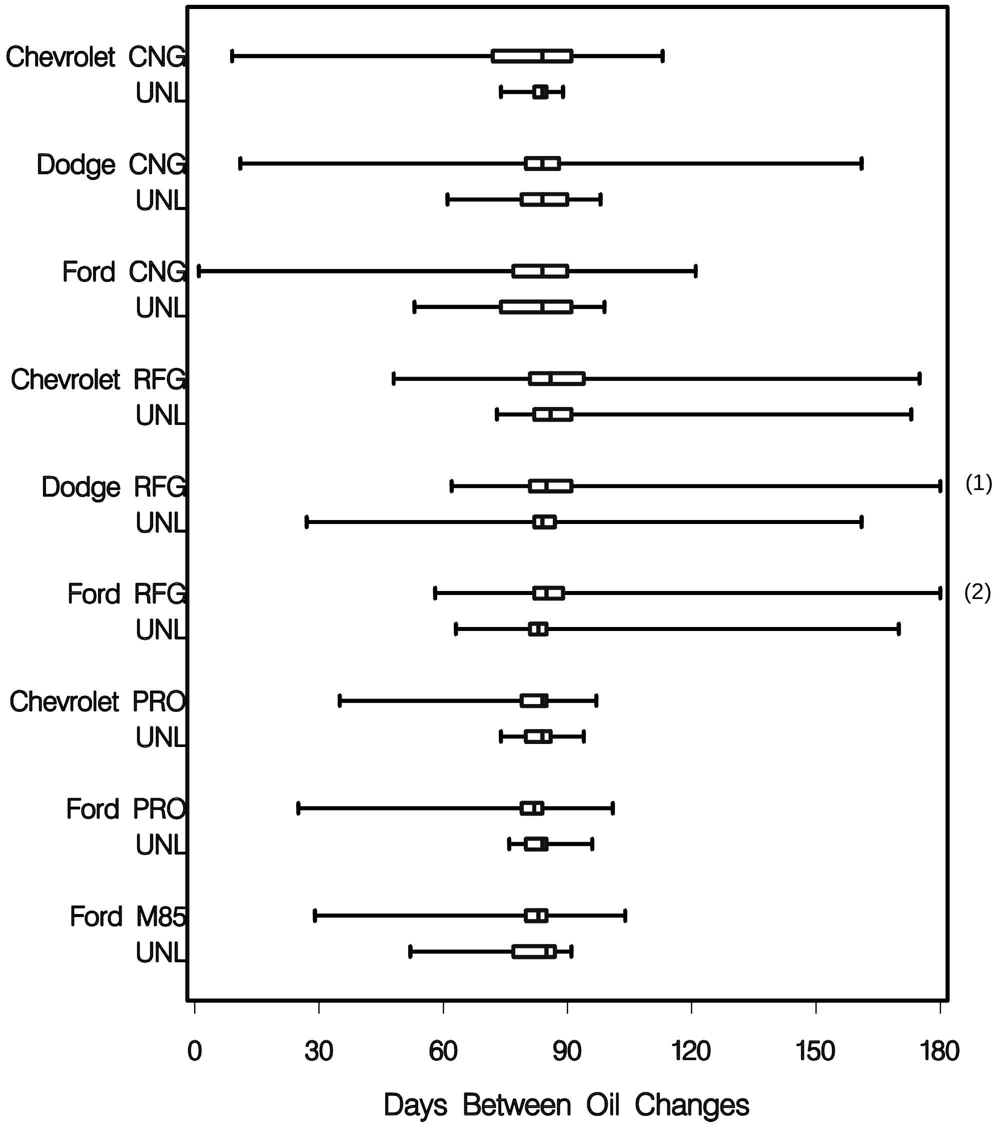
Engine Metals. The analysis of used oil samples collected during oil changes included determining the concentrations of 12 metals commonly used in various engine parts. Potential sources of these metals were described in Table 5. Nine of the metals were consistently detected in the engine oil of vehicles from one or more fleets. Titanium was never found above the detection limit of one part per million (1 ppm), and vanadium was detected in fewer than 5 percent of the oil samples, but never above the 12 ppm level. Silver, which has a detection limit of 0.1 ppm, was never found at levels above 0.4 ppm.

Using the approach described in Appendix B, the total amount of each metal removed from the engine was calculated for each oil change interval. The total does not include the elemental mass in large particles (diameters greater than 10 µm). The cumulative weight of each metal was determined each time a vehicle's oil was changed. An illustration of the resulting data is shown in Figure 6. In this example, the cumulative weight of iron removed from Ford propane gas engines is plotted against vehicle miles. Each line represents an individual vehicle. The number of each oil change (1 through 8) is shown at each oil change mileage. Similar plots were generated for each fleet and for each of the nine metals. They were



(1) One oil change interval at 8,452 miles.
(2) One oil change interval at 8,938 miles.

Figure 4. Box and Whisker Plots of the Distribution of Miles Between Oil Changes



[(1)] One oil change interval at 252 days.
[(2)] One oil change interval at 257 days.

Figure 5. **Box and Whisker Plots of the Distribution of Days Between Oil Changes**

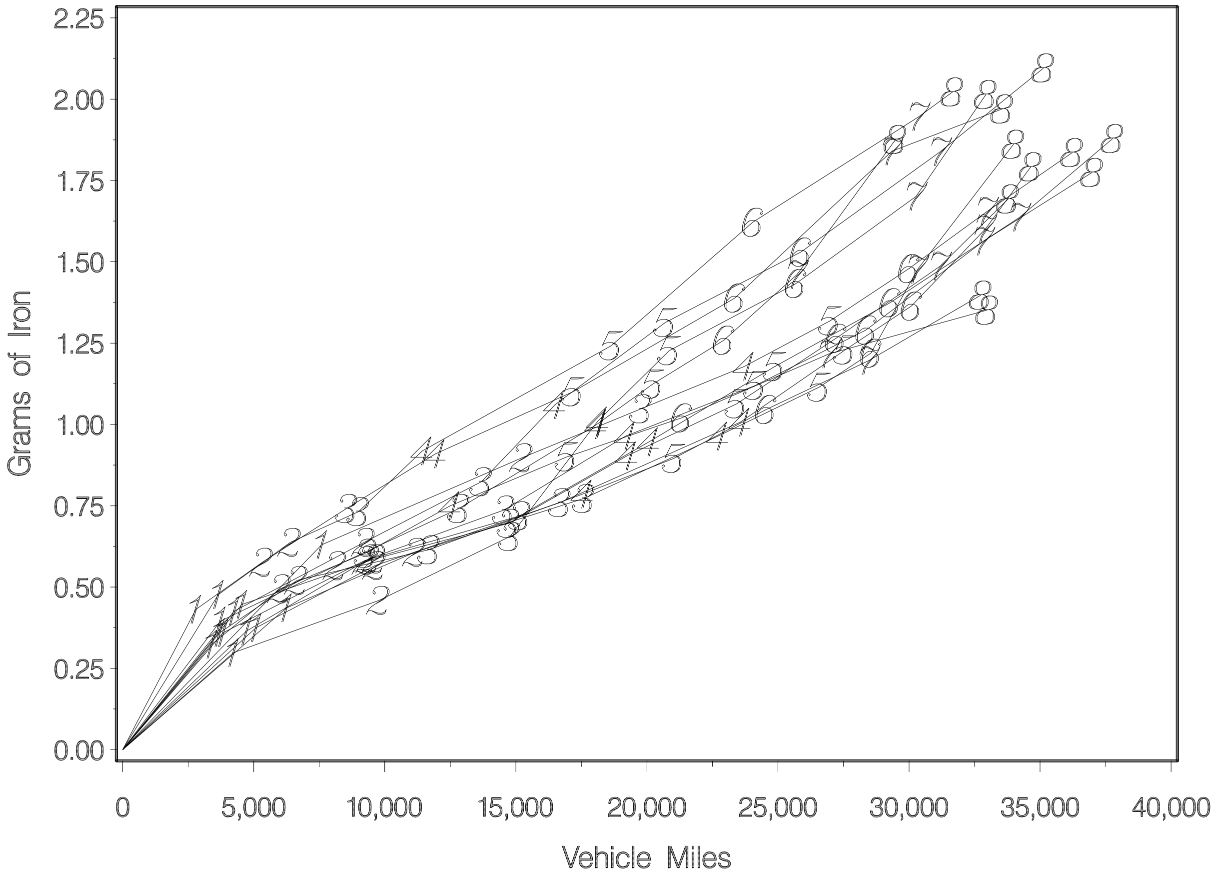


Figure 6. Cumulative Weight of Iron Removed from 13 Ford Propane Gas Engines Versus Vehicle Miles (Plotting Symbols Represent Oil Change Numbers)

reviewed to determine if there were any problem vehicles and to establish the level of consistency of the data among vehicles. No problems with individual vehicles were identified.

The average cumulative amount of metal removed at selected mileages (2,500 miles and 5,000 to 40,000 miles in increments of 5,000 miles) was then calculated for each fleet using the interpolated values of individual vehicles. Appendix C contains plots of the average cumulative weight of engine metal removed from CleanFleet vehicles. Each line represents the average for a fleet. In this discussion a fleet is defined by a unique combination of manufacturer, type of fuel, and location. Thus, at each location, the group of three unleaded vehicles from each manufacturer is treated as a separate fleet. The bold lines correspond to the alternative fuel fleets and the dashed lines represent the control fleets. Chevrolet, Dodge, and Ford fleets are indicated by the triangle, diamond, and circle; respectively. Fleet averages were calculated at the selected mileages if at least half of the vehicles had reached the indicated mileage as of its last reported oil change.

Thus, for each fleet, data may be available for a few vehicles at the higher mileages, but the results are not shown because the average lacks statistical precision.

At each demonstration site a group of three control vehicles from the same manufacturer is treated as a separate fleet. As discussed earlier, statistical comparisons of control fleets from the same manufacturer at different locations did not indicate significant differences across locations. This finding was used to impute missing data (i.e., replace missing data with average values from vehicles in the same fleet). Otherwise, the reported averages were obtained only from the control vehicles at each location. This was done to present a more complete picture.

Tables 7a and 7b contain estimates of the average cumulative weight of each of nine metals removed from vehicle engines through oil changes and consumption in the first 10,000 and 20,000 miles of operation. These mileage levels were chosen for statistical treatment because most vehicles had accumulated at least 20,000 miles. Most vehicles achieved 20,000 miles after the fifth or sixth oil change when the rate of metal accumulation begins to stabilize.

The number of vans in each fleet that achieved 10,000 or 20,000 miles as of the last reported oil change is listed in the last row of Tables 7a and 7b. However, because a sufficient number of vehicles in the alternative fuel and control fleets at Los Angeles and the Dodge CNG fleet at Irvine did not achieve 20,000 miles as of the last oil change, estimates for these fleets were projected from the estimated accumulations at 15,000 miles. Notice, however, that the projected estimates from the control fleets at these locations are generally consistent with the averages for vehicles from the same manufacturer at different locations. For example, the average iron loss in Ford unleaded vans at the CNG, propane gas, and M-85 demonstration sites ranges from 1.444 to 1.695 grams. The projected estimate for the Ford unleaded vans at the RFG site is 1.930 grams—well within the expected statistical uncertainties.

Each estimate is accompanied by a standard error determined from a statistical regression analysis. The standard errors characterize the statistical uncertainty of these estimates. Confidence intervals (95 percent) on these averages can be calculated by adding and subtracting two times the standard error. The shaded boxes in Tables 7a and 7b indicate that the differences between average values for the control and alternative fuel fleets are statistically significant (i.e., the data suggest that there is a systematic difference in the averages). Because of the large number of comparisons that were made (nine comparisons for each metal), the significance level applied to each difference was adjusted to 0.6 percent using the Bonferroni method, resulting in an overall significance level of 5 percent. This means that, if there were no differences between fleets, there would be less than a 5 percent chance of incorrectly concluding that an observed difference is statistically significant.

Results of this analysis are summarized in Table 7c. Relative differences in the engine metal accumulations that were significantly different from zero at an overall error rate of 5 percent are displayed. In nearly all of the instances for which the differences were statistically significant, the alternative fuel vehicles had lower levels of metal removal. The levels of nickel, aluminum, lead, and tin removed from the Chevrolet CNG and propane gas engines were generally between 20 percent and 90 percent less than the levels removed from the Chevrolet unleaded engines. (Molybdenum levels were substantially lower.) The Chevrolet RFG engines also had lower levels of iron and chromium at 10,000 miles and lower levels of aluminum and molybdenum at both 10,000 and 20,000 miles. Dodge CNG engines had levels of nickel, lead, tin, and molybdenum removal that were between 20 percent and 80 percent lower than the Dodge

Table 7a. Average Cumulative Engine Metal Loss (grams) at 10,000 Miles (with Standard Errors)[a]

Metal	Fuel Type	CNG Chevrolet	CNG Dodge	CNG Ford	RFG Chevrolet	RFG Dodge	RFG Ford	Propane Gas Chevrolet	Propane Gas Ford	M-85 Ford
Iron	Alt Fuel	1.791 (0.137)	1.622 (0.148)	0.551 (0.137)	1.242 (0.137)	0.877 (0.148)	0.868 (0.148)	1.522 (0.137)	0.636 (0.101)	4.557 (0.081)
	Unleaded	2.301 (0.210)	1.884 (0.210)	1.043 (0.210)	2.305 (0.210)	1.638 (0.210)	1.046 (0.210)	1.804 (0.210)	0.972 (0.210)	0.935 (0.210)
Chromium	Alt Fuel	0.064 (0.008)	0.031 (0.009)	0.071 (0.008)	0.031 (0.008)	0.029 (0.009)	0.050 (0.009)	0.058 (0.008)	0.072 (0.006)	0.107 (0.005)
	Unleaded	0.079 (0.013)	0.066 (0.013)	0.080 (0.013)	0.080 (0.013)	0.067 (0.013)	0.093 (0.013)	0.079 (0.013)	0.093 (0.013)	0.083 (0.013)
Nickel	Alt Fuel	0.021 (0.004)	0.021 (0.004)	0.027 (0.004)	0.041 (0.004)	0.034 (0.004)	0.009 (0.004)	0.016 (0.004)	0.018 (0.003)	0.052 (0.002)
	Unleaded	0.040 (0.006)	0.049 (0.006)	0.022 (0.006)	0.036 (0.006)	0.063 (0.006)	0.026 (0.006)	0.036 (0.006)	0.024 (0.006)	0.026 (0.006)
Aluminum	Alt Fuel	0.218 (0.015)	0.186 (0.017)	0.089 (0.015)	0.228 (0.015)	0.155 (0.017)	0.140 (0.017)	0.191 (0.015)	0.082 (0.011)	0.118 (0.009)
	Unleaded	0.317 (0.023)	0.170 (0.023)	0.179 (0.023)	0.442 (0.023)	0.169 (0.023)	0.238 (0.023)	0.478 (0.023)	0.239 (0.023)	0.196 (0.023)
Lead	Alt Fuel	0.688 (0.113)	2.542 (0.122)	1.183 (0.113)	1.345 (0.113)	2.474 (0.122)	1.449 (0.122)	0.782 (0.113)	1.379 (0.083)	1.294 (0.067)
	Unleaded	1.455 (0.172)	2.852 (0.172)	1.470 (0.172)	1.369 (0.172)	2.276 (0.172)	1.584 (0.172)	1.570 (0.172)	1.724 (0.172)	1.604 (0.172)
Copper	Alt Fuel	1.472 (0.134)	1.300 (0.145)	1.219 (0.134)	2.332 (0.134)	1.165 (0.145)	1.652 (0.145)	1.786 (0.134)	1.429 (0.099)	0.783 (0.080)
	Unleaded	1.626 (0.205)	0.933 (0.205)	0.982 (0.205)	1.798 (0.205)	1.790 (0.205)	1.390 (0.205)	1.752 (0.205)	0.990 (0.205)	1.246 (0.205)
Tin	Alt Fuel	0.052 (0.025)	0.354 (0.027)	0.207 (0.025)	0.266 (0.025)	0.344 (0.027)	0.344 (0.027)	0.039 (0.025)	0.341 (0.018)	0.392 (0.015)
	Unleaded	0.459 (0.038)	0.559 (0.038)	0.342 (0.038)	0.271 (0.038)	0.487 (0.038)	0.339 (0.038)	0.497 (0.038)	0.457 (0.038)	0.309 (0.038)
Molybdenum	Alt Fuel	0.008 (0.004)	0.008 (0.005)	0.000 (0.004)	0.060 (0.004)	0.004 (0.005)	0.001 (0.005)	0.009 (0.004)	0.000 (0.003)	0.001 (0.003)
	Unleaded	0.176 (0.007)	0.036 (0.007)	0.000 (0.007)	0.159 (0.007)	0.024 (0.007)	0.000 (0.007)	0.173 (0.007)	0.000 (0.007)	0.003 (0.007)
Antimony	Alt Fuel	0.079 (0.016)	0.199 (0.018)	0.049 (0.016)	0.053 (0.016)	0.170 (0.018)	0.071 (0.018)	0.032 (0.016)	0.040 (0.012)	0.037 (0.010)
	Unleaded	0.012 (0.025)	0.184 (0.025)	0.002 (0.025)	0.083 (0.025)	0.109 (0.025)	0.009 (0.025)	0.010 (0.025)	0.007 (0.025)	0.079 (0.025)
Number of Vans Reaching 10,000 Miles	Alt Fuel	7	6	7	7	6	6	7	13	20
	Unleaded	3	3	3	3	3	3	3	3	3

(a) Shaded pairs indicate difference is statistically significant.

Table 7b. Average Cumulative Engine Metal Loss (grams) at 20,000 Miles (with Standard Errors)[a]

Metal	Fuel Type	CNG Chevrolet	CNG Dodge	CNG Ford	RFG Chevrolet	RFG Dodge	RFG Ford	Propane Gas Chevrolet	Propane Gas Ford	M-85 Ford
Iron	Alt Fuel	3.025 (0.235)	2.502 (0.765)	1.496 (0.235)	1.936 (0.700)	1.355 (0.842)	1.258 (0.278)	2.367 (0.235)	1.048 (0.173)	9.071 (0.151)
	Unleaded	3.374 (0.359)	3.365 (0.359)	1.695 (0.359)	2.881 (1.631)	2.725 (1.002)	1.930 (1.191)	2.715 (0.359)	1.531 (0.359)	1.444 (0.440)
Chromium	Alt Fuel	0.093 (0.014)	0.052 (0.042)	0.148 (0.014)	0.062 (0.039)	0.053 (0.046)	0.095 (0.016)	0.094 (0.014)	0.125 (0.010)	0.199 (0.009)
	Unleaded	0.120 (0.021)	0.112 (0.021)	0.137 (0.021)	0.135 (0.089)	0.124 (0.056)	0.209 (0.066)	0.128 (0.021)	0.149 (0.021)	0.127 (0.026)
Nickel	Alt Fuel	0.029 (0.006)	0.029 (0.019)	0.044 (0.006)	0.062 (0.018)	0.053 (0.021)	0.030 (0.007)	0.020 (0.006)	0.035 (0.004)	0.106 (0.004)
	Unleaded	0.058 (0.008)	0.075 (0.008)	0.039 (0.008)	0.076 (0.040)	0.110 (0.025)	0.048 (0.030)	0.052 (0.008)	0.051 (0.008)	0.031 (0.010)
Aluminum	Alt Fuel	0.438 (0.021)	0.328 (0.074)	0.209 (0.021)	0.531 (0.068)	0.243 (0.081)	0.305 (0.025)	0.380 (0.021)	0.178 (0.015)	0.194 (0.014)
	Unleaded	0.552 (0.032)	0.301 (0.032)	0.338 (0.032)	0.567 (0.156)	0.375 (0.098)	0.535 (0.115)	0.843 (0.032)	0.426 (0.032)	0.399 (0.039)
Lead	Alt Fuel	0.983 (0.128)	2.846 (0.495)	1.682 (0.128)	1.920 (0.454)	3.253 (0.540)	2.071 (0.152)	1.028 (0.128)	1.875 (0.094)	1.881 (0.082)
	Unleaded	2.022 (0.196)	3.604 (0.196)	2.446 (0.196)	1.778 (1.024)	2.872 (0.655)	2.996 (0.764)	2.136 (0.196)	2.570 (0.196)	2.206 (0.240)
Copper	Alt Fuel	1.622 (0.143)	2.827 (0.639)	1.357 (0.143)	3.811 (0.585)	3.185 (0.699)	2.516 (0.170)	1.921 (0.143)	1.606 (0.105)	1.021 (0.092)
	Unleaded	1.905 (0.219)	1.392 (0.219)	1.213 (0.219)	3.817 (1.336)	2.903 (0.841)	2.533 (0.989)	2.050 (0.219)	1.256 (0.219)	1.460 (0.268)
Tin	Alt Fuel	0.052 (0.024)	0.570 (0.107)	0.217 (0.024)	0.290 (0.098)	0.457 (0.117)	0.371 (0.028)	0.039 (0.024)	0.354 (0.018)	0.485 (0.015)
	Unleaded	0.500 (0.037)	0.638 (0.037)	0.388 (0.037)	0.331 (0.220)	0.615 (0.142)	0.462 (0.165)	0.517 (0.037)	0.476 (0.037)	0.316 (0.045)
Molybdenum	Alt Fuel	0.015 (0.006)	0.012 (0.020)	0.000 (0.006)	0.072 (0.018)	0.005 (0.021)	0.001 (0.008)	0.016 (0.006)	0.001 (0.005)	0.001 (0.004)
	Unleaded	0.248 (0.010)	0.049 (0.010)	0.000 (0.010)	0.219 (0.041)	0.035 (0.026)	0.000 (0.030)	0.278 (0.010)	0.000 (0.010)	0.005 (0.012)
Antimony	Alt Fuel	0.129 (0.027)	0.274 (0.082)	0.125 (0.027)	0.056 (0.075)	0.285 (0.090)	0.104 (0.032)	0.067 (0.027)	0.137 (0.020)	0.063 (0.018)
	Unleaded	0.035 (0.042)	0.275 (0.042)	0.039 (0.042)	0.203 (0.174)	0.128 (0.108)	0.022 (0.128)	0.032 (0.042)	0.030 (0.042)	0.115 (0.051)
Number of Vans Reaching 20,000 Miles	Alt Fuel	7	3	7	3	3	5	7	13	17
	Unleaded	3	3	3	1	1	0	3	3	2

(a) Shaded pairs indicate difference is statistically significant.

Table 7c. Statistically Significant Differences Between Engine Metal Accumulations in Alternative Fuel and Unleaded Gasoline Vehicles at 10,000 and 20,000 Miles

Metal	Mileage	CNG Chevrolet	CNG Dodge	CNG Ford	RFG Chevrolet	RFG Dodge	RFG Ford	Propane Gas Chevrolet	Propane Gas Ford	M-85 Ford
Iron	10,000 20,000	- (a) -	- -	- -	-46% -	-46% -	- -	- -	- -	+390% +530%
Chromium	10,000 20,000	- -	- -	- -	-61% -	- -	- -	- -	- -	- -
Nickel	10,000 20,000	- -50%	-57% -65%	- -	- -	-46% -	- -	-56% -62%	- -	+100% +240%
Aluminum	10,000 20,000	-31% -21%	- -	-50% -38%	-48% -32%	- -	-41% -	-60% -67%	-66% -58%	-40% -51%
Lead	10,000 20,000	-53% -51%	- -23%	- -31%	- -	- -	- -	-50% -52%	- -27%	- -
Copper	10,000 20,000	- -	- +75%	- -	- -	- -	- -	- -	- -	- -
Tin	10,000 20,000	-89% -90%	-37% -	-39% -44%	- -	-29% -37%	- -	-92% -92%	- -36%	- +53%
Molybdenum	10,000 20,000	-95% -94%	-78% -	- -	-62% -68%	- -	- -	-95% -94%		
Antimony	10,000 20,000	- -	- -	- -	- -	- -	- -	- -	- -	- -

[a] Indicates that the difference was not statistically significant at the 0.6% level. (Overall error rate for all nine comparisons is less than 5%.)

unleaded engines. Copper removal levels in the Dodge CNG engines were 75 percent higher. Dodge RFG engines had lower levels of iron, nickel, and tin removal compared to the control vans. Removal levels of alumunim, lead, and tin from the Ford CNG and propane gas engines were beween 25 percent and 65 percent lower than the levels found in the unleaded control engines.

Except for higher copper removal levels in the Dodge CNG engines, the Ford M-85 vans were the only alternative fuel vehicles that had consistently higher levels of metal removal compared to the control vans. The average weight of iron removed from the engine during the first 20,000 miles was 9.1 grams versus 1.4 grams for the unleaded control vans (a 530 percent difference). Nickel removal rates were 240 percent higher and tin removal rates were 53 percent higher. On the other hand, aluminum removal rates were 51% lower in the M-85 engines. There were no measurable differences in the engine metal removal rates between the M-85 engines with premium hard blocks and those with standard engine blocks.

The rate of engine metal accumulation can be affected by many different factors, including fuel and oil properties and vehicle and engine specifications such as the size and type of engine, number of cold starts, and choice of materials and anti-wear treatments for key engine parts. Vehicle duty cycles and preventive maintenance practices can also affect accumulation rates. As discussed earlier, these factors are often confounded so it is difficult to isolate their effects. However, the results from the CleanFleet demonstration provide some useful insight into the effects of the oil change frequency and duty cycle factors. For example, the consistency of the average engine metal accumulation rates among the control vehicles at different locations demonstrated that time-scheduled (compared to mileage-scheduled) preventive maintenance can accommodate significant variations in vehicle duty cycles.

The information on the frequency of oil changes presented earlier raises an important question about the impact of preventive maintenance practices on engine durability. Specifically, what effect does the number of miles between oil changes have on engine metal wear rates? This was answered in part by looking at the average accumulation rates of selected metals (iron, lead, aluminum, and copper) in fleets having vehicles that experienced large variations in the miles between oil changes. For example, the 12 unleaded gasoline vans (three vans from each of four locations) averaged between 1,800 and 4,800 miles between oil changes. The statistical analysis did not indicate that the number of miles between oil changes had an effect on engine metal accumulation rates. Similar analyses were performed for all fleets; however, in most cases there is not much variation in the average miles between oil changes among vehicles.

Contaminants, Additives, and Oil Properties. The figures in Appendix D describe the statistical distributions of levels of engine contaminants, oil additives, and oil properties obtained from the analysis of used oil from CleanFleet vehicles. Within each fleet, the predicted ranges and average values obtained from the analysis of the first and last oil changes, and all oil changes combined, are presented graphically. Results are presented in this format because the levels of many of these parameters, especially the contaminants, are quite different for the first oil change. The predicted ranges were calculated using approximate 95 percent prediction intervals (i.e., 95 percent of the values are expected to fall within the range indicated). For reference, the average number of miles between oil changes is shown beneath each predicted range. The mileage scale is shown on the right vertical axis. A tabular presentation of these results also is provided in Appendix D. The tables list the number of oil changes, average oil miles, number of oil analyses, and the average and standard deviation of each parameter.

Contaminant levels in a new engine are often quite high during the first few thousand miles. For example, Figure D-1 shows that the silicon levels in the used oil are usually over 200 ppm at the first oil change, but drop to less than 50 ppm by the sixth to tenth oil change. Sodium and potassium levels exhibited similar patterns. Water was only detected above the detection limit of 0.05 percent in six oil samples. The maximum level was 0.3 percent, but it was not detected more than once in the same vehicle. The analysis detects liquid fuel levels above 0.5 percent. The maximum level observed was 8.0 percent in a Dodge unleaded van.

Information on the concentrations of oil additives is provided in Figures D-5 through D-9. Boron levels generally start out low at the first oil change, then increase toward the base oil level by the third or fourth oil change. Phosphorus and zinc levels are usually constant, but the levels of calcium and magnesium exhibit various patterns depending on the type of fuel and vehicle manufacturer.

For completeness, Figures D-10 through D-13 describe the distributions of oil properties. However, these results can be somewhat misleading because for most fleets the levels of TBN, viscosity, and nitration were found to be changing with the number of miles driven. An analysis of these trends is presented in the following section.

Vehicle manufacturers have not defined specific operating or warning limits for oil properties. Also, general warning limits established for gasoline engines may not be appropriate for a specific environment nor may they be applicable to alternative fuels. However, for reference, the generally accepted warning limits for oil oxidation and nitration in gasoline engines are presented in Figures D-12 and D-13. All nitration levels and all but two of the oxidation levels were less than or equal to 15, which is considered to be in the “good” range.

Changes in Oil Properties. Statistical regression analysis demonstrated that, in general, the average values for TBN, viscosity, and nitration, determined at the end of an oil change interval, change as the number of miles accumulated during that interval increases. Figures 7a, 7b, and 7c contain plots illustrating the behavior of each property. The curves, shown only for the range of oil mileage observed for each fleet, are the best fitting regression models to the actual data. None of the fleets showed significant dependence of oxidation level on miles driven during an oil change interval.

Total Base Number. TBN is a measure of the amount of overbase additives present in the engine oil. A decline in TBN occurs as the overbase in the oil is consumed to neutralize acidic combustion products that enter the oil sump. In general, the longer an oil has been in use, the higher the amount of combustion products that have been neutralized, thereby reducing the TBN. Average TBN levels at the end of the oil change interval decreased exponentially with the number of miles travelled during the oil change interval. This relationship was statistically significant for all fleets. However, the sensitivity of the final TBN value to miles driven varied among fuel types and manufacturers. The CNG vans from all three manufacturers showed the least sensitivity of TBN to miles driven during oil change intervals up to 5,000 miles. On the other hand, unleaded vans showed the highest sensitivity to miles driven during the oil change interval.

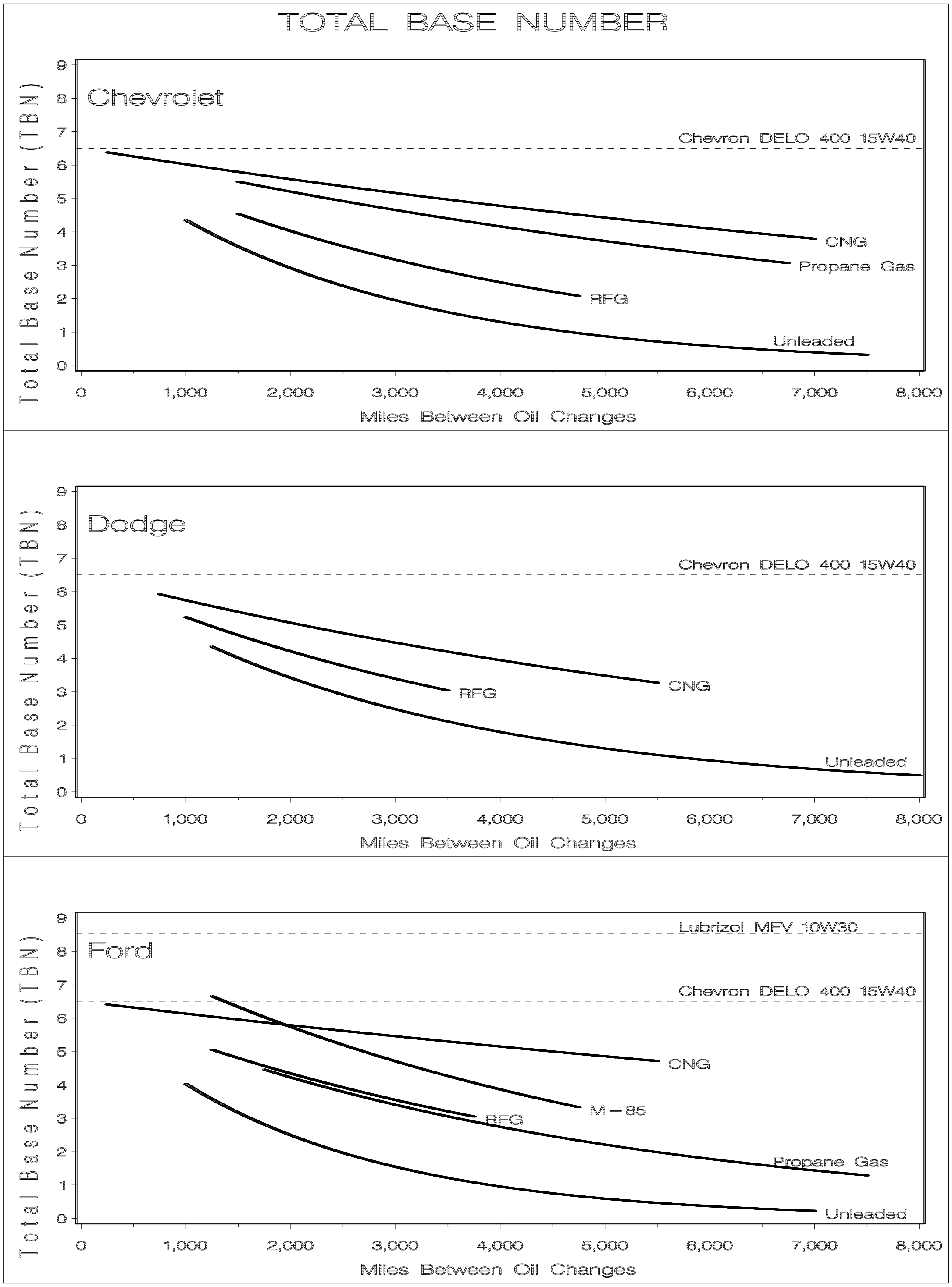


Figure 7a. Estimated Total Base Number of Used Oil Versus Number of Miles Between Oil Changes for Each Combination of Vehicle Manufacturer and Fuel Type

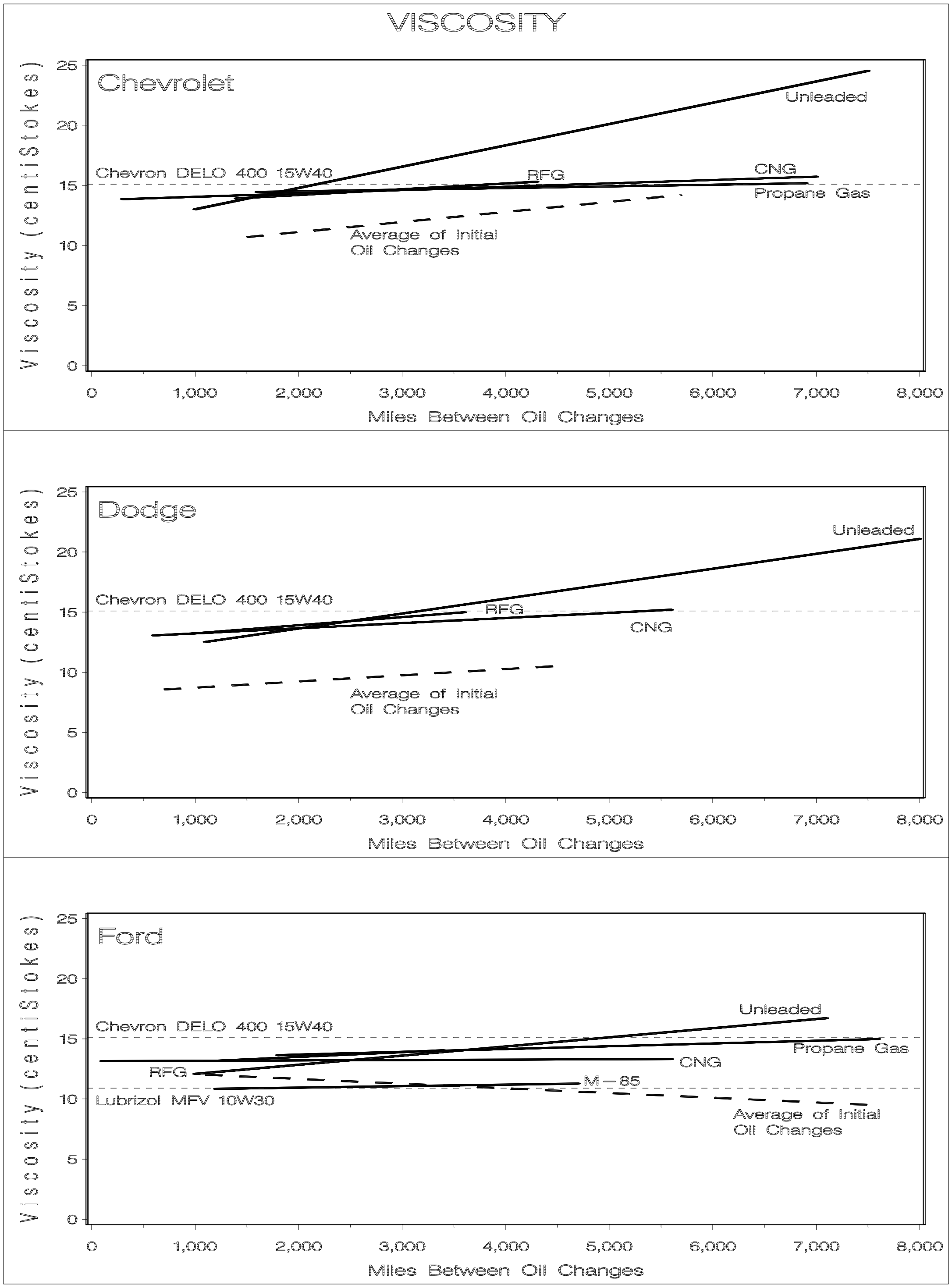


Figure 7b. Estimated Viscosity of Used Oil Versus Number of Miles Between Oil Changes for Each Combination of Vehicle Manufacturer and Fuel Type

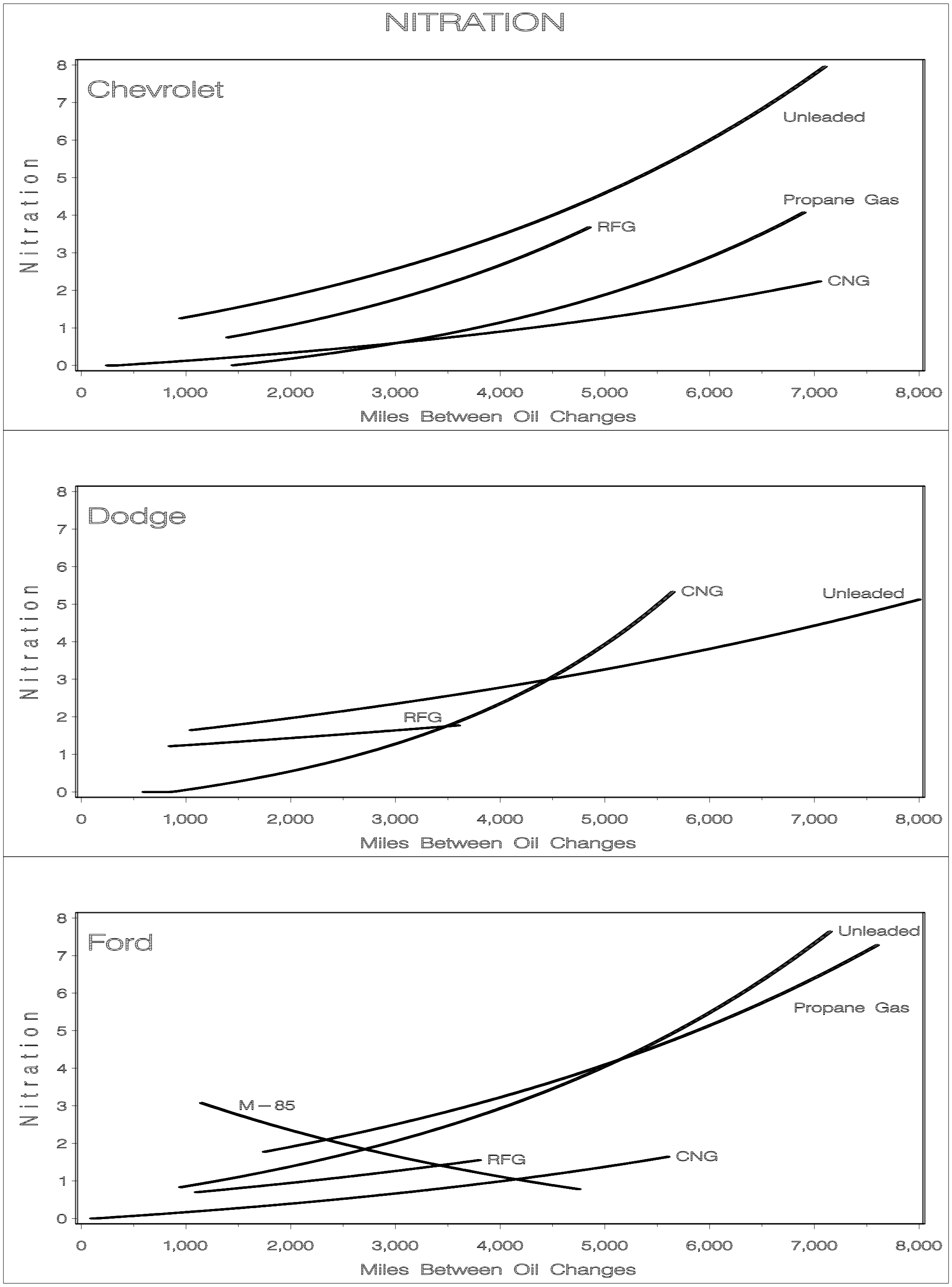


Figure 7c. Estimated Nitration of Used Oil Versus Number of Miles Between Oil Changes for Each Combination of Vehicle Manufacturer and Fuel Type

Oil Viscosity. Average final viscosity levels showed either no effect, or a slight linear (increasing or decreasing) relationship, to the number of miles driven during oil change intervals of between 1,000 and 8,000 miles. The regression analysis indicated a statistically significant increase in oil viscosity (versus the number of miles between oil changes) for the Chevrolet CNG and unleaded fleets; Dodge CNG, RFG, and unleaded fleets; and Ford propane gas, and unleaded fleets. In some cases the average final viscosity levels for fleets that travelled only one or two thousand miles during the oil change interval was lower than that of unused oil. Because oil changes were generally scheduled every 84 days, the vehicles with fewer miles between oil changes were likely to have fewer miles at sustained speeds compared to the number of cold starts. During a cold start, excess raw fuel and condensing combustion gases can get into the oil past the piston rings. Unless the vehicle's duty cycle allowed some sustained operation at normal operating temperatures, these crankcase contaminants remained in the oil and diluted it, causing lower viscosity.

In addition, the measured viscosity of oil removed at the initial oil change was found by the regression analysis to be the same for all fleets but statistically lower than that found in unused oil or used oil collected at subsequent oil changes. The lower viscosity levels found at the initial oil change may be due to fuel dilution, the manufacturers' use of a different oil for the initial fill, or other start-up conditions. Another possible explanation is that blow-by is higher when the vehicles are new and the rings have not fully seated. This blow-by can dilute the oil and contribute to lower oil viscosity levels.

Nitration. With the exception of the M-85 fleet, nitration levels were found to increase exponentially as the miles driven during the oil change interval varied from 1,000 to 8,000. The relationship between nitration levels and the number of miles between oil changes was statistically significant for all but the Dodge and Ford RFG fleets. However, the RFG fleets were driven on shorter routes; and thus, tended to have fewer than 4,000 miles between oil changes. The positive relationship between nitration and oil change mileage is expected as nitration is related to the TBN. As TBN decreases, nitration of the oil from acidic combustion products should increase. Although there is an exponential relationship between final nitration level and the number of miles driven during the latest oil change interval, none of the vehicles had oil nitration values out of the “good” range (0 to 15) established for gasoline-powered vehicles. Nitration levels in the Chevrolet CNG and propane gas fleets exhibited no significant trends.

The final oil nitration levels for M-85 vans appear to have a decreasing exponential relationship with the number of miles accumulated during the oil change interval. To explain this apparent reduction in nitration levels, it is important to realize that these curves do not necessarily describe how nitration levels will behave following an oil change. For example, the nitration curve for the M-85 vehicles does not necessarily indicate that nitration levels will start high, then decrease as the vehicle is driven. These data were obtained from several vehicles operating on different duty cycles. The curves show, for example, that the average nitration level in M-85 vehicles driven 1,200 miles in 84 days (the scheduled time between oil changes) is approximately 3, while the average nitration level for similar vehicles driven 4,500 miles in the same time interval is less than 1. Although no M-85 data were available for mileage above 4,500, eventually oil nitration is expected to increase as was seen with the other fuels. Since low-mileage duty cycles for other fuels did not produce high nitration in the oil, the data could indicate a propensity for the M-85 combustion blow-by to degrade the oil more quickly or that the MFV oil is less resistant to degradation by blow-by contamination. As was seen with the TBN and viscosity, low mileage duty cycles, especially with liquid fuels, are often detrimental to oil life.

Comparison of Oil Properties. Table 8 contains the estimated relative differences in oil properties at 3,000 miles for each alternative fuel fleet compared to the oil properties in the corresponding control fleet. For example, the average level of TBN in a Chevrolet CNG van at 3,000 miles is 165 percent higher than the average level observed in a Chevrolet unleaded van. The estimated levels were determined from the regression model discussed in the previous section. The estimate of the relative difference is subject to a possible error of ±55 percent at the 95 percent confidence level (i.e., the average relative difference is between 110 percent and 260 percent with 95 percent confidence). The comparison is made at 3,000 miles because the oil change intervals for all fleets permit valid comparisons at this mileage level.

In general, the CNG vans retained significantly higher levels of TBN (80 percent to 253 percent) and had lower levels of viscosity (-12 percent to 0 percent) and nitration (-77 percent to -46 percent) compared to unleaded vans. However, the differences varied considerably among vehicle manufacturers. Propane gas and M-85 vans also retained higher levels of TBN (120 percent to 139 percent for propane gas and 132 percent for M-85) compared to unleaded vans; but the differences in viscosity and nitration were highly dependent on vehicle technology. RFG vans from all three manufacturers retained higher levels of TBN (37 percent to 130 percent) and lower levels of nitration (-39 percent to -30 percent) than the control vans. Otherwise, the only other statistically significant difference in oil properties between RFG and unleaded vans was the viscosity levels in the Chevrolet vans.

The comparisons of TBN and viscosity levels between the M-85 and unleaded vans are based on normalized values relative to their respective baseline oil properties. For example, the viscosity of oil in the M-85 vans at 3,000 miles is nearly unchanged from the baseline level of 10.9 centistoke. On the other hand, viscosity of the oil in the unleaded vans was estimated to be slightly less than the baseline of 15.1 centistoke. Thus, the viscosity of oil in M-85 vans at 3,000 miles, relative to the baseline level of Lubrizol MFV 10W30 oil, is estimated to be 13 percent higher than the viscosity of oil in unleaded vans relative to the baseline level in Chevron DELO 400 15W40 oil. In any case, the overall change in viscosity levels for all fleets appears to be within acceptable ranges.

Table 8. Normalized Relative Differences[a] in Total Base Number, Viscosity, and Nitration of Used Oil After 3,000 Miles

	Total Base Number		
Alternative Fuel	**Chevrolet**	**Dodge**	**Ford**
CNG	165 ± 55[b]	80 ± 33	253 ± 50
Propane Gas	139 ± 50		120 ± 33
M-85			132 ± 32
RFG	62 ± 47	37 ± 24	130 ± 36

	Viscosity		
Alternative Fuel	**Chevrolet**	**Dodge**	**Ford**
CNG	-12 ± 3	NSD[c]	NSD
Propane Gas	-12 ± 4		NSD
M-85			13 ± 2
RFG	-11 ± 4	NSD	NSD

	Nitration		
Alternative Fuel	**Chevrolet**	**Dodge**	**Ford**
CNG	-77 ± 9	-46 ± 14	-68 ± 9
Propane Gas	-77 ± 11		22 ± 19
M-85			-19 ± 13
RFG	-32 ± 19	-30 ± 20	-39 ± 17

[a] Normalized difference (%) at 3,000 miles compared with unleaded gasoline. TBN and viscosity are normalized to baseline levels.

[b] 95% confidence bound on the estimated relative difference.

[c] NSD = No significant difference ($p = .05$).

Engine Teardown

Approach

During planning of the CleanFleet demonstration it was recognized that the two-year period would not permit a complete assessment of the possible impact of the alternative fuels on long-term engine durability. While maintenance activities were monitored and recorded, no major service or repairs (e.g., cylinder head reconditioning) were expected because the engines typically have a multi-year useful life in this type of application. To compensate, the experimental plan included two special durability assessment features: (1) periodic oil analyses and (2) selected end-of-test engine teardowns and visual inspections. Adding these assessment features was a cost-effective means of gleaning additional information concerning the durability of the various alternative fuel engines. The possibility of detailed analysis of engine wear (involving before and after test measurements of key parts) was considered, but was rejected as being beyond the scope of the program.

With regard to the end-of-demonstration teardown activity, it was decided to disassemble and inspect two engines in each of the alternative fuel/vehicle manufacturer combinations. It was also decided that the teardown comparisons would focus on a qualitative assessment of the condition of a given alternative fuel engine versus its nearly identical control engine—i.e., to assess whether the condition of the alternative fuel engine parts indicated any marked improvement or loss in durability versus parts from a control fuel engine for which the long-term durability was known to be satisfactory. Because this inspection strategy required the control fuel engine to be otherwise identical to the alternative fuel engine examined, the engine teardowns were restricted to samples of the Ford fleets (all of which were powered by 4.9-liter, 6 cylinder engines) and the Dodge fleets (all of which were powered by 5.2-liter, V8 engines). The availability of nearly identical control engines did not exist for (1) the Chevrolet fleets (which utilized 4.3-liter, V6 engines in the control vehicles and 5.7-liter, V8 engines in the gaseous fueled vehicles) or (2) the electric vehicle fleet.

The basic process for implementing the teardowns and inspections at the conclusion of the demonstration was as follows:

1. Battelle selected the sample vehicles from which the engines would be removed for inspection. (The vehicles selected were representative of the fuel/vehicle manufacturer combination and, where possible, had comparable accumulated mileages in the range of 20,000 to 30,000 miles and had had their emissions tested.)

2. On a mutually convenient schedule, FedEx delivered each of the selected vehicles to the appropriate dealership in the Los Angeles area to have an engine change-out operation performed—i.e., to have the CleanFleet demonstration engine removed and replaced with a new or rebuilt engine.

3. The engine change-out was performed and the engines were packaged for shipment.

4. FedEx delivered the removed CleanFleet engines to two different Detroit area teardown facilities—one selected by Ford and one selected by Chrysler. (Vehicle availability and engine

change-out scheduling resulted in the Ford group of ten engines being disassembled and inspected several weeks prior to the Chrysler group of six engines. The Ford group included two engines each for the following fuels—CNG, propane gas, reformulated gasoline, M-85, and unleaded gasoline. The Dodge group included two engines each for the following fuels—CNG, reformulated gasoline, and unleaded gasoline.)

5. The engines from each of the manufacturers were disassembled as a group at their selected facilities and spread out on adjacent benches. The parts were placed on adjacent benches to facilitate review on both an individual engine basis and an "A versus B" comparison basis (i.e., with the inspection team being able to quickly walk back and forth to directly compare parts from Engine "A" to parts from Engine "B").

6. Engine specialists from Battelle examined the disassembled engines part by part, carefully looking for and noting any differences in the appearance of the alternative fuel engine parts compared to their counterparts from the control engines and the other alternative fuel engines.

7. The Battelle inspection team shared its observations with any of the company's own engineers who were on hand; some parts of particular interest were selected for photographs and/or retention; and the remaining parts were turned over to the company representatives for disposal.

Types of Data Collected. Data collected by means of the engine teardown inspections were primarily in the form of written observations on each of the parts examined by the Battelle inspection team. In some instances, the written notations were augmented by means of documentary photos and/or retention of selected parts for further examination (e.g., precision weighing).

As noted above, a detailed analysis of engine wear, with before and after measurements of key parts was beyond the scope of this program. The data collection objective of the teardown inspections, therefore, was to use a cost-effective visual inspection to determine whether or not there were any significant differences in wear (or other degradation patterns, such as combustion deposit accumulation) that might have implications for long-term durability or maintenance requirements. The alternative of not performing even a visual teardown type of inspection was considered but rejected because it would effectively relegate the demonstration engines to being "black boxes" with no clues as to what latent damage might have existed that could require significant maintenance actions after additional operation.

It should be noted that, despite the lack of pre-test measurements, visual inspections of the type used to gather the data can be fairly sensitive to minute amounts of wear. This is so because new engine parts (e.g., the cylinder bores, the piston skirts, and the piston rings) typically have very fine "tool marks" that are visible on their wearing surfaces. The degree to which these tool marks are still visible after a period of operation is, therefore, a sensitive indicator of wear.

Teardown Inspection Procedures. The teardown inspection of the selected Ford and Dodge engines was handled as two separate events. Availability/scheduling of the subject vehicles resulted in the five pairs of Ford engines being inspected first and the three pairs of Dodge engines being inspected last. The teardown inspections for the two groups of engines were performed at two different facilities arranged for by the vehicle manufacturers. In each case, all of the engines for a given manufacturer were disassembled at once and the parts spread out on adjacent tables to facilitate both (1) individual engine inspections and (2) engine-to-engine comparisons.

The comparisons of interest were between the alternative fuel engines and the corresponding unleaded gasoline control engines. However, other comparisons of interest included comparing (1) the parts from engine “A” for a given fuel to engine “B” for that same fuel (primarily to assess consistency between the two engines and to capture any differences in condition potentially attributable to differences in accumulated mileage) and (2) the parts from engines that operated on two different alternative fuels. Where some differences in accumulated mileage existed, the inspection team attempted to either compare the engines from each pair that had the closest number of accumulated miles or to make allowances for the differences.

In each case, the Battelle inspection team gave its initial attention to viewing and assessing the appearance of a given part (e.g., the cylinder bores) on the unleaded gasoline control engines. Using this initial step as a sort of calibration procedure, the team members then looked at the same component(s) on each of the other engines and noted their observations. This process was repeated until each of the components in each of the engines was inspected and the observations noted. In instances where the engines had a multiplicity of a given part (e.g., pistons or valves), each part was examined individually but the note taking was focused on the nominal condition of the subject group of parts. In general, the inspection team members worked independently except when it became appropriate to confer on particularly interesting or noteworthy findings.

Results

The primary results of the engine teardown inspections are summarized in Table 9. As indicated by its title, Table 9 is a summary of the teardown observation highlights. Table 9 focuses on the components/systems for which visually appreciable differences were observed between the alternative fuel engine parts and the control engine parts. Included in this group of components/system were the

- Cylinder bores
- Pistons
- Piston rings
- Rod bearings
- Main bearings
- Intake valves
- Exhaust valves and seats
- Rocker arms and rocker arm pivots.

Table 9. Engine Teardown Observation Highlights

Vehicle Manufacturer	Fuel	Selected Engine Components/Systems[(a)]	Appreciable Differences in Appearance Versus the Corresponding UNL[(b)] Baseline Parts
Ford	CNG	Cylinder Bores	Slight vertical scuffing on the major thrust surfaces, especially near top ring land location at TDC[(c)]. Some "pitting" evident on minor thrust surfaces in top ring land location at TDC.
		Pistons	Essentially devoid of any composition deposits on the piston sides and in the piston ring grooves. Very light, mottled deposit coating on piston top. Some "pock marks" seen in the top ring land area on the minor thrust side. [Note: special pistons were used to achieve a compression ration of 11:1.]
		Piston Rings	Less worn than the UNL counterparts.
		Rod Bearings	Less worn than the UNL counterparts.
		Main Bearings	Equal or less worn than the UNL counterparts.
		Intake Valves	Appreciable (i.e., approximately 1/8 to 3/16-inch thick glob) deposit buildup on the valve stem at the inspection of the tulip section.
		Exhaust Valves and Seats	Valve faces and seats show appreciable regression.
		Rocker Arms and Pivots	Slightly more wear than UNL counterparts.
	Propane Gas	Cylinder Bores	Cylinder walls have a very minor etched or discolored appearance. The top of the cylinder bores have a slight deposit buildup. Honing pattern is still clearly visible.
		Pistons	Essentially free of deposits except for light dark layer on piston top. Distinct contact pattern on the upper piston skirt surface on both the major and minor thrust faces.
		Piston Rings	Less worn than the UNL counterparts (and any of the other Ford alternative fuel engines).
		Rod Bearings	Significantly less worn than the UNL counterparts.

Table 9. Engine Teardown Observation Highlights (Continued)

Vehicle Manufacturer	**Fuel**	**Selected Engine Components/Systems[(a)]**	**Appreciable Differences in Appearance Versus the Corresponding UNL[(b)] Baseline Parts**
Ford (Continued)	Propane Gas (Continued)	Main Bearings	Wear comparable to the UNL counterparts.
		Intake Valves	Moderate deposit buildup on the port side of the “tulip” and a moderately large (approximately 1/8 to 1/4-inch thick irregular glob) deposit buildup on the valve stem at or just above the intersection with the tulip section.
		Exhaust Valves and Seats	Valve faces and seats show appreciable recession. The receded surfaces have a “hammered” and “wavy” appearance.
		Rocker Arms and Pivots	Essentially the same wear as the UNL counterparts.
	Reformulated Gasoline	Cylinder Bores	Essentially the same wear as the UNL counterparts.
		Pistons	Light deposit buildup on the top of the pistons and on the top ring land is slightly greater than for the UNL pistons. Wear pattern on pistons is essentially the same as for the UNL counterparts.
		Piston Rings	Wear slightly less than the UNL counterparts.
		Rod Bearings	Essentially the same wear as the UNL counterparts.
		Main Bearings	Essentially the same wear as the UNL counterparts.
		Intake Valves	Essentially the same wear as the UNL counterparts.
		Exhaust Valves and Seats	No appreciable recession; wear is essentially the same as for the UNL counterparts.
		Rocker Arms and Pivots	Essentially the same wear as the UNL counterparts.
	M-85	Cylinder Bores	Main part of bores has a slightly “etched” appearance. “Etching” on some bores appears most strongly above the travel path of the top ring. Bore wear appears greatest near the extremes of the ring travel, but honing pattern is still clearly visible.
		Pistons	Deposits were minimal. Skirt wear appears to be slightly greater than for the UNL counterpart.
		Piston Rings	Significantly more wear than the UNL counterparts.

Table 9. Engine Teardown Observation Highlights (Continued)

Vehicle Manufacturer	Fuel	Selected Engine Components/Systems[a]	Appreciable Differences in Appearance Versus the Corresponding UNL[b] Baseline Parts
Ford (Continued)	M-85 (Continued)	Rod Bearings	Essentially the same wear as the UNL counterparts.
		Main Bearings	Considerably more wear than the UNL counterparts—definitely into copper layer.
		Intake Valves	Slightly greater buildup of a black deposit on the port side of the tulip than for the UNL counterparts.
		Exhaust Valves and Seats	Significant regression of the valve faces; minor recession of the valve seats.
		Rocker Arms and Pivots	Significant wear of both the rocker arms and the pivots, resulting in an appreciable step between adjacent worn and unworn areas.
Dodge	CNG	Cylinder Bores	Slightly more wear than UNL counterparts, but honing pattern still visible. Some pitting appearance seen at upper and lower ring turnaround points. Less deposit buildup than for UNL counterparts.
		Pistons	Slightly more skirt wear than for UNL counterparts, but still minimal in amount. Ring grooves very clean. No varnish on sides of pistons. Some hard black deposit buildup on top ring land with vertical striations indicating rubbing against the bores.
		Piston Rings	Essentially the same wear as the UNL counterparts.
		Rod Bearings	Essentially the same wear as the UNL counterparts.
		Intake Valves	Medium to heavy (i.e., 1/8 to 1/4-inch thick irregular soft glob) deposit buildup on the valve stem at or just above the intersection with the tulip section.
		Exhaust Valves and Seats	Essentially the same wear as the UNL counterparts.
		Rocker Arms and Pivots	Essentially the same wear as the UNL counterparts.

Table 9. Engine Teardown Observation Highlights (Continued)

Vehicle Manufacturer	Fuel	Selected Engine Components/Systems[a]	Appreciable Differences in Appearance Versus the Corresponding UNL[b] Baseline Parts
Dodge (Continued)	Reformulated Gasoline	Cylinder Bores	Essentially the same wear as the UNL counterparts.
		Pistons	Essentially the same wear as the UNL counterparts.
		Piston Rings	Some engine-to-engine variation, but essentially the same wear as the UNL counterparts.
		Rod Bearings	Essentially the same wear as the UNL counterparts.
		Main Bearings	Essentially the same wear as the UNL counterparts.
		Intake Valves	Essentially the same wear as the UNL counterparts.
		Exhaust Valves and Seats	Essentially the same wear as the UNL counterparts.
		Rocker Arms and Pivots	Essentially the same wear as the UNL counterparts.

(a) Components/systems selected for comparison because differences were observed.
(b) UNL = Unleaded gasoline (the baseline fuel).
(c) TDC = Top dead center.

To some readers it may be of equal importance that, for another large group of components/ systems, the visual inspection revealed essentially *no* apparently meaningful differences between the parts from the alternative fuel engines and their control engine counterparts. Included in this group of components/systems were the

- Crankshafts
- Timing gears
- Push rods
- Stem and tip portions of the valves
- Piston pin and piston pin bores
- Camshafts and lifters/followers
- Lifter bores
- Valve guides
- Cylinder heads.

None of the engines subjected to teardown inspection was disassembled because of a failure to operate satisfactorily or because of a suspected serious problem. On the contrary, it was expected that there would be few if any noteworthy findings at this relatively low accumulated mileage. Furthermore, even among the parts where some appreciable differences were seen (e.g., the cylinder bores), the parts were generally in satisfactory condition (e.g., the cylinder bores exhibited generally acceptable wear patterns, the honing patterns were clearly visible, and there were no fingernail detectable wear ridges at the top of the bores). Most of the observations noted in Table 9 are based on very close scrutiny of the parts, not on glaring differences or problems.

Discussion

Vehicle Maintenance

Low maintenance costs, high availability, and high utilization are three of the leading vehicle attributes important to a fleet operator. Accordingly, the CleanFleet program plan contained provisions for acquiring and analyzing data to facilitate an assessment of these particular attributes. The basic goal of this effort was to determine what, if any, significant differences in maintenance requirements fleet operators might expect, based on their selection of a given alternative fuel.

The various fleets evaluated in the CleanFleet demonstration represented a snapshot of the best vehicles and alternative fuel technologies that (1) were available for acquisition for commercial service in 1992, (2) met FedEx requirements for operations, and (3) were backed by the three domestic manufacturers—Ford, Dodge, and Chevrolet. As a result, considerable variation existed in the level of development of the systems evaluated. The presentation of key findings and observations that follows is aimed at providing a balanced assessment of the maintenance results. Each of the findings and observations is provided with a rationale that reflects the level of development issues. Where appropriate, reference is made to figures and tables already presented.

1. Both the baseline (i.e., control) vehicles, which operated on unleaded gasoline, and the RFG fueled vehicles completed the demonstration without incurring any maintenance specifically related to fuel.

   This finding was not unexpected, considering that all of these vehicles were high-volume, mature production vehicles featuring (1) highly evolved engines and fuel systems and (2) fuels formulated for their use without modification of the vehicles. Even using the slightly larger base of comparison based on a computer search of the ATA codes most likely to contain fuel-related maintenance activities (see Table 2b), there was no statistically significant difference in the frequency of maintenance between the RFG and unleaded gasoline fueled vans. A similar lack of statistically significant difference is indicated by (1) the computer search involving *all* non-accident repair orders for the RFG/ unleaded fuel group pairs (see Table 2a) and (2) a review of the summary of maintenance costs data displayed in Figures 3a and 3b.

2. On a total vehicle basis, the CNG, propane gas, and M-85 fueled vans required non-preventive maintenance at frequencies ranging from 11 to 42 percent more often than the respective control vans operating on unleaded gasoline (see Table 2a) and at costs generally 50 to 80 percent higher than for the corresponding control vans at the same locations (see Figure 3a). With regard to only the ATA categories likely to contain fuel-related maintenance items, however, the CNG, propane gas, and M-85 fueled vans required non-preventive maintenance at frequencies ranging from 46 to 183 percent more often than the respective control vans operating on unleaded gasoline (see Table 2b) and at costs two to four times those of the corresponding control vans at the same locations (see Figure 3b).

Most of the fuel-related maintenance activities were associated with the following types of components and subsystems:

- Fuel level gauges
- Mixture control valves
- Gas mass flow sensors
- Fuel lockoff valves
- Pressure regulator diaphragms
- Throttle body grommets and gaskets
- Fuel line fittings
- Control module software and fuses
- Fuel injectors.

These types of component and subsystem problems are an indication of the need for further development, not an indication of insolvable problems caused by the fuel being used.

Stated in a slightly different way, the reliability and parts cost of this particular equipment (including both the hardware and embedded software, if any) is not on a par with that which would be expected when a mature state of development is reached. Furthermore, the labor costs for diagnosing and repairing such systems should also decrease as maintenance of mature versions of the subject systems become more routine than an initial exposure/learning curve problem. Figure 3b shows that the total maintenance costs for the three most similar engine/ alternative fuel combinations (i.e., the Ford M-85, propane gas, and CNG vans) are all quite similar and within a multiplier of about 3 times the low average value for the Ford control vans.

It should be noted that the types of maintenance actions described above for the CNG, propane gas, and M-85 vans are relatively minor—not involving major overhaul or engine replacement. This finding is consistent with the fact that the basic engine systems used in each of these vans are highly evolved, mature systems. By comparison, the electric-powered G-Vans were not highly evolved, mature production vehicles and did require replacement of basic powertrain systems (e.g., several lead-acid battery packs, battery monoblocks, and traction motors) during the course of this relatively brief demonstration. In this regard, however, it should also be noted that the G-Van that was converted to Ni-Cd batteries required no maintenance from the time it was introduced into the demonstration in November 1993, except for replacing a fuse in the controller.

3. In general, the average vehicle availability for the liquid and gaseous fueled vehicles (see Table 3) was not significantly different between the alternative fuel vans and their respective unleaded gasoline control counterparts. The average vehicle utilization, however, was 1 to 11 percentage points less than the average availability and up to 9 percent lower than the utilization of unleaded gasoline fueled counterparts.

   Several possible inferences and rationales for these results are presented in the preceding text. It should be noted here that the high availability ratings encountered in this particular fleet setting are strongly affected by the way availability is calculated—i.e., vehicles are not considered unavailable if they are being worked on during periods outside the normal operation times of 7:00 AM to 8:00 PM, Monday through Saturday. Also, the degree of utilization is influenced by other factors such as the availability of spare vehicles, differences in driver preferences for certain vehicles, variations in maintenance scheduling practices, and the interchangeability of the vehicles regarding parameters such as range.

4. Faced with a need for comparing different vehicles having alternative fuel technologies that represent different levels of development, the most reliable yardstick is probably the number of repair orders per 100 service days, used in conjunction with data on the control vehicles operating at the same location as the alternative fuel vehicles being evaluated.

   The use of 100 service days is a good normalizing factor. Using the number of repair orders, rather than maintenance costs, tends to eliminate the heavy skewing that can occur because of differences in the costs or estimates of costs for developmental level parts and services and variations in vendor service response capabilities.

   Making comparisons with control vehicles operating at the same locations as the alternative fuel vehicles eliminates skewing based on location-to-location differences in such factors as duty cycles, maintenance practices, and local dealer support.

5. The maintenance problems encountered with the less developed systems evaluated in CleanFleet are not insolvable, but should be expected to persist in the short term with vehicles featuring the same or similar developmental systems.

   Fleet operators planning near-term acquisitions of vehicles incorporating developmental (or even initial limited production release of) alternative fuel systems should consider the potential for learning curve-type problems when they select vendors and warranty provisions and plan their maintenance programs.

   While the maintenance problems encountered in CleanFleet do not appear to be insolvable, some are likely to require significant development to be resolved in an economical but comprehensive manner to assure satisfactory long-term performance.

VEHICLE MAINTENANCE

Oil Consumption and Analysis

Data on oil consumption and the analysis of used oil samples were collected from all gaseous and liquid fueled CleanFleet vehicles throughout the first year of the demonstration. At least four oil changes were performed on nearly all vehicles during this period. The data were analyzed to help identify performance problems with individual vehicles and to assess the overall health of individual fleets. The analysis of used oil samples provided information on the wear rates of engine metals and the levels of other oil contaminants, additives, and properties. Oil consumption for individual vehicles was monitored, and average consumption rates were calculated for each fleet. The important observations and conclusions are as follows:

- Ongoing monitoring of changes in the oil properties and the amounts of wear metals and contaminants in the oil at the time of the oil changes for each individual vehicle revealed several areas to watch but no evidence of catastrophic wear or serious coolant or fuel leaks into the oil.

- The metal removal plots in Appendix C indicate that the areas to watch included (1) the removal of iron on the M-85 vehicles and (2) the removal of molybdenum on the unleaded Chevrolet vans. The oil analysis indicated that an average of 9.1 grams of iron was removed from the M-85 engines in the first 20,000 miles. The amount of iron removed could be greater or less than 9.1 grams depending on the amount trapped in the filter and the amount that may have been contributed by the fuel. This finding helped to direct the engine teardown inspections discussed in the next section.

- There appears to be no appreciable sensitivity of metal removal rates to oil change frequency despite a fairly wide range of mileages between oil changes. This may be attributable to the FedEx policy of scheduling oil changes based on time rather than miles driven. Fewer miles accumulate between oil changes for vehicles driven on short urban routes than for vehicles driven on longer highway routes.

- Oils used in the gaseous fueled engines tended to contain lesser quantities of all of the major wear metals except copper. However, not all of the differences relative to the control vehicles were statistically significant.

- In nearly all cases, viscosity remained within acceptable values (9 to 20 centistokes) at each oil change.

- The gaseous fuels—CNG and propane gas—resulted in less decline in TBN than their unleaded counterparts. It may, therefore, be possible to extend the oil change interval for these fuels, provided the other measures of oil degradation stay within acceptable limits.

- Average rates of oil consumption through leakage or combustion exhaust are less than one quart per 10,000 miles for all fleets of vehicles.

- There is no evidence of a CleanFleet vehicle experiencing performance problems associated with engine wear.

Engine Teardown

As indicated previously, it is unusual to perform engine teardown inspections after accumulating only 20,000 to 30,000 miles on vehicles for which the nominal life in this kind of service is in excess of 100,000 miles. However, not performing at least a visual inspection would leave many questions unanswered regarding possible latent damage or degradation.

The observations presented in Table 9 confirm the expectation of relatively minor wear damage or other degradation despite the developmental nature of many of the engines. Nonetheless, a few apparent "tendencies" in wear or other forms of potentially fuel related degradation are worth noting even though (a) the present performance may be adequate or (b) it is expected that further development will provide any needed improvement. These tendencies are briefly discussed below.

1. The intake valves of the gaseous fueled engines displayed a noticeable buildup of deposits on the back side (i.e., port side) at or near the juncture of the valve stem and the "tulip" section of the valve. This tendency was observed on all the CNG and propane gas engines inspected and none of the liquid fueled engines. This deposit is presumed to be formed from lubricating oil that works its way down through the clearance space between the valve stem and the guide and is "baked" onto the base of the stem. Similar quantities of oil probably travel down the stems of the intake valves of the liquid fueled engines, but are washed away by the incoming fuel (some of which may have special additives to accomplish this).

2. The exhaust valves and seats of the gaseous fueled engines tended to exhibit a form of wear sometimes referred to as recession. This tendency was seen on the Ford CNG and propane gas engines, but not the Chrysler CNG engines. This form of wear is characterized by the wearing away of the valve faces into a concave shape while the mating seat becomes convex. This tendency is not uncommon because the dry gaseous fuels do not facilitate the buildup of a light carbonaceous layer of deposit on the valve face/valve seat interface, which serves to prevent or minimize wear of the underlying metallic surfaces. Because this type of wear is not uncommon, gaseous fueled engines usually feature special valve or seat materials to minimize or eliminate this tendency. Other means of improving this situation include changing the design of the cam profiles to achieve lower seating velocities and modifying the oil specified.

3. The exhaust valves and seats of the M-85 fueled engines also exhibited appreciable recession (but mostly of the valve faces). This may have occurred because the methanol fuel lacked the "lubricity" of the other liquid fuels used in CleanFleet. The fact that the engine oil specified for the M-85 fueled engines was different than that used in all the other CleanFleet vehicles may have exerted a positive or negative synergism in the amount of recession seen on these parts.

4. For both the Ford and Dodge engines, there was little to distinguish the RFG engine parts from the unleaded gasoline control engine parts. Some slight differences were seen in the color and amount of deposits, but these were not consistent or clear.

5. One of the few marked differences in the cumulative metal removal rates indicated by the analyses of the used oil samples was the amount of iron seen in the samples taken from the M-85 fueled engines. Accordingly, the inspection team looked carefully for candidate sources for the removed iron. The only probable sources were the rocker arms and the rocker arm pivots (of which there are 12 each per engine). While the wear interface for these parts on the control engines showed only a light “polish” type of wear, all of these parts on both the M-85 fueled engines exhibited a significant amount of wear easily seen as a sharp step between adjacent worn and unworn areas.

By both (1) comparing the weights of the badly worn parts and the lightly worn parts and (2) performing cursory calculations of the volume of metal removed, the inspection team determined that the wear seen on the rocker arms and pivots could account for the amount of iron seen in the associated oil samples. With the available information, it cannot be determined whether or not this wear of the rocker arms and pivots is attributable to the fuel, the different oil used with the M-85 fueled engines, or some other cause.

APPENDIX A

Repair Order Summaries

APPENDIX A

Repair Order Summaries

The maintenance activities performed on CleanFleet Vehicles are detailed in Tables A-2 through A-7. The contents of each report are described below. Each report aggregates the maintenance information according to the five categories shown in Table A-1.

Table A-1. Maintenance Report Categories

Category	ATA System Codes	Description
All	000 - 092	All repairs except for accidents and fuel contamination related repairs
Selected ATA	All codes listed below	Summation of three groups below. These are the ATA codes judged most likely to be “fuel-related”
Instruments	003	Instrument ATA codes
Electrical Group	030 - 035	All electrical group ATA codes
Engine/Fuel	040 - 048	All engine and fuel system ATA codes

Table A-2 summarizes the amount of preventative maintenance (PM) accomplished on each vehicle fleet. This work consists mainly of oil changes and other such scheduled activities, but also includes other items such as some brake changes. One would not expect to see a large difference between the alternative-fueled vehicles and their control counterparts.

Table A-3 shows the number of non-preventative maintenance (non-PM) repair orders needed for each vehicle fleet. Non-PM repairs are accomplished in response to a *perceived* problem with the vehicle. Someone decides that a mechanic should examine the vehicle to determine the nature of the problem and repair the vehicle before returning it to service. The alternative fuel vehicles, being new and different, may have received more attention than the control vehicles (i.e., the personnel dealing with these vehicles may have been more sensitive to discrepancies from expected behavior than they were with the unleaded vehicles). The degree to which this additional attention affected the number of repair actions requested is unknown. However, there is little reason to believe that the degree of extra attention given to the alternative fuel vehicles significantly varied from one fleet to another. The possible exception to this observation would involve the RFG fleets, since RFG may have been viewed as just “a different kind of gasoline.”

Table A-4 summarizes the labor hours devoted to non-PM repair orders for each vehicle fleet. An analysis of the labor hours per 10,000 miles shows that the alternative fuel fleets generally required more overall non-PM maintenance labor than the unleaded control vehicles. Also, the maintenance labor in the selected ATA code category were much higher for the alternative fuel vehicles than for the control vehicles. A single exception to both of these trends is demonstrated by the overall maintenance labor for the Ford RFG fleet.

Table A-5 summarizes the labor costs for non-PM repair orders for each vehicle fleet. An analysis of the labor cost per 10,000 miles shows that the alternative fuel fleets generally required more overall non-PM maintenance labor than the unleaded control vehicles. Also, the maintenance labor cost in the selected ATA code category were much higher for the alternative fuel vehicles than for the control vehicles. A single exception to both of these trends is demonstrated by the overall maintenance labor for the Ford RFG fleet.

Table A-6 summarizes the cost of parts for non-PM repair orders for each vehicle fleet. An analysis of the parts cost per 10,000 miles shows that the alternative fuel fleets generally had higher parts cost for overall non-PM maintenance than the unleaded control vehicles. Also, the parts cost in the selected ATA code category were much higher for the alternative fuel vehicles than for the control vehicles. Exceptions to both of these trends are demonstrated by the overall cost of parts for the Ford RFG fleet. Also, the Chevrolet and Dodge RFG fleets show higher cost of parts for all non-PM maintenance actions than for those in the selected ATA code category.

Table A-7 summarizes the total cost for non-PM repair orders for each vehicle fleet. An analysis of the total cost per 10,000 miles shows that the alternative fuel fleets generally had higher total cost for overall non-PM maintenance than the unleaded control vehicles. Also, the total cost in the selected ATA code category was much higher for the alternative fuel vehicles than for the control vehicles. Exceptions to both of these trends are demonstrated by the overall total cost for the Ford RFG fleet. Also, the Chevrolet RFG fleet shows a higher total cost for all non-PM maintenance actions than for those in the selected ATA code category.

Table A-2. Preventive Maintenance (PM) Summary

Vehicle OEM	Fuel Type	No. of Vans	Average Service Days per Van	Average Miles Driven per Van	System[a]	Average PMs per Van	Average Service Days per PM	Average Miles Driven per PM	Average Labor Hours per PM	Average Labor Cost per PM	Average Parts Cost per PM
Irvine											
Chevrolet	CNG	7	441	26,812	All	8.6	51	3,128	3.2	68.3	22.4
					Selected ATA Codes	8.3	53	3,236	0.0	0.0	4.1
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	0.0	–	–	0.0	0.0	0.0
					Engine/Fuel	8.3	53	3,236	0.0	0.0	4.1
	Unleaded	3	573	39,663	All	9.0	64	4,407	3.2	65.3	33.8
					Selected ATA Codes	9.0	64	4,407	0.0	0.0	3.6
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	0.0	–	–	0.0	0.0	0.0
					Engine/Fuel	9.0	64	4,407	0.0	0.0	3.6
Dodge	CNG	7	460	22,639	All	8.6	54	2,641	3.0	62.8	18.1
					Selected ATA Codes	8.0	57	2,830	0.0	0.0	5.7
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	0.3	1,610	79,238	0.0	0.0	1.8
					Engine Fuel	8.0	57	2,830	0.0	0.0	3.9
	Unleaded	3	544	42,685	All	9.7	56	4,416	3.4	68.2	17.5
					Selected ATA Codes	9.0	60	4,743	0.0	0.0	5.7
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	0.3	1,633	128,055	0.0	0.0	1.9
					Engine/Fuel	9.0	60	4,743	0.0	0.0	3.9

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[a] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-2. Preventive Maintenance (PM) Summary (Continued)

Vehicle OEM	Fuel Type	No. of Vans	Average Service Days per Van	Average Miles Driven per Van	System[a]	Average PMs per Van	Average Service Days per PM	Average Miles Driven per PM	Average Labor Hours per PM	Average Labor Cost per PM	Average Parts Cost per PM
Ford	CNG	7	455	29,533	All	8.1	56	3,627	3.4	69.7	21.1
					Selected ATA Codes	8.1	56	3,627	0.0	0.5	6.7
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	0.4	1,061	68,910	0.0	0.2	1.2
					Engine/Fuel	8.1	56	3,627	0.0	0.3	5.5
	Unleaded	3	630	39,439	All	9.3	68	4,226	3.4	66.8	22.2
					Selected ATA Codes	9.0	70	4,382	0.0	0.0	5.3
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	0.0	–	–	0.0	0.0	0.0
					Engine/Fuel	9.0	70	4,382	0.0	0.0	5.3
Los Angeles											
Chevrolet	RFG	7	608	19,740	All	9.1	66	2,159	3.1	68.0	31.5
					Selected ATA Codes	7.9	77	2,512	0.1	1.5	2.7
					Instruments	0.1	4,253	138,181	0.0	0.6	0.0
					Electrical Group	0.1	4,253	138,181	0.0	0.2	0.0
					Engine/Fuel	7.9	77	2,512	0.0	0.8	2.7
	Unleaded	3	660	16,176	All	9.3	71	1,733	3.2	69.2	28.0
					Selected ATA Codes	7.3	90	2,206	0.5	9.6	12.3
					Instruments	0.7	991	24,264	0.1	1.9	0.5
					Electrical Group	1.3	495	12,132	0.3	7.0	9.4
					Engine/Fuel	7.0	94	2,311	0.0	0.7	2.5

[a] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-2. Preventive Maintenance (PM) Summary (Continued)

Vehicle OEM	Fuel Type	No. of Vans	Average Service Days per Van	Average Miles Driven per Van	System[a]	Average PMs per Van	Average Service Days per PM	Average Miles Driven per PM	Average Labor Hours per PM	Average Labor Cost per PM	Average Parts Cost per PM
Dodge	RFG	7	605	18,246	All	8.9	68	2,060	3.2	69.3	21.7
					Selected ATA Codes	7.7	78	2,365	0.0	0.9	4.0
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	0.7	847	25,545	0.0	0.7	1.0
					Engine/Fuel	7.7	78	2,365	0.0	0.2	3.0
	Unleaded	3	607	25,697	All	9.3	65	2,753	3.5	75.6	51.8
					Selected ATA Codes	8.3	73	3,084	0.0	0.4	2.8
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	0.3	1,822	77,090	0.0	0.4	0.0
					Engine/Fuel	8.3	73	3,084	0.0	0.0	2.8
Ford	RFG	7	648	20,984	All	9.3	70	2,260	3.0	65.5	33.1
					Selected ATA Codes	8.1	80	2,577	0.0	0.3	4.7
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	0.3	2,269	73,444	0.0	0.3	1.8
					Engine/Fuel	8.1	80	2,577	0.0	0.0	2.9
	Unleaded	3	647	18,944	All	9.7	67	1,960	3.0	66.7	15.1
					Selected ATA Codes	9.0	72	2,105	0.1	1.8	3.8
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	1.0	647	18,944	0.1	1.2	0.5
					Engine/Fuel	8.7	75	2,186	0.0	0.7	3.3

[a] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-2. Preventive Maintenance (PM) Summary (Continued)

Vehicle OEM	Fuel Type	No. of Vans	Average Service Days per Van	Average Miles Driven per Van	System(a)	Average PMs per Van	Average Service Days per PM	Average Miles Driven per PM	Average Labor Hours per PM	Average Labor Cost per PM	Average Parts Cost per PM
Rialto											
Chevrolet	PRO	7	432	35,519	All	8.4	51	4,214	2.6	60.6	21.7
					Selected ATA Codes	8.4	51	4,214	0.1	2.2	5.5
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	1.6	275	22,603	0.1	1.9	1.3
					Engine/Fuel	8.4	51	4,214	0.0	0.4	4.2
	Unleaded	3	502	38,758	All	9.0	56	4,306	3.2	70.9	60.2
					Selected ATA Codes	9.0	56	4,306	0.4	7.5	13.9
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	2.7	188	14,534	0.3	6.8	9.7
					Engine/Fuel	9.0	56	4,306	0.0	0.7	4.3
Ford	PRO	13	522	39,521	All	9.0	58	4,391	2.9	67.2	42.6
					Selected ATA Codes	8.9	59	4,429	0.2	4.2	16.3
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	1.6	323	24,465	0.1	3.1	10.0
					Engine/Fuel	8.9	59	4,429	0.0	1.1	6.2
	Unleaded	3	572	42,452	All	8.7	66	4,898	2.9	66.9	54.2
					Selected ATA Codes	8.7	66	4,898	0.2	4.2	10.8
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	1.0	572	42,452	0.1	2.5	1.7
					Engine/Fuel	8.7	66	4,898	0.1	1.7	9.1

(a) All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-2. Preventive Maintenance (PM) Summary (Continued)

Vehicle OEM	Fuel Type	No. of Vans	Average Service Days per Van	Average Miles Driven per Van	System[a]	Average PMs per Van	Average Service Days per PM	Average Miles Driven per PM	Average Labor Hours per PM	Average Labor Cost per PM	Average Parts Cost per PM
Santa Ana											
Ford	M-85	20	521	24,969	All	8.1	64	3,083	2.8	55.1	30.6
					Selected ATA Codes	8.1	64	3,083	0.0	0.7	11.0
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	0.7	802	38,413	0.0	0.7	6.6
					Engine/Fuel	8.1	64	3,083	0.0	0.0	4.5
	Unleaded	3	595	25,221	All	9.0	66	2,802	2.8	55.4	18.9
					Selected ATA Codes	9.0	66	2,802	0.0	0.0	4.8
					Instruments	0.0	–	–	0.0	0.0	0.0
					Electrical Group	0.0	–	–	0.0	0.0	0.0
					Engine/Fuel	9.0	66	2,802	0.0	0.0	4.8

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[a] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-3. Non-PM Repair Orders[a]

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average ROs per Van	Average ROs per 10,000 Miles	Average ROs per 100 Service Days	Average Service Days per Non-PM RO	Average Miles Driven per Non-PM RO
Irvine								
Chevrolet	CNG	All	367	52.4	19.6	11.9	8	511
		Selected ATA Codes	183	26.1	9.8	5.9	17	1,026
		Instruments	5	0.7	0.3	0.2	618	37,536
		Electrical Group	117	16.7	6.2	3.8	26	1,604
		Engine/Fuel	78	11.1	4.2	2.5	40	2,406
	Unleaded	All	144	48.0	12.1	8.4	12	826
		Selected ATA Codes	36	12.0	3.0	2.1	48	3,305
		Instruments	4	1.3	0.3	0.2	430	29,748
		Electrical Group	25	8.3	2.1	1.5	69	4,760
		Engine/Fuel	11	3.7	0.9	0.6	156	10,817
Dodge	CNG	All	383	54.7	24.2	11.9	8	414
		Selected ATA Codes	185	26.4	11.7	5.7	17	857
		Instruments	16	2.3	1.0	0.5	201	9,905
		Electrical Group	88	12.6	5.6	2.7	37	1,801
		Engine/Fuel	87	12.4	5.5	2.7	37	1,822
	Unleaded	All	180	60.0	14.1	11.0	9	711
		Selected ATA Codes	57	19.0	4.5	3.5	29	2,247
		Instruments	5	1.7	0.4	0.3	327	25,611
		Electrical Group	31	10.3	2.4	1.9	53	4,131
		Engine/Fuel	21	7.0	1.6	1.3	78	6,098

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[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-3. Non-PM Repair Orders[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average ROs per Van	Average ROs per 10,000 Miles	Average ROs per 100 Service Days	Average Service Days per Non-PM RO	Average Miles Driven per Non-PM RO
Ford	CNG	All	319	45.6	15.4	10.0	10	648
		Selected ATA Codes	157	22.4	7.6	4.9	20	1,317
		Instruments	17	2.4	0.8	0.5	187	12,161
		Electrical Group	73	10.4	3.5	2.3	44	2,832
		Engine/Fuel	74	10.6	3.6	2.3	43	2,794
	Unleaded	All	144	48.0	12.2	7.6	13	822
		Selected ATA Codes	50	16.7	4.2	2.6	38	2,366
		Instruments	2	0.7	0.2	0.1	946	59,158
		Electrical Group	45	15.0	3.8	2.4	42	2,629
		Engine/Fuel	3	1.0	0.3	0.2	630	39,439
Los Angeles								
Chevrolet	RFG	All	295	42.1	21.3	6.9	14	468
		Selected ATA Codes	110	15.7	8.0	2.6	39	1,256
		Instruments	4	0.6	0.3	0.1	1,063	34,545
		Electrical Group	103	14.7	7.5	2.4	41	1,342
		Engine/Fuel	13	1.9	0.9	0.3	327	10,629
	Unleaded	All	115	38.3	23.7	5.8	17	422
		Selected ATA Codes	44	14.7	9.1	2.2	45	1,103
		Instruments	4	1.3	0.8	0.2	495	12,132
		Electrical Group	35	11.7	7.2	1.8	57	1,386
		Engine/Fuel	6	2.0	1.2	0.3	330	8,088

[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-3. Non-PM Repair Orders[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average ROs per Van	Average ROs per 10,000 Miles	Average ROs per 100 Service Days	Average Service Days per Non-PM RO	Average Miles Driven per Non-PM RO
Dodge	RFG	All	207	29.6	16.2	4.9	20	617
		Selected ATA Codes	75	10.7	5.9	1.8	56	1,703
		Instruments	9	1.3	0.7	0.2	471	14,192
		Electrical Group	59	8.4	4.6	1.4	72	2,165
		Engine/Fuel	10	1.4	0.8	0.2	424	12,772
	Unleaded	All	116	38.7	15.0	6.4	16	665
		Selected ATA Codes	32	10.7	4.2	1.8	57	2,409
		Instruments	0	0.0	0.0	0.0	–	–
		Electrical Group	31	10.3	4.0	1.7	59	2,487
		Engine/Fuel	1	0.3	0.1	0.1	1,822	77,090
Ford	RFG	All	241	34.4	16.4	5.3	19	609
		Selected ATA Codes	118	16.9	8.0	2.6	38	1,245
		Instruments	1	0.1	0.1	0.0	4,538	146,887
		Electrical Group	112	16.0	7.6	2.5	41	1,311
		Engine/Fuel	6	0.9	0.4	0.1	756	24,481
	Unleaded	All	121	40.3	21.3	6.2	16	470
		Selected ATA Codes	54	18.0	9.5	2.8	36	1,052
		Instruments	1	0.3	0.2	0.1	1,941	56,833
		Electrical Group	50	16.7	8.8	2.6	39	1,137
		Engine/Fuel	3	1.0	0.5	0.2	647	18,944

[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-3. Non-PM Repair Orders[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average ROs per Van	Average ROs per 10,000 Miles	Average ROs per 100 Service Days	Average Service Days per Non-PM RO	Average Miles Driven per Non-PM RO
Rialto								
Chevrolet	PRO	All	465	66.4	18.7	15.4	6	535
		Selected ATA Codes	164	23.4	6.6	5.4	18	1,516
		Instruments	3	0.4	0.1	0.1	1,007	82,879
		Electrical Group	75	10.7	3.0	2.5	40	3,315
		Engine/Fuel	104	14.9	4.2	3.4	29	2,391
	Unleaded	All	183	61.0	15.7	12.1	8	635
		Selected ATA Codes	53	17.7	4.6	3.5	28	2,194
		Instruments	3	1.0	0.3	0.2	502	38,758
		Electrical Group	30	10.0	2.6	2.0	50	3,876
		Engine/Fuel	22	7.3	1.9	1.5	69	5,285
Ford	PRO	All	648	49.8	12.6	9.5	10	793
		Selected ATA Codes	254	19.5	4.9	3.7	27	2,023
		Instruments	12	0.9	0.2	0.2	566	42,814
		Electrical Group	104	8.0	2.0	1.5	65	4,940
		Engine/Fuel	139	10.7	2.7	2.0	49	3,696
	Unleaded	All	148	49.3	11.6	8.6	12	861
		Selected ATA Codes	53	17.7	4.2	3.1	32	2,403
		Instruments	3	1.0	0.2	0.2	572	42,452
		Electrical Group	34	11.3	2.7	2.0	50	3,746
		Engine/Fuel	16	5.3	1.3	0.9	107	7,960

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[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-3. Non-PM Repair Orders[(a)] (Continued)

Vehicle OEM	Fuel Type	System[(b)]	Total Non-PM ROs	Average ROs per Van	Average ROs per 10,000 Miles	Average ROs per 100 Service Days	Average Service Days per Non-PM RO	Average Miles Driven per Non-PM RO
Santa Ana								
Ford	M-85	All	649	32.5	13.0	6.2	16	769
		Selected ATA Codes	264	13.2	5.3	2.5	39	1,892
		Instruments	38	1.9	0.8	0.4	274	13,141
		Electrical Group	142	7.1	2.8	1.4	73	3,517
		Engine/Fuel	92	4.6	1.8	0.9	113	5,428
	Unleaded	All	79	26.3	10.4	4.4	23	958
		Selected ATA Codes	31	10.3	4.1	1.7	58	2,441
		Instruments	7	2.3	0.9	0.4	255	10,809
		Electrical Group	23	7.7	3.0	1.3	78	3,290
		Engine/Fuel	2	0.7	0.3	0.1	892	37,832

(a) See Table B-2 for number of vans, service days, and miles driven.
(b) All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-4. Non-PM Labor Hours[a]

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Labor Hours per Van	Average Labor Hours per Non-PM ROs	Average Labor Hours per 10,000 Miles	Average Labor Hours per 100 Service Days
Irvine							
Chevrolet	CNG	All	367	52.8	1.0	19.7	12.0
		Selected ATA Codes	183	28.4	1.1	10.6	6.4
		Instruments	5	0.2	0.3	0.1	0.1
		Electrical Group	117	9.3	0.6	3.5	2.1
		Engine/Fuel	78	18.9	1.7	7.0	4.3
	Unleaded	All	144	49.8	1.0	12.6	8.7
		Selected ATA Codes	36	8.7	0.7	2.2	1.5
		Instruments	4	0.8	0.6	0.2	0.1
		Electrical Group	25	3.4	0.4	0.9	0.6
		Engine/Fuel	11	4.5	1.2	1.1	0.8
Dodge	CNG	All	383	68.7	1.3	30.4	14.9
		Selected ATA Codes	185	36.9	1.4	16.3	8.0
		Instruments	16	1.9	0.8	0.8	0.4
		Electrical Group	88	6.1	0.5	2.7	1.3
		Engine/Fuel	87	28.9	2.3	12.8	6.3
	Unleaded	All	180	70.0	1.2	16.4	12.9
		Selected ATA Codes	57	16.9	0.9	4.0	3.1
		Instruments	5	0.3	0.2	0.1	0.1
		Electrical Group	31	6.9	0.7	1.6	1.3
		Engine/Fuel	21	9.7	1.4	2.3	1.8

[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-4. Non-PM Labor Hours[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Labor Hours per Van	Average Labor Hours per Non-PM ROs	Average Labor Hours per 10,000 Miles	Average Labor Hours per 100 Service Days
Ford	CNG	All	319	39.7	0.9	13.4	8.7
		Selected ATA Codes	157	15.0	0.7	5.1	3.3
		Instruments	17	1.4	0.6	0.5	0.3
		Electrical Group	73	5.0	0.5	1.7	1.1
		Engine/Fuel	74	8.7	0.8	2.9	1.9
	Unleaded	All	144	32.6	0.7	8.3	5.2
		Selected ATA Codes	50	8.6	0.5	2.2	1.4
		Instruments	2	0.1	0.1	0.0	0.0
		Electrical Group	45	7.7	0.5	1.9	1.2
		Engine/Fuel	3	0.8	0.8	0.2	0.1
Los Angeles							
Chevrolet	RFG	All	295	50.8	1.2	25.7	8.4
		Selected ATA Codes	110	18.6	1.2	9.4	3.1
		Instruments	4	2.0	3.6	1.0	0.3
		Electrical Group	103	13.9	0.9	7.0	2.3
		Engine/Fuel	13	2.7	1.4	1.4	0.4
	Unleaded	All	115	27.9	0.7	17.3	4.2
		Selected ATA Codes	44	6.9	0.5	4.2	1.0
		Instruments	4	0.7	0.5	0.4	0.1
		Electrical Group	35	5.3	0.5	3.3	0.8
		Engine/Fuel	6	0.8	0.4	0.5	0.1

[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-4. Non-PM Labor Hours[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Labor Hours per Van	Average Labor Hours per Non-PM ROs	Average Labor Hours per 10,000 Miles	Average Labor Hours per 100 Service Days
Dodge	RFG	All	207	51.1	1.7	28.0	8.4
		Selected ATA Codes	75	12.7	1.2	7.0	2.1
		Instruments	9	2.4	1.9	1.3	0.4
		Electrical Group	59	6.6	0.8	3.6	1.1
		Engine/Fuel	10	3.7	2.6	2.0	0.6
	Unleaded	All	116	52.5	1.4	20.4	8.6
		Selected ATA Codes	32	5.6	0.5	2.2	0.9
		Instruments	0	0.0	–	0.0	0.0
		Electrical Group	31	5.6	0.5	2.2	0.9
		Engine/Fuel	1	0.0	0.0	0.0	0.0
Ford	RFG	All	241	36.4	1.1	17.3	5.6
		Selected ATA Codes	118	12.2	0.7	5.8	1.9
		Instruments	1	0.1	0.5	0.0	0.0
		Electrical Group	112	11.3	0.7	5.4	1.7
		Engine/Fuel	6	0.8	1.0	0.4	0.1
	Unleaded	All	121	46.2	1.1	24.4	7.1
		Selected ATA Codes	54	9.9	0.6	5.2	1.5
		Instruments	1	0.2	0.5	0.1	0.0
		Electrical Group	50	9.3	0.6	4.9	1.4
		Engine/Fuel	3	0.4	0.4	0.2	0.1

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[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-4. Non-PM Labor Hours[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Labor Hours per Van	Average Labor Hours per Non-PM ROs	Average Labor Hours per 10,000 Miles	Average Labor Hours per 100 Service Days
Rialto							
Chevrolet	PRO	All	465	93.6	1.4	26.4	21.7
		Selected ATA Codes	164	41.5	1.8	11.7	9.6
		Instruments	3	0.1	0.3	0.0	0.0
		Electrical Group	75	8.7	0.8	2.5	2.0
		Engine/Fuel	104	32.7	2.2	9.2	7.6
	Unleaded	All	183	63.2	1.0	16.3	12.6
		Selected ATA Codes	53	15.8	0.9	4.1	3.1
		Instruments	3	1.0	1.0	0.3	0.2
		Electrical Group	30	6.6	0.7	1.7	1.3
		Engine/Fuel	22	8.2	1.1	2.1	1.6
Ford	PRO	All	648	50.6	1.0	12.8	9.7
		Selected ATA Codes	254	23.9	1.2	6.0	4.6
		Instruments	12	0.5	0.5	0.1	0.1
		Electrical Group	104	4.4	0.6	1.1	0.9
		Engine/Fuel	139	18.9	1.8	4.8	3.6
	Unleaded	All	148	34.7	0.7	8.2	6.1
		Selected ATA Codes	53	11.7	0.7	2.7	2.0
		Instruments	3	0.8	0.8	0.2	0.1
		Electrical Group	34	6.5	0.6	1.5	1.1
		Engine/Fuel	16	4.4	0.8	1.0	0.8

(a) See Table B-2 for number of vans, service days, and miles driven.
(b) All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-4. Non-PM Labor Hours[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Labor Hours per Van	Average Labor Hours per Non-PM ROs	Average Labor Hours per 10,000 Miles	Average Labor Hours per 100 Service Days
Santa Ana							
Ford	M-85	All	649	32.9	1.0	13.2	6.3
		Selected ATA Codes	264	11.5	0.9	4.6	2.2
		Instruments	38	0.9	0.5	0.4	0.2
		Electrical Group	142	3.8	0.5	1.5	0.7
		Engine/Fuel	92	6.8	1.5	2.7	1.3
	Unleaded	All	79	26.3	1.0	10.4	4.4
		Selected ATA Codes	31	6.6	0.6	2.6	1.1
		Instruments	7	2.6	1.1	1.0	0.4
		Electrical Group	23	3.4	0.4	1.4	0.6
		Engine/Fuel	2	0.6	0.9	0.2	0.1

[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-5. Non-PM Labor Costs[a]

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Labor Cost per Van	Average Labor Cost per Non-PM RO	Average Labor Cost per 10,000 Miles	Average Labor Cost per 100 Service Days
Irvine							
Chevrolet	CNG	All	367	1093.3	20.9	407.8	247.7
		Selected ATA Codes	183	579.5	22.2	216.1	131.3
		Instruments	5	4.4	6.1	1.6	1.0
		Electrical Group	117	194.8	11.7	72.6	44.1
		Engine/Fuel	78	380.4	34.1	141.9	86.2
	Unleaded	All	144	1028.3	21.4	259.3	179.4
		Selected ATA Codes	36	177.7	14.8	44.8	31.0
		Instruments	4	15.4	11.6	3.9	2.7
		Electrical Group	25	71.4	8.6	18.0	12.5
		Engine/Fuel	11	90.9	24.8	22.9	15.9
Dodge	CNG	All	383	1413.3	25.8	624.3	307.3
		Selected ATA Codes	185	754.7	28.6	333.4	164.1
		Instruments	16	37.7	16.5	16.6	8.2
		Electrical Group	88	133.8	10.6	59.1	29.1
		Engine/Fuel	87	583.2	46.9	257.6	126.8
	Unleaded	All	180	1432.4	23.9	335.6	263.2
		Selected ATA Codes	57	350.1	18.4	82.0	64.3
		Instruments	5	6.0	3.6	1.4	1.1
		Electrical Group	31	145.9	14.1	34.2	26.8
		Engine/Fuel	21	198.2	28.3	46.4	36.4

[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-5. Non-PM Labor Costs[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Labor Cost per Van	Average Labor Cost per Non-PM RO	Average Labor Cost per 10,000 Miles	Average Labor Cost per 100 Service Days
Ford	CNG	All	319	834.5	18.3	282.6	183.6
		Selected ATA Codes	157	322.8	14.4	109.3	71.0
		Instruments	17	27.0	11.1	9.1	5.9
		Electrical Group	73	107.4	10.3	36.4	23.6
		Engine/Fuel	74	188.4	17.8	63.8	41.4
	Unleaded	All	144	687.1	14.3	174.2	109.0
		Selected ATA Codes	50	189.8	11.4	48.1	30.1
		Instruments	2	1.6	2.5	0.4	0.3
		Electrical Group	45	171.8	11.5	43.6	27.2
		Engine/Fuel	3	16.4	16.4	4.2	2.6
Los Angeles							
Chevrolet	RFG	All	295	1080.9	25.6	547.6	177.9
		Selected ATA Codes	110	381.4	24.3	193.2	62.8
		Instruments	4	41.1	71.8	20.8	6.8
		Electrical Group	103	285.3	19.4	144.5	47.0
		Engine/Fuel	13	55.1	29.7	27.9	9.1
	Unleaded	All	115	631.3	16.5	390.3	95.6
		Selected ATA Codes	44	150.0	10.2	92.7	22.7
		Instruments	4	13.9	10.5	8.6	2.1
		Electrical Group	35	116.9	10.0	72.3	17.7
		Engine/Fuel	6	19.1	9.6	11.8	2.9

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[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-5. Non-PM Labor Costs[(a)] (Continued)

Vehicle OEM	Fuel Type	System[(b)]	Total Non-PM ROs	Average Labor Cost per Van	Average Labor Cost per Non-PM RO	Average Labor Cost per 10,000 Miles	Average Labor Cost per 100 Service Days
Dodge	RFG	All	207	1086.4	36.7	595.4	179.6
		Selected ATA Codes	75	265.2	24.8	145.4	43.8
		Instruments	9	50.2	39.0	27.5	8.3
		Electrical Group	59	139.9	16.6	76.7	23.1
		Engine/Fuel	10	75.2	52.6	41.2	12.4
	Unleaded	All	116	1094.0	28.3	425.7	180.1
		Selected ATA Codes	32	117.0	11.0	45.5	19.3
		Instruments	0	0.0	–	0.0	0.0
		Electrical Group	31	117.0	11.3	45.5	19.3
		Engine/Fuel	1	0.0	0.0	0.0	0.0
Ford	RFG	All	241	799.8	23.2	381.2	123.4
		Selected ATA Codes	118	270.6	16.1	128.9	41.7
		Instruments	1	1.8	12.7	0.9	0.3
		Electrical Group	112	251.9	15.7	120.0	38.8
		Engine/Fuel	6	16.9	19.7	8.1	2.6
	Unleaded	All	121	998.3	24.8	526.9	154.3
		Selected ATA Codes	54	218.0	12.1	115.1	33.7
		Instruments	1	3.3	9.8	1.7	0.5
		Electrical Group	50	205.0	12.3	108.2	31.7
		Engine/Fuel	3	9.7	9.7	5.1	1.5

[(a)] See Table B-2 for number of vans, service days, and miles driven.

[(b)] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-5. Non-PM Labor Costs[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Labor Cost per Van	Average Labor Cost per Non-PM RO	Average Labor Cost per 10,000 Miles	Average Labor Cost per 100 Service Days
Rialto							
Chevrolet	PRO	All	465	1980.1	29.8	557.5	458.9
		Selected ATA Codes	164	850.6	36.3	239.5	197.1
		Instruments	3	2.1	4.9	0.6	0.5
		Electrical Group	75	190.8	17.8	53.7	44.2
		Engine/Fuel	104	657.7	44.3	185.2	152.4
	Unleaded	All	183	1358.0	22.3	350.4	270.3
		Selected ATA Codes	53	334.7	18.9	86.4	66.6
		Instruments	3	19.9	19.9	5.1	4.0
		Electrical Group	30	141.1	14.1	36.4	28.1
		Engine/Fuel	22	173.7	23.7	44.8	34.6
Ford	PRO	All	648	1075.4	21.6	272.1	205.9
		Selected ATA Codes	254	494.2	25.3	125.0	94.6
		Instruments	12	9.3	10.1	2.3	1.8
		Electrical Group	104	103.6	12.9	26.2	19.8
		Engine/Fuel	139	381.3	35.7	96.5	73.0
	Unleaded	All	148	766.7	15.5	180.6	134.0
		Selected ATA Codes	53	261.2	14.8	61.5	45.7
		Instruments	3	15.0	15.0	3.5	2.6
		Electrical Group	34	152.9	13.5	36.0	26.7
		Engine/Fuel	16	93.4	17.5	22.0	16.3

(a) See Table B-2 for number of vans, service days, and miles driven.

(b) All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-5. Non-PM Labor Costs[(a)] (Continued)

Vehicle OEM	Fuel Type	System[(b)]	Total Non-PM ROs	Average Labor Cost per Van	Average Labor Cost per Non-PM RO	Average Labor Cost per 10,000 Miles	Average Labor Cost per 100 Service Days
Santa Ana							
Ford	M-85	All	649	659.3	20.3	264.1	126.5
		Selected ATA Codes	264	229.1	17.4	91.8	43.9
		Instruments	38	18.5	9.7	7.4	3.6
		Electrical Group	142	74.6	10.5	29.9	14.3
		Engine/Fuel	92	136.0	29.6	54.5	26.1
	Unleaded	All	79	532.5	20.2	211.1	89.5
		Selected ATA Codes	31	130.8	12.7	51.9	22.0
		Instruments	7	51.5	22.1	20.4	8.6
		Electrical Group	23	67.2	8.8	26.6	11.3
		Engine/Fuel	2	12.2	18.3	4.8	2.0

(a) See Table B-2 for number of vans, service days, and miles driven.

(b) All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-6. Non-PM Parts Costs[a]

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Parts Cost per Van	Average Parts Cost per Non-PM RO	Average Parts Cost per 10,000 Miles	Average Parts Cost per 100 Service Days
Irvine							
Chevrolet	CNG	All	367	2138.9	40.8	797.7	484.6
		Selected ATA Codes	183	1522.8	58.3	568.0	345.0
		Instruments	5	2.3	3.2	0.8	0.5
		Electrical Group	117	269.8	16.1	100.6	61.1
		Engine/Fuel	78	1250.7	112.2	466.5	283.3
	Unleaded	All	144	1324.3	27.6	333.9	231.0
		Selected ATA Codes	36	632.0	52.7	159.3	110.2
		Instruments	4	14.3	10.7	3.6	2.5
		Electrical Group	25	305.8	36.7	77.1	53.3
		Engine/Fuel	11	311.9	85.1	78.6	54.4
Dodge	CNG	All	383	1926.2	35.2	850.8	418.8
		Selected ATA Codes	185	1179.5	44.6	521.0	256.5
		Instruments	16	14.1	6.2	6.2	3.1
		Electrical Group	88	236.4	18.8	104.4	51.4
		Engine/Fuel	87	929.0	74.7	410.3	202.0
	Unleaded	All	180	2637.2	44.0	617.8	484.5
		Selected ATA Codes	57	379.4	20.0	88.9	69.7
		Instruments	5	0.0	0.0	0.0	0.0
		Electrical Group	31	181.1	17.5	42.4	33.3
		Engine/Fuel	21	198.4	28.3	46.5	36.4

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[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-6. Non-PM Parts Costs[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Parts Cost per Van	Average Parts Cost per Non-PM RO	Average Parts Cost per 10,000 Miles	Average Parts Cost per 100 Service Days
Ford	CNG	All	319	1197.8	26.3	405.6	263.5
		Selected ATA Codes	157	462.5	20.6	156.6	101.7
		Instruments	17	7.1	2.9	2.4	1.6
		Electrical Group	73	121.0	11.6	41.0	26.6
		Engine/Fuel	74	334.4	31.6	113.2	73.6
	Unleaded	All	144	889.0	18.5	225.4	141.0
		Selected ATA Codes	50	249.8	15.0	63.3	39.6
		Instruments	2	0.0	0.0	0.0	0.0
		Electrical Group	45	248.0	16.5	62.9	39.3
		Engine/Fuel	3	1.8	1.8	0.5	0.3
Los Angeles							
Chevrolet	RFG	All	295	859.4	20.4	435.3	141.5
		Selected ATA Codes	110	271.6	17.3	137.6	44.7
		Instruments	4	4.5	7.8	2.3	0.7
		Electrical Group	103	247.1	16.8	125.2	40.7
		Engine/Fuel	13	20.1	10.8	10.2	3.3
	Unleaded	All	115	326.5	8.5	201.9	49.4
		Selected ATA Codes	44	109.1	7.4	67.4	16.5
		Instruments	4	0.0	0.0	0.0	0.0
		Electrical Group	35	78.0	6.7	48.2	11.8
		Engine/Fuel	6	31.1	15.5	19.2	4.7

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[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-6. Non-PM Parts Costs[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Parts Cost per Van	Average Parts Cost per Non-PM RO	Average Parts Cost per 10,000 Miles	Average Parts Cost per 100 Service Days
Dodge	RFG	All	207	662.2	22.4	362.9	109.4
		Selected ATA Codes	75	120.4	11.2	66.0	19.9
		Instruments	9	21.2	16.5	11.6	3.5
		Electrical Group	59	51.9	6.2	28.4	8.6
		Engine/Fuel	10	47.4	33.2	26.0	7.8
	Unleaded	All	116	423.0	10.9	164.6	69.6
		Selected ATA Codes	32	108.7	10.2	42.3	17.9
		Instruments	0	0.0	–	0.0	0.0
		Electrical Group	31	107.2	10.4	41.7	17.6
		Engine/Fuel	1	1.5	4.5	0.6	0.2
Ford	RFG	All	241	363.1	10.5	173.1	56.0
		Selected ATA Codes	118	160.2	9.5	76.3	24.7
		Instruments	1	0.0	0.0	0.0	0.0
		Electrical Group	112	148.4	9.3	70.7	22.9
		Engine/Fuel	6	11.8	13.8	5.6	1.8
	Unleaded	All	121	532.7	13.2	281.2	82.3
		Selected ATA Codes	54	154.0	8.6	81.3	23.8
		Instruments	1	0.0	0.0	0.0	0.0
		Electrical Group	50	154.0	9.2	81.3	23.8
		Engine/Fuel	3	0.0	0.0	0.0	0.0

[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-6. Non-PM Parts Costs[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Parts Cost per Van	Average Parts Cost per Non-PM RO	Average Parts Cost per 10,000 Miles	Average Parts Cost per 100 Service Days
Rialto							
Chevrolet	PRO	All	465	4882.6	73.5	1374.6	1131.5
		Selected ATA Codes	164	2577.0	110.0	725.5	597.2
		Instruments	3	0.0	0.0	0.0	0.0
		Electrical Group	75	450.2	42.0	126.8	104.3
		Engine/Fuel	104	2126.8	143.1	598.8	492.9
	Unleaded	All	183	3402.7	55.8	877.9	677.3
		Selected ATA Codes	53	741.9	42.0	191.4	147.7
		Instruments	3	27.7	27.7	7.2	5.5
		Electrical Group	30	271.1	27.1	69.9	54.0
		Engine/Fuel	22	443.1	60.4	114.3	88.2
Ford	PRO	All	648	1170.1	23.5	296.1	224.1
		Selected ATA Codes	254	520.6	26.6	131.7	99.7
		Instruments	12	0.0	0.0	0.0	0.0
		Electrical Group	104	89.2	11.2	22.6	17.1
		Engine/Fuel	139	431.4	40.3	109.2	82.6
	Unleaded	All	148	765.0	15.5	180.2	133.7
		Selected ATA Codes	53	234.6	13.3	55.3	41.0
		Instruments	3	0.0	0.0	0.0	0.0
		Electrical Group	34	118.2	10.4	27.8	20.7
		Engine/Fuel	16	116.4	21.8	27.4	20.3

[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-6. Non-PM Parts Costs[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Parts Cost per Van	Average Parts Cost per Non-PM RO	Average Parts Cost per 10,000 Miles	Average Parts Cost per 100 Service Days
Santa Ana							
Ford	M-85	All	649	1086.2	33.5	435.0	208.3
		Selected ATA Codes	264	735.1	55.7	294.4	141.0
		Instruments	38	10.3	5.4	4.1	2.0
		Electrical Group	142	119.3	16.8	47.8	22.9
		Engine/Fuel	92	605.5	131.6	242.5	116.1
	Unleaded	All	79	494.7	18.8	196.2	83.2
		Selected ATA Codes	31	121.3	11.7	48.1	20.4
		Instruments	7	0.0	0.0	0.0	0.0
		Electrical Group	23	119.3	15.6	47.3	20.0
		Engine/Fuel	2	2.1	3.1	0.8	0.3

[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-7. Non-PM Total Costs[(a)]

Vehicle OEM	Fuel Type	System[(b)]	Total Non-PM ROs	Average Total Cost per Van	Average Total Cost per Non-PM RO	Average Total Cost per 10,000 Miles	Average Total Cost per 100 Service Days
Irvine							
Chevrolet	CNG	All	367	3232.2	61.6	1205.5	732.2
		Selected ATA Codes	183	2102.3	80.4	784.1	476.3
		Instruments	5	6.6	9.3	2.5	1.5
		Electrical Group	117	464.6	27.8	173.3	105.3
		Engine/Fuel	78	1631.1	146.4	608.4	369.5
	Unleaded	All	144	2352.6	49.0	593.2	410.4
		Selected ATA Codes	36	809.7	67.5	204.1	141.2
		Instruments	4	29.7	22.3	7.5	5.2
		Electrical Group	25	377.2	45.3	95.1	65.8
		Engine/Fuel	11	402.8	109.8	101.5	70.3
Dodge	CNG	All	383	3339.5	61.0	1475.1	726.1
		Selected ATA Codes	185	1934.2	73.2	854.3	420.5
		Instruments	16	51.8	22.7	22.9	11.3
		Electrical Group	88	370.2	29.4	163.5	80.5
		Engine/Fuel	87	1512.2	121.7	668.0	328.8
	Unleaded	All	180	4069.6	67.8	953.4	747.7
		Selected ATA Codes	57	729.6	38.4	170.9	134.0
		Instruments	5	6.0	3.6	1.4	1.1
		Electrical Group	31	327.0	31.6	76.6	60.1
		Engine/Fuel	21	396.5	56.6	92.9	72.9

[(a)] See Table B-2 for number of vans, service days, and miles driven.

[(b)] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-7. Non-PM Total Costs[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Total Cost per Van	Average Total Cost per Non-PM RO	Average Total Cost per 10,000 Miles	Average Total Cost per 100 Service Days
Ford	CNG	All	319	2032.3	44.6	688.1	447.0
		Selected ATA Codes	157	785.3	35.0	265.9	172.8
		Instruments	17	34.2	14.1	11.6	7.5
		Electrical Group	73	228.4	21.9	77.3	50.2
		Engine/Fuel	74	522.8	49.5	177.0	115.0
	Unleaded	All	144	1576.1	32.8	399.6	250.0
		Selected ATA Codes	50	439.6	26.4	111.5	69.7
		Instruments	2	1.6	2.5	0.4	0.3
		Electrical Group	45	419.8	28.0	106.4	66.6
		Engine/Fuel	3	18.2	18.2	4.6	2.9
Los Angeles							
Chevrolet	RFG	All	295	1940.3	46.0	982.9	319.4
		Selected ATA Codes	110	653.0	41.6	330.8	107.5
		Instruments	4	45.5	79.7	23.1	7.5
		Electrical Group	103	532.3	36.2	269.7	87.6
		Engine/Fuel	13	75.1	40.5	38.1	12.4
	Unleaded	All	115	957.9	25.0	592.2	145.1
		Selected ATA Codes	44	259.1	17.7	160.2	39.2
		Instruments	4	13.9	10.5	8.6	2.1
		Electrical Group	35	194.9	16.7	120.5	29.5
		Engine/Fuel	6	50.2	25.1	31.0	7.6

[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-7. Non-PM Total Costs[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Total Cost per Van	Average Total Cost per Non-PM RO	Average Total Cost per 10,000 Miles	Average Total Cost per 100 Service Days
Dodge	RFG	All	207	1748.6	59.1	958.3	289.0
		Selected ATA Codes	75	385.6	36.0	211.4	63.7
		Instruments	9	71.4	55.5	39.1	11.8
		Electrical Group	59	191.7	22.7	105.1	31.7
		Engine/Fuel	10	122.5	85.8	67.1	20.3
	Unleaded	All	116	1517.0	39.2	590.4	249.7
		Selected ATA Codes	32	225.6	21.2	87.8	37.1
		Instruments	0	0.0	–	0.0	0.0
		Electrical Group	31	224.1	21.7	87.2	36.9
		Engine/Fuel	1	1.5	4.5	0.6	0.2
Ford	RFG	All	241	1162.9	33.8	554.2	179.4
		Selected ATA Codes	118	430.8	25.6	205.3	66.5
		Instruments	1	1.8	12.7	0.9	0.3
		Electrical Group	112	400.2	25.0	190.7	61.7
		Engine/Fuel	6	28.7	33.5	13.7	4.4
	Unleaded	All	121	1530.9	38.0	808.1	236.6
		Selected ATA Codes	54	372.0	20.7	196.4	57.5
		Instruments	1	3.3	9.8	1.7	0.5
		Electrical Group	50	359.0	21.5	189.5	55.5
		Engine/Fuel	3	9.7	9.7	5.1	1.5

[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-7. Non-PM Total Costs[a] (Continued)

Vehicle OEM	Fuel Type	System[b]	Total Non-PM ROs	Average Total Cost per Van	Average Total Cost per Non-PM RO	Average Total Cost per 10,000 Miles	Average Total Cost per 100 Service Days
Rialto							
Chevrolet	PRO	All	465	6862.7	103.3	1932.1	1590.3
		Selected ATA Codes	164	3427.6	146.3	965.0	794.3
		Instruments	3	2.1	4.9	0.6	0.5
		Electrical Group	75	641.0	59.8	180.5	148.5
		Engine/Fuel	104	2784.5	187.4	783.9	645.3
	Unleaded	All	183	4760.7	78.0	1228.3	947.5
		Selected ATA Codes	53	1076.6	60.9	277.8	214.3
		Instruments	3	47.6	47.6	12.3	9.5
		Electrical Group	30	412.2	41.2	106.4	82.0
		Engine/Fuel	22	616.8	84.1	159.1	122.8
Ford	PRO	All	648	2245.6	45.0	568.2	430.0
		Selected ATA Codes	254	1014.8	51.9	256.8	194.3
		Instruments	12	9.3	10.1	2.3	1.8
		Electrical Group	104	192.8	24.1	48.8	36.9
		Engine/Fuel	139	812.7	76.0	205.6	155.6
	Unleaded	All	148	1531.7	31.0	360.8	267.7
		Selected ATA Codes	53	495.9	28.1	116.8	86.7
		Instruments	3	15.0	15.0	3.5	2.6
		Electrical Group	34	271.1	23.9	63.9	47.4
		Engine/Fuel	16	209.8	39.3	49.4	36.7

[a] See Table B-2 for number of vans, service days, and miles driven.

[b] All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

Table A-7. Non-PM Total Costs[(a)] (Continued)

Vehicle OEM	Fuel Type	System[(b)]	Total Non-PM ROs	Average Total Cost per Van	Average Total Cost per Non-PM RO	Average Total Cost per 10,000 Miles	Average Total Cost per 100 Service Days
Santa Ana							
Ford	M-85	All	649	1745.6	53.8	699.1	334.8
		Selected ATA Codes	264	964.2	73.0	386.2	184.9
		Instruments	38	28.8	15.1	11.5	5.5
		Electrical Group	142	193.9	27.3	77.7	37.2
		Engine/Fuel	92	741.5	161.2	297.0	142.2
	Unleaded	All	79	1027.2	39.0	407.3	172.6
		Selected ATA Codes	31	252.1	24.4	100.0	42.4
		Instruments	7	51.5	22.1	20.4	8.6
		Electrical Group	23	186.4	24.3	73.9	31.3
		Engine/Fuel	2	14.2	21.4	5.6	2.4

(a) See Table B-2 for number of vans, service days, and miles driven.

(b) All systems include ATA system codes 000 through 079.
Instruments include ATA system code 003.
Electrical Group includes ATA system codes 030 through 035.
Engine/Fuel systems include ATA system codes 040 through 048.

APPENDIX B

Data Analysis Approach

APPENDIX B

Data Analysis Approach

The approaches used to analyze the data from measurements of elements in used motor oil and properties of the used oil are summarized in this appendix:

- Modeling wear rate of engine metals
- Statistical analysis of engine metal removal rates
- Statistical modeling of oil properties.

Modeling of Engine Metals

The amount of metals removed from the engine during each oil change interval is calculated from the reported concentrations of engine metals in the used oil and information on oil consumption determined from oil additions and dipstick levels at each oil change. The calculations are based on differential equations derived from the following assumptions:

- Elements are entering the engine oil at a constant rate
- Oil is leaving the engine (through leakage or combustion exhaust) at a constant rate
- As oil is lost from the engine, the elements contained in the oil are lost at the same rate
- Oil is added in one-quart increments, and it is not added until the oil level is down one quart.

In graphical form, the assumed behavior of the oil concentration level is shown in Figure B-1. This example graph represents the predicted element concentration history for a vehicle that was driven 3,000 miles, had a quart of oil added at 2,000 miles, had an initial element concentration of 0 ppm, and a final concentration of about 17 ppm. Notice that although the rate of material entering the oil is assumed constant, the concentration increase is not linear with time. This effect is due to the decreasing volume of oil in the sump. Because the concentration of critical engine metals in the oil is known only at the beginning of an interval (when fresh oil is added) and at the oil change (through the spectrochemical oil analysis), a way of calculating the concentration at any time during the interval was needed to predict the amount of metals leaving the engine. The differential equation that describes this behavior and important steps in its derivation are shown below.

By definition

$$C = \frac{M}{V} \qquad \text{(B-1)}$$

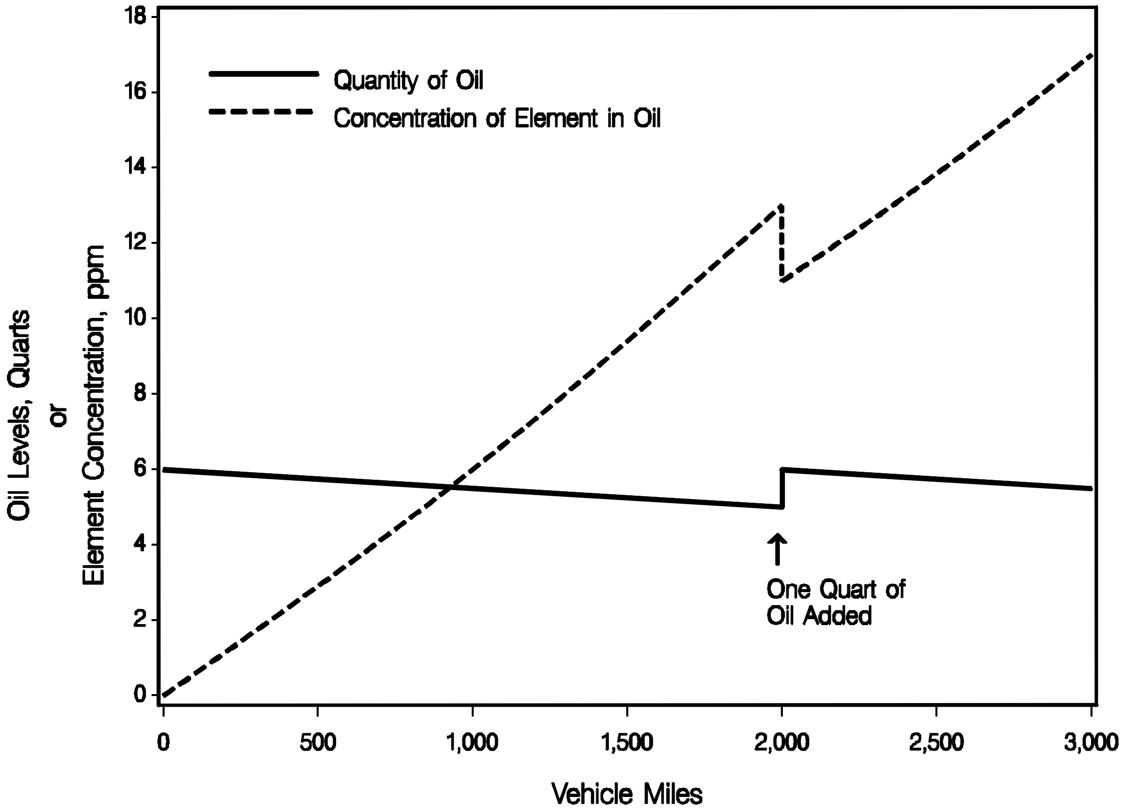

Figure B-1. Behavior of Element Concentrations in Engine Oil

where

C = concentration by volume of the element in the oil
M = mass of the element in the oil
V = total sump volume.

Differentiating one obtains

$$dC = \frac{VdM - MdV}{V^2} \tag{B-2}$$

Also by definition

$$dV = -Q_O dt \tag{B-3}$$

and

$$dM = -Q_O C dt + Q_E dt \tag{B-4}$$

where

Q_O = the volume flow rate of oil leaving the engine
Q_E = mass flow rate of the element into the oil.

Substituting equations (B-3) and (B-4) into equation (B-2) and simplifying one obtains

$$dC = \frac{Q_E \, dt}{V} \tag{B-5}$$

and by integration

$$C = C_O - \frac{Q_E}{Q_O} \ln\left(1 - \frac{Q_O}{V} t\right) \tag{B-6}$$

This is the basic equation for any interval between oil additions or changes. For example, in Figure B-1, equation (B-6) defines the concentration at the 2,000 mile mark. Between 2,000 miles and the oil change at 3,000 miles, the same equation can be used except that the initial concentration, C_O, is equal to the final concentration of the first interval, C, multiplied by a dilution factor for the added quart of oil. Solving for Q_O and summing the various intervals between oil additions, the general solution is:

$$Q_E = \frac{Q_O \left[C_O - \left(\frac{V}{V-1} \right)^N C_E \right]}{\left[\ln\left(1 - \frac{Q_O}{V} \tau \right) \right] \sum_{i=0}^{N} \left(\frac{V}{V-1} \right)^i + \left(\frac{V}{V-1} \right)^N \ln\left(1 - \frac{Q_O}{V} \tau_r \right)} \tag{B-7}$$

where

N = number of one-quart oil additions
τ = number of miles between one-quart oil additions
τ_r = number of miles between the last one-quart oil addition and the oil change.

In this analysis, the concentration of elements is in terms of mass of element per mass of oil (rather than volume of oil), so the volume of oil must be changed to a mass of oil by including a density term ρ as shown below.

$$Q_E = \frac{Q_O\,\rho\left[C_O - \left(\frac{V}{V-1}\right)^N C_E\right]}{\left[\ln\left(1 - \frac{Q_O}{V}\tau\right)\right]\sum_{i=0}^{N}\left(\frac{V}{V-1}\right)^i + \left(\frac{V}{V-1}\right)^N \ln\left(1 - \frac{Q_O}{V}\tau_r\right)} \tag{B-8}$$

In order to calculate the terms, τ, τ_r, and Q_O, the following equations are given.

$$\tau = \frac{M_F - M_I}{N + D} \tag{B-9}$$

$$\tau_r = M_F - M_I - (N\tau) \tag{B-10}$$

$$Q_O = \frac{N+D}{M_F - M_I} \tag{B-11}$$

where

M_F = final mileage in the oil change interval
M_I = initial mileage in the oil change interval.

The term, D, represents the amount of oil below a full sump present at the oil change. For example, D would be 0.5 for a vehicle that is one-half quart low at the oil change.

The above equations enable one to determine an average, constant removal rate of material from the engine over each individual oil change interval. By observing the removal rate of critical engine elements for each oil change, trends for normal behavior for the engine quickly become established.

Statistical Analysis of Engine Metal Removal Rates

Statistical comparisons of the removal rates of metals were made between each alternative fuel fleet and its control fleet. (Control fleets consist of vehicles from the same manufacturer but operating on regular unleaded gasoline.) Comparisons were based on the average weight of metal removed from the engines at various mileage levels. However, prior to performing this comparison, a number of preliminary analyses were needed. Because of the statistical advantages of combining data from control vehicles at different demonstration sites, statistical regression analysis was performed to determine if the rates of engine metal removal among control vehicles from the same manufacturer are consistent across sites. Such differences could occur as a result of differences in duty cycles or maintenance practices at the demonstration sites. The analysis did not reveal any significant site-to-site differences.

Out of the 918 oil changes reported, 60 oil changes were performed in which oil samples were not collected. Because many of these missing data were from the initial oil changes, it was necessary to estimate values for vehicles with missing data using the estimated metal removal rates from vehicles in the same fleet with complete data. This was done by fitting regression models to the available data from vehicles in the same fleet. Then, the estimated metal loss rate was used to “impute” values for vehicles with missing data. The regression model was

$$TM_{ijk} \text{ (grams)} = R_{ij} \times OM_{ijk} + e, \qquad \text{(B-12)}$$

where

TM_{ijk} = total engine metal removed during the jth oil change interval from vehicle k of fleet i

R_{ij} = rate of engine metal removal per mile during the jth oil change interval for fleet i

OM_{ijk} = number of miles driven between the j-1st and jth oil change for vehicle k of fleet i (OM is referred to as "oil miles")

e = random effect associated with measurement error and differences among vehicles within the same fleet.

The rationale for this approach is that it permits the maximum use of available data. Without this approach, the data from oil changes following the one with missing data could not be used to calculate cumulative metal removal. Because the level of data completeness achieved was 93 percent, the potential bias from this method is expected to be minimal.

The next step in the analysis was to calculate for each vehicle the cumulative weight of each metal removed from the engine at each oil change. For each vehicle the cumulative weight removed was calculated by

$$CWM_{ijk} = \sum_{l \le j} TM_{ilk} \qquad \text{(B-13)}$$

and

$$COM_{ijk} = \sum_{l \le j} OM_{ilk} \qquad \text{(B-14)}$$

where

CWM_{ijk} = cumulative weight of metals removed from vehicle k of fleet i by the jth oil change

COM_{ijk} = total mileage on vehicle k of fleet i at the jth oil change (cumulative oil miles).

Plots of CWM versus total miles (COM) were reviewed to determine the level of consistency among vehicles of the same fleet and to identify statistical outliers. The plots showed a high degree of consistency among vehicles.

Finally, for each fleet, the average cumulative metal removed at specific mileage levels (2,500, 5,000, 10,000, 15,000, and 20,000) was calculated using interpolated values from individual vehicles. Regression methods were used to estimate average levels for each fleet, determine the precision of these averages, and identify significant differences in the averages between each alternative fuel fleet and its control fleet.

The degree to which the number of miles between oil changes affects metal accumulation rates was also investigated. Plots of the estimated cumulative weights of selected metals versus the average miles between oil changes were prepared for each fleet. This was done because there were substantial differences in the number of miles between oil changes among the various fleets, including fleets of control vehicles at different demonstration sites. The presence of a trend within fleets would indicate that the length of the oil change interval should be considered in the statistical treatment of the data. No such trend was observed.

Statistical Modeling of Oil Properties

The oil properties monitored at each oil change include total base number, viscosity, nitration, and oxidation. The relationship between these properties and the miles driven since the last oil change is of particular interest to fleet operators because of the potential impact on the preventive maintenance schedule.

For each fleet, the values of each property were initially plotted against oil miles (miles since the last oil change) to determine if there were significant trends. The potential effects of cumulative vehicle miles on the properties was also investigated. Several empirical models were fitted to the data and tested for goodness-of-fit. The best-fitting models for total base number (TBN), viscosity (V), and nitration (N) at each oil change are

$$\log(\mathrm{TBN}/\mathrm{TBN}_O) = \beta_1 \text{ x } \mathrm{OM} + \epsilon_1, \tag{B-15}$$

$$\log(V) = \alpha_2 + \beta_2 \text{ x } \mathrm{OM} + \epsilon_2, \tag{B-16}$$

and

$$N = \alpha_3 + \beta_3 \text{ x } \mathrm{OM} + \epsilon_3, \tag{B-17}$$

where TBN_o is the average measured TBN in unused oil samples; OM is the miles driven since the last oil change; $ß_1$, α_2, $ß_2$, α_3, and $ß_4$ are constants; and ϵ_i (i= 1,2,3) are independent random errors that are assumed to be approximately normally distributed. Separate models were fitted to the measured properties at the initial oil change, if warranted.

Statistical regression analysis was used to test for significant trends (i.e., nonzero slope ß) for each fleet and to compare the oil properties for each alternative fuel fleet with the corresponding control fleet. The comparisons were based on the predicted oil properties at 3,000 miles following an oil change.

APPENDIX C

Average Engine Metal Removal

Iron

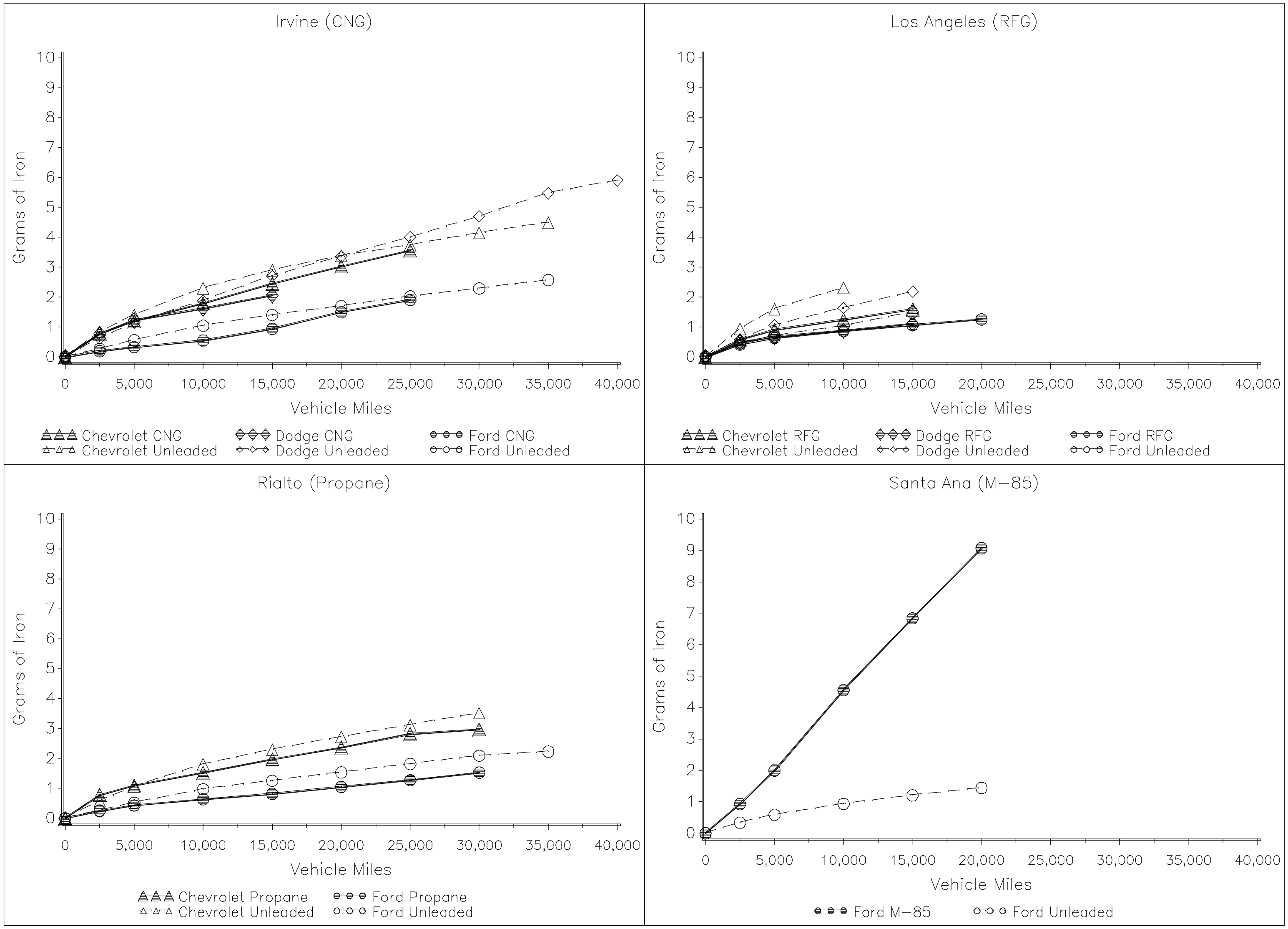

Figure C-1. Average Cumulative Weight of Iron Removed from Engines Versus Vehicle Miles

Chromium

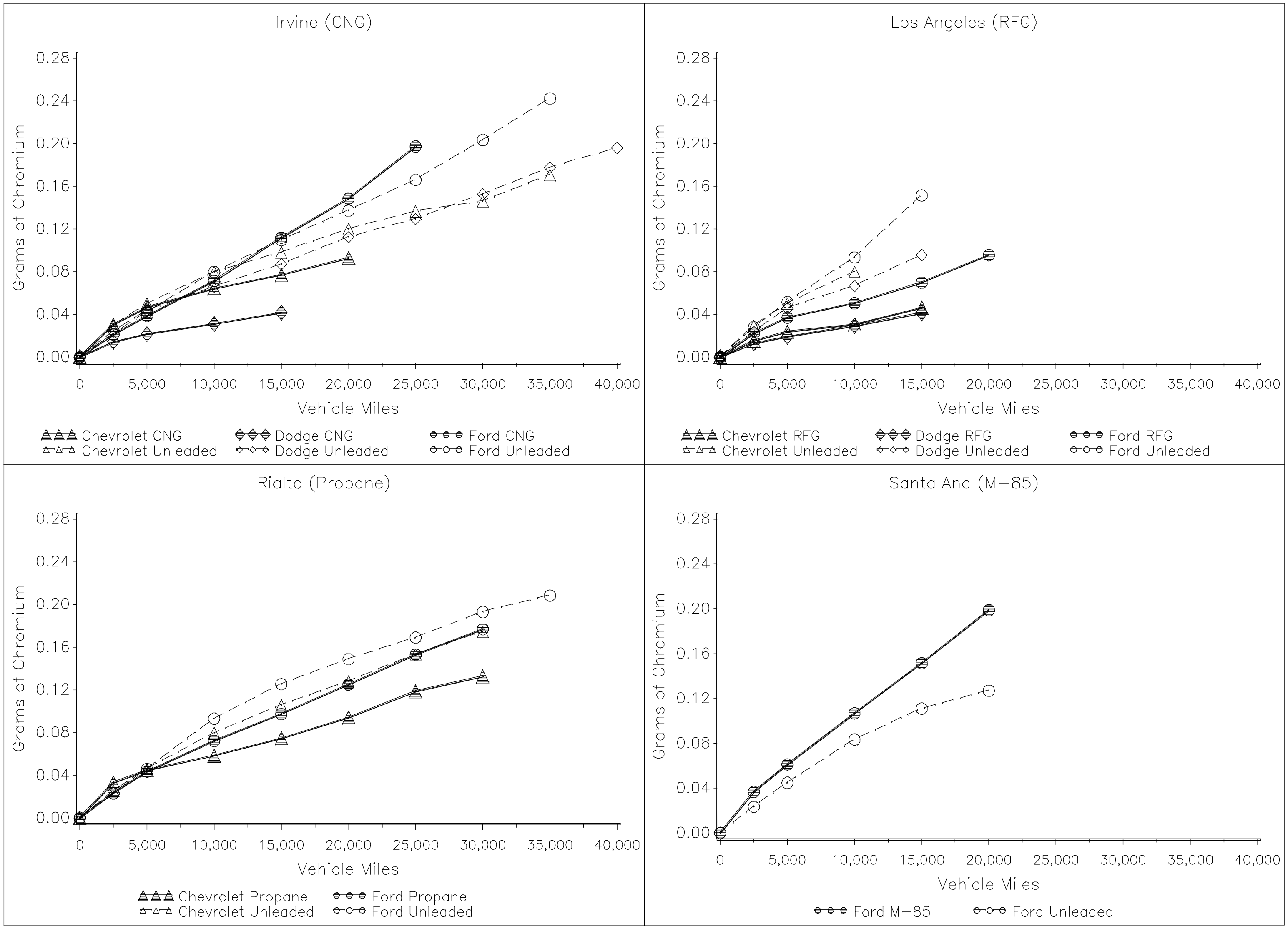

Figure C-2. Average Cumulative Weight of Chromium Removed from Engines Versus Vehicle Miles

Nickel

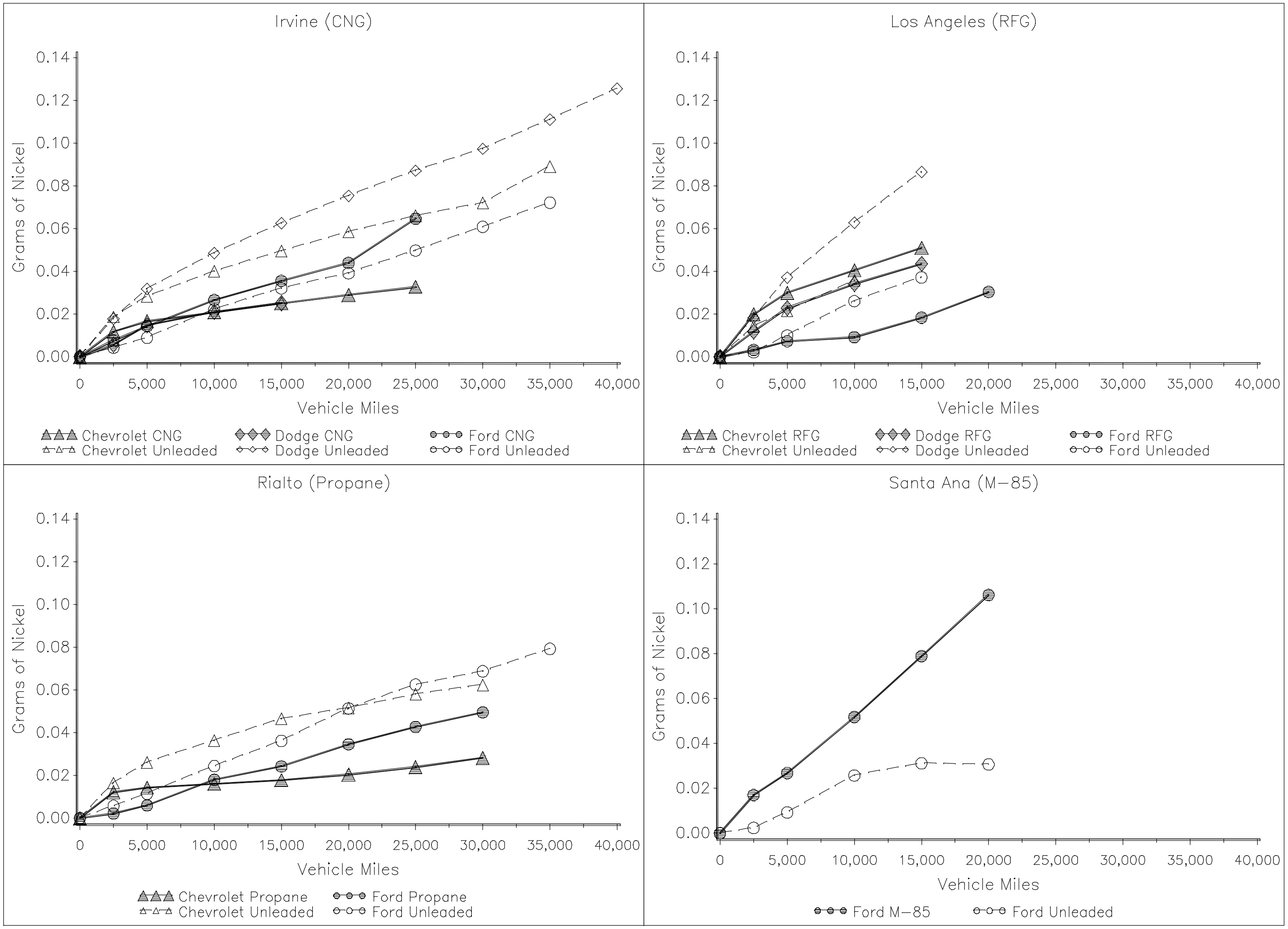

Figure C-3. Average Cumulative Weight of Nickel Removed from Engines Versus Vehicle Miles

Aluminum

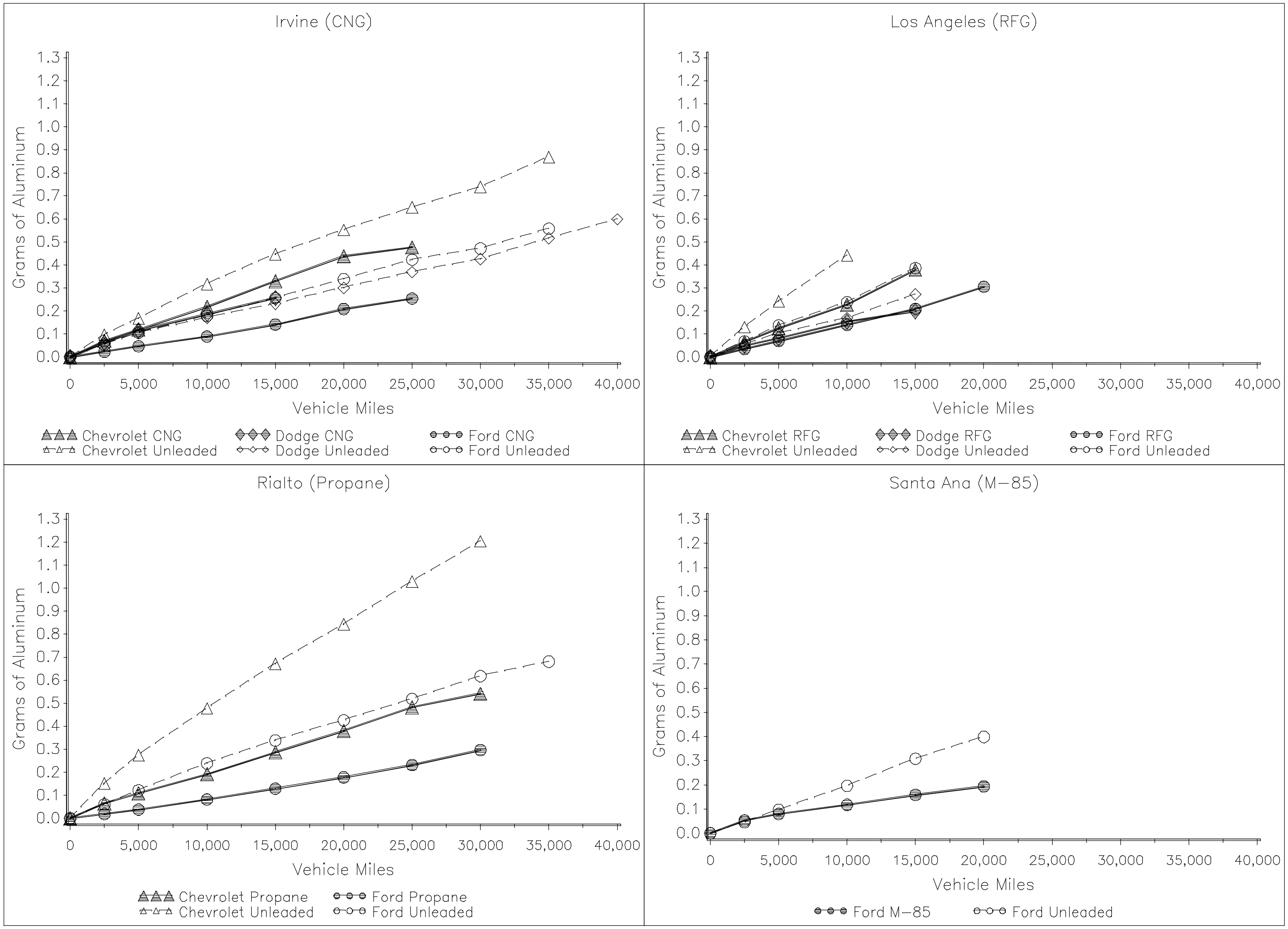

Figure C-4. Average Cumulative Weight of Aluminum Removed from Engines Versus Vehicle Miles

Lead

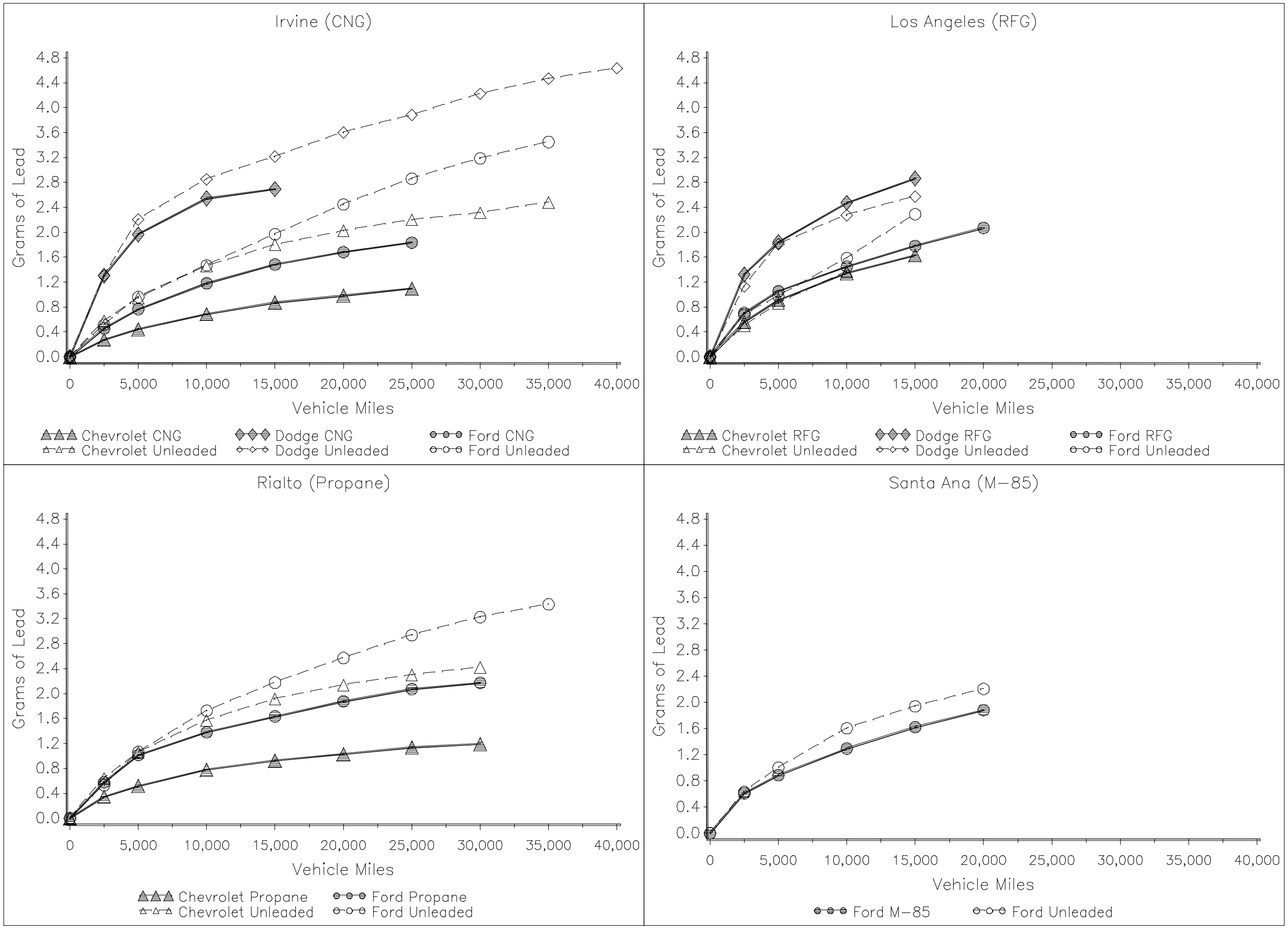

Figure C-5. Average Cumulative Weight of Lead Removed from Engines Versus Vehicle Miles

Copper

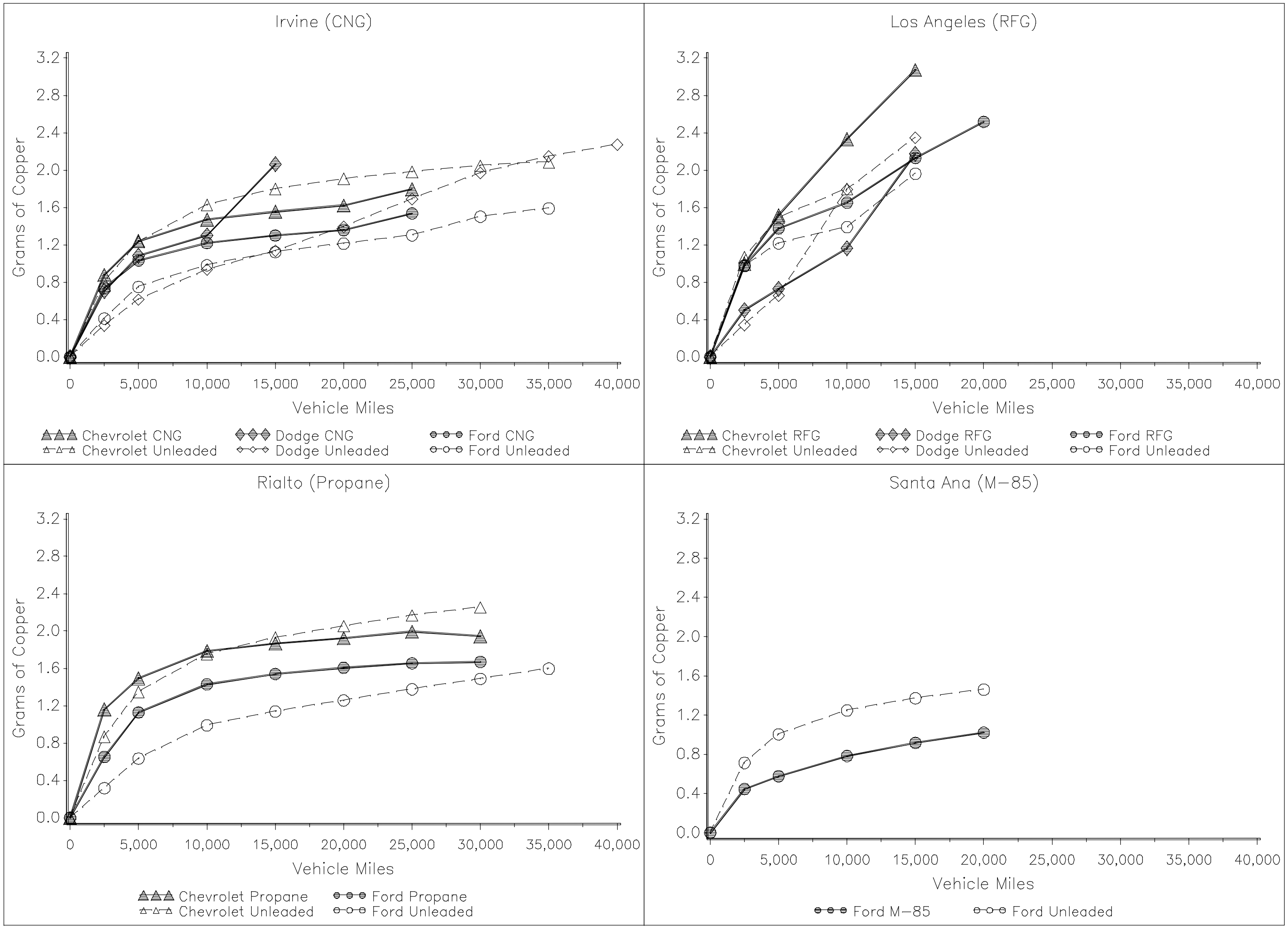

Figure C-6. Average Cumulative Weight of Copper Removed from Engines Versus Vehicle Miles

Tin

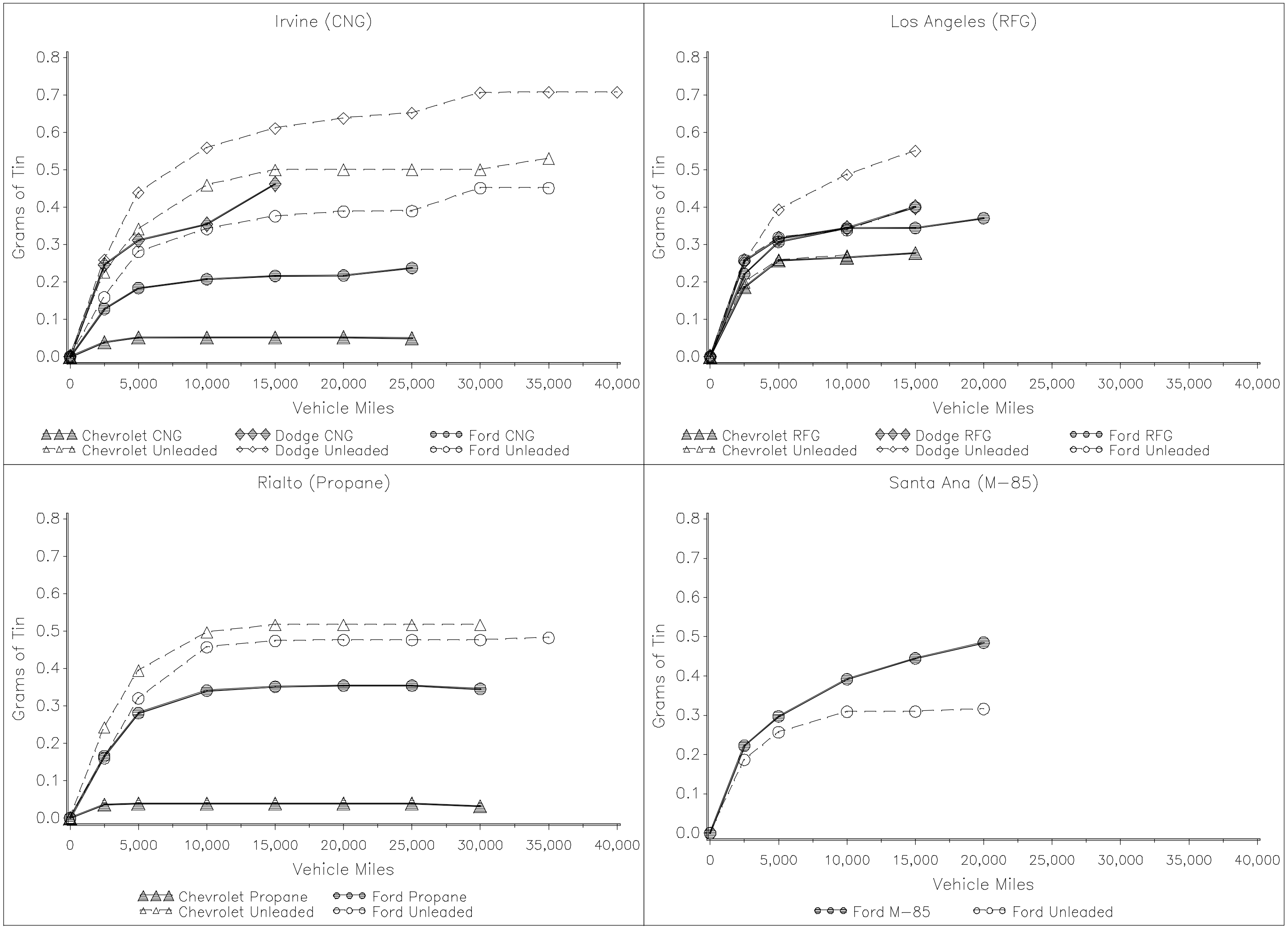

Figure C-7. Average Cumulative Weight of Tin Removed from Engines Versus Vehicle Miles

Molybdenum

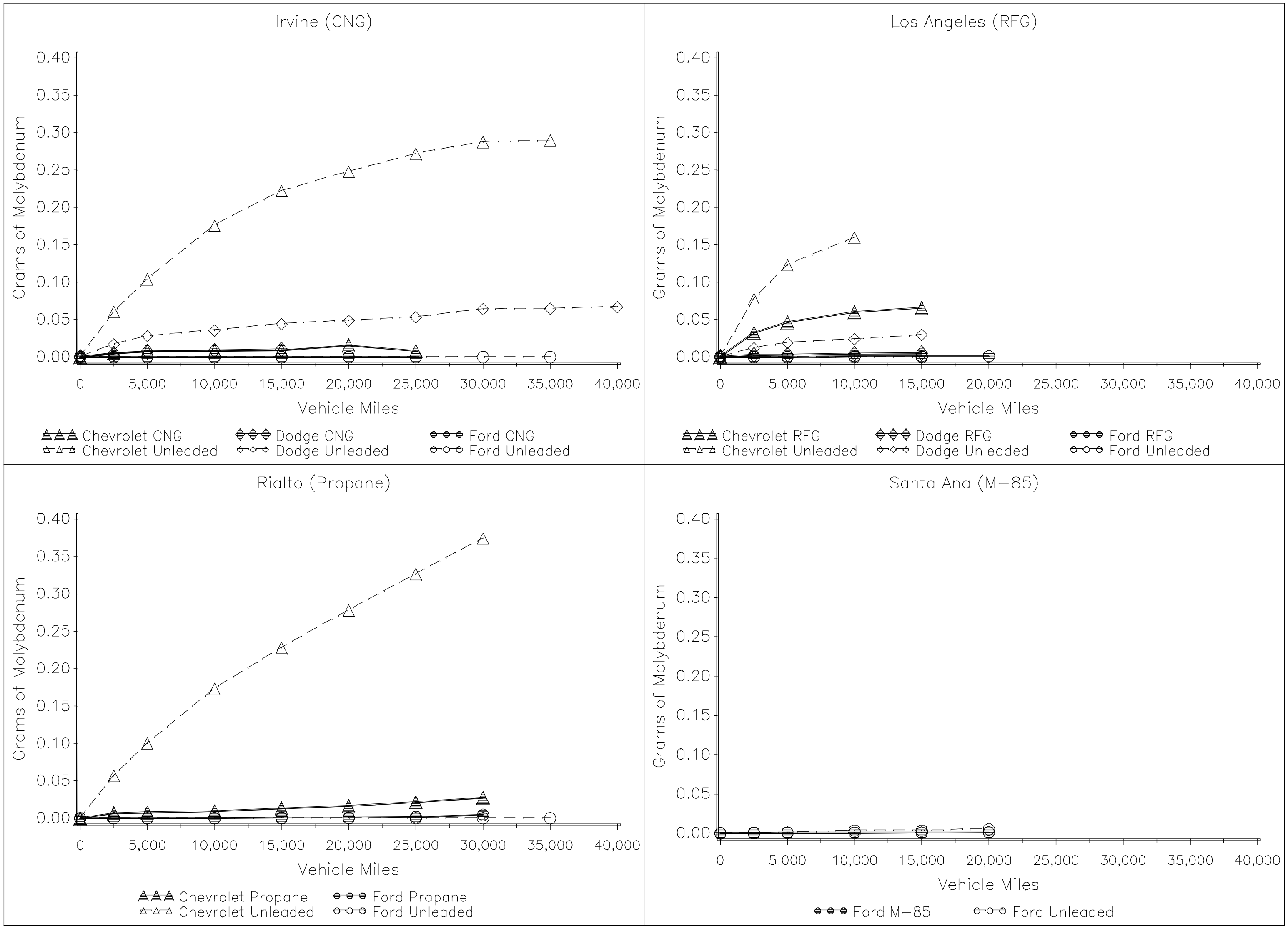

Figure C-7. Average Cumulative Weight of Molybdenum Removed from Engines Versus Vehicle Miles

Antimony

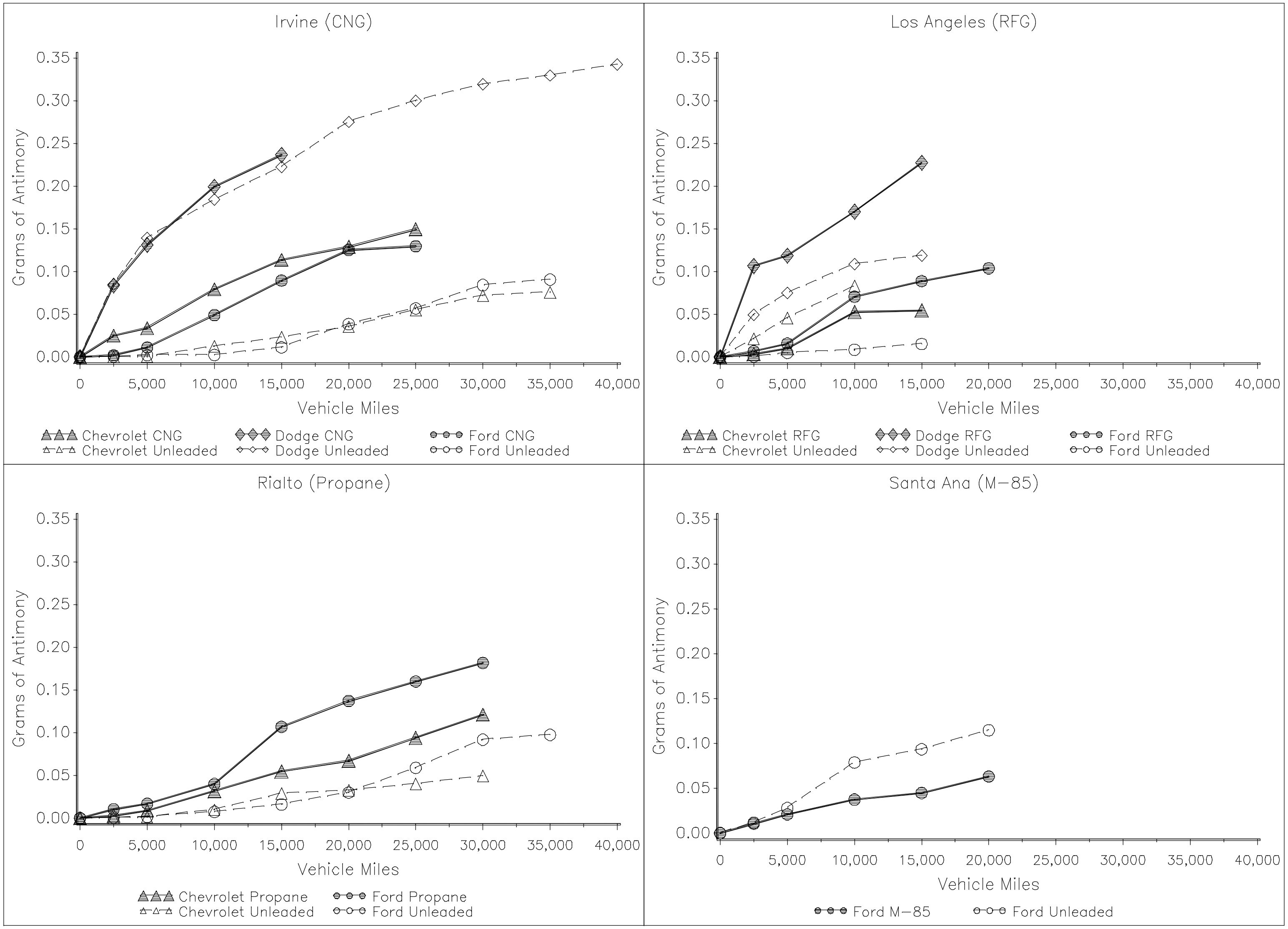

Figure C-9. Average Cumulative Weight of Antimony Removed from Engines Versus Vehicle Miles

APPENDIX D

Oil Contaminant, Additive, and Property Levels

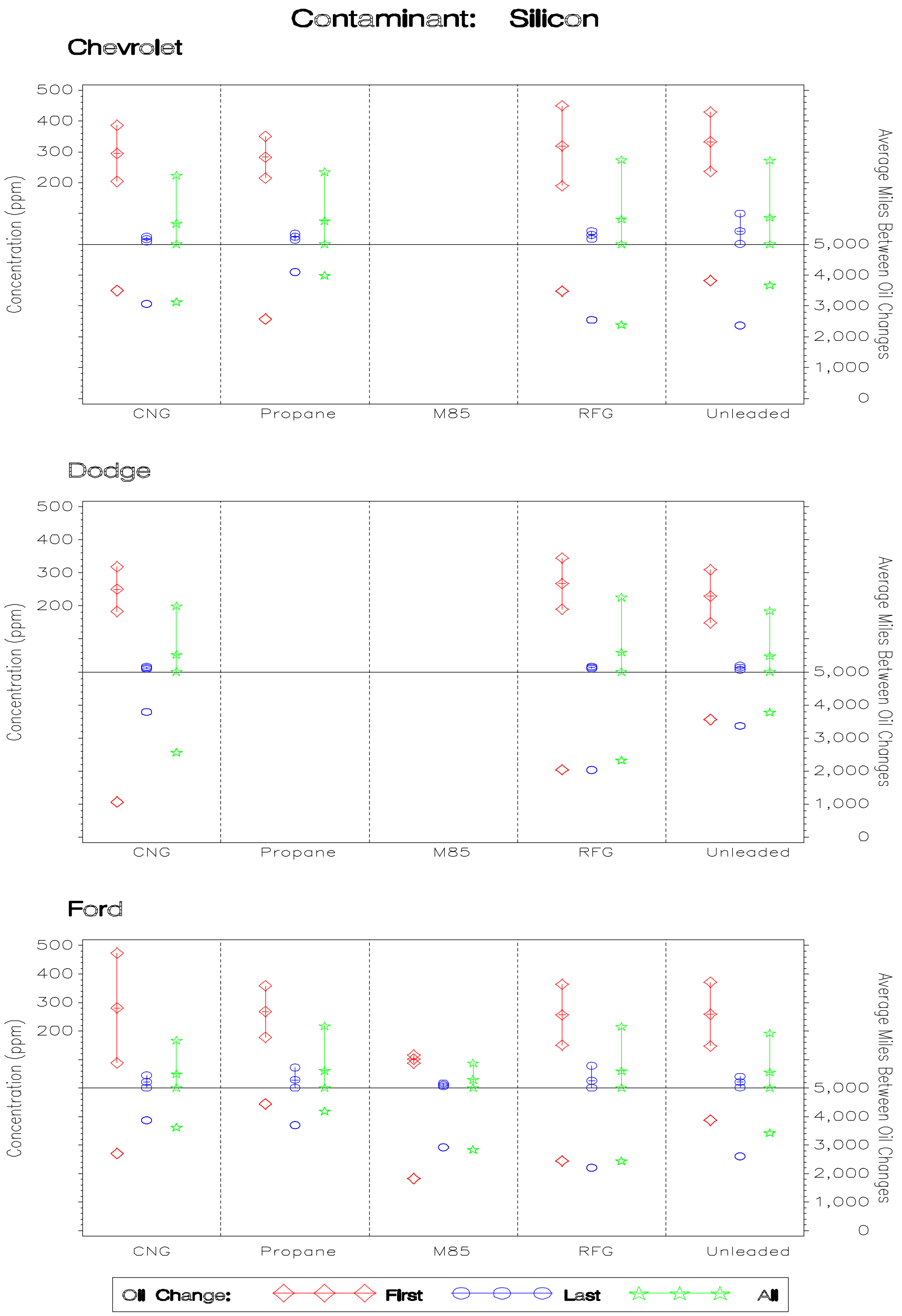

Figure D-1. Average Silicon Concentration in Used Oil, with 95% Prediction Bounds, at First and Last Oil Changes and for All Oil Changes

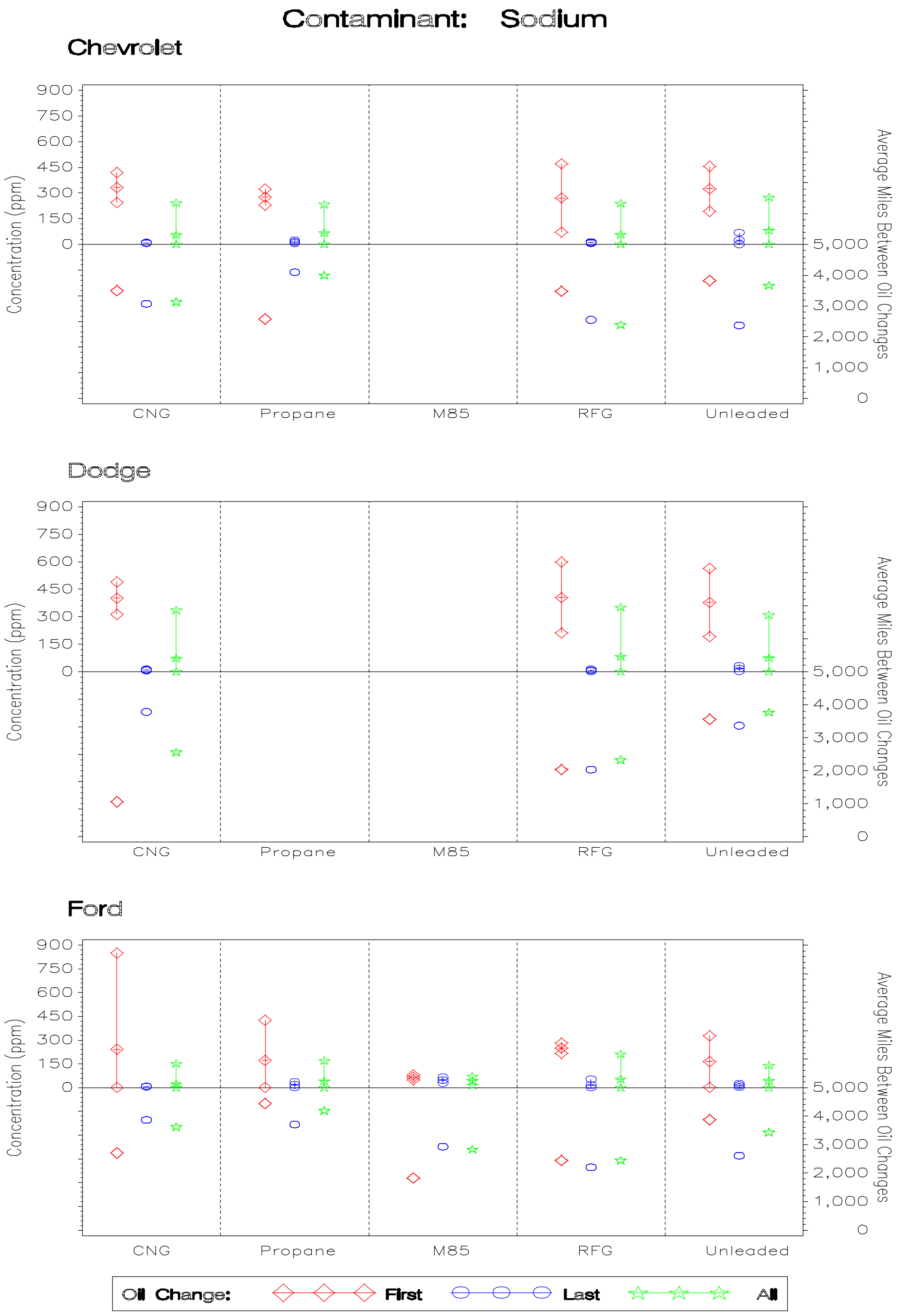

Figure D-2. Average Sodium Concentration in Used Oil, with 95% Prediction Bounds, at First and Last Oil Changes and for All Oil Changes

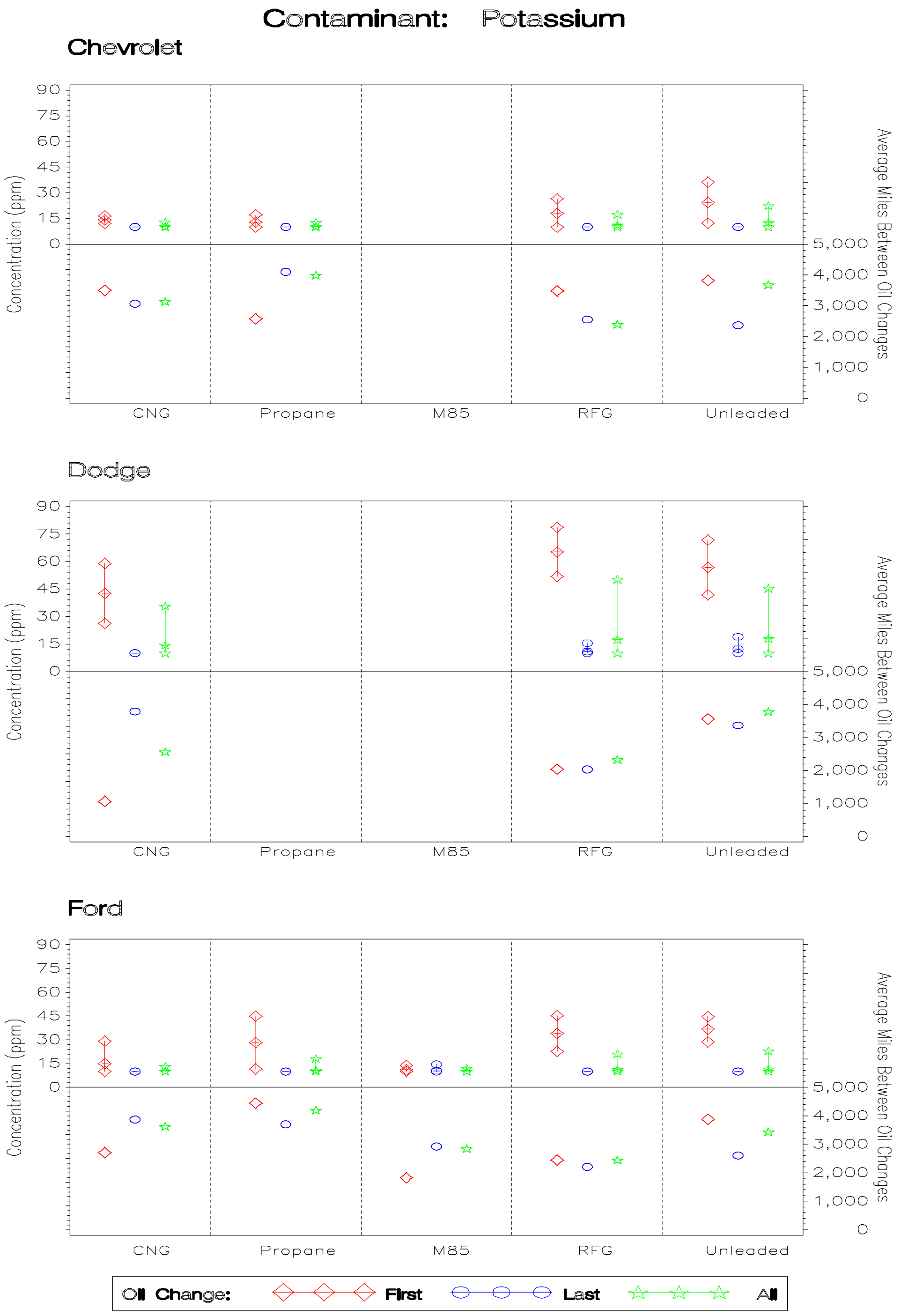

Figure D-3. Average Potassium Concentration in Used Oil, with 95% Prediction Bounds, at First and Last Oil Changes and for All Oil Changes

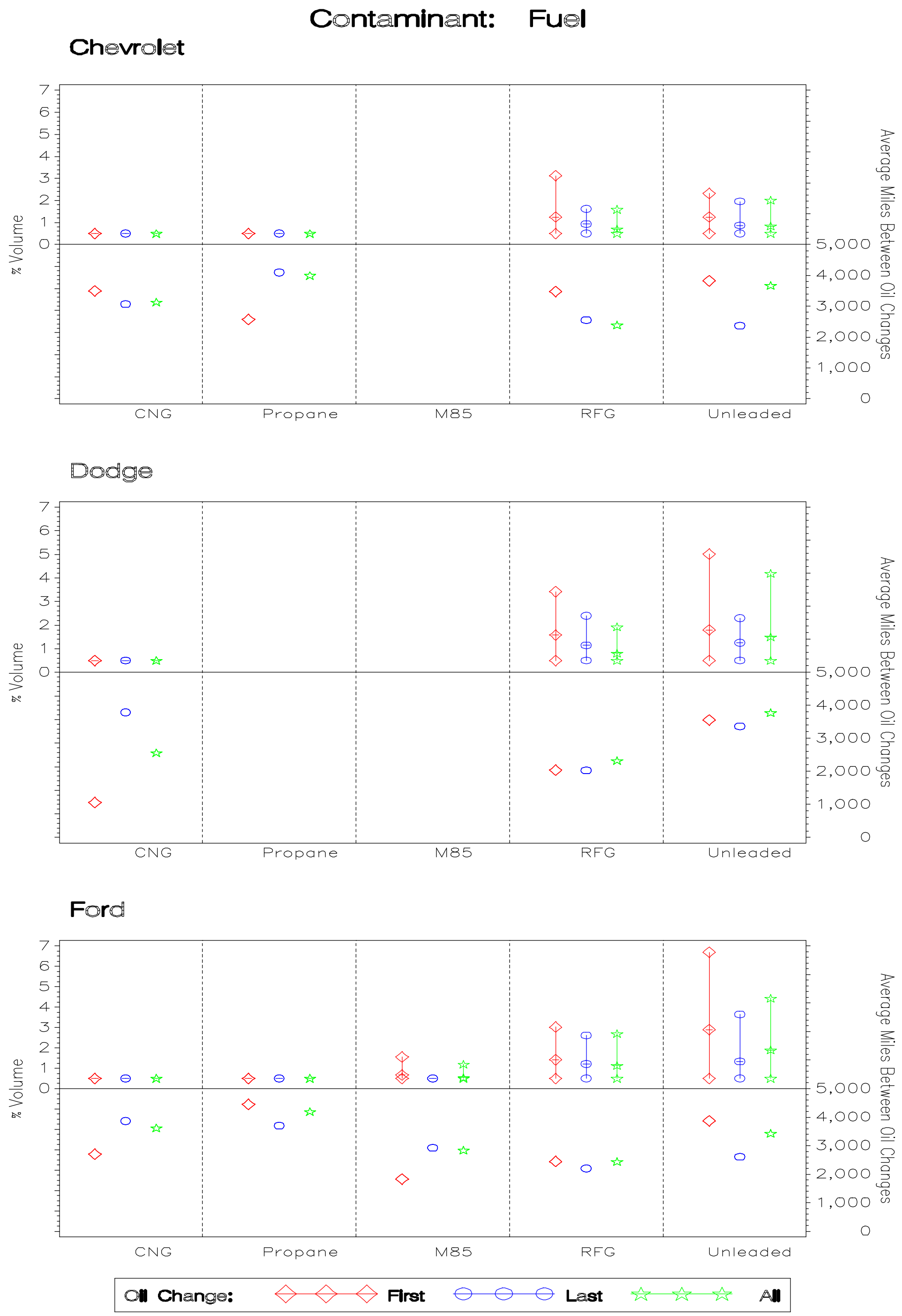

Figure D-4. Average Fuel Concentration in Used Oil, with 95% Prediction Bounds, at First and Last Oil Changes and for All Oil Changes

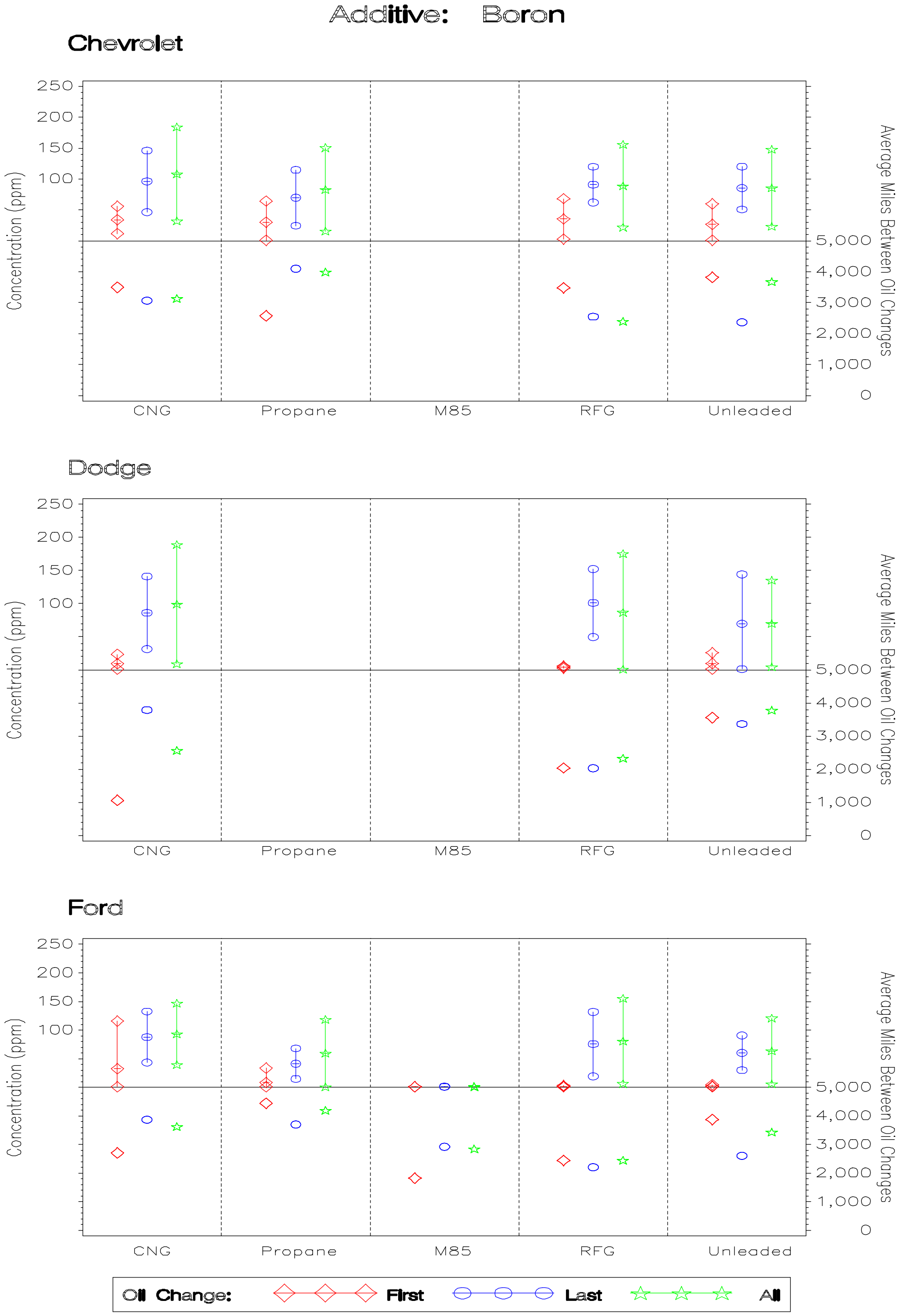

Figure D-5. Average Boron Concentration in Used Oil, with 95% Prediction Bounds, at First and Last Oil Changes and for All Oil Changes

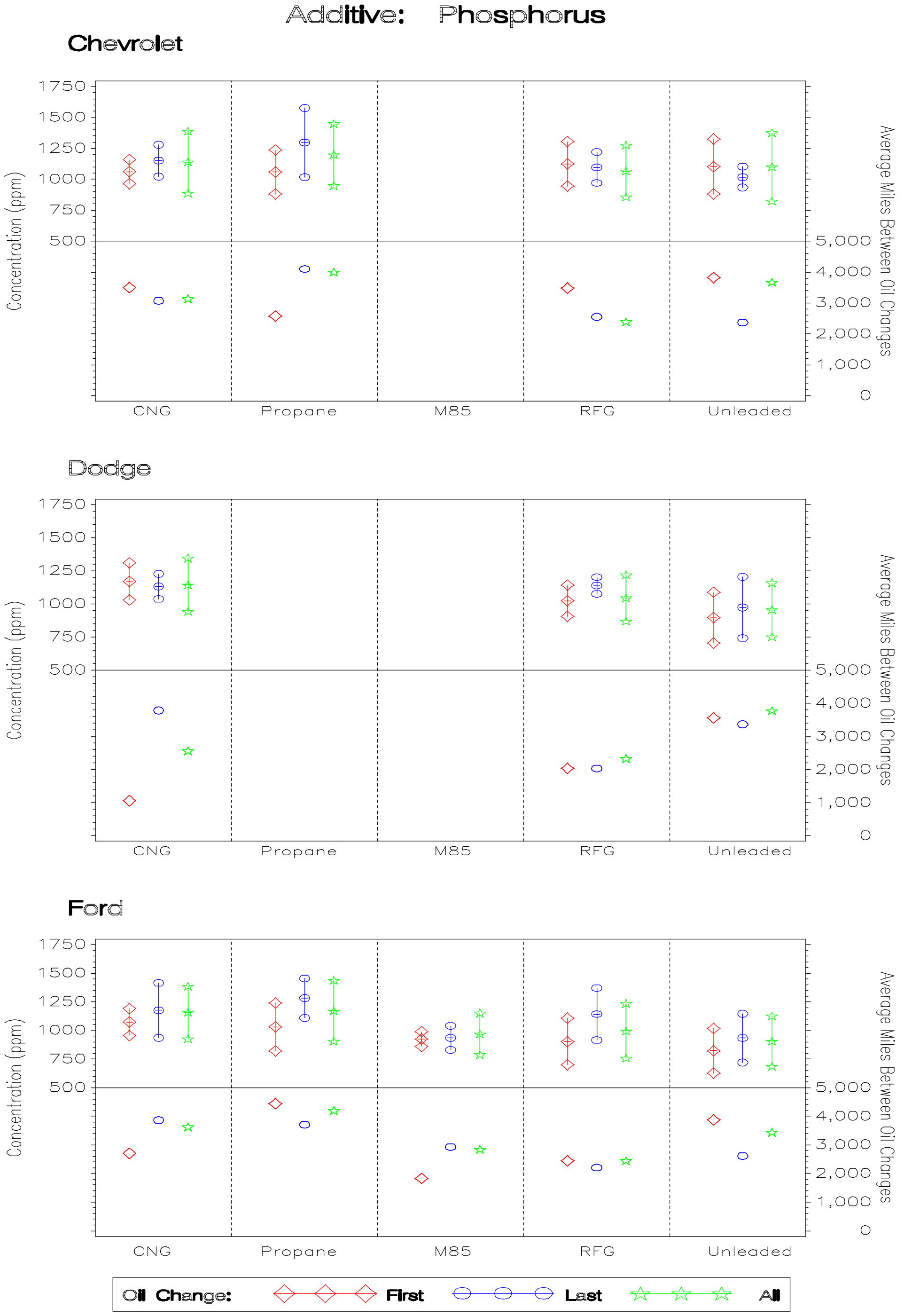

Figure D-6. Average Phosphorus Concentration in Used Oil, with 95% Prediction Bounds, at First and Last Oil Changes and for All Oil Changes

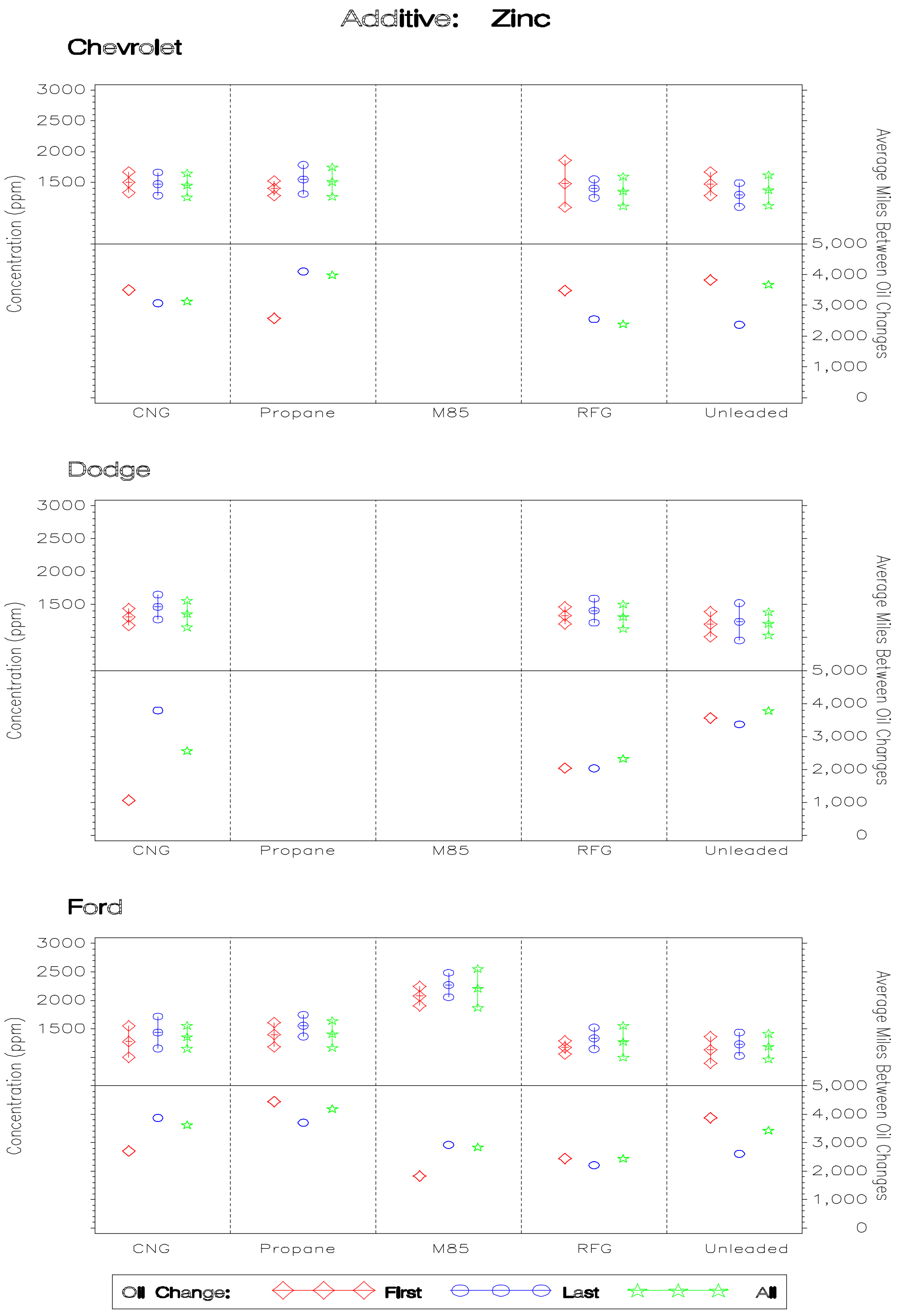

Figure D-7. Average Zinc Concentration in Used Oil, with 95% Prediction Bounds, at First and Last Oil Changes and for All Oil Changes

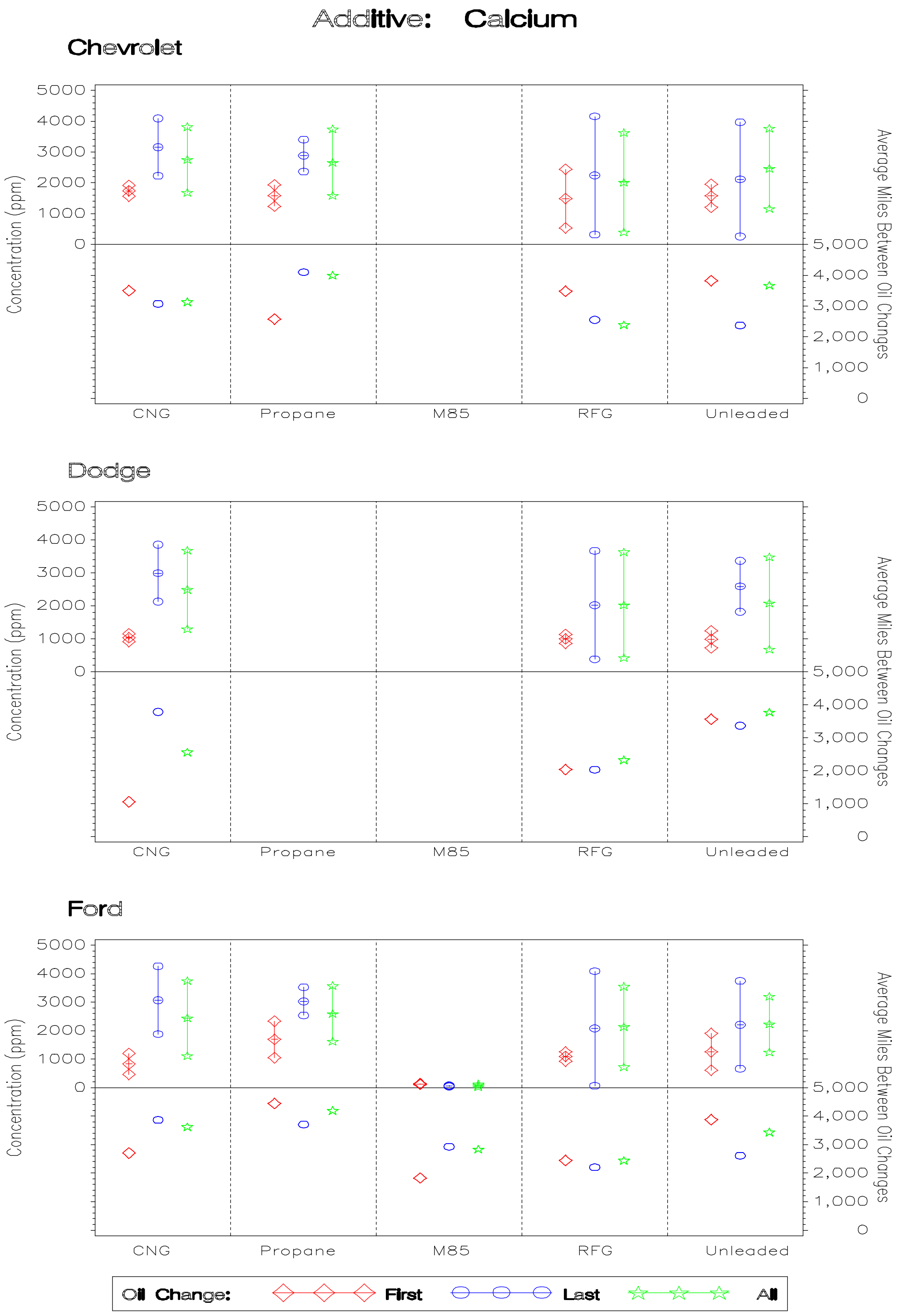

Figure D-8. Average Calcium Concentration in Used Oil, with 95% Prediction Bounds, at First and Last Oil Changes and for All Oil Changes

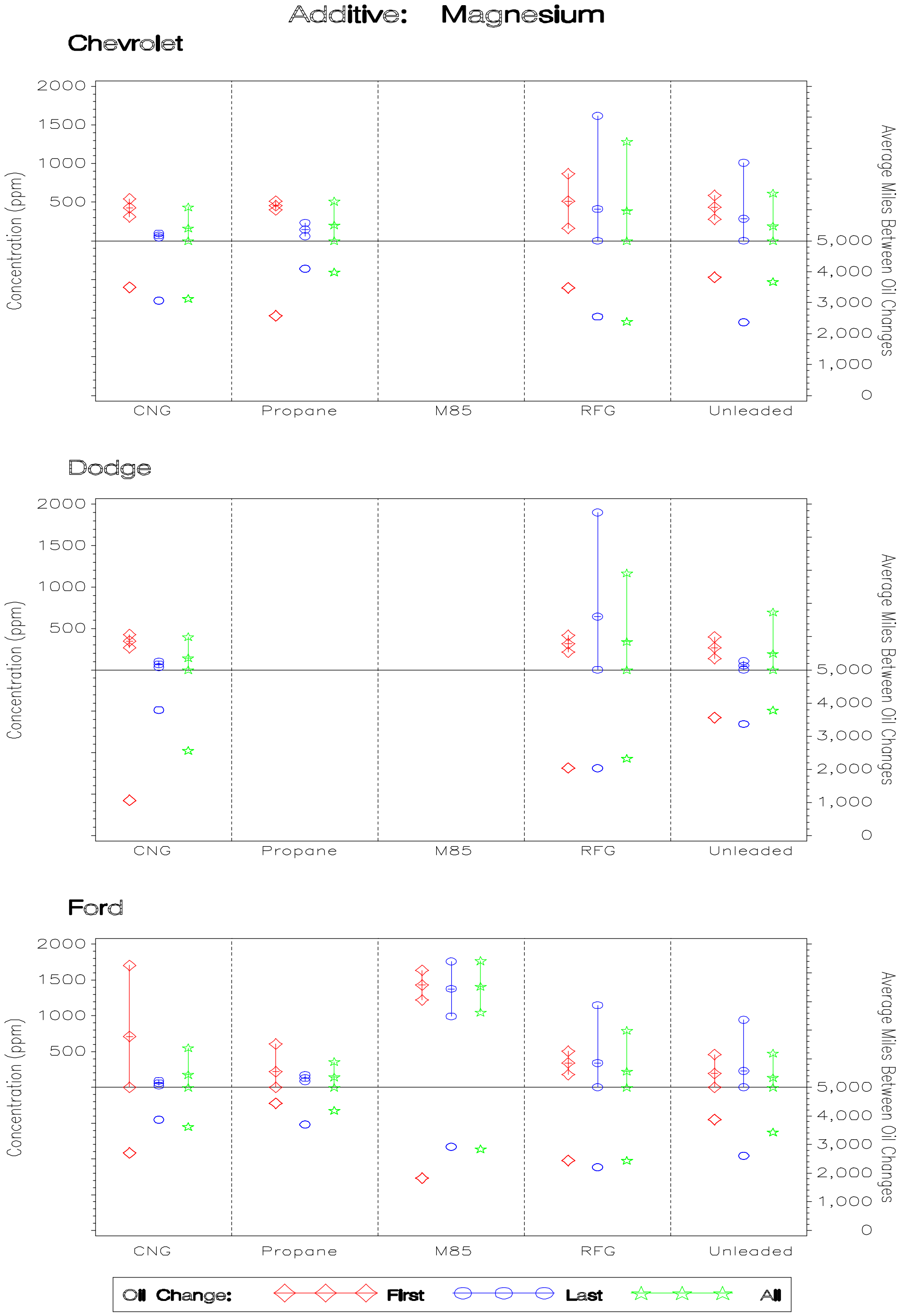

Figure D-9. Average Magnesium Concentration in Used Oil, with 95% Prediction Bounds, at First and Last Oil Changes and for All Oil Changes

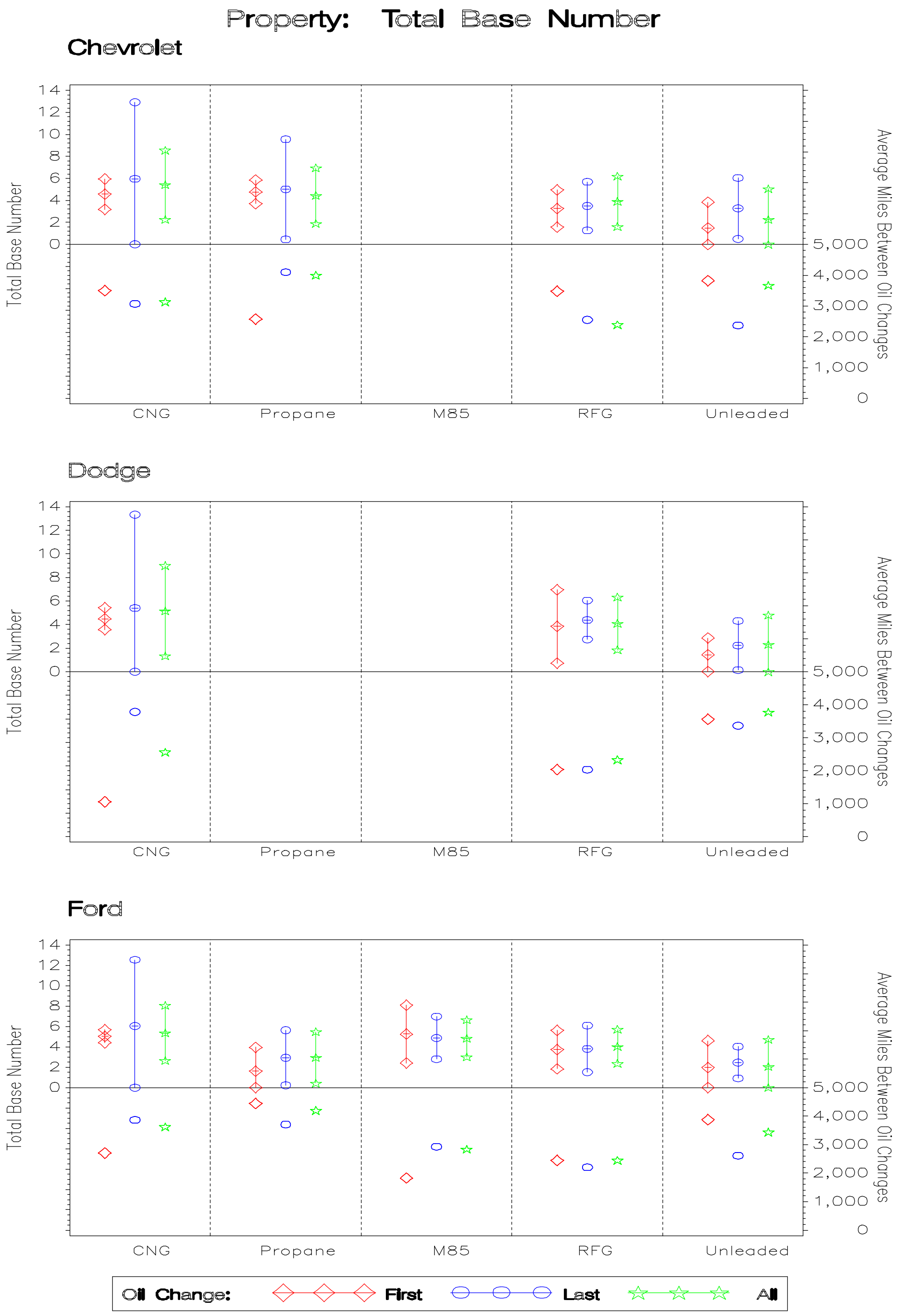

Figure D-10. Average Total Base Number of Used Oil, with 95% Prediction Bounds, at First and Last Oil Changes and for All Oil Changes

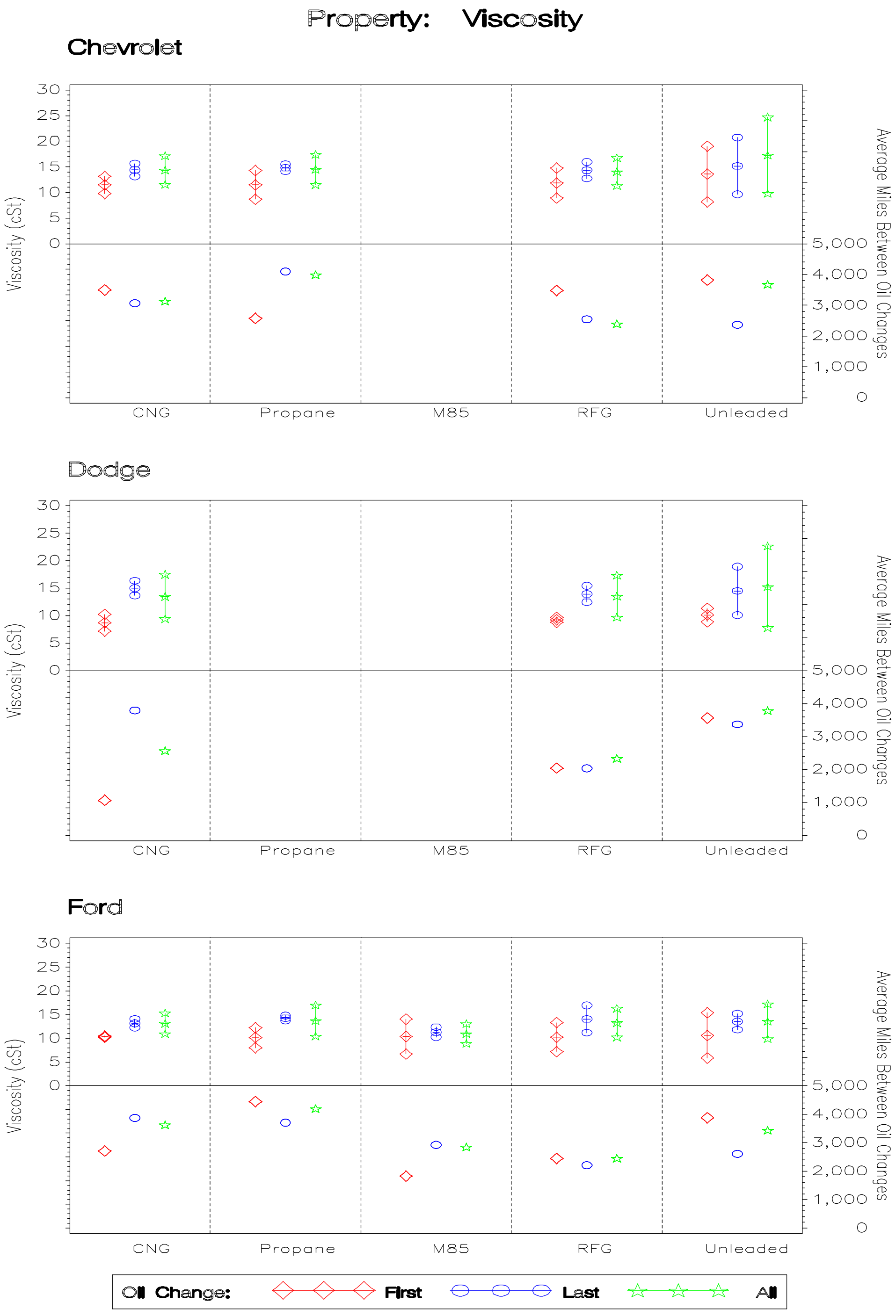

Figure D-11. Average Viscosity of Used Oil, with 95% Prediction Bounds, at First and Last Oil Changes and for All Oil Changes

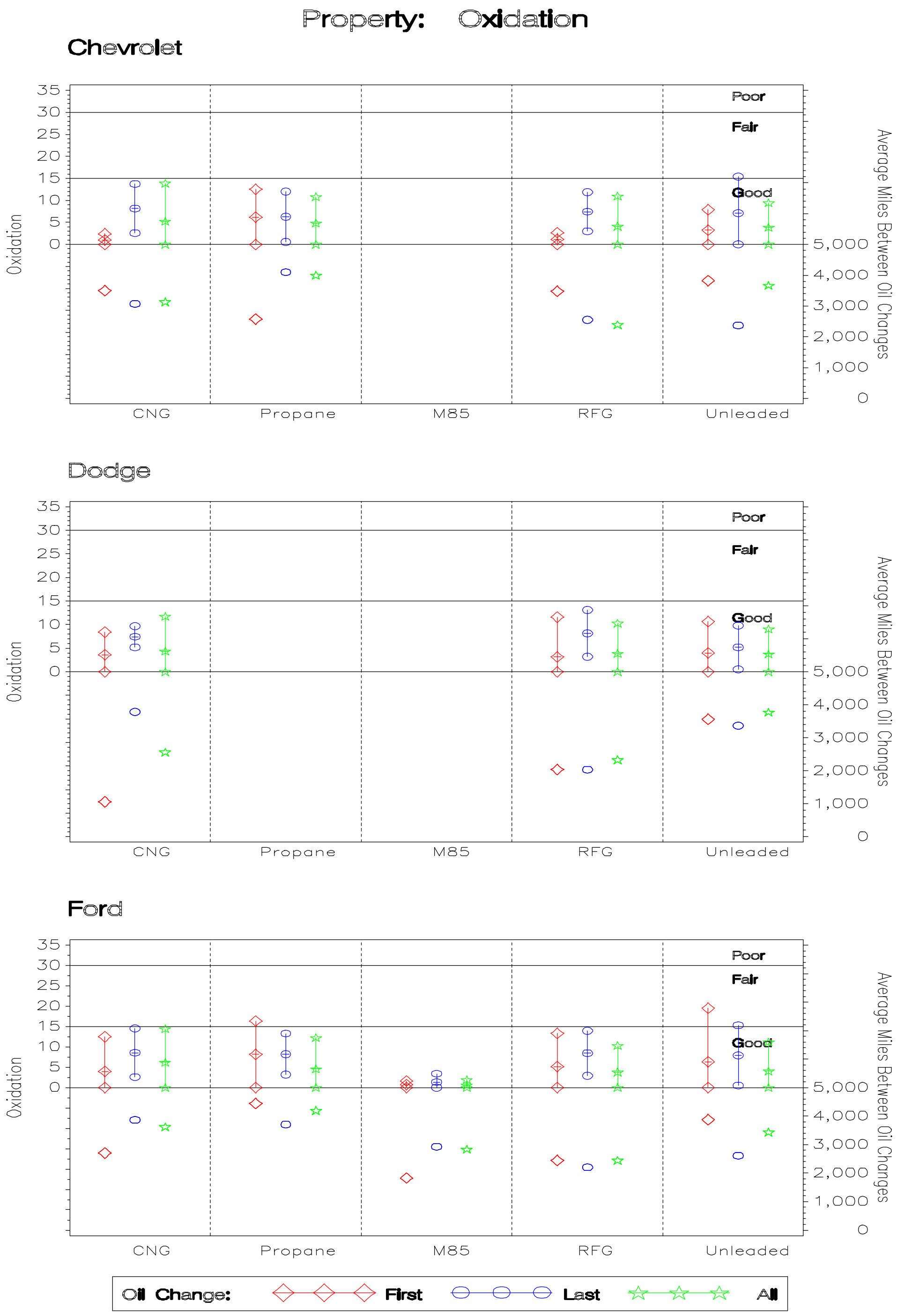

Figure D-12. Average Oxidation of Used Oil, with 95% Prediction Bounds, at First and Last Oil Changes and for All Oil Changes

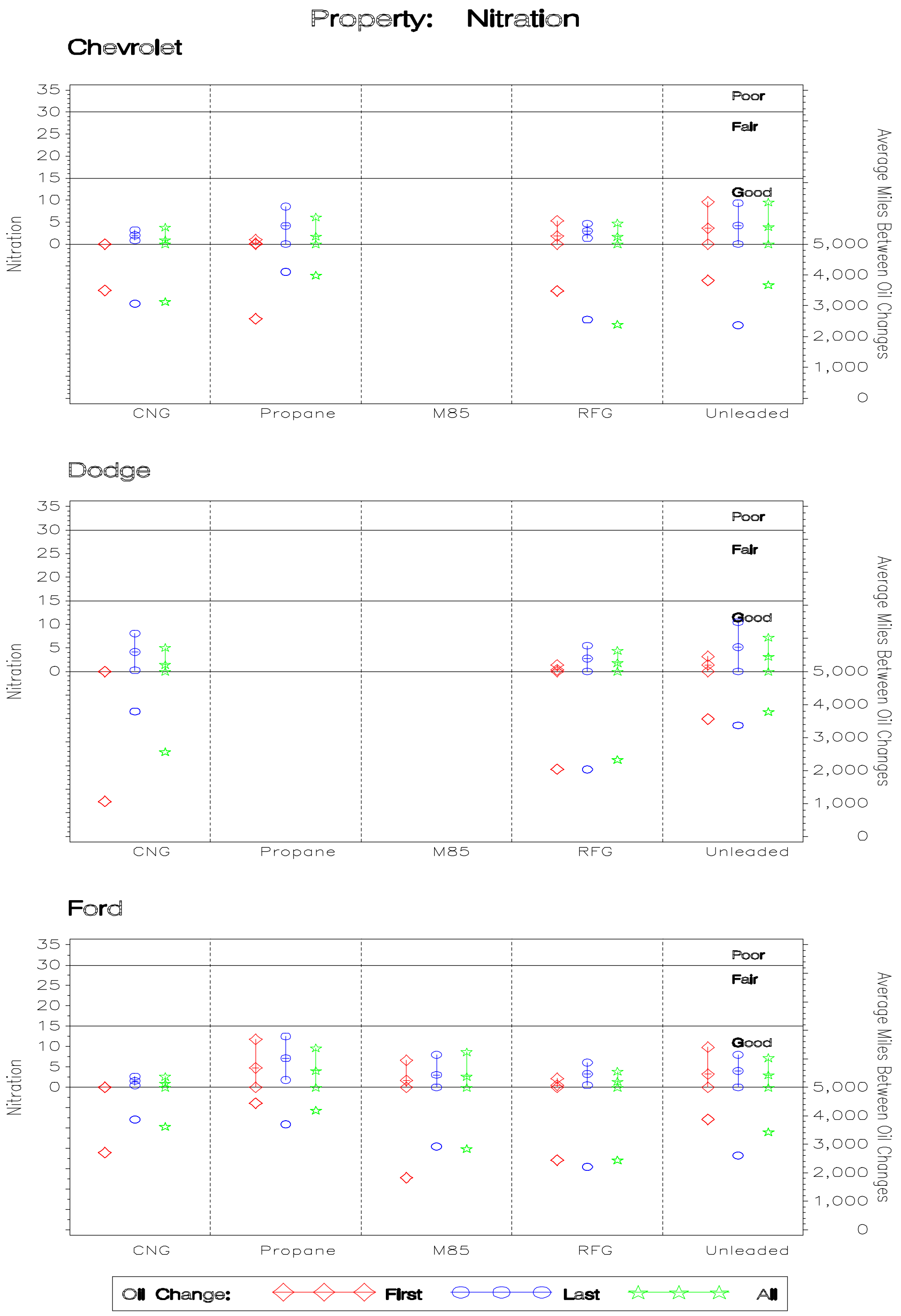

Figure D-13. Average Nitration of Used Oil, with 95% Prediction Bounds, at First and Last Oil Changes and for All Oil Changes

Table D-1. Average and Standard Deviation (SD) of Measured Oil Properties at the First and Last Oil Changes and for All Oil Changes

Location	Vehicle Manufacturer	Fuel	Oil Change	Number of Oil Changes	Avg. Oil Miles[a]	Number of Oil Analyses	Silicon Avg. (SD)	Sodium Avg. (SD)	Potassium Avg. (SD)	Fuel (%vol) Avg. (SD)
Chevron DELO 15W40 base oil[b]							2.0(1.4)	27.5(6.4)	10.0(-)[f]	- (-)[c]
Lubrizol MEV 10W30 base oil[d]							10.5(2.1)	9.0(1.4)	10.0(-)	0.1(-)
Irvine	CHEVY	CNG	First	7	3495	5	295.0(45.6)	332.6(43.7)	14.2(1.1)	0.5(0.0)
			Last	7	3068	7	16.7(4.1)	9.0(1.2)	10.0(0.0)	0.5(0.0)
			All	58	3134	54	67.4(78.5)	56.3(93.3)	10.4(1.3)	0.5(0.0)
		UNL	First	3	4113	3	333.7(29.7)	287.7(23.1)	27.7(4.0)	1.3(0.3)
			Last	3	2421	3	35.3(11.8)	16.3(3.5)	10.0(0.0)	1.1(0.8)
			All	27	4475	25	85.8(97.4)	79.0(88.7)	14.3(6.4)	0.9(0.6)
	DODGE	CNG	First	7	1059	5	250.8(33.9)	401.6(44.3)	42.6(8.1)	0.5(0.0)
			Last	7	3786	7	12.4(1.7)	9.7(1.8)	10.0(0.0)	0.5(0.0)
			All	59	2566	52	52.2(74.1)	74.4(131.3)	14.4(10.6)	0.5(0.0)
		UNL	First	3	3610	2	255.5(4.9)	442.5(3.5)	54.0(9.9)	0.8(0.4)
			Last	3	4527	3	12.7(5.0)	21.7(8.1)	14.3(3.8)	1.3(0.3)
			All	27	4362	23	46.8(68.6)	79.5(120.3)	19.8(12.4)	1.6(1.6)
	FORD	CNG	First	7	2704	2	281.0(96.2)	242.0(304.1)	15.0(7.1)	0.5(-)
			Last	7	3866	7	21.7(11.4)	6.9(0.7)	10.0(0.0)	0.5(0.0)
			All	57	3627	49	50.1(58.7)	23.7(64.8)	10.2(1.4)	0.5(0.0)
		UNL	First[e]	3	-	0	- (-)	- (-)	- (-)	- (-)
			Last	3	2644	3	17.0(2.6)	14.3(2.3)	10.0(0.0)	0.8(0.3)
			All	27	4197	24	34.0(20.2)	34.3(28.2)	10.4(1.2)	1.5(1.1)
Rialto	CHEVY	PRO	First	7	2572	6	282.5(33.8)	276.0(23.4)	12.8(2.1)	0.5(0.0)
			Last	7	4097	7	24.7(4.9)	15.3(4.2)	10.0(0.0)	0.5(0.0)
			All	59	3994	57	76.5(79.2)	67.5(83.7)	10.4(1.2)	0.5(0.0)
		UNL	First	3	4096	3	318.7(70.5)	305.3(47.9)	19.5(2.1)	0.8(0.6)
			Last	3	3170	3	68.0(39.0)	49.3(22.8)	10.0(0.0)	0.5(0.0)
			All	27	4209	27	96.7(88.4)	98.3(84.7)	11.6(2.7)	0.6(0.4)
	FORD	PRO	First	13	4445	13	267.9(45.2)	172.5(126.8)	28.3(8.3)	0.5(0.0)
			Last	13	3703	13	28.8(21.4)	17.5(9.3)	10.0(0.0)	0.5(0.0)
			All	118	4195	117	61.5(78.4)	43.3(64.3)	10.7(3.7)	0.5(0.0)
		UNL	First	3	6317	3	303.7(49.8)	58.0(2.0)	38.5(3.5)	1.2(1.2)
			Last	3	3299	3	34.7(9.6)	21.3(2.3)	10.0(0.0)	0.7(0.3)
			All	27	4586	27	74.4(85.4)	37.3(15.8)	12.7(7.7)	1.3(0.8)

Table D-1. Average and Standard Deviation (SD) of Measured Oil Properties at the First and Last Oil Changes and for All Oil Changes (Continued)

Location	Vehicle Manufacturer	Fuel	Oil Change	Number of Oil Changes	Avg. Oil Miles[(a)]	Number of Oil Analyses	Silicon Avg. (SD)	Sodium Avg. (SD)	Potassium Avg. (SD)	Fuel (%vol) Avg. (SD)
Los Angeles	CHEVY	RFG	First	7	3478	6	319.3(64.9)	271.3(100.0)	18.0(4.2)	1.3(0.9)
			Last	7	2548	7	30.1(6.3)	10.1(1.8)	10.0(0.0)	0.9(0.3)
			All	55	2392	48	82.2(95.9)	58.0(91.6)	11.3(3.0)	0.7(0.4)
		UNL	First	3	2976	2	352.5(55.9)	409.5(70.0)	24.0(9.9)	1.8(0.4)
			Last	3	1511	3	24.7(8.1)	10.3(1.5)	10.0(0.0)	1.0(0.5)
			All	23	2041	21	76.2(95.9)	69.7(119.1)	11.6(4.8)	1.0(0.7)
	DODGE	RFG	First	7	2039	6	267.5(38.7)	405.2(96.8)	65.3(6.7)	1.6(0.9)
			Last	7	2030	7	13.0(1.7)	7.9(2.3)	10.9(2.3)	1.1(0.6)
			All	55	2330	48	60.0(83.1)	83.4(134.7)	17.4(16.4)	0.8(0.6)
		UNL	First	3	3522	3	212.0(45.7)	335.0(101.5)	59.5(6.4)	2.5(1.8)
			Last	3	2202	3	13.0(1.0)	13.3(2.5)	10.0(0.0)	1.2(0.8)
			All	25	3172	22	51.4(68.9)	75.7(115.0)	15.9(14.9)	1.4(1.0)
	FORD	RFG	First	7	2446	6	257.0(53.4)	249.3(16.5)	34.0(5.7)	1.4(0.8)
			Last	7	2205	7	25.9(26.1)	15.4(19.2)	10.0(0.0)	1.2(0.7)
			All	57	2448	51	60.6(77.4)	53.3(80.1)	11.2(5.0)	1.1(0.8)
		UNL	First	3	1994	3	257.0(66.1)	224.7(24.8)	33.0(-)	3.5(2.3)
			Last	3	1970	3	14.3(0.6)	10.3(1.5)	10.0(0.0)	2.5(2.0)
			All	26	2198	24	61.3(80.9)	52.8(70.3)	12.7(8.2)	2.4(1.4)
Santa Ana	FORD	M85	First	20	1829	20	101.5(7.1)	64.3(7.6)	11.1(1.4)	0.7(0.4)
			Last	20	2925	20	11.3(2.6)	47.2(9.1)	10.5(2.0)	0.5(0.0)
			All	164	2845	162	30.1(29.0)	44.1(13.8)	10.2(0.9)	0.5(0.3)
		UNL	First	3	3307	3	217.3(7.0)	210.3(14.7)	- (-)	4.0(1.0)
			Last	3	2527	3	17.0(2.6)	10.3(1.5)	10.0(0.0)	1.3(0.3)
			All	27	2717	27	52.4(62.3)	52.6(60.7)	10.3(0.8)	2.4(1.4)
ALL	CHEVY	UNL	First	9	3822	8	332.8(48.1)	324.8(65.7)	24.3(6.0)	1.3(0.5)
			Last	9	2368	9	42.7(28.5)	25.3(21.6)	10.0(0.0)	0.9(0.5)
			All	77	3676	73	87.1(92.8)	83.5(96.4)	12.5(5.0)	0.8(0.6)
	DODGE	UNL	First	6	3557	5	229.4(40.2)	378.0(92.8)	56.8(7.5)	1.8(1.6)
			Last	6	3364	6	12.8(3.3)	17.5(7.0)	12.2(3.4)	1.3(0.5)
			All	52	3780	45	49.0(68.0)	77.6(116.4)	18.0(13.7)	1.5(1.3)
	FORD	UNL	First	12	3873	9	259.3(55.9)	164.3(81.3)	36.7(4.0)	2.9(1.9)
			Last	12	2610	12	20.8(9.5)	14.1(5.0)	10.0(0.0)	1.3(1.2)
			All	107	3438	102	56.0(68.4)	44.3(48.9)	11.5(5.7)	1.9(1.3)

[(a)] Average miles between oil changes.
[(b)] Used in all vehicles except Ford M-85.
[(c)] No results were obtained.
[(d)] Used only in Ford M-85 vehicles.
[(e)] Oil samples were not collected.
[(f)] Fewer than two results were obtained.

Table D-2. Average and Standard Deviation (SD) of Measured Oil Properties at the First and Last Oil Changes and for All Oil Changes

Location	Vehicle Manufacturer	Fuel	Oil Change	Number of Oil Changes	Avg. Oil Miles (a)	Number of Oil Analyses	Boron Avg. (SD)	Phosphorus Avg. (SD)	Zinc Avg. (SD)	Calcium Avg. (SD)	Magnesium Avg. (SD)
Chevron DELO 15W40 base oil (b)							166.0(1.4)	1055(6)	1236(37)	2315(35)	57(38)
Lubrizol MEV 10W30 base oil (c)							4.5(2.1)	1118(110)	2200(127)	43(18)	2462(776)
Irvine	CHEVY	CNG	First	7	3495	5	33.8(11.1)	1062(49)	1499(84)	1743(88)	426(58)
			Last	7	3068	7	96.1(24.9)	1151(65)	1471(94)	3159(466)	70(13)
			All	58	3134	54	107.9(38.0)	1139(125)	1451(97)	2751(533)	164(137)
		UNL	First	3	4113	3	22.7(16.3)	1167(37)	1471(69)	1661(120)	486(56)
			Last	3	2421	3	94.7(15.5)	984(55)	1240(57)	2497(99)	50(25)
			All	27	4475	25	82.1(31.4)	1131(111)	1374(115)	2626(460)	136(140)
	DODGE	CNG	First	7	1059	5	9.2(7.2)	1170(70)	1312(64)	1032(60)	346(40)
			Last	7	3786	7	86.1(27.4)	1132(47)	1463(94)	2988(433)	67(17)
			All	59	2566	52	99.3(45.0)	1143(101)	1360(101)	2491(597)	143(127)
		UNL	First	3	3610	2	5.0(1.4)	969(52)	1263(78)	998(37)	305(18)
			Last	3	4527	3	46.3(31.9)	910(110)	1172(134)	2367(106)	30(6)
			All	27	4362	23	70.2(31.3)	981(95)	1221(74)	2250(458)	124(93)
	FORD	CNG	First	7	2704	2	32.5(41.7)	1074(59)	1276(139)	830(184)	710(498)
			Last	7	3866	7	87.9(22.3)	1175(120)	1436(140)	3065(595)	58(17)
			All	57	3627	49	93.3(26.8)	1157(114)	1357(101)	2438(658)	178(187)
		UNL	First (d)	3	-	0	- (-)	-(-)	-(-)	-(-)	-(-)
			Last	3	2644	3	68.0(18.4)	928(50)	1230(59)	2546(206)	53(17)
			All	27	4197	24	61.8(17.4)	925(91)	1224(89)	2391(260)	135(129)
Rialto	CHEVY	PRO	First	7	2572	6	30.0(17.2)	1059(89)	1401(59)	1586(173)	455(28)
			Last	7	4097	7	69.6(22.6)	1297(139)	1544(118)	2882(259)	146(44)
			All	59	3994	57	83.0(33.7)	1198(125)	1509(120)	2664(539)	205(153)
		UNL	First	3	4096	3	33.7(15.3)	1119(115)	1548(68)	1645(134)	385(85)
			Last	3	3170	3	75.3(21.7)	1020(29)	1314(162)	2364(264)	156(97)
			All	27	4209	27	82.0(30.1)	1160(110)	1443(116)	2573(613)	185(141)
	FORD	PRO	First	13	4445	13	8.5(12.5)	1031(105)	1398(107)	1690(321)	218(194)
			Last	13	3703	13	41.2(13.4)	1281(86)	1555(96)	3025(247)	130(21)
			All	118	4195	117	59.2(29.8)	1171(133)	1410(118)	2599(487)	144(107)
		UNL	First	3	6317	3	3.7(0.6)	927(92)	1265(55)	1668(129)	26(14)
			Last	3	3299	3	49.3(3.5)	954(114)	1264(170)	2459(284)	117(29)
			All	27	4586	27	50.7(19.5)	970(103)	1228(142)	2340(347)	94(48)

Table D-2. Average and Standard Deviation (SD) of Measured Oil Properties at the First and Last Oil Changes and for All Oil Changes (Continued)

Location	Vehicle Manufacturer	Fuel	Oil Change	Number of Oil Changes	Avg. Oil Miles [(a)]	Number of Oil Analyses	Boron Avg. (SD)	Phosphorus Avg. (SD)	Zinc Avg. (SD)	Calcium Avg. (SD)	Magnesium Avg. (SD)
Los Angeles	CHEVY	RFG	First	7	3478	6	35.5(16.4)	1125(90)	1476(190)	1487(477)	515(176)
			Last	7	2548	7	90.9(14.5)	1096(63)	1397(75)	2238(959)	412(602)
			All	55	2392	48	88.9(33.5)	1067(105)	1354(121)	2018(808)	392(447)
		UNL	First	3	2976	2	22.5(26.2)	985(128)	1367(74)	1360(236)	430(71)
			Last	3	1511	3	85.7(14.2)	1050(5)	1327(30)	1475(2E3)	647(461)
			All	23	2041	21	94.2(31.7)	987(136)	1285(86)	2140(788)	265(322)
	DODGE	RFG	First	7	2039	6	4.2(0.8)	1024(59)	1336(65)	996(67)	316(51)
			Last	7	2030	7	100.9(25.6)	1138(32)	1408(92)	2020(821)	643(629)
			All	55	2330	48	86.7(44.4)	1045(87)	1320(93)	2030(801)	342(413)
		UNL	First	3	3522	3	12.7(9.8)	848(91)	1160(94)	975(182)	242(77)
			Last	3	2202	3	92.7(29.3)	1037(96)	1305(137)	2809(463)	71(26)
			All	25	3172	22	70.0(34.9)	929(103)	1204(104)	1898(859)	277(331)
	FORD	RFG	First	7	2446	6	1.5(0.8)	903(102)	1173(58)	1093(81)	341(81)
			Last	7	2205	7	75.6(28.2)	1142(113)	1333(94)	2075(1E3)	340(404)
			All	57	2448	51	80.9(37.2)	996(119)	1279(140)	2139(705)	223(286)
		UNL	First	3	1994	3	1.3(0.6)	793(60)	1056(96)	1075(143)	300(72)
			Last	3	1970	3	61.7(13.3)	1036(74)	1247(63)	1257(1E3)	694(513)
			All	26	2198	24	70.8(35.0)	893(109)	1154(105)	1944(692)	233(300)
Santa Ana	FORD	M85	First	20	1829	20	1.0(0.0)	925(32)	2076(85)	128(8)	1429(104)
			Last	20	2925	20	1.1(0.2)	935(53)	2270(107)	57(9)	1377(192)
			All	164	2845	162	1.0(0.2)	969(91)	2214(172)	77(24)	1409(180)
		UNL	First	3	3307	3	1.3(0.6)	747(6)	1067(25)	1027(23)	257(15)
			Last	3	2527	3	62.3(21.4)	811(42)	1179(125)	2550(98)	56(6)
			All	27	2717	27	72.1(34.0)	840(97)	1159(89)	2219(460)	92(64)
ALL	CHEVY	UNL	First	9	3822	8	26.8(16.5)	1103(111)	1474(96)	1580(189)	434(77)
			Last	9	2368	9	85.2(17.3)	1018(42)	1294(96)	2112(926)	284(363)
			All	77	3676	73	85.5(31.1)	1100(138)	1374(124)	2466(650)	191(213)
	DODGE	UNL	First	6	3557	5	9.6(8.1)	897(96)	1201(95)	984(131)	267(65)
			Last	6	3364	6	69.5(37.4)	973(116)	1239(141)	2588(386)	51(28)
			All	52	3780	45	70.1(32.7)	955(102)	1213(89)	2078(699)	199(250)
	FORD	UNL	First	12	3873	9	2.1(1.3)	822(98)	1129(117)	1256(324)	194(133)
			Last	12	2610	12	60.3(15.1)	932(106)	1230(103)	2203(771)	230(357)
			All	107	3438	102	63.7(28.7)	907(110)	1192(113)	2227(489)	136(171)

[(a)] Average miles between oil changes. [(b)] Used in all vehicles except Ford M-85. [(c)] Used only in Ford M-85 vehicles. [(d)] Oil samples were not collected.

Table D-3. Average and Standard Deviation (SD) of Measured Oil Properties at the First and Last Oil Changes and for All Oil Changes

Location	Vehicle Manufacturer	Fuel	Oil Change	Number of Oil Changes	Avg. Oil Miles(a)	Number of Oil Analyses	Viscosity Avg. (SD)	TBN Avg. (SD)	Oxidation Avg. (SD)	Nitration Avg. (SD)
Chevron DELO 15W40 base oil(b)							15.1(0.7)	6.5(1.4)	- (-)(c)	- (-)(c)
Lubrizol MFV 10W30 base oil(d)							10.9(0.6)	8.5(0.7)	- (-)(c)	- (-)(c)
Irvine	CHEVY	CNG	First	7	3495	5	11.5(0.8)	4.6(0.7)	1.0(0.7)	0.0(0.0)
			Last	7	3068	7	14.4(0.6)	6.0(3.5)	8.1(2.8)	2.0(0.6)
			All	58	3134	54	14.4(1.4)	5.4(1.6)	5.2(4.3)	1.0(1.5)
		UNL	First	3	4113	3	13.4(1.5)	0.4(0.6)	4.3(2.5)	3.0(1.0)
			Last	3	2421	3	14.6(0.6)	2.3(2.0)	3.0(2.6)	3.7(2.1)
			All	27	4475	25	18.3(3.8)	1.8(1.4)	3.4(2.4)	3.9(2.4)
	DODGE	CNG	First	7	1059	5	8.7(0.8)	4.5(0.5)	3.6(2.4)	0.0(0.0)
			Last	7	3786	7	15.0(0.7)	5.4(4.0)	7.4(1.1)	4.1(2.0)
			All	59	2566	52	13.5(2.0)	5.2(1.9)	4.4(3.7)	1.5(1.8)
		UNL	First	3	3610	2	10.0(0.8)	1.7(0.7)	2.0(1.4)	1.0(0.0)
			Last	3	4527	3	14.2(3.2)	1.8(1.3)	4.3(2.9)	6.7(2.5)
			All	27	4362	23	15.2(3.5)	2.1(1.2)	3.4(2.6)	3.6(2.0)
	FORD	CNG	First	7	2704	2	10.4(0.1)	5.0(0.3)	4.0(4.2)	0.0(0.0)
			Last	7	3866	7	13.2(0.5)	6.0(3.3)	8.6(3.0)	1.6(0.5)
			All	57	3627	49	13.1(1.1)	5.4(1.4)	6.2(4.1)	1.0(0.8)
		UNL	First(e)	3	-	0	- (-)	- (-)	- (-)	- (-)
			Last	3	2644	3	13.4(0.3)	3.0(0.6)	6.3(3.8)	3.3(2.5)
			All	27	4197	24	14.4(1.4)	1.9(1.4)	3.9(3.5)	3.0(1.7)
Rialto	CHEVY	PRO	First	7	2572	6	11.5(1.4)	4.8(0.5)	6.2(3.2)	0.2(0.4)
			Last	7	4097	7	14.8(0.3)	5.0(2.3)	6.3(2.9)	4.1(2.2)
			All	59	3994	57	14.5(1.5)	4.4(1.3)	4.8(3.0)	1.8(2.2)
		UNL	First	3	4096	3	15.4(3.1)	2.2(0.7)	3.3(2.3)	5.7(4.0)
			Last	3	3170	3	17.5(4.0)	3.5(0.5)	7.7(3.8)	6.3(3.1)
			All	27	4209	27	18.9(3.2)	1.8(1.3)	4.3(2.6)	5.6(2.9)
	FORD	PRO	First	13	4445	13	10.1(1.1)	1.6(1.2)	8.2(4.1)	4.8(3.5)
			Last	13	3703	13	14.3(0.3)	2.9(1.4)	8.2(2.5)	7.2(2.7)
			All	118	4195	117	13.7(1.6)	3.0(1.3)	4.6(3.8)	4.1(2.8)
		UNL	First	3	6317	3	13.7(0.3)	0.3(0.5)	12.0(7.9)	7.3(0.6)
			Last	3	3299	3	14.5(0.7)	2.1(0.3)	4.0(2.6)	5.0(2.6)
			All	27	4586	27	14.9(1.3)	1.0(0.8)	4.5(4.1)	5.3(1.6)

Table D-3. Average and Standard Deviation (SD) of Measured Oil Properties at the First and Last Oil Changes and for All Oil Changes (Continued)

Location	Vehicle Manufacturer	Fuel	Oil Change	Number of Oil Changes	Avg. Oil Miles[a]	Number of Oil Analyses	Viscosity Avg. (SD)	TBN Avg. (SD)	Oxidation Avg. (SD)	Nitration Avg. (SD)
Los Angeles	CHEVY	RFG	First	7	3478	6	11.8(1.5)	3.3(0.8)	1.2(0.8)	1.8(1.7)
			Last	7	2548	7	14.4(0.8)	3.5(1.1)	7.4(2.2)	3.0(0.8)
			All	55	2392	48	14.1(1.4)	3.9(1.2)	4.1(3.4)	1.7(1.5)
		UNL	First	3	2976	2	11.2(2.7)	2.1(1.3)	1.5(2.1)	1.5(2.1)
			Last	3	1511	3	13.4(0.8)	4.0(1.2)	10.7(1.5)	2.7(1.2)
			All	23	2041	21	13.9(1.5)	3.3(0.9)	3.8(3.4)	1.8(1.3)
	DODGE	RFG	First	7	2039	6	9.2(0.2)	3.9(1.6)	3.2(4.2)	0.3(0.5)
			Last	7	2030	7	13.9(0.8)	4.4(0.8)	8.1(2.5)	2.7(1.4)
			All	55	2330	48	13.5(1.9)	4.1(1.1)	3.9(3.2)	1.8(1.3)
		UNL	First	3	3522	3	10.2(0.6)	1.2(0.8)	5.3(3.8)	1.7(1.2)
			Last	3	2202	3	14.8(1.2)	2.6(0.7)	6.0(1.7)	3.7(2.1)
			All	25	3172	22	15.2(4.0)	2.6(1.2)	4.2(2.7)	2.8(2.0)
	FORD	RFG	First	7	2446	6	10.3(1.5)	3.7(0.9)	5.2(4.1)	0.5(0.8)
			Last	7	2205	7	14.1(1.4)	3.8(1.1)	8.4(2.8)	3.3(1.4)
			All	57	2448	51	13.3(1.5)	4.0(0.8)	3.8(3.3)	1.4(1.3)
		UNL	First	3	1994	3	8.7(0.2)	3.0(0.6)	6.0(4.4)	0.7(0.6)
			Last	3	1970	3	12.8(0.8)	3.0(0.6)	10.7(1.5)	3.0(0.0)
			All	26	2198	24	12.2(1.7)	3.0(1.1)	4.3(3.5)	1.5(1.3)
Santa Ana	FORD	M85	First	20	1829	20	10.4(1.8)	5.3(1.4)	0.8(0.4)	1.7(2.5)
			Last	20	2925	20	11.3(0.5)	4.9(1.0)	1.4(1.0)	3.1(2.5)
			All	164	2845	162	11.0(1.0)	4.8(0.9)	0.6(0.7)	2.7(3.0)
		UNL	First	3	3307	3	9.4(0.9)	2.6(0.2)	1.0(0.0)	1.7(2.1)
			Last	3	2527	3	13.4(0.8)	1.8(0.8)	10.7(1.5)	4.7(2.1)
			All	27	2717	27	12.9(1.5)	2.4(1.1)	3.7(3.3)	2.1(1.7)
ALL	CHEVY	UNL	First	9	3822	8	13.6(2.7)	1.5(1.2)	3.3(2.3)	3.6(3.0)
			Last	9	2368	9	15.2(2.8)	3.3(1.4)	7.1(4.1)	4.2(2.5)
			All	77	3676	73	17.3(3.7)	2.3(1.4)	3.9(2.8)	3.9(2.8)
	DODGE	UNL	First	6	3557	5	10.1(0.6)	1.4(0.7)	4.0(3.3)	1.4(0.9)
			Last	6	3364	6	14.5(2.2)	2.2(1.0)	5.2(2.3)	5.2(2.6)
			All	52	3780	45	15.2(3.7)	2.3(1.3)	3.8(2.6)	3.2(2.0)
	FORD	UNL	First	12	3873	9	10.6(2.4)	2.0(1.3)	6.3(6.6)	3.2(3.3)
			Last	12	2610	12	13.5(0.8)	2.5(0.8)	7.9(3.7)	4.0(2.0)
			All	107	3438	102	13.6(1.8)	2.1(1.3)	4.1(3.6)	3.0(2.1)

(a) Average miles between oil changes.

(b) Used in all vehicles except Ford M-85.

(c) No results were obtained. Oxidation and nitration were not measured in base oil.

(d) Used only in Ford M-85 vehicles.

(e) Oil samples were not collected.