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ALTERNATIVE-FUELED TRUCK DEMONSTRATION NATURAL GAS PROGRAM: CATERPILLAR G3406LE DEVELOPMENT AND DEMONSTRATION

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A/F	Air/fuel (ratio)
A.G.A.	American Gas Association
A/R	Area/radius
ARB	California Air Resources Board
ASTM	American Society for Testing and Materials
ATAAC	Air-to-air aftercooler
bhp	Brake horsepower
bkW	Brake kilowatt(s)
bkW-hr	Brake kilowatts per hour
BMEP	Brake mean effective pressure
BSFC	Brake specific fuel consumption
BTDC	Before top dead center
Btu	British thermal unit
CBD	Central Business District
CEC	California Energy Commission
cfm	Cubic feet per minute
CFR	Code of Federal Regulations
CFV	Critical flow venturi
CIM	Caterpillar Interface Module
cm	Centimeter(s)
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CVS	Constant volume sampling
DC	Direct current
DDC	Detroit Diesel Corporation
DDT	Digital diagnostic tool
DNPH	2,4-dinitrophenyl hydrazine
DOE	U.S. Department of Energy
ECM	Electronic control module
EGO	Exhaust gas oxygen
EPA	U.S. Environmental Protection Agency
ETF	Emissions Testing Facility (MTA)
FTA	Federal Transit Administration
FTP	Federal Test Procedure
g	Grams(s)
gal	Gallon(s)
g/bhp-hr	Grams per brake horsepower hour
GJ	Gigajoules
HC	Hydrocarbon(s)
HCHO	Formaldehyde
HHV	Higher heating value
hp	Horsepower
hr	Hour(s)
in	Inch(es)
in H_2O	Inches of water
kg	Kilogram(s)
kJ	Kilojoules

km	Kilometers
kph	Kilometers per hour
kPa	Kilopascal(s)
kW	Kilowatt(s)
lb	Pound(s)
lb-ft	Pound-foot(feet)
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
m^3	Cubic meters
m^3/min	Cubic meters per minute
Mfr	Manufacturer
MIB	Magneto interface box
mpg	Miles per gallon
mmH_2O	Millimeters of water
mph	Miles per hour
MTA	Los Angeles County Metropolitan Transportation Authority
NFPA	National Fire Protection Association
NGV	Natural gas vehicle
N·m	Newton-meter(s)
NMHC	Non-methane hydrocarbon(s)
NO_x	Oxides of nitrogen
NREL	National Renewable Energy Laboratory
O_2	Oxygen
OCTA	Orange County Transportation Authority
PG&E	Pacific Gas and Electric Company
PID	Proportional-integral-derivative
PM	Particulate matter
ppm	Parts per million
psi	Pounds per square inch
psig	Pounds per square inch gauge
rpm	Revolutions-per-minute
s	Seconds
SCAQMD	South Coast Air Quality Management District
scf	Standard cubic feet
scfm	Standard cubic feet per minute
SCRTD	Southern California Rapid Transit District (now MTA)
SoCalGas	Southern California Gas Company
V	Volt(s)
Vons	The Vons Companies, Inc.
°	Degree(s)
°C	Degrees Celsius
°F	Degrees Fahrenheit
*	Multiplied by
/	Divided by

SECTION 1

INTRODUCTION

1.1 ALTERNATIVE-FUELED TRUCK DEMONSTRATION OVERVIEW

In 1990, the California Energy Commission (CEC), the South Coast Air Quality Management District (SCAQMD), and the Southern California Gas Company (SoCalGas) joined together to sponsor the development and demonstration of compressed natural gas (CNG) engines for Class 8 heavy-duty line-haul trucking applications. This program, complementing an existing methanol-fueled heavy-duty truck demonstration program, became part of an overall Alternative-Fueled Truck Demonstration Program whose goal was to advance the technological development of alternative-fueled engines.

In 1992, the U.S. Department of Energy (DOE), through the National Renewable Energy Laboratory (NREL), joined the partnership to cosponsor the development and demonstration of CNG heavy-duty engines for trucking applications.

At the start of the Natural Gas Program, the development of natural gas heavy-duty engines was in its infancy and all engine manufacturers were concentrating on transit bus applications. Only one manufacturer, Caterpillar, Inc., was willing to develop an engine suitable for demonstration in a heavy-duty line-haul trucking application. In 1991, Acurex Environmental Corporation, as program manager for the Alternative-Fueled Truck Demonstration Program, issued a subcontract to Caterpillar to develop a CNG version of Caterpillar's 3406 industrial gas engine. Following its development, the G3406LE prototype engine was installed in a Ford LTLA-9000 AeroMax tractor operated by the Vons Companies, Inc. (Vons). The demonstration continued for 14 months, with the vehicle accumulating more than 48,270 km (30,000 mi).

Currently, efforts are underway in the Alternative-Fueled Truck Demonstration Program to develop a natural gas version of the Detroit Diesel Corporation (DDC) Series 60 engine and to demonstrate it in representative trucking applications.

1.2 COMPRESSED NATURAL GAS IN HEAVY-DUTY TRUCKING APPLICATIONS

The technical challenges involved in developing natural gas heavy-duty engines and vehicles are greater than those for methanol heavy-duty engines, which were developed in the 1980s by several manufacturers, and commercialized in 1991 by one manufacturer, DDC. Compared to methanol, natural gas is less amenable to compression ignition, on which all diesel engine designs are based. However, the forces driving the development of alternative-fueled heavy-duty engines were eventually sufficient to generate substantial interest in natural gas heavy-duty engines. Natural gas offers the emissions and energy security benefits of methanol fuel, plus a lower net energy cost.

To adapt an existing diesel engine design for combustion of natural gas, fundamental changes are required. Because natural gas will not readily compression-ignite, even with a glow plug, the simplest alternative combustion system is homogeneous charge spark ignition. The minimum changes to a diesel engine required to accomplish this are an entirely redesigned fuel system, addition of an ignition system and spark plugs, and addition of a throttle. In addition, piston redesign is highly desirable to provide a lower compression ratio and more suitable combustion chamber geometry. The redesigned piston should incorporate redesigned piston rings for good oil control under vacuum conditions. Additional measures for oil control may also be required. The turbocharger must be revised to include a wastegate, or another form of boost control must be used. Modifications may also be necessary to deal with the higher heat rejection and higher exhaust temperatures of the natural gas engine. Alternative combustion systems for natural gas, such as direct in-cylinder injection, present greater technical challenges.

The storage of natural gas aboard a vehicle and the means of delivering it to the engine are also radically different from conventional liquid-fuel storage and delivery systems. Natural gas must either be highly compressed (up to 24,822 kPa [3,600 psi]), or liquefied (at or below -162°C

[260°F]), to obtain maximum storage density. Storage options for either case entail higher technology, weight, and cost impacts than those for conventional liquid fuels. Of the two storage options for natural gas, the technology for CNG on-board storage is more mature than that for liquefied natural gas (LNG) on-board storage. Delivery of natural gas from CNG tanks to the engine requires that the pressure be reduced and controlled to a constant low pressure by a pressure regulator. In a typical installation, engine coolant is circulated to the pressure regulator to counteract the cooling effect of the gas as it expands in the regulator, thereby preventing problems caused by ice formation. Design standards for CNG vehicular fuel systems, e.g., National Fire Protection Association (NFPA) 52 — *Standard for Compressed Natural Gas Vehicular Fuel Systems,* require that certain grades of materials and components be used. Check valves and safety devices are also required at key locations. Examples are a check valve adjacent to the refueling receptacle to prevent accidental discharge of natural gas, and overtemperature and overpressure relief valves on each CNG cylinder. While the CNG on-board system is substantially different from a diesel fuel system, the serviceability and reliability of both are expected to be comparable.

The greatest challenge in using CNG in a heavy-duty trucking application is achieving adequate range with the limited energy storage density of CNG, compounded by the lower efficiency of a throttled engine. Using the maximum available space on a typical Class 8 tractor for storage of CNG, a usable range exceeding 4,600 km (300 mi) may be difficult to achieve. Apart from the delay and inconvenience of fuel stops on long trips, CNG filling stations are not numerous as yet, so long routes would require detailed planning. Applications for which CNG heavy-duty trucks would be best suited are short-haul and intracity pickup and delivery, with distances traveled on one driving shift within the vehicle's range. Ideally, the vehicle would be filled with CNG at the vehicle's home base, or at a CNG station located on a regularly traveled route segment. Substituting CNG for diesel in short-distance applications would yield the emission benefits of CNG where they are needed the most — in urban areas.

The use of natural gas in place of diesel fuel in heavy-duty engines offers substantial reductions in emissions of NO_x, an ozone precursor difficult to control in diesel engines. As a domestic resource, natural gas offers economic and energy security advantages over petroleum fuels.

In summary, meeting the technical challenges posed by CNG is considered possible, and worthwhile in relation to the emissions and energy security benefits promised by substituting CNG for diesel in heavy-duty vehicles.

1.3 OBJECTIVES

The overall objective of the Alternative-Fueled Truck Demonstration's Natural Gas Program is to demonstrate the technical feasibility of CNG in Class 8 heavy-duty vehicles. The secondary objectives of the Caterpillar G3406LE demonstration project were:

- To develop a low-emissions, CNG-fueled Caterpillar 3406 engine designed for heavy-duty trucking applications
- To integrate the engine into a Class 8 tractor
- To determine the performance, emissions, and durability of the engine and vehicle during a 1-year demonstration period

SECTION 2

FIELD EVALUATION DESCRIPTION

2.1 HOST SITE

2.1.1 The Vons Companies, Inc.

Vons operates several retail grocery chains in California and Nevada, which hold a significant share of the markets they serve. The retail outlets receive their grocery products from several strategically located distribution centers. Vons operates its own trucking fleet to transport commodities from suppliers to the distribution centers and to deliver individual loads of groceries to the retail stores. Vons was chosen as a host site for this project because of Vons':

- Use of the Caterpillar 3406 engine in its fleet
- Interest in participating in the project
- Proximity to a local Caterpillar dealer
- Vehicle support capabilities maintained at Vons distribution centers

The distribution center chosen as the home base of the demonstration vehicle is located at 4300 North Shirley Avenue in El Monte, California. This center serves approximately 360 retail stores in a large geographical area that includes Santa Barbara, California; Bakersfield, California; San Diego, California; and Las Vegas, Nevada.

2.1.2 Fleet Characteristics

Vons' fleet of Class 8 tractors numbers approximately 420. About 180 of these are based at the El Monte distribution center. Approximately 300 of Vons' 600 trailers are also based at El Monte. The majority of the Class 8 tractor fleet is comprised of model year 1990 to 1993 Ford LTLA-9000 tractors. Most of these are powered by the Caterpillar 3406B diesel engine. A small number have the DDC Series 60 power plant. The remainder of the tractor fleet consists mainly of 1986 model year International (now Navistar) tractors with Cummins NTC power plants.

2.1.3 Maintenance Facilities

Class 8 tractors based at the El Monte distribution center are serviced at the fully equipped truck maintenance facility located there. The facility operates on a three-shift schedule, 24 hours per day, with a total of 10 mechanics. Six indoor service bays provide space for scheduled maintenance, general repair, and overhaul work including major unit replacement. Unscheduled engine maintenance on Class 8 tractors is generally covered by warranty, and is thus performed by the engine dealer. The local Caterpillar dealer is Power Systems Associates (Power Systems), located at 10006 Rose Hills Road in Whittier, California, less than 16 km (10 mi) from the El Monte distribution center. Power Systems is the power plant division of a major Caterpillar engine and off-road equipment dealership. The truck service shop at Power Systems has 17 covered service bays, and employs 15 mechanics who work 10 hours per day, on a staggered 4-days-per-week basis.

2.1.4 Route Characteristics

The route choice for this demonstration resulted from Vons' preference that the CNG tractor be tested under the most rugged and varied conditions that occur on a single route within Vons' transportation system. The route chosen is known as the Bakersfield route, and involves transporting a load of groceries from the distribution center in El Monte to Bakersfield via the Los Angeles freeway system, Interstate 5, and State Highway 99. The Bakersfield route is shown in Figure 2-1. A typical roundtrip is 400 to 450 km (250 to 280 mi), and includes deliveries to as many as four different stores in the Bakersfield area. A wide variety of operating conditions are encountered: city stop-and-go, level highway, highway hill climbing, and highway downgrade. The section of Interstate 5 known as the Grapevine, which includes the Tejon Pass, with a 1,261-m (4,138-ft) elevation, is traversed. Winter weather conditions on the Tejon Pass can include rain, fog, and freezing temperatures, whereas summer ambient temperatures in Bakersfield often exceed

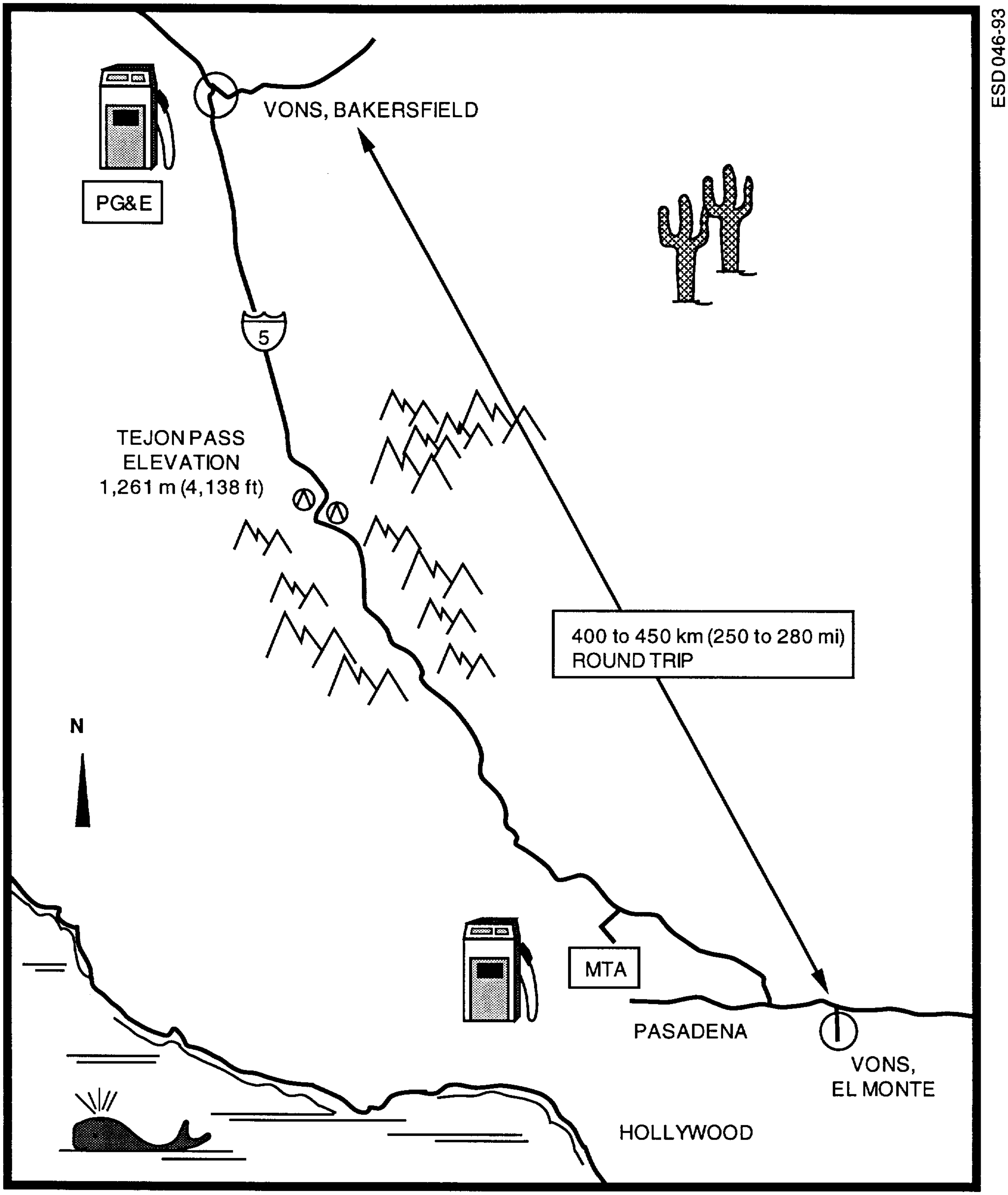

Figure 2-1. Bakersfield route map

37.8°C (100°F). Thus, this route truly offers a wide range of temperatures and operating conditions in which to test a vehicle's engine and fuel system.

2.2 VEHICLES

2.2.1 Demonstration Vehicle

Following Vons' selection as a host site, an appropriate vehicle was selected into which the natural gas engine and fuel system could be installed. Vons purchased a fleet of 50 new 1992 Class 8 tractors just as the engine was being readied by Caterpillar. Vons equipment No. 9207, a 1992 Ford LTLA-9000 tractor equipped with a Caterpillar 3406B, 261-kW (350-hp) diesel engine, was selected for conversion to natural gas operation for this project. Figure 2-2 depicts tractor 9207 before its conversion. The specifications of this vehicle prior to and after its conversion are listed in Table 2-1.

Figure 2-2. Tractor 9207 before its conversion

Table 2-1. Demonstration and control vehicle specifications

Vehicle	Pre-conversion	Post-conversion	Diesel Control
Equipment no.	9207	9207	9200
Manufacturer	Ford	Ford	Navistar
Year and model	1992 LTLA-9000	1992 LTLA-9000	1992 9400 6x4
Body style	Conventional	Conventional	Conventional
Wheelbase	424 cm (167 in)	424 cm (167 in)	434 cm (171 in)
Curb weight	8,318 kg (18,340 lb)	8,986 kg (19,810 lb)	8,842 kg (19,492 lb)
Fuel capacity	757 L (200 gal)	233 m^3 (8,224 scf)	757 L (200 gal)
Engine manufacturer	Caterpillar	Caterpillar	Caterpillar
Engine model	3406B ATAAC	G3406LE	3406B ATAAC
Horsepower	261 kW (350 hp) @ 1,800 rpm	261 kW (350 hp) @ 2,000 rpm	261 kW (350 hp) @ 1,800 rpm
Torque	1,831 N·m (1,350 lb-ft) @ 1,200 rpm	1,607 N·m (1,185 lb-ft) @ 1,200 rpm	1,831 N·m (1,350 lb-ft) @ 1,200 rpm
Transmission manufacturer	Eaton-Fuller	Eaton-Fuller	Eaton-Fuller
Transmission model	RTX-12609B	RTLO 14613B	RTX-12609B
Transmission type	Manual	Manual	Manual
No. of speeds	9	13	9
Rear axle type	Non-locking	Non-locking	Non-locking
Rear axle ratio	4.10:1	4.10:1	4.10:1

2.2.2 Control Vehicles

Vons equipment No. 9206, a 1992 Ford LTLA-9000 identical to the demonstration vehicle 9207, was originally the designated control vehicle. Unfortunately, vehicle 9206 was involved in a collision before the demonstration began, and Vons substituted it with equipment number 9200, a 1992 Navistar 9400 tractor, also powered by a Caterpillar 3406B 261-kW (350-hp) diesel engine. Additional specifications are shown in Table 2-1. Although a different model from No. 9207, No. 9200 was chosen as the control vehicle because of its frequent use on the Bakersfield route. This vehicle served as the diesel control for fuel economy and engine maintenance comparison purposes. However, Acurex Environmental was able to procure the use of a 1992 Ford LTLA-9000 tractor identical in specification to tractor 9207 for performance and weight comparisons.

2.3 FUELING FACILITIES

2.3.1 MTA Sun Valley CNG Station

This project made use of an existing heavy-duty vehicle CNG station located 4.8 km (3 mi) off the El Monte to Bakersfield route, in Sun Valley, California. The site of the CNG station is the Los Angeles County Metropolitan Transportation Authority (MTA) (formerly the Southern California Rapid Transit District [SCRTD]) vehicle base at 11900 Branford Street in Sun Valley. This CNG station, which began operation in 1992, was constructed to service 10 CNG-fueled buses operated by MTA. Two 18.4-m^3/min (650-scfm) compressors, shown in Figure 2-3, pressurize gas to 24,822 kPa (3,600 psi); fuel is delivered at this pressure to a Sherex 5000 connector for the CNG buses. A Sherex 1000 fuel connector with 20,685-kPa (3,000-psi) fuel delivery, the system used by the demonstration vehicle, is also provided. This CNG station was designated as the primary fueling facility in the planning stages of the demonstration.

2.3.2 PG&E Bakersfield CNG Station

An existing CNG station in Bakersfield was designated as a secondary fueling facility. This station, owned and operated by Pacific Gas and Electric (PG&E), is located at 4101 Wible Road in Bakersfield, California, within 1.6 km (1 mi) of Highway 99 at its southern approach to Bakersfield. This facility was designed to service light- and medium-duty CNG vehicles, and has two 6.23-m^3/min (220-scfm) compressors and an 850-m^3 (30,000-scf) CNG storage capacity. Here, the demonstration vehicle was serviced by a Sherex 1000 fuel connector at a maximum fuel delivery pressure of 20,685 kPa (3,000 psi).

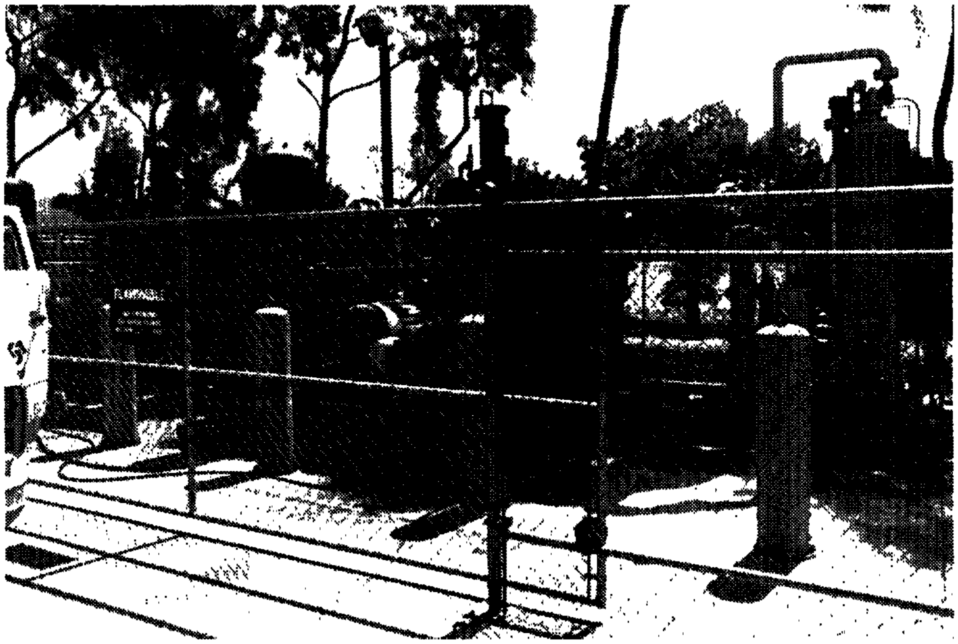

Figure 2-3. Sun Valley CNG station

SECTION 3

ENGINE DEVELOPMENT AND INSTALLATION

3.1 ENGINE DEVELOPMENT

Caterpillar, Inc., performed the design and development of the engine for this project under subcontract to Acurex Environmental, and provided the information for this section.[1]

3.1.1 Design and Build Prototype

3.1.1.1 Design Objectives

The design objectives established for the natural gas engine were:

- To develop a low-NO_x G3406 natural gas engine for vehicular application, with emission levels below proposed emission regulations and with good driveability as well
- To achieve NO_x levels of 2.68 g/bkW-hr (2.0 g/bhp-hr) on the U.S. Environmental Protection Agency (EPA) transient emission test
- To optimize the engine's fuel consumption without compromising the emission target
- To fit the engine with production diesel attachments into the envelope of a Ford AeroMax 120, LTLA-9000 truck chassis

The performance and emission goals for this engine design are shown in Table 3-1.

3.1.1.2 Technical Approach

Several engine technologies were considered for this project, including stoichiometric with a 3-way catalyst, lean-burn with an oxidizing catalyst, dual-fuel (pilot ignition), and direct gas injection. Also considered was jacket water aftercooling versus air-to-air aftercooling.

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[1] *Caterpillar G3406 Mobile, Low Emission Engine for the Vons Companies, Inc. of El Monte, CA,* final report, Engine Division, Caterpillar, Inc., Mossville, Illinois, June 1993.

Table 3-1. Engine design goals

Power	261 kW (350 bhp)
Rated speed	2,000 rpm
Torque	1,242 N·m (919 lb-ft)
Torque rise	20%
Speed for peak torque	1,300 rpm max.
BSFC @ peak torque	10,469 kJ/bkW-hr (7,400 Btu/bhp-hr)
BSFC @ rated power	11,035 kJ/bkW-hr (7,800 Btu/bhp-hr)
NO_x	268 g/bkW-hr (2.0 g/bhp-hr)
CO	20.8 g/bkW-hr (15.5 g/bhp-hr)
NMHC	1.5 g/bkw-hr (1.1 g/bhp-hr)
PM	0.07 g/bkW-hr (0.05 g/bhp-hr)

Lean-burn was the combustion strategy chosen because it offers low NO_x emissions; reasonable development costs; and, relative to the stoichiometric strategy, low fuel consumption and low heat rejection. Air-to-air aftercooling was chosen over jacket water aftercooling because it offered higher detonation-limited horsepower. The cooler charge air with air-to-air aftercooling is also thought to help reduce NO_x emissions.

3.1.1.3 Design for Low NO_x Emissions

A lean-burn engine has a narrow air/fuel (A/F) ratio range in which it can operate with low NO_x emissions without lean misfire. Richer than optimum, NO_x is higher than desired; conditions are also more favorable for detonation. Lean misfire can occur if the engine is run too close to the lean limit. To allow tight control of the engine A/F ratio for good performance and emissions, A/F ratio control, timing control, and electronic governing were specified.

The A/F ratio control system was designed with an engine electronic control, a lean oxygen sensor, an inlet air temperature sensor, an inlet manifold pressure sensor, a gas control valve, and an electronic actuator for controlling the gas valve.

The design of the ignition system and timing control made use of the engine driven magneto, an interface box, timing control electronics, a top dead center sensor, an engine speed sensor, ignition coils, spark plug extenders, and spark plugs. The standard precious metal spark plugs used in Caterpillar G3406 industrial engines were specified. A special interface module, the Caterpillar Interface Module (CIM), was designed for high-temperature under-hood application.

The governor design employed the electronic engine control, governor actuator, and engine speed pickup. A nonlinear control linkage was designed to link the actuator with the throttle.

As a result of the lean-burn strategy, it was necessary to specify a turbocharger of higher capacity than that of the stoichiometric industrial engine on which this design is based.

3.1.1.4 Design for Mobile Application

Several internal components of the industrial engine required redesign for the lean-burn mobile application. A low-overlap camshaft and 11:1 compression ratio pistons were designed in order to achieve the desired combustion parameters. For good oil control at part-throttle, higher contact pressure oil rings and new valve guide stem seals were designed. Several external engine components also required redesign or replacement. The rear-located turbocharger of the industrial engine would interfere with a tractor's firewall, so a diesel truck engine exhaust manifold was substituted and the turbocharger was located at mid-engine. The truck exhaust manifold outlet orients the turbocharger downward. However, the 10.2-cm (4-inch) thick wastegate adapter required for the mobile gas engine would cause the turbocharger to interfere with the frame rail if the downward orientation were retained. The solution adopted was to invert the manifold, orienting the turbocharger upward. Although this caused the turbocharger to interfere with the standard air cleaner of the Ford AeroMax tractor, a feasible remedy, relocation of the air cleaner, was devised. Ford agreed to provide a suitable custom air filter installation for the demonstration vehicle.

The resulting turbocharger exhaust outlet pointed directly toward the firewall, high in the engine compartment. A custom exhaust duct was engineered, with two small-radius elbows to duct the exhaust away from the engine and down past the frame rail. The exhaust outlet duct incorporated the oxygen sensor mount and a separate passage for exhaust entry via the wastegate. Heat shielding was provided for the oxygen sensor, in this location close to the turbine housing.

The gas regulators of the industrial engine were unsuitable for a mobile application because of their low pressure rating and because their large diaphragms were susceptible to road vibrations, interfering with their ability to regulate pressure accurately. Twin Impco model TPEV-1 CNG regulators were specified to replace the original regulators.

The throttle body of the industrial engine was mounted above the intake manifold, with a long curved pipe connecting it to the carburetor. Packaging of the mobile engine resulted in mounting of the carburetor to one side of the engine, toward the front, connected to the throttle body with a shorter pipe. The throttle body was relocated to the side of the inlet manifold. This arrangement resulted in favorable geometry for plumbing the carburetor inlet to the charge air cooler.

3.1.2 Prototype Building, Testing, and Development

3.1.2.1 Prototype Building

A production G3406 industrial engine was purchased and sent to the Caterpillar Technical Center in Peoria, Illinois. New pistons, a new camshaft, a new cylinder head, and all special components designed for the lean-burn mobile application were installed. In addition, several external components and accessories were added or replaced to configure the engine for a truck. These included a front sump oil pan, an oil level gauge, an air compressor, a front crank pulley, an electric starting motor, and coolant hoses. Right and left views of the engine are shown in Figures 3-1 and 3-2, respectively.

3.1.2.2 Performance Development

When the engine was run initially, minor functional problems were noted and corrected. Performance development began with sizing of the turbocharger. The compressor housing originally fitted to the prototype put the compressor in the center of its map in a high-efficiency zone;

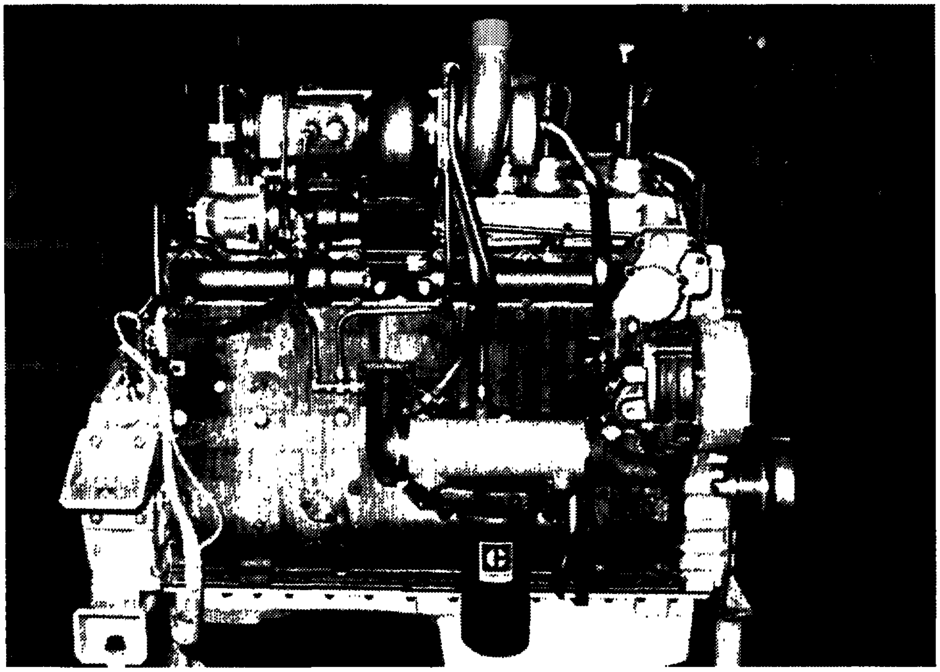


Figure 3-1. Caterpillar G3406LE, right side

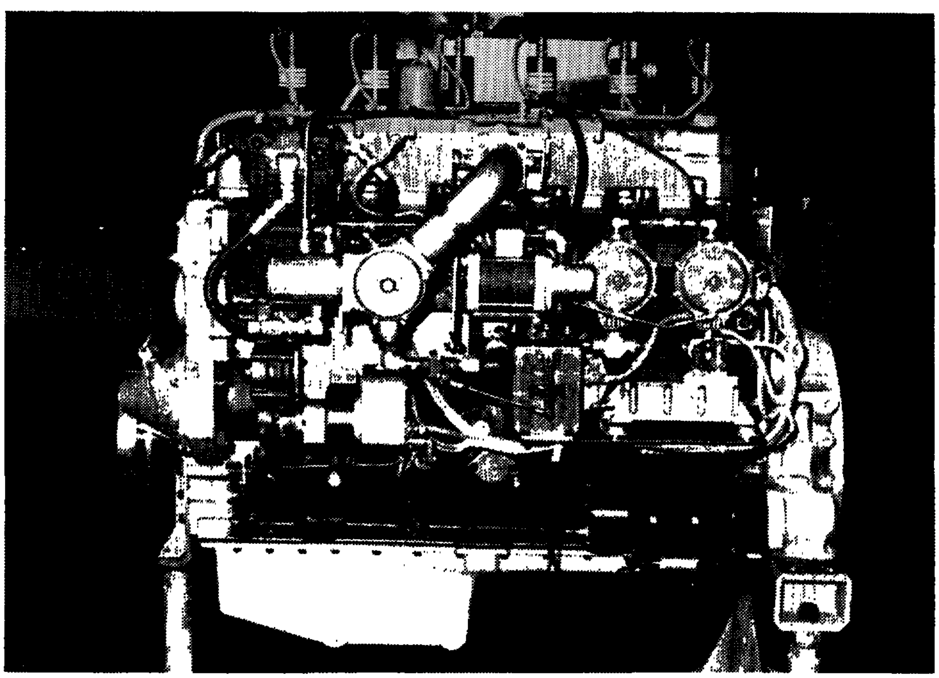


Figure 3-2. Caterpillar G3406LE, left side

however, the engine's performance indicated that the turbine housing area/radius (A/R) was too large. Lug capability was improved to 1,380 rpm with a smaller turbine housing, but this did not meet the goal. The next smaller turbine housing was installed, and yielded a peak torque of 1,600 N·m (1,180 ft-lb) at 1,200 rpm. Data from the lug tests are shown in Table 3-2.

Following sizing of the turbocharger, the gas control valve was mapped over the engine's operating range. The valve demonstrated a flow range that allowed A/F ratios of from 3 to 7.5 percent (wet) oxygen at most operating conditions. The mapping results were used to set up gain rates in the control software.

Further mapping of inlet air temperature and pressure versus A/F ratio and timing was performed over the engine's operating range. The maps were stored in the engine's A/F ratio

Table 3-2. Lug tests

Parameter	Compressor Housing 1			Compressor Housing 2			Compressor Housing 3		
Speed (rpm)	2,000	1,660	1,560	2,002	1,665	1,395	2,000	1,668	1,193
Power (kW)	261	253	251	261	268	232	261	263	200
Torque (N·m)	1,245	1,457	1,538	1,246	1,540	1,595	1,243	1,506	1,600
Air in (°C)	24	26	26	24	24	24	26	25	25
Compressor out (°C)	136	132	130	136	132	123	136	131	119
Inlet manifold (°C)	44	40	38	42	41	38	42	41	34
Turbine inlet (°C)	718	708	696	725	695	659	715	683	622
Turbo outlet (°C)	606	605	593	609	586	561	600	574	525
Boost (kPa)	104	106	111	108	104	97	105	104	95
Manifold pressure (kPa)	84	95	97	79	97	94	82	96	91
Exhaust manifold pressure (kPa)	78	66	64	86	79	65	95	86	91
Ambient pressure (kPa)	99.8	99.8	99.8	100.3	100.3	100.3	100.3	100.3	100.3

control, which uses the mapped brake mean effective pressure (BMEP) to set timing and A/F ratio. This made closed-loop operation possible.

However, a problem surfaced as a result of closed-loop operation. As designed, the control operates in open loop at loads below 25 percent. The transition between open- and closed-loop modes was not smooth, as it required the gas control valve to make a large correction. To resolve this problem, a modification to the gas regulators, to reduce the gas pressure from 152 to 51 mmH_2O (6 to 2 inches of water [in H_2O]) above boost pressure, allowed the control valve to make a smooth transition and resulted in satisfactory performance.

New governing strategies adopted from diesel engine electronic controls were programmed into the controller. Parameters were adjusted to obtain a stable idle. A test of transient performance, to the extent permitted on a water brake dynamometer, showed good results. During the test, "false" detonation was indicated by the detonation sensors. The standard control retards ignition timing when detonation is detected. This strategy, developed for the industrial engine, takes 6 minutes to return to the original timing when detonation retard has taken place. Resolution of the "false" detonation and reprogramming of the detonation control strategy were not within the scope of this project. Therefore, the detonation retard was disabled, and it was decided that the engine would be set up with suitable operating margins.

Horsepower and torque curves of the G3406LE engine are shown in Figure 3-3.

3.1.2.3 Emissions Development

Steady-state emissions were measured according to the 11-mode test. Previous experience had shown good correlation between the steady-state 11-mode test and the EPA transient cycle. The engine was initially set at 6.55 percent oxygen (wet) ($\lambda = 1.46$) and 27° before top dead center (BTDC) timing, but emissions at rated load were too high. The engine was reset to 6.9 percent oxygen (wet) ($\lambda = 1.50$) and emissions were remeasured. Aggregate NO_x from the 11-mode test was 2.57 g/bkW-hr (1.92 g/bhp-hr). The results are shown in Table 3-3.

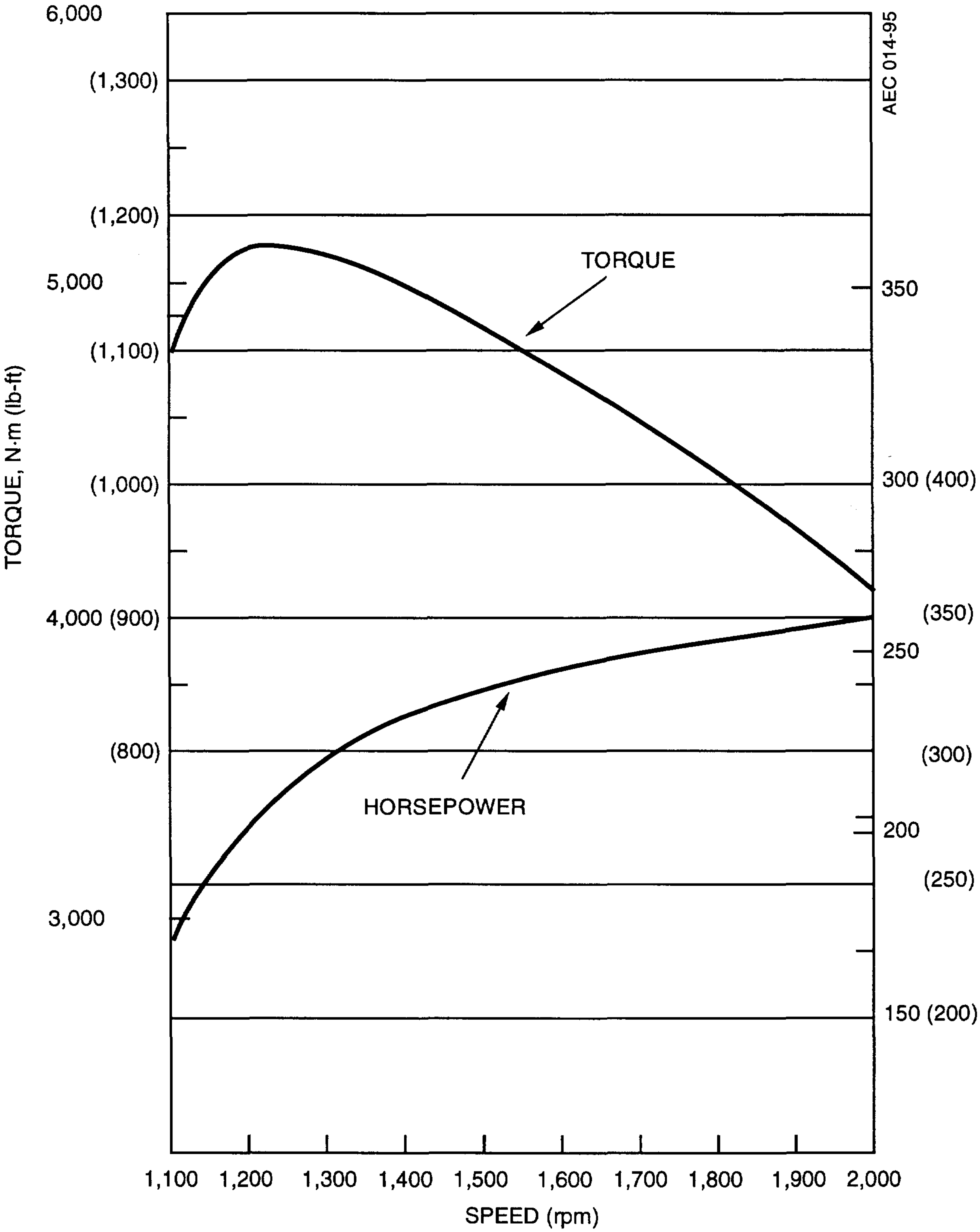


Figure 3-3. Horsepower and torque curves of the G3406LE engine

Table 3-3. 11-mode emission test results

Mode	Speed	% Load	Weighting Factor	NO_x	CO	O_2 % (dry)	λ
1	Low idle	0	0.20	45 ppm	50 ppm	4.9	1.26
2	Peak torque	0	0.08	70 ppm	80 ppm	4.9	1.26
3	Peak torque	25	0.08	3.35 g/bkW-hr (2.5 g/bhp-hr)	3.35 g/bkW-hr (2.5 g/bhp-hr)	6.4	1.37
4	Peak torque	50	0.08	3.22 g/bkW-hr (2.4 g/bhp-hr)	3.22 g/bkW-hr (2.4 g/bhp-hr)	7.8	1.47
5	Peak torque	75	0.08	3.15 g/bkW-hr (2.35 g/bhp-hr)	2.95 g/bkW-hr (2.2 g/bhp-hr)	7.8	1.47
6	Peak torque	100	0.08	3.02 g/bkW-hr (2.25 g/bhp-hr)	1,455 g/bkW-hr (1,085 g/bhp-hr)	7.9	1.48
7	Rated	0	0.08	75 ppm	100 ppm	4.8	1.26
8	Rated	25	0.08	2.28 g/bkW-hr (1.7 g/bhp-hr)	3.35 g/bkW-hr (2.5 g/bhp-hr)	6.9	1.41
9	Rated	50	0.08	2.16 g/bkW-hr (1.61 g/bhp-hr)	3.25 g/bkW-hr (2.42 g/bhp-hr)	7.4	1.44
10	Rated	75	0.08	2.40 g/bkW-hr (1.79 g/bhp-hr)	3.14 g/bkW-hr (2.34 g/bhp-hr)	7.7	1.46
11	Rated	100	0.08	2.19 g/bkW-hr (1.63 g/bhp-hr)	3.02 g/bkW-hr (2.25 g/bhp-hr)	7.9	1.48
Aggregate			1.00	2.57 g/bkW-hr (1.92 g/bhp-hr)	2.98 g/bkW-hr (2.22 g/bhp-hr)	6.5	1.38

3.1.2.4 Endurance Test

Minor updates were made to the control box prior to the endurance test. Several relays were added to control the stop/start logic of the engine. A 3-second purge cycle was added to the cranking sequence to prevent backfires in the exhaust system. A relay was added to control the fan clutch; logic was programmed to operate the fan in response to inlet manifold air temperatures above 40°C (104°F). This measure was designed to maximize the aftercooler's effectiveness and guard against detonation.

A 125-hour endurance test was run on Caterpillar's ET-29 test cycle. The sequence of this cycle is shown in Table 3-4. No problems were found during the endurance test. Oil consumption for the test was 0.201 g/bkW-hr (0.150 g/bhp-hr).

3.1.2.5 Transient Emission Test

A transient emission test was to be conducted at the EPA facility in Ann Arbor, Michigan. However, several problems unrelated to the engine were encountered at EPA. In addition, the test cell throttle controller was unable to successfully operate the engine on the transient cycle. Thus, the transient emission test was aborted.

3.2 FUEL SYSTEM

Acurex Environmental designed the CNG tractor's fuel system, and also procured its major components and oversaw Power Systems' installation of the system in the vehicle.

3.2.1 Design Requirements

The CNG fuel system's capacity was determined based on the initial target range of 400 km (250 mi) originally provided by Vons. Subsequently, it was learned that the route varied from 400 to 450 km (250 to 280 mi). Vons also provided a fuel economy estimate of 39.1L/100 km (6 mi/gal) for diesel tractor-trailers on the Bakersfield route. A 10-percent thermal efficiency deficit was assumed for the natural gas engine. It was also assumed that 10 percent of the CNG

Table 3-4. Caterpillar ET-29 test cycle

Step	Duration[a] (s)	Speed	Load
1	30	Low idle	Idle load
2	30	High idle	Idle load
3	90	Rated	Rated
4	90	Peak torque + 100 rpm	Wide open throttle

[a]Total duration was 4 minutes.

fuel in the tanks would be unusable because of the need to maintain a minimum storage pressure for engine operation. The required CNG capacity was estimated as shown in the following equation, which includes a further 10-percent factor as a margin to compensate for reduced fuel density due to the heating effect of fast-fill refueling.

$$250\ mi \times \left[\frac{1\ gal}{6.0\ mi}\right] \times \left[\frac{136\ scf\ gas}{gal\ diesel}\right] \times 1.1^3 = 7{,}541\ scf \qquad \textbf{(3-1)}$$

Prior to the start of the fuel system's designing, applicable codes and standards for CNG vehicle fuel system design were identified and consulted. These were:

- National Fire Protection Association (NFPA) 52 — *Standard for Compressed Natural Gas Vehicular Fuel Systems*
- *California Code of Regulations, Title 13, Motor Vehicles, Division 2,* Department of California Highway Patrol
- *Requirements for Natural Gas Vehicle (CNG) Conversion Kits,* American Gas Association (A.G.A.)

These codes and the physical constraints of the Ford LTLA-9000 tractor defined the space envelope that could be used for mounting the CNG tanks and fuel system. The space in which the existing twin 379-L (100-gal) diesel tanks were mounted was identified as the most attractive location for the CNG tanks. The significant boundaries of this mounting arrangement were identified as follows:

- The vertical planes that define the maximum width of the tractor (244 cm [96 in])
- The horizontal plane at the minimum ground clearance of 25.4 cm (10 in) (loaded). This is established by the NFPA 52 requirement that no part of the container or its appurtenances extend below the minimum road clearance of the vehicle when the vehicle is loaded to its gross weight. On the Ford LTLA-9000 tractor, the minimum road clearance of 25.4 cm (10 in) occurs at the center of the rear differential housing.

- The horizontal plane even with the top of the frame rails. This gives protection to the cylinders in an extreme trailer breakover angle, in which the lower front edge of the trailer makes contact with the frame rails. This occurs when the tractor encounters a steep incline.
- The surfaces defined by the necessary clearance for the front wheel fenders and rear wheel mudflaps
- The inboard space delimiters established by the vehicle's basic structure and driveline, i.e., the frame rails and transmission

The final design criteria were established and prioritized in the following order:

- Safety. The tanks, their mounts, plumbing, and all fuel system hardware should meet NFPA 52 requirements for safe operation.
- Capacity. The tanks should provide the necessary CNG storage capacity to achieve the design range. Pressure regulators, valves, and plumbing should be sized to ensure that the engine's peak fuel flow requirement is met at the minimum tank pressure.
- Weight. Added weight must be kept to a minimum to minimize the loss of vehicle payload.
- Simplicity. The fuel system will be used and serviced by personnel who are not specialists in CNG systems.
- Cost. The lowest cost approach meeting the above criteria was pursued.

3.2.2 Design and Specification

3.2.2.1 Tanks and Mounts

As the first step in designing the CNG tank geometry, the selection of commercially available CNG cylinders was reviewed. Using sketches of the available space, Acurex Environmental arrived at a final tank geometry. The fuel system design is shown schematically in Figure 3-4.

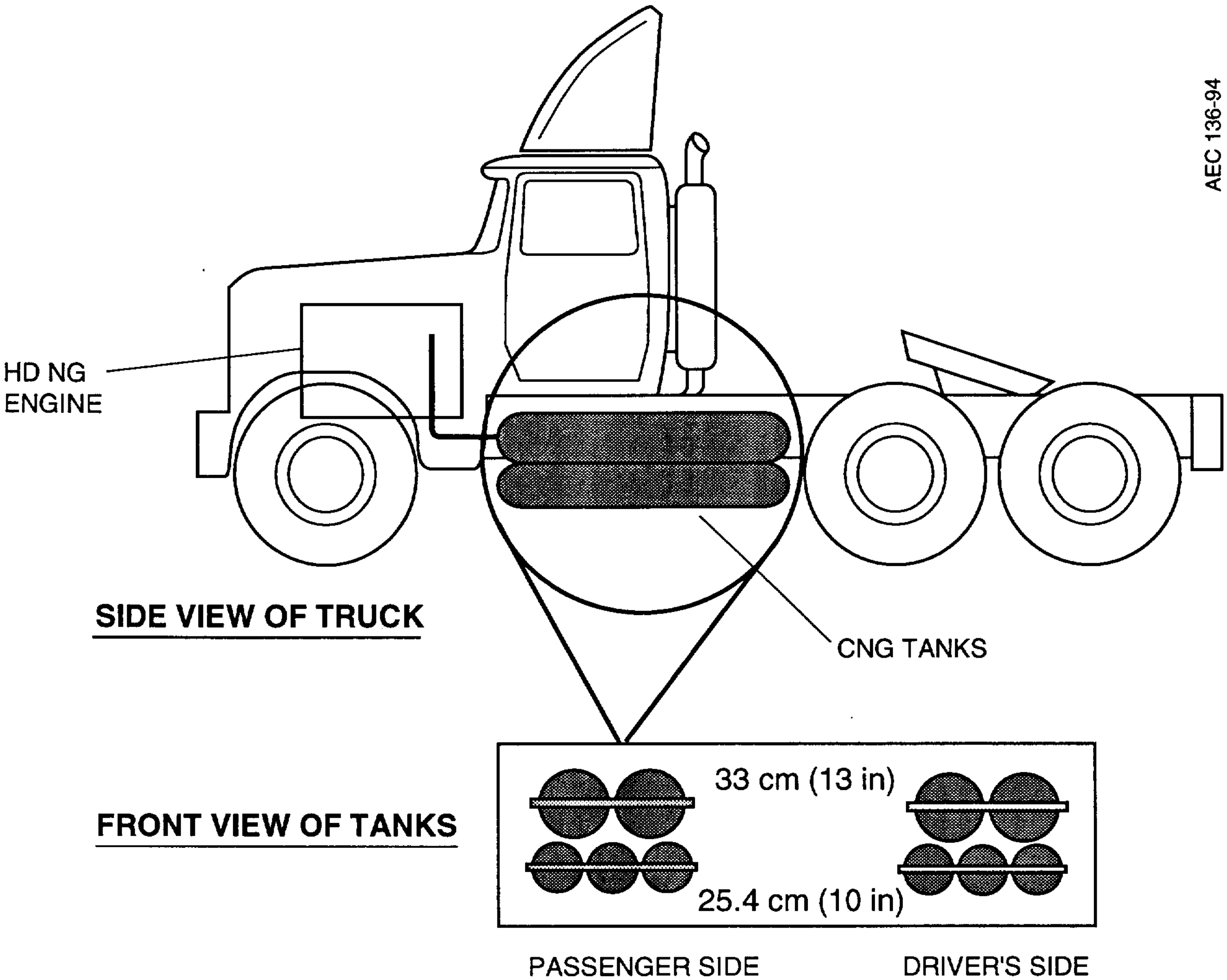


Figure 3-4. CNG fuel system

The tanks selected were composite-reinforced aluminum cylinders manufactured by CNG Cylinder Company of North America. The advantages of these tanks were low mass (compared to steel), availability of suitable sizes, availability of custom-designed support brackets, and attractive cost. The maximum standard length that would fit in the available space between the front and rear wheels was 180 cm (72 in); the next size up was 213 cm (84 in). A combination of six 25.4-cm (10-in) diameter and four 33-cm (13-in) diameter cylinders, rated at 20,685 kPa (3,000 psi), was chosen to make best use of the available height and width inside the mounting envelope. The total capacity of these tanks is 233 m^3 (8,224 scf), well in excess of the target capacity of 213 m^3 (7,541 scf).

A mounting system utilizing the tank manufacturer's custom support brackets and twin 4-inch-square structural steel tubes was engineered. The beams were sized according to NFPA 52 requirements to support 8 times the weight of the full tanks along six axes running forward, backward, up, down, left and right with respect to the tractor. Support for each beam is provided by two 1.6-cm (5/8-in) diameter grade 5 bolts. The joint design is such that the beams rest 0.32 cm (1/8 in) above the upper flange of the frame rails, and the bolts do not clamp the beam against its supports. Thus, any flexing of the beams is transmitted through the beam and taken as beam bending rather than imposing a torque on the frame rails. This pinned arrangement allows some flexing as the truck experiences cornering forces and concomitant frame movement. Both Ford and CNG Cylinder Company approved the design.

Additional support of the lower inside tanks was accomplished by bolting steel angles to the frame rails. The tanks are assembled into rigid pods of five tanks with the aid of vertical stiffeners between the cylinder brackets.

The maximum rearward placement of the rear transverse beam was constrained by trailer swing and breakover, while the maximum forward placement of the front transverse beam was governed by the transmission shift lever. The tanks themselves were positioned as far forward as possible, in order to achieve the best load distribution on the transverse beams within the geometric constraints.

The cylinders are mounted with the valves in the rearward position. The cylinders are rotated in their brackets such that all valve handles are oriented downward and all safety relief vents are oriented upward. The rear location of the cylinder valves avoids the risk of damage from road debris kicked up by the front wheels. To comply with NFPA 52, guard plates were specified for protection of the fronts of the tanks. The material selected for the guards was polished 0.48-cm (3/16-in) American Society for Testing and Materials (ASTM) 3003 aluminum diamond plate. This material is light, ductile (for bends and debris abuse), and attractive in appearance. A similar guard plate of the same material was specified for the rear of the tanks to protect valves and piping.

3.2.2.2 Plumbing and Hardware

Design criteria for the piping and related hardware were safety, low fill times, ability to provide required flow to the engine, simplicity, ease of maintenance, and reasonable cost. Tubing specified in this design is seamless type 304 stainless steel in 1.27-cm (1/2-in) and 0.95-cm (3/8-in) diameters. Stainless steel was chosen for its corrosion resistance and strength. The 1.27-cm (1/2-in) tubing has a 1.24-mm (0.049-in) wall thickness and is rated to 24,133 kPa (3,500 psi). The 0.95-cm (3/8-in) tubing has a 0.89-mm (0.035-in) wall thickness and is rated to 22,754 kPa (3,300 psi). The design specifies that stainless steel tubing be attached to the vehicle structure by tube clamps with silicone rubber cushions. Clamps are spaced no more than 61 cm (24 in) apart in order to comply with NFPA 52 requirements.

The key components of the fuel system and their function are shown in Figure 3-5, and are as follows. Fuel enters the system through a Sherex SR 1020 receptacle. This receptacle was chosen to be compatible with the Sherex nozzles at MTA in Sun Valley and at PG&E in Bakersfield. The Sherex SR 1020 receptacle has an internal check valve, and connects to the vehicle's fuel system via a 0.95-cm (3/8-in) Swagelok® fitting. A Swagelok port connector increases the 0.95-cm (3/8-in) port to 1.27 cm (1/2 in) before entering a Swagelok check valve. This check

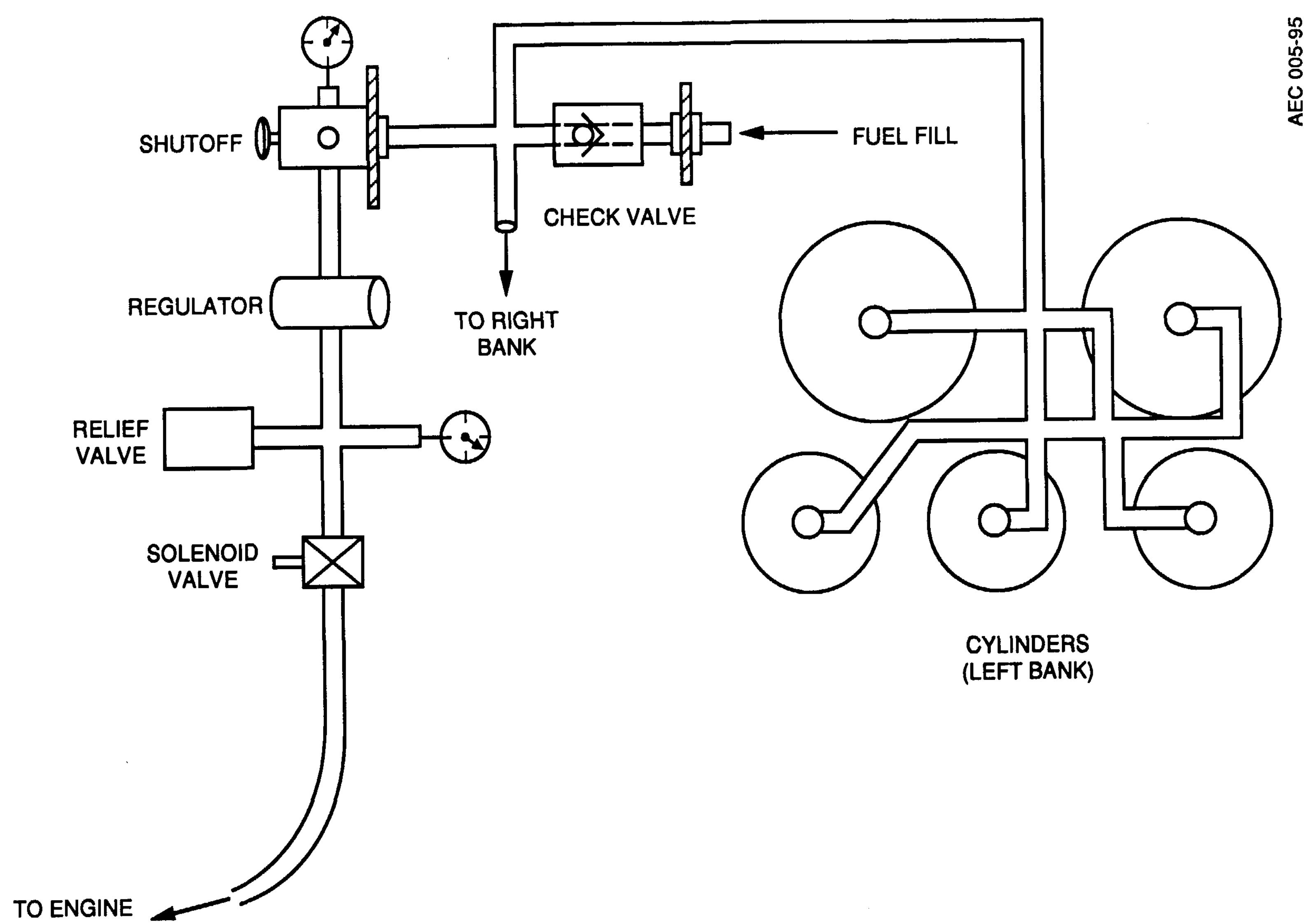


Figure 3-5. Layout of fuel system

valve is the primary system check valve. The check valve in the Sherex receptacle may be considered a backup check valve. Suitable plumbing and manifolding is provided to connect the CNG cylinders to the fill line. Each CNG cylinder incorporates a valve-mounted safety relief device, a CG-9, designed to vent when the temperature rises above 103°C (217°F). Another safety relief device, a CG-5, is fitted at the front end of each tank. This device is designed to vent when the temperature rises above 100°C (212°F) and the pressure above 26,029 kPa (3,775 psig).

Attached to each CG-5 relief device is a 90° elbow designed to route any vented gas upwards within 45° of vertical. Each elbow is capped by a threaded plastic cap to prevent rain and debris from entering but still allow any gas to escape in the event of an overpressure or over-temperature condition.

The engine fuel supply flows through a quarter-turn ball valve rated at 41,370 kPa (6,000 psi). With the valve closed, the fuel in the tanks is isolated from the remainder of the fuel system and the vehicle will not run. From the shutoff valve, fuel flows to a high-pressure gauge. The gauge incorporates a pressure transducer that, with an optional sending circuit, is capable of driving the stock fuel gauge in the truck.

Fuel flow continues to the primary pressure regulator. The regulator chosen was a Tescom model 269-507-261, which is rated at 20,685 kPa (3,000 psi) and has a 1,034 kPa (150-psig) nominal outlet pressure. This regulator was chosen because it is both reliable and compact. The regulator is warmed with engine coolant during operation to prevent it from freezing up.

Fuel at the regulated pressure continues into a 1.27-cm (1/2-in) cross, attached to which are a pressure gauge and an overpressure relief valve. The overpressure relief valve is set at 1,724 kPa (250 psig) and is designed to protect the downstream components in the event of a regulator failure. The relief valve vents to the atmosphere. The pressure gauge indicates regulator outlet pressure. The nominal running pressure is 1,034 kPa (150 psig) and the nominal static pressure 1,172 to 1,310 kPa (170 to 190 psig).

Downstream of the cross is a normally closed solenoid valve. This valve is a Konan model S401WF15V9CF5, rated at 1,034 kPa (150 psig) and designed to operate on 12 VDC. This valve was chosen for its Underwriters Laboratory approval, low flow restriction, and suitable pressure rating. The valve is enabled by ignition voltage. An oil pressure switch with normally closed and normally open contacts directs starter voltage to the valve and then, after the oil pressure rises to 21 kPa (3 psig), routes ignition voltage to the valve. An impact switch located at the fuse panel behind the passenger seat is wired in series with the valve and is designed to open in the event of a collision, effectively stopping the flow of gas to the engine. Should the engine die but the ignition remain on, the oil pressure switch will de-energize the solenoid valve and stop the flow of gas to the engine.

3.3 VEHICLE CONVERSION

Vons tractor 9207 accumulated 116,361 km (72,319 mi) in service in its original configuration as a diesel vehicle before its conversion to CNG operation. Thus, the vehicle was already thoroughly broken in by the time it was delivered to Power Systems for conversion.

Acurex Environmental directed installation of the Caterpillar G3406LE engine in place of the Caterpillar 3406B ATAAC diesel engine. Engine replacement was relatively straightforward because of the fundamental similarity of the two engines. The engine mountings, coolant connections, and fan geometry of the diesel engine were maintained for the natural gas engine. The mounting base of the magneto interface box (MIB) mounted on the left (driver's) side of the natural gas engine had to be trimmed to prevent it from interfering with the steering shaft. The oil pan was removed during installation in order to clear the front axle and ease engine installation clearances.

The tractor was factory-equipped with a Fuller RTX 14609B 9-speed manual transmission, but Caterpillar and Ford determined that an Eaton RTLO 14613B 13-speed transmission would better match the torque characteristics of the CNG engine. This transmission was loaned to the project by Eaton and installed in place of the original transmission. The drive shaft was shortened slightly to accommodate the 13-speed transmission.

The position of the turbocharger on the natural gas engine was different from that of the original diesel engine because of the space required for the waste gate. This affected the location and orientation of air inlet and exhaust outlet flanges. The standard under-the-hood air cleaner was located close to the turbocharger inlet. The turbocharger on the CNG engine interfered with the air cleaner in its standard location. For this reason, Ford engineered an air cleaner located under the radiator. The inlet for this system was on the left side of the hood with a mating boot connector on the left headlight housing, as shown in Figure 3-6. The redesigned air inlet system was not available during conversion of the vehicle, so a temporary system was installed. The interim system consisted of an air inlet and air filter behind the front bumper, and ducting to the turbocharger inlet, as shown in Figure 3-7. The air-conditioner drier and associated piping were also relocated due to their interference with the turbocharger. Figure 3-8 shows the engine installed in the vehicle.

An entirely new exhaust system was installed. A blanket-type insulation was installed on most of the exhaust tubing to protect nearby components and to retain heat in the exhaust upstream of the catalytic converter. The initial single muffler/catalyst unit was installed vertically on the right (passenger) side of the tractor. A custom-designed support structure, shown in Figure 3-9, was fabricated to clear the CNG tanks and provide support for the heavy muffler/catalyst unit.

The CNG cylinders, mounts, plumbing, and hardware were installed according to the design generated by Acurex Environmental. The requirement to relocate some existing hardware on the vehicle was foreseen in the design, and was carried out at this time. The muffler support bracket mounted on the right frame rail interfered with optimum mounting of the CNG tanks. The factory muffler mounting bracket and mast were removed, and a custom bracket that allowed optimum CNG tank mounting was fitted.

It was also necessary to relocate the air tanks mounted beneath the cab. This was accomplished by fabricating custom brackets and remounting the tanks between the frame rails behind the transmission. The original air hose, fittings, and routing were retained.

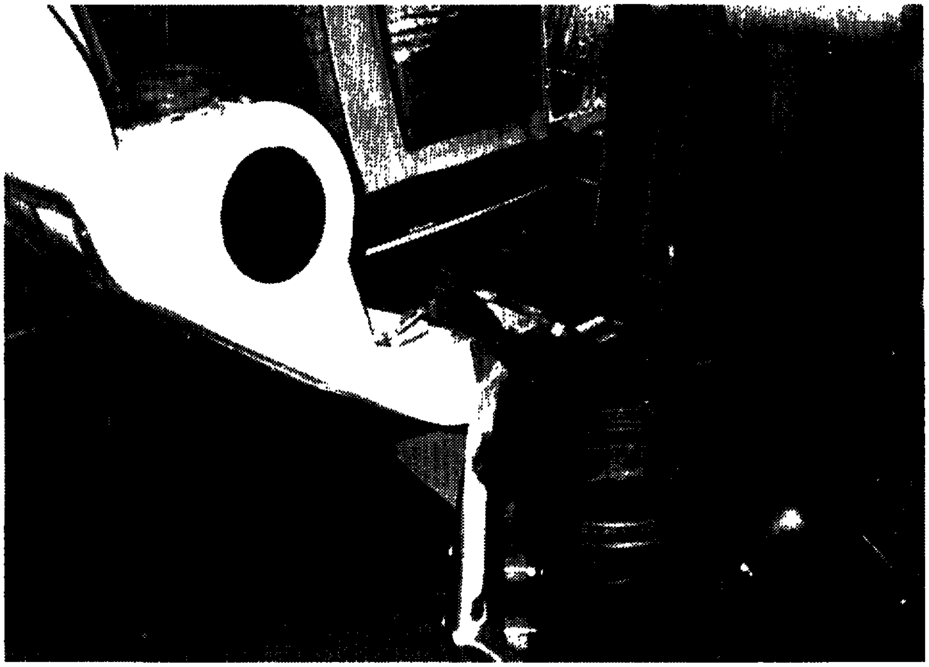


Figure 3-6. Redesigned air filter

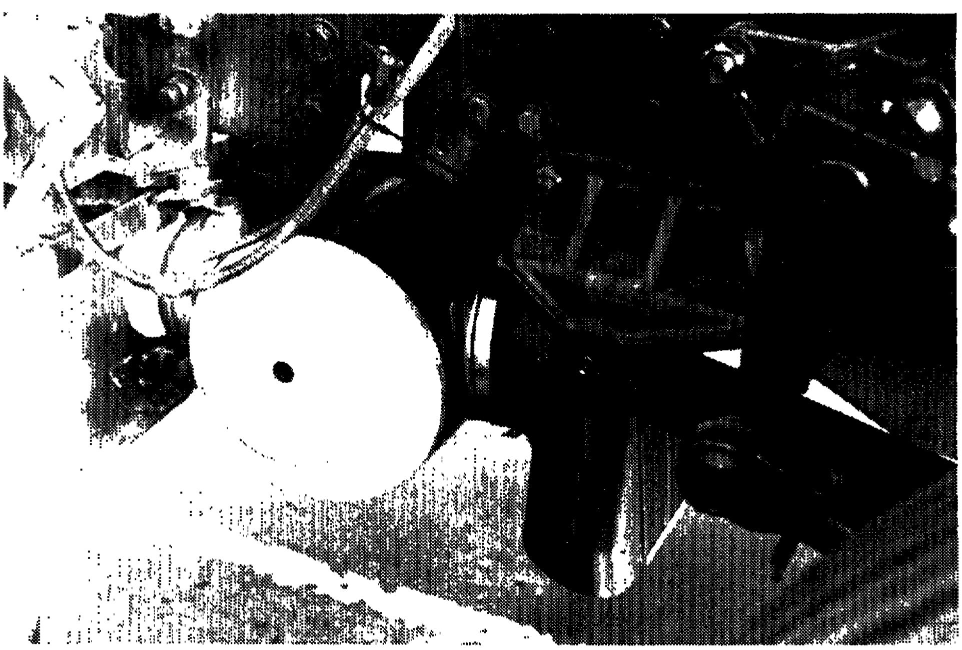


Figure 3-7. Interim air filter

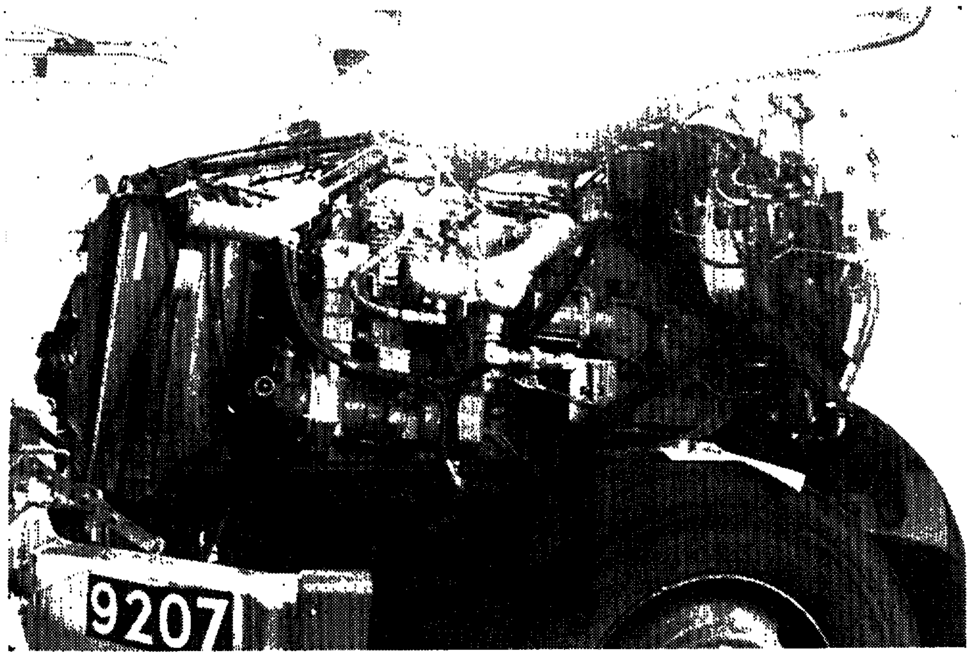


Figure 3-8. G3406LE engine installed in the tractor

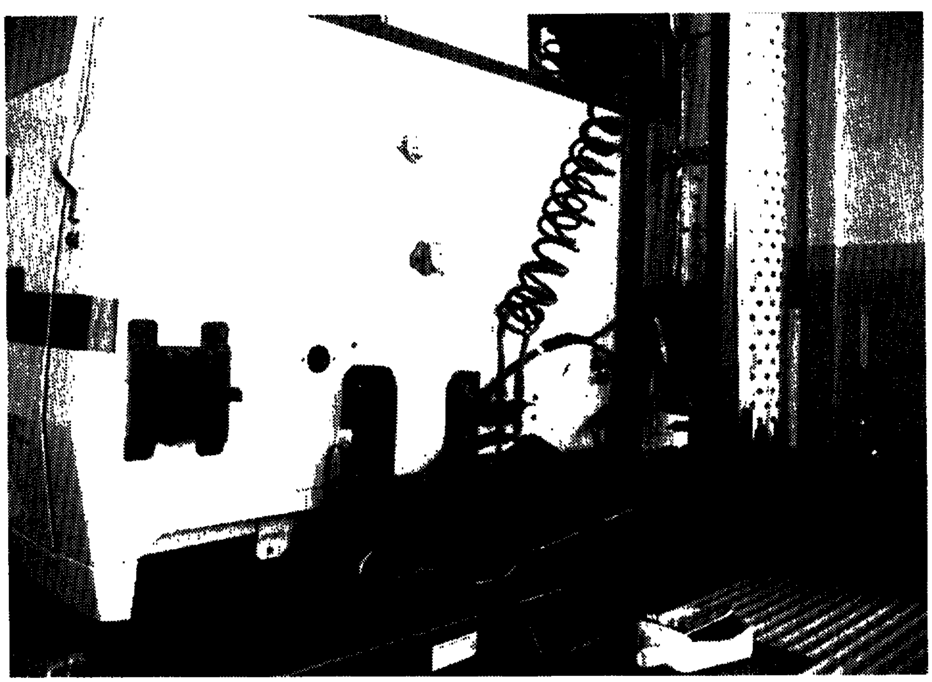


Figure 3-9. Muffler/stack support

The battery box, with four 12-V batteries, was originally located on the right frame rail behind the diesel fuel tank. This was remounted directly behind the cab.

An effort was made to wire the primary fuel pressure gauge transducer to the dash-mounted fuel tank gauge using the circuit provided by the manufacturer. The circuit was wired according to the manufacturer's instructions; however, the dash-mounted fuel gauge did not respond correctly. This task was suspended while conversion of the vehicle continued.

When the engine and fuel system installation was complete, an engine functional check and cooling system audit were performed at Power Systems on the chassis dynamometer. A view of this test in progress is shown in Figure 3-10.

The engine's A/F ratio was monitored during transients. The software had been programmed to drive the engine rich during a load acceptance, and to lean the engine when load was removed. It was observed that, during shifting, the control was doing the opposite of what it was supposed to do, resulting in poor engine response characteristics.

The problem was diagnosed as slow response from the oxygen sensor. The boss in which the sensor was mounted was heavily shielded when it was developed for the generator set engine. This was required to keep the sensor out of the direct exhaust flow, but this caused the sensor to cool down and lose accuracy. Fixing this problem would have required a significant amount of engine testing.

Therefore, the A/F ratio control on the truck was disabled. The gas control valve actuator was programmed to a fixed position to maintain a constant A/F ratio. Running the engine is this mode resulted in good engine performance. The truck was left in this operating mode for the remainder of the project.

The cooling audit results indicated that the existing cooling system was functional to ambient temperatures of 47°C (116°F). Had the 43°C (110°F) target not been reached, a larger radiator, provided by Ford, would have been installed in place of the original radiator to increase the vehicle's cooling capacity.

Figure 3-10. Cooling audit

During the cooling audit, Caterpillar noted that the exhaust backpressure with the single catalyst and muffler exceeded the maximum backpressure specified for this engine. A consequence of excessive exhaust backpressure is higher combustion temperatures caused by poorer breathing. As a result, Caterpillar modified the spark advance to maintain an adequate margin against detonation. It was estimated that this measure reduced the engine's maximum horsepower by 10 percent. Caterpillar initiated the procurement of a second catalyst/muffler unit for a dual-exhaust system; however, the CNG tractor was permitted to operate in service with a single exhaust until this unit was delivered in April 1993, 5 months into the field evaluation.

3.4 FIELD EVALUATION

Several engineering improvements were made to the CNG tractor and its engine during the field evaluation. These improvements are summarized in Table 3-5 and discussed below.

Table 3-5. Field evaluation summary

Date	Improvement Made
October 1992	Heat insulation added to muffler and turbocharger
January 1993	Min-max governor strategy
April 1993	Change from single to dual exhaust
August 1993	Improved radiator fan control with plastic-bodied thermistor
August 1993	Installation of dash-mounted pressure indicator

3.4.1 Heat Shields

During the first month of the field evaluation, Vons discovered that the CNG tractor's exhaust heat was higher than that of a diesel engine and had caused the deterioration of wires near the turbocharger and of the rubber seal around the rear cab window near the muffler. To remedy this situation, Vons replaced the affected items, installed a shield with insulation around the turbocharger, and added insulation to the muffler; this insulation is shown in Figure 3-11. No further heat deterioration occurred in these areas.

3.4.2 Governor Reconfiguration

The CNG tractor's electronic governor was reconfigured by Caterpillar in January 1993, approximately 2 months into the field evaluation. The goal of the reconfiguration was to improve throttle response and eliminate a low-frequency surge at cruise. The initial governor configuration used a speed error determination to select one of two gain factors, high or low, in controlling the throttle plate response to the throttle pedal. High gain was invoked only if the speed error, i.e., the difference between rpm demanded (inferred from throttle position) and actual rpm, was more than 200 rpm. This was intended to provide rapid throttle plate response to the throttle pedal when needed. The low gain factor was intended to provide a stable idle and smooth response to small changes in throttle pedal position.

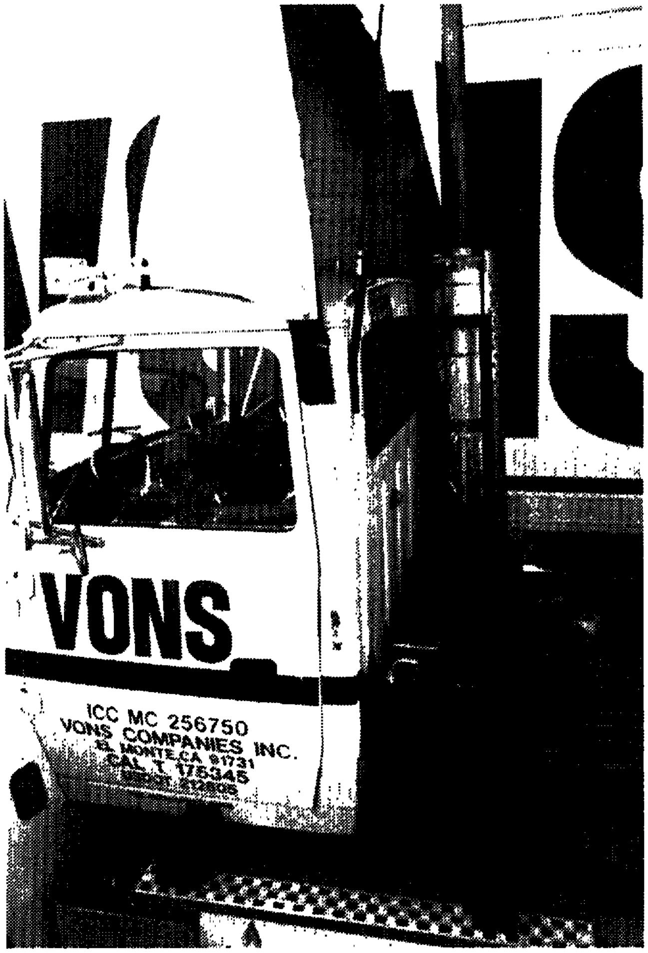


Figure 3-11. Heat insulation

Several concepts were considered for reconfiguring the electronic governor. One was to modify the existing proportional/integral/derivative (PID) governor strategy, replacing the "speed error" signal with "absolute speed" as the input variable for selecting the gain factor. In this approach, the high and low gain factors were supplanted by a full menu of gain factors, each used for a specific rpm range. The concept finally adopted was to program the governor such that movement of the throttle plate between its minimum and maximum positions corresponds linearly to movement of the throttle pedal between its minimum and maximum positions. This is referred to as a "min-max" strategy. A feature of this approach is that the governor will intervene and close the throttle as needed to prevent the engine from exceeding its maximum allowable, or high-idle, speed. In addition, the governor will regulate the throttle position at idle to maintain the correct idle speed. Caterpillar implemented the min-max strategy after road tests showed that it gave the most satisfactory response to driver input.

3.4.3 Dual Exhaust

From the initial tests of the CNG engine following its installation in the vehicle, it was known that the single catalyst/muffler exhaust system was too restrictive for the engine. At 6 months into the demonstration, a second catalyst/muffler unit was supplied by Caterpillar. The installation of the dual exhaust system, shown in Figure 3-12, was engineered by Acurex Environmental, and performed by Power Systems. Location of the second catalyst/muffler unit on the left side of the tractor, opposite the original single exhaust stack, required relocation and replumbing of much of the CNG fuel system, including the fuel receptacle, pressure regulator, and pressure gauges. The original gas panel is shown in Figure 3-13, and the redesigned panel in Figure 3-14. The routing of the exhaust pipe to the original catalyst/muffler was retained; however, a "Y" joint was substituted for the elbow just above the point where the pipe passes vertically between the right frame rail and the transmission. The second branch of the exhaust system begins at this point, with a horizontal tube crossing over to the left side of the chassis. The second catalyst/muffler and exhaust stack is installed in a configuration that is an exact mirror image of the original catalyst/muffler and stack. An identical custom support structure for the left side exhaust was specified, fabricated, and installed. A horizontal tie bar was added, joining the tops of the twin supports for added stability. Figure 3-12 shows the completed dual-exhaust system.

When this work was completed, the vehicle was tested on the dynamometer at Power Systems to measure full-load exhaust backpressure. Earlier tests with the single exhaust indicated that the exhaust backpressure was 14 kPa (56 in H_2O), twice the Caterpillar-specified maximum of 7 kPa (28 in H_2O). Testing with the dual-exhaust system installed showed a full-load exhaust

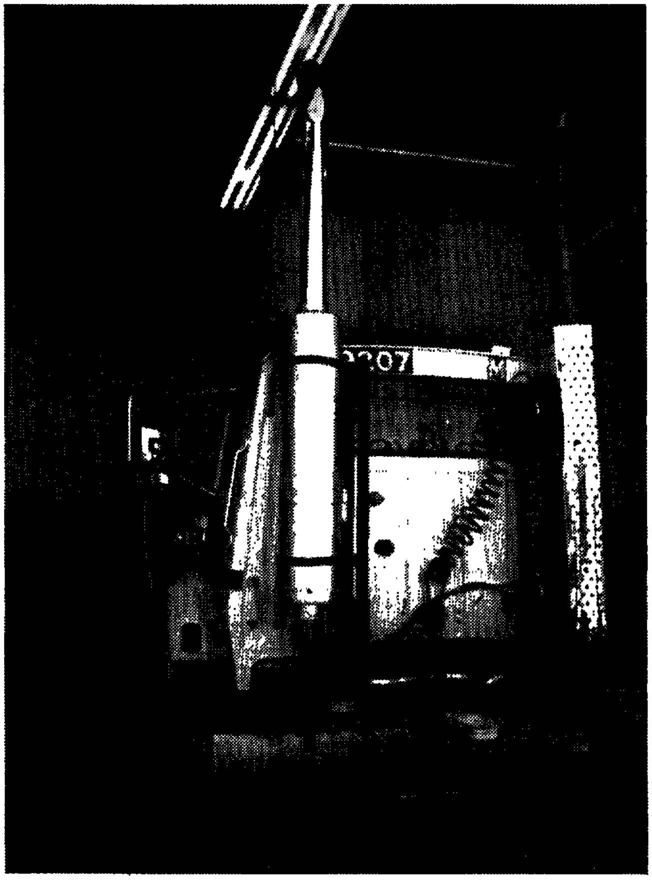


Figure 3-12. Dual exhaust

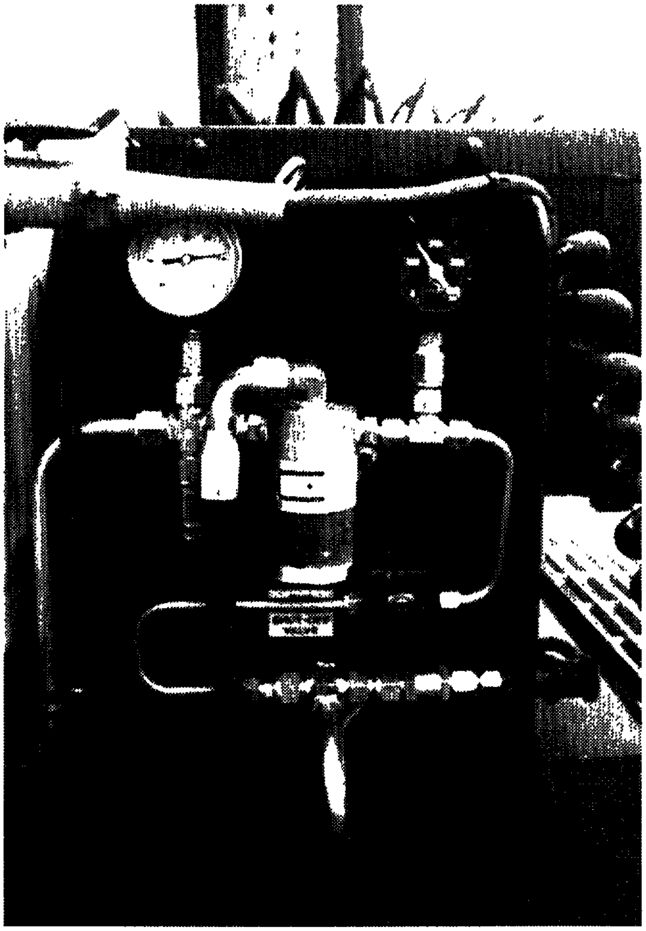


Figure 3-13. Original gas panel

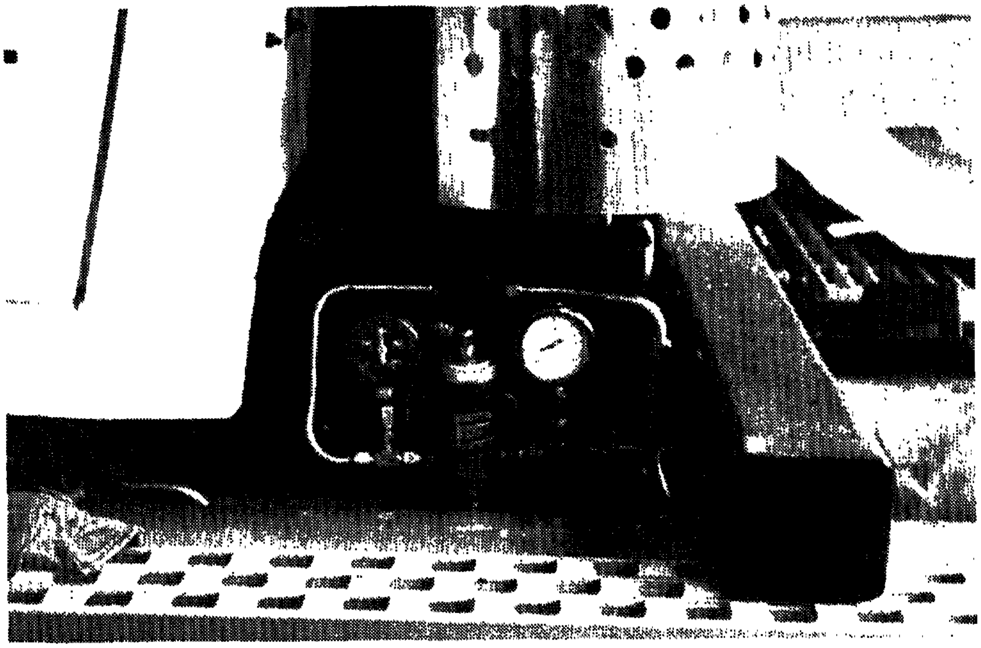


Figure 3-14. Redesigned gas panel

backpressure of only 3.5 kPa (14 in H_2O), half the 7 kPa (28 in H_2O) maximum. This result enabled Caterpillar to reprogram the spark timing back to the optimal setting established during their development of the engine. Operational data from the field evaluation showed an increase in fuel economy following installation of the dual exhaust. However, because the dual exhaust was installed during a period when accurate fuel metering was unavailable, and because other changes, such as engine returning, were also made during this period, it is impossible to quantify the effects of the dual exhaust alone on fuel economy.

3.4.4 Radiator Fan Control

About 9 months into the demonstration, the CNG tractor's driver alerted Acurex Environmental that there was an apparent anomaly in the duty cycle of the clutch-operated radiator fan. The driver reported that, following ascent of the Grapevine, the radiator fan remained engaged for an extended period while the vehicle cruised or coasted downhill with its air conditioning off and the driver's coolant temperature gauge showing a normal temperature. The fan is controlled by the air conditioning system, the engine coolant temperature, and the inlet manifold air temperature. Under boost conditions, the inlet air temperature is raised by adiabatic heating in the turbocompressor, and the air must be cooled in the aftercooler prior to entering the inlet manifold. A thermistor mounted in the inlet manifold will cause the radiator fan to engage at a set temperature, increasing the effectiveness of the aftercooler when necessary.

Caterpillar, Vons, Power Systems, and Acurex Environmental investigated the hardware and control inputs affecting the fan. A preliminary test indicated that all hardware was operating correctly. Attention was turned to the thermistor mounted in the inlet manifold of the engine. Caterpillar provided a table of the voltage-temperature relationship of this unit, and advised Acurex Environmental of the switching parameters that govern fan operation. A test was run, which showed that the fan was being switched on and off at the correct voltage outputs generated by the thermistor. However, the next test, run with a calibrated thermocouple mounted in the inlet manifold near the thermistor, showed that the thermistor response lagged behind the true inlet air temperature by several minutes during transient operation. The programming of the control is such that the fan will turn on, when the thermistor indicates a temperature of 40°C (104°F), and off, when it indicates a decrease to 35°C (95°F). Operation of the fan is required when the engine is at high boost levels, in order to increase the effectiveness of the aftercooler in cooling the inlet air charge. The inlet air must be cooled in the aftercooler to below 54°C (130°F) to maintain an adequate margin against detonation in this engine. The test showed that, following an excursion to high power, the fan would remain on almost indefinitely under 32°C (89°F) ambient conditions because of high thermal inertia, and perhaps because of heat conductivity of the brass-bodied thermistor. In this test, the thermocouple indicated that following a high power excursion the inlet manifold air temperature quickly returned to a few degrees above ambient. This indicated that the fan may have been operating in service far more than necessary.

Fortunately, Caterpillar had identified the same problem in their 3500 family of gas engines and had just updated the thermistor for that engine series. Caterpillar agreed to engineer the same update for the G3406LE engine in this demonstration. The update consisted of a new plastic-bodied thermistor, and a new personality module with programming changes. The programming changes consisted of look-up table revisions for compatibility with the new thermistor, and revised switching points. The switching points were revised, at Acurex Environmental's suggestion, to take advantage of the faster response of the new thermistor and thereby maximize the potential fuel economy gain. The new components were installed in August 1993.

Testing showed that the temperature response of the new thermistor was virtually instantaneous, and it was noted that the fan cycled off immediately following the end of a high-power excursion. Operational data from the field evaluation showed an increase in fuel economy following this engineering change. However, because the change was made during a period when accurate fuel metering was unavailable, and because other changes, such as conversion to dual exhaust, were also made in this period, it is impossible to quantify the effects of the fan control change alone on fuel economy.

3.4.5 In-dash Pressure Gauge

During the vehicle conversion, a device to drive the standard dash-mounted fuel gauge as a CNG pressure indicator was tested, but could not be made to work properly. Working with the manufacturer of the original device, Acurex Environmental suggested another approach, which proved successful, and which resulted in the manufacturer releasing a new product — a remote pressure indicator matched to the transducer output, which mounts in place of the stock fuel gauge. Acurex Environmental obtained this pressure receiver, shown in Figure 3-15, and successfully installed it in the vehicle in July 1993.

3.5 MAINTENANCE FACILITY MODIFICATIONS

No maintenance facility modifications were made. The vehicle was worked on outdoors or under covered maintenance bays that were open to the outdoors. Through safety training, the

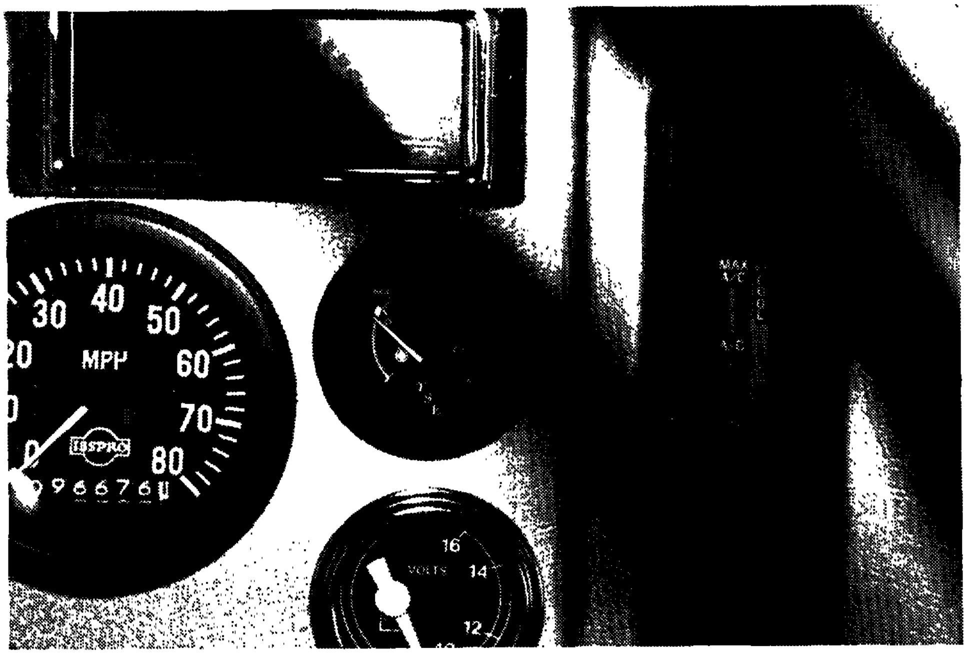


Figure 3-15. Fuel pressure indicator

mechanics were well informed about the properties and potential hazards of CNG, and the need for CNG leaks to be avoided whether indoors or outdoors.

SECTION 4

FIELD EVALUATION

4.1 VEHICLE OPERATIONS

4.1.1 Chronology

The field evaluation phase of this project began on October 12, 1992, with the vehicle's inaugural voyage to Bakersfield, California, and ended with its final trip to Bakersfield on December 1, 1993. During this 14-month period, the vehicle accumulated 52,082 in-service km (32,369 in-service mi) and 829 engine hours. Table 4-1 summarizes the operating data gathered in the field evaluation. Overall uptime in Table 4-1 is defined as the number of days operated divided by the number of days the vehicle would have operated had it experienced no mechanical problems. CNG-specific uptime is defined as the number of days operated divided by the number of days the vehicle would have operated had it experienced no engine- or fuel-related mechanical problems. Figure 4-1 shows the CNG tractor in service.

Table 4-1. Operational data summary

Date entered service	10/12/92
In-service mileage through December 1993	52,082 km (32,369 mi)
Engine hours through December 1993	829
Fuel economy	50.6 diesel-equivalent L/100 km (4.64 mi/diesel-equivalent gal)
Fuel economy compared to control vehicle	30% lower
Overall uptime	49%
CNG-specific uptime	63%

Figure 4-1. CNG tractor in service

Table 4-2 is a monthly chronology of the field evaluation, showing days of operation, significant occurrences, and explanations of downtime. Figure 4-2 shows the monthly mileage of the CNG tractor. The fuel economy of the CNG and diesel control tractors is shown in Figure 4-3.

4.1.2 User Survey

When the field evaluation was well underway, a user survey was prepared and given to key personnel involved in the demonstration. Table 4-3 lists the personnel participating in the survey.

A copy of the survey, with all responses to each question tabulated, is included in Appendix A. The survey results indicated that fuel economy and range, as expected, were the major issues. Downtime was also an issue, while safety was generally viewed positively. The vehicle's performance and the fuel system's simplicity were also viewed positively. The mechanics

Table 4-2. Chronology of significant events

Date	Significant Event
October 12, 1992	Inaugural trip to Bakersfield, California
December 3, 1992	CNG tractor "grounded" because of incompatibility of interim air filter with wet weather; redesigned air filter not yet received from Ford
January 7, 1993	New min-max governor strategy implemented with good results
January 23, 1993	Installation of all-weather air filter completed
January 25-July 22, 1993	Fuel metering at Sun Valley CNG station unavailable because of meter failure
March 15, 1993	First report of engine misfire
April 13, 1993	Press events in Burbank and Bakersfield
April 19-30, 1993	Installation of dual-exhaust system
June 8, 1993	Cause of misfire traced to spark plug gap
June 14-18, 1993	Replacement of primary regulator because of contamination
June 25, 1993	Overhaul of fuel solenoid valve because of contamination
July 8, 1993	Performance test of CNG tractor
July 20, 1993	Hill-climb test of CNG tractor
July 22-28, 1993	Investigation of radiator fan control
July 28, 1993	Installation of dash-mounted fuel pressure gauge
July 29, 1993	Full engine tune-up prior to emission test
August 20, 1993	Revision of radiator fan control
September 15-16, 1993	Attempted emission test at MTA; aborted because of dynamometer malfunction
October 20-November 10, 1993	Detection and repair of failed turbocharger wastegate valve
December 1, 1993	Last in-service trip to Bakersfield
December 16, 1993	Replacement of failed exhaust oxygen sensor
January 27-28, 1994	Emission test at MTA
February 9, 1994	Inspection of CNG cylinders; discovery of significant surface damage

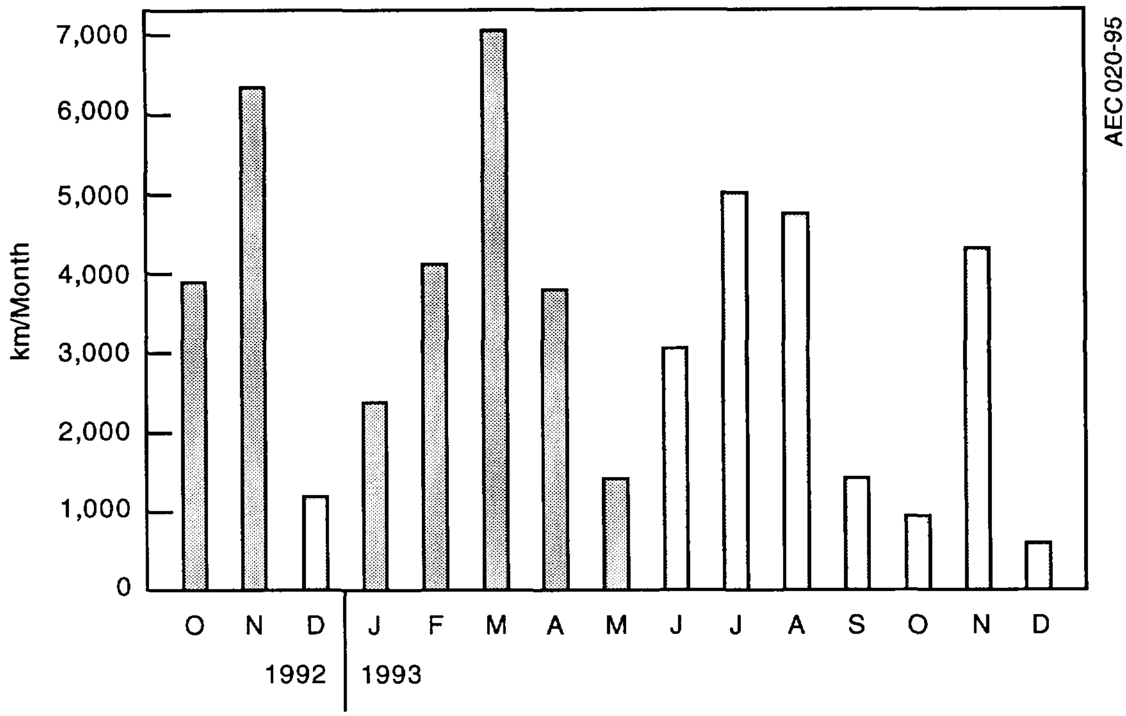


Figure 4-2. Monthly mileage of the CNG tractor

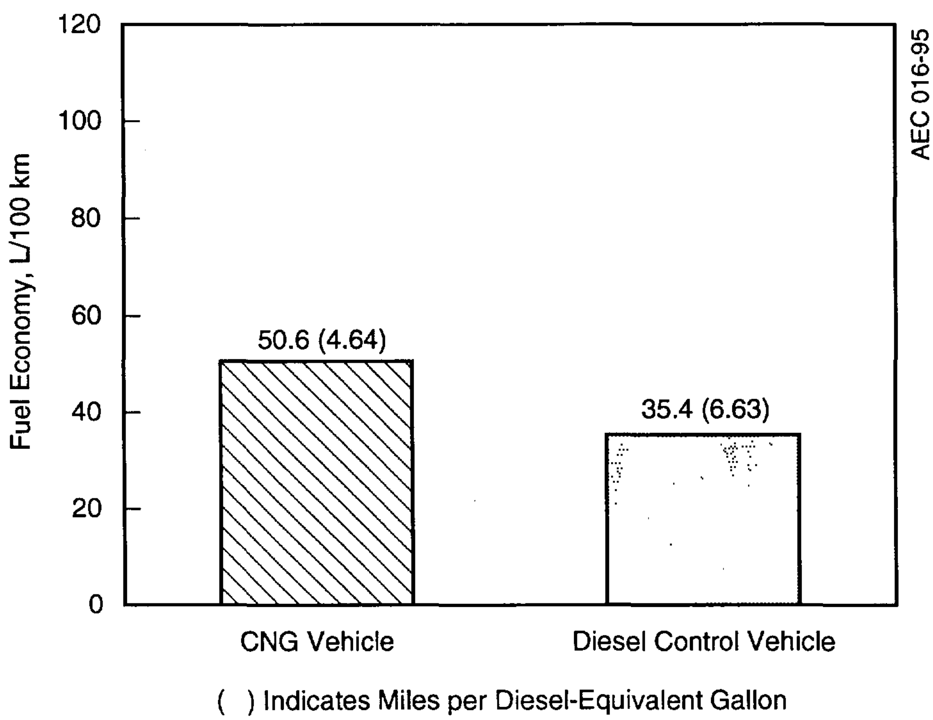


Figure 4-3. Fuel economy of the CNG and diesel tractors

Table 4-3. Participants in user survey

Rick Webb	Operator	Vons
Alan Yamamoto	Mechanic	Vons
Cliff Sheridan	Maintenance Supervisor	Vons
Don Kuchenbecker	Maintenance Manager	Vons
Paul Wolkow	Mechanic	Power Systems
Frank Rytych	Lead Mechanic	Power Systems
Bill Turner	Truck Shop Foreman	Power Systems
Kevin Campbell	Truck Service Manager	Power Systems

interviewed indicated a desire for more documentation and more troubleshooting guidance. Respondents were generally in favor of future natural gas vehicle purchases by their companies.

4.1.3 Operational Issues

4.1.3.1 Fuel Economy

The in-use fuel economy of the CNG tractor was disappointingly low at the beginning of the field evaluation. Observed fuel economy in the first 2 months of the field evaluation was 54.7 diesel-equivalent L/100 km (4.3 mi/diesel-equivalent gal), versus 35 L/100 km (6.7 mi/gal) observed for the diesel control vehicle during the same period. These observations compare to estimates made at the design stage of 39.1 L/100 km (6.0 mi/gal), for diesel tractors on this route, and 43.5 L/100 km (5.4 mi/gal), for the CNG tractor. The low fuel economy made it necessary to fuel the vehicle twice per trip, in Sun Valley and in Bakersfield. Several engineering improvements were implemented during the field evaluation, as described in Section 3.4. The net improvement in fuel economy, to 50.6 L/100 km (4.64 mi/gal), realized from these improvements could theoretically eliminate the need to refuel twice per trip on shorter round trips, e.g., 400 km (250 mi); however, this was not tested in practice because of the potential inconvenience of running out of fuel.

4.1.3.2 Axle Ratio

The rear axle ratio of the CNG tractor was not changed when the vehicle was converted to CNG operation. In highway use, the truck was driven at speeds from 89 to 93 km/hr (55 to 58 mph). The torque characteristics of the CNG engine led the driver to cruise in the next-to-top gear of the 13-speed transmission. Ideally, the rear axle ratio of the vehicle would have been matched to the desired cruise rpm in top gear. This benefits acceleration by allowing the use of all the transmission speeds for acceleration to cruising speed, and normally benefits fuel economy as well by ensuring that the engine is operated at its most efficient rpm during cruise. As the CNG tractor did not undergo this level of refinement, its full acceleration potential and fuel economy potential may not have been realized.

4.1.3.3 CNG Stations

Unlike the diesel tractors in Vons' fleet, which are fueled at the El Monte distribution center at the end of each trip, the CNG tractor was required to deviate from its route for fuel. Fueling at the Sun Valley CNG station entailed a detour of 10.5 km (6.5 mi). The time spent off the route for fueling at MTA was typically 40 minutes. More time was required when the tractor was not fueled immediately upon its arrival. Fueling at the Bakersfield CNG station, located only half a mile off the main route, required about 25 minutes due mainly to the longer fill time.

4.2 PERFORMANCE TESTING

4.2.1 Acceleration

Acceleration tests were conducted on the CNG tractor and a diesel control tractor, each towing a trailer containing a typical load. For each vehicle, six runs were timed back-to-back in opposite directions on a single length of road. The road used for testing the CNG tractor is a length of 4-lane divided road adjacent to State Highway 99, about 1.6 km (1 mi) south of Alameda, Kern County, California, as shown in Figure 4-4. The diesel control tractor was tested on Valley Boulevard in Pomona, California, in the vicinity of Temple Avenue. The averaged results are illustrated in Figure 4-5. Test data and calculations appear in Appendix B.

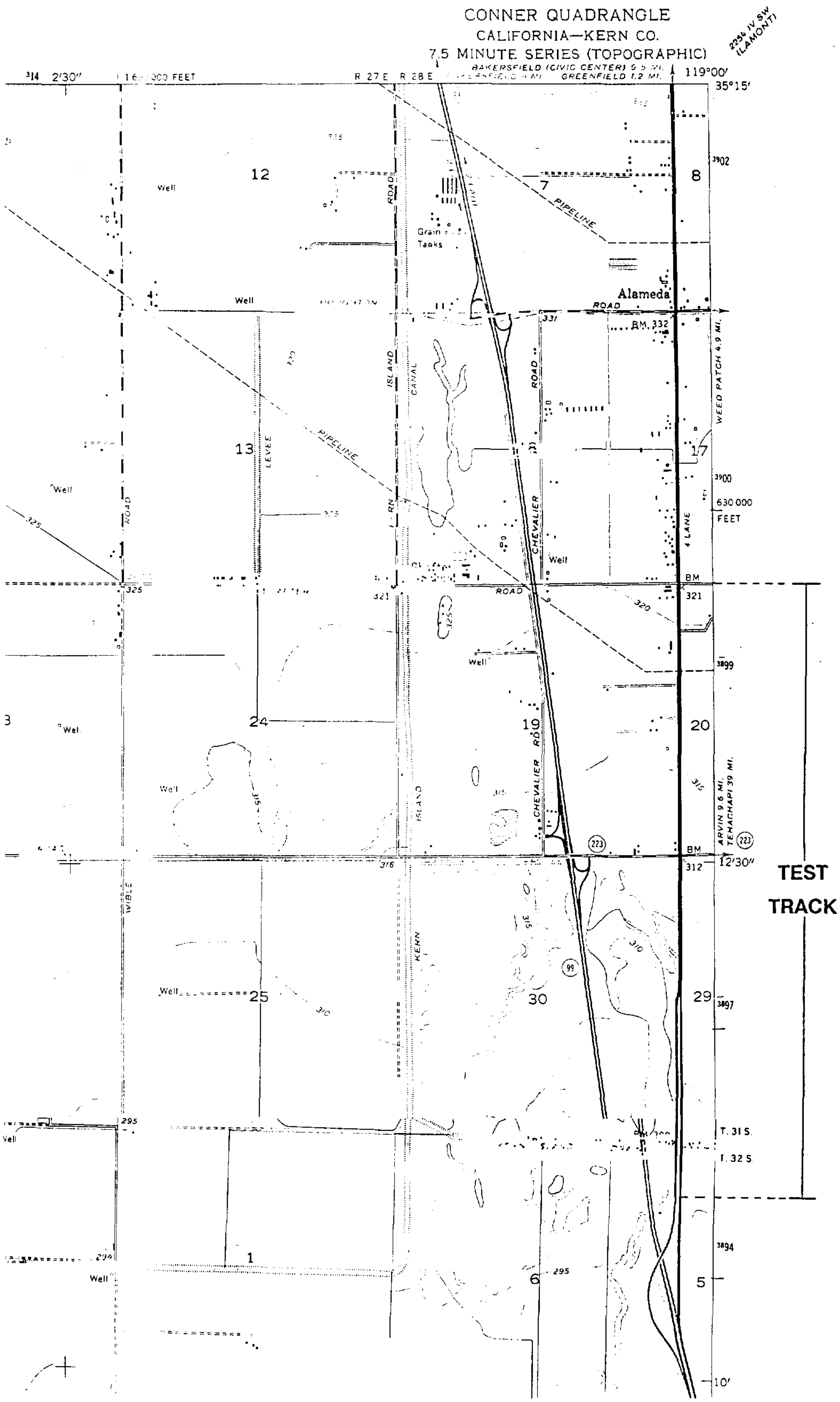


Figure 4-4. Road used in performance testing

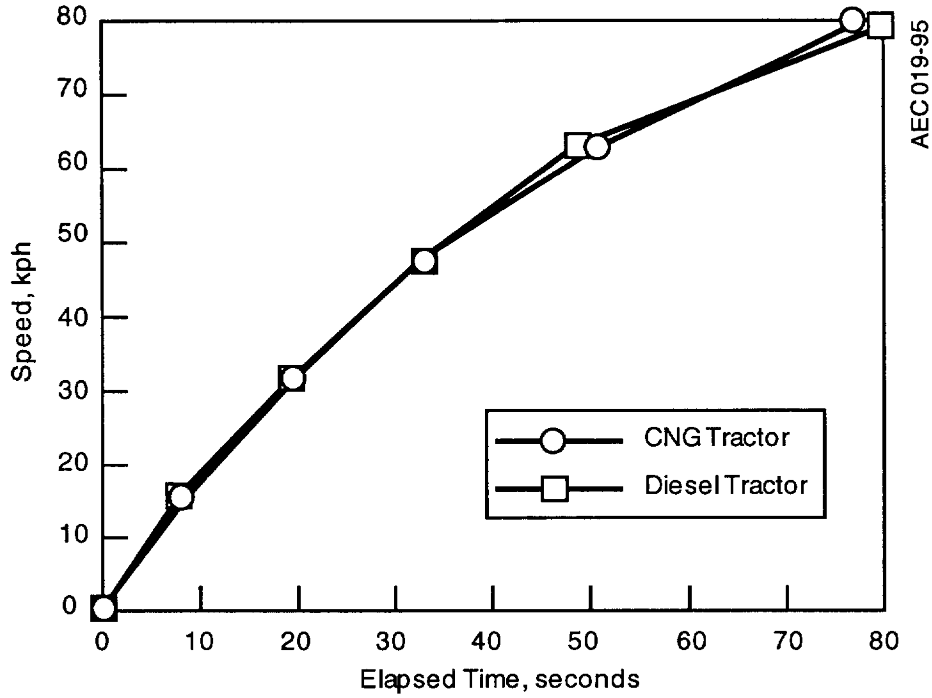


Figure 4-5. Acceleration performance of the CNG and diesel tractors

4.2.2 Hill Climb

Hill-climb tests were also conducted with the CNG tractor and a diesel control tractor, both towing a trailer containing a typical load. Both tests were run on Kellogg Hill, one of the larger hills found in the greater Los Angeles freeway system, located on the San Bernardino Freeway immediately west of the Pomona city limit. The results are illustrated in Figure 4-6. Test data and calculations are presented in Appendix B.

4.3 MAINTENANCE

4.3.1 Preventive Maintenance

Scheduled maintenance of the non-fuel-related systems of the CNG tractor was performed by Vons according to its established fleet practice. Appendix B includes a compilation of the labor and materials expended for scheduled maintenance during the field evaluation.

Additional preventive maintenance practices were instituted for this vehicle, the most important of which was frequent, regular oil analysis. This was accomplished by drawing samples

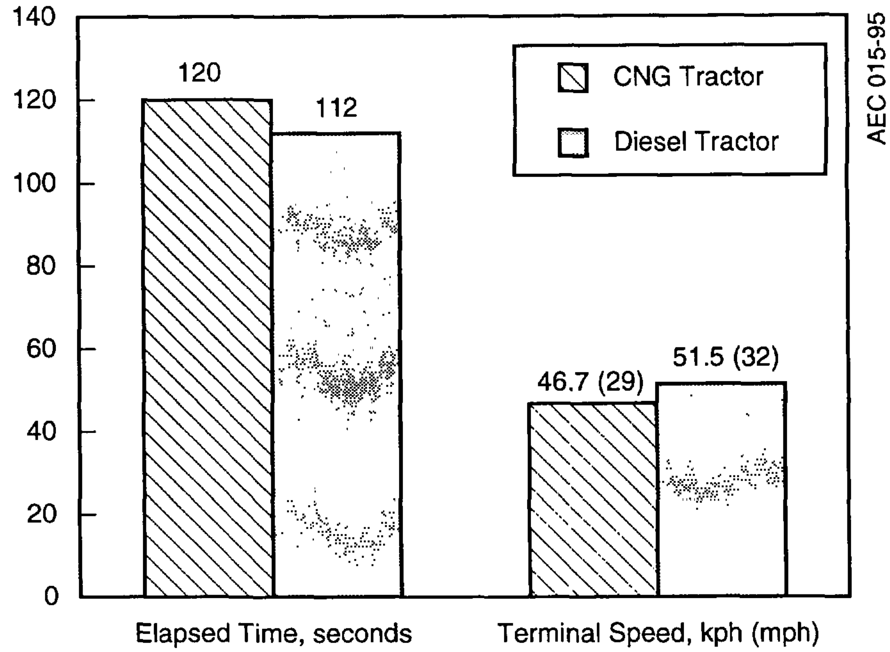
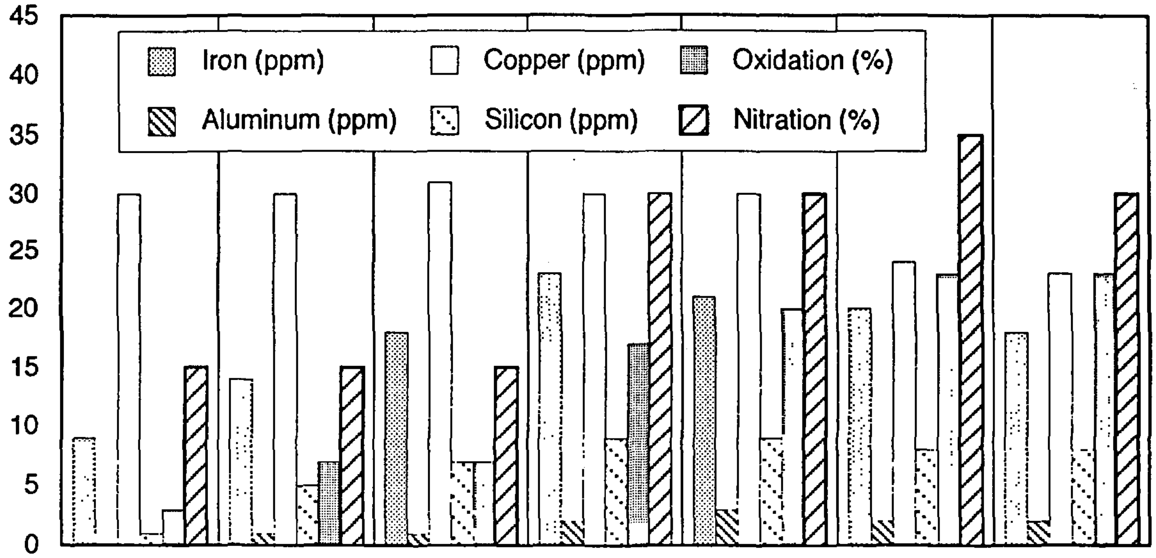


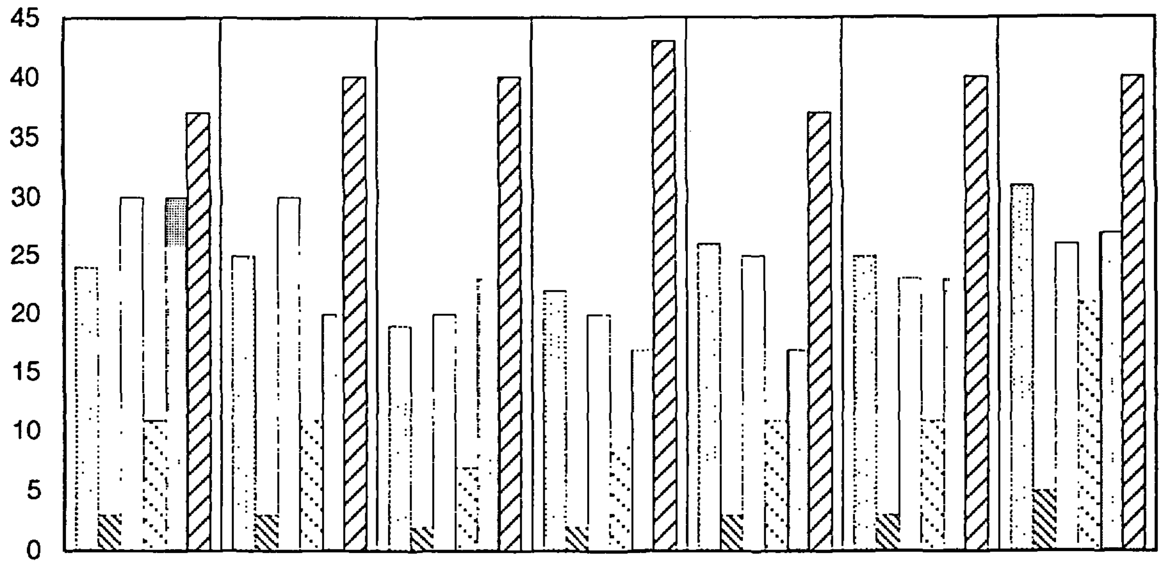
Figure 4-6. Hill-climb performance of the CNG and diesel tractors

of crankcase oil when the engine was hot, at operating intervals of approximately 50 hours; by measuring oil properties and contaminant levels; and by determining oxidation and nitration levels for each sample. Caterpillar requested the oxidation and nitration analyses to establish an oil drain interval for this engine. The crankcase oil showed no significant deterioration in more than 800 hours of operation, and was not drained during the course of the field evaluation. The oil analysis history of the CNG tractor is plotted in Figure 4-7. The high water content shown in an early sample was attributed to the sample being drawn when the engine was cold.

Acurex Environmental performed frequent, routine visual and functional inspections of the fuel system during the field evaluation. These inspections gave the field support engineer the opportunity to note any visual or functional changes in the CNG storage tanks and fuel system. Checks of the pressure gauge readings and leak-down tests using the manual valve allowed for the early detection of problems in the primary regulator and in the solenoid shutoff valve. These



Sample Date	10/15/92	11/12/92	12/2/92	1/29/93	2/22/93	3/10/93	3/29/93
Total km	2,171	7,672	11,747	14,174	16,502	21,247	25,128
(Total mi)	(1,349)	(4,768)	(7,301)	(8,809)	(10,256)	(13,205)	(15,617)
Total Hours	31	113	175	216	253	328	390
Oil Added L (qt)	0 (0)	1.9 (2)	1.9 (2)	3.8 (4)	1.9 (2)	3.8 (4)	2.8 (3)



Sample Date	4/7/93	6/13/93	7/9/93	8/10/93	8/25/93	10/11/93	11/29/93
Total km	28,040	33,226	36,407	39,721	43,589	46,204	50,362
(Total mi)	(17,427)	(20,650)	(22,627)	(24,687)	(27,091)	(28,716)	(31,300)
Total Hours	434	522	573	629	688	730	800
Oil Added L (qt)	4.7 (5)	3.8 (4)	2.8 (3)	2.8 (3)	2.8 (3)	0 (0)	6.6 (7)

Figure 4-7. CNG tractor oil analysis history

problems are further described in Section 4.3.2.7. Routine inspection of the CNG storage tanks did not entail the rigorous procedure used on February 9, 1994, at which time surface damage was found on two cylinders in areas not visible to a standing observer.

4.3.2 Problems, Reliability, and Durability

4.3.2.1 Air Filter

The CNG tractor entered service with an interim air filter installation in which the air filter and its inlet were placed immediately behind the front bumper. It was envisaged that the specially designed air filter installation engineered by Ford would become available soon after the tractor's introduction into service. Ford's design featured an air inlet in the upper hood area, with provision for the separation of water from the air prior to the air filter. However, the permanent air filter was not readied in time for the onset of winter driving conditions on the CNG tractor's route.

Caterpillar was concerned about the interim air filter's exposure to moisture during wet road conditions, and asked that the tractor not be driven in wet conditions. This effectively grounded the CNG tractor from December 3, 1992 to January 25, 1993, when it returned to service with Ford's permanent air filter installed.

4.3.2.2 Fuel Solenoid Wiring Fault

On March 1, 1993, while the truck was enroute to Bakersfield in regular service, its engine died without warning. The driver attempted to restart the engine, but although it cranked normally, it did not fire. As a result, the truck had to be towed back to El Monte. The following day, the engine started normally.

Diagnostic efforts focused on the electronic control box in the cab. None of the checks or engine tests revealed a fault, and the engine operated normally during all the checks. Caterpillar surmised that a relay might have developed a bad connection, leading to the initial engine shutdown. It was hypothesized that the bad connection was restored by ordinary road vibrations during towing. The relay controlling the fuel solenoid valve was seen as the likely location of the intermittent bad connection. A check indicated that all of the relays were properly installed in their sockets and were free of corrosion.

The truck was placed back into service on March 3, 1993, but the engine died before the truck left the Vons yard. Because it could not be restarted, it became possible to isolate the problem. An overspeed protection device was wired in-line with the fuel solenoid to prevent inadvertent engine overspeeding, such as had occurred during the governor development performed by Caterpillar in January 1993. However, one of the wires connected to this device had broken at the terminal, cutting power to the fuel solenoid. Evidently, the plastic boot on the terminal had held the connection together, and was responsible for the intermittent fault. To correct this problem, ignition voltage was wired directly to the fuel solenoid, bypassing the overspeed device. Caterpillar indicated at this time that the device was no longer needed, as the governor development was complete. As removal of the device would have entailed the installation of a cover plate and a new gasket, the device was left in place. It was verified that the truck would start and run properly, and the truck was returned to service on March 4, 1993.

4.3.2.3 Misfire

Engine misfiring was first reported by the driver on March 15, 1993. This was investigated immediately, but was not verified through dynamometer testing until after the dual-exhaust system was installed in April 1993. Initial efforts to diagnose and eliminate the misfire began with the verification of the A/F ratio, and proceeded on to the testing and replacement of much of the ignition hardware, including the spark plugs, the spark plug extenders, the transformers, and the magneto. An old and a new spark plug are shown in Figure 4-8. Success was finally achieved when it was realized that spark plug gaps were spreading in use, at a much greater rate than Caterpillar had anticipated based upon its experience with stationary natural gas engines. From measurements of spark plug gap and occurrences of misfire under load, it was determined that misfiring was entirely absent with spark plugs newly gapped to the 0.38-mm (0.015-in) specification, but would occur under load if the spark plug gaps were 0.4 mm (0.016 in) or greater. Spreading of spark plug

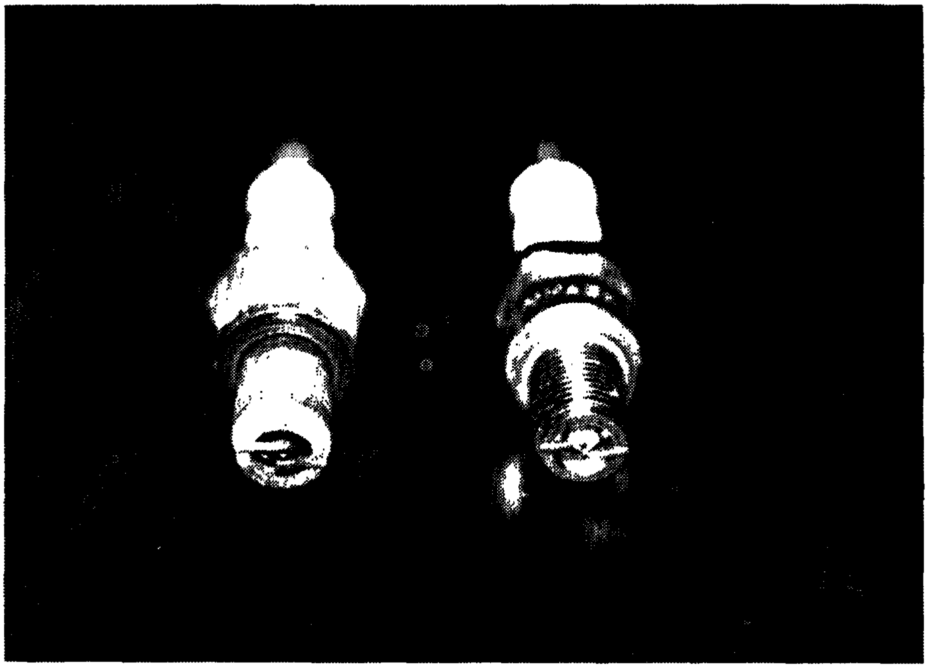


Figure 4-8. Old and new dual-ground strap spark plugs

gaps from 0.38 to 0.4 mm (0.015 to 0.016 in) was observed to occur about every 100 hours of engine operation. In response to the spark plug gap spreading problem, Acurex Environmental reset the spark plug gaps to 0.34 mm (0.0135 in) — 0.038 mm (0.0015 in) smaller than Caterpillar's recommendation — to allow for some spreading and to extend the interval for spark plug regapping. Subsequent measurements revealed that spark plug gaps had spread to about 0.38 mm (0.015 in) over the next 200 hours of engine operation. Misfiring did not recur in this period; however, accumulation of engine hours did not continue, so what additional spark plug gap spreading will occur after 200 more hours of operation is unknown.

4.3.2.4 Exhaust Leaks

Exhaust leaks from various joints near the turbocharger outlet and wastegate assembly were a recurring problem during the field evaluation. The root cause of these leaks was inadequate support of the exhaust pipe attached to the turbocharger outlet. As a result, road vibrations and perhaps thermal expansion caused excessive movement of these joints, in turn causing wear of the ring-type seals and separation of the joints. Figure 4-9 shows the area of the exhaust system in which leaks repeatedly occurred. Additional support was provided following each occurrence of a leak; it is believed that the final configuration provided the support needed to prevent further exhaust leaks in this area. Figure 4-10 shows the exhaust pipe bracket as finally modified. The repair records of the diesel control vehicle indicate that it also required exhaust repairs on several occasions.

4.3.2.5 Personality Module

During troubleshooting of the misfire problem, unrelated problems were discovered in the personality module of the electronic control module (ECM). It was discovered that the ignition

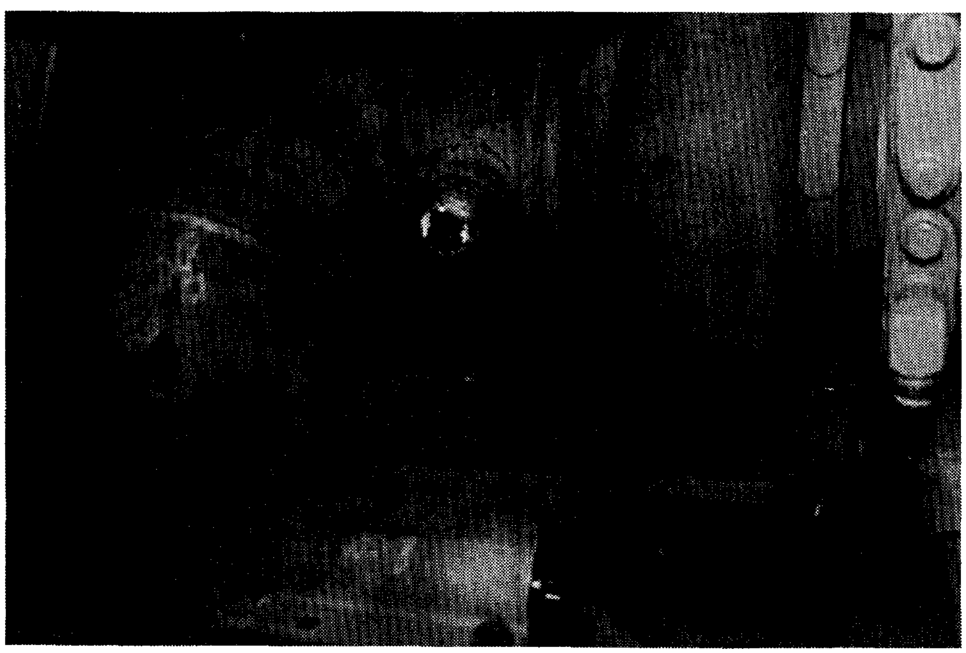


Figure 4-9. Exhaust leak area

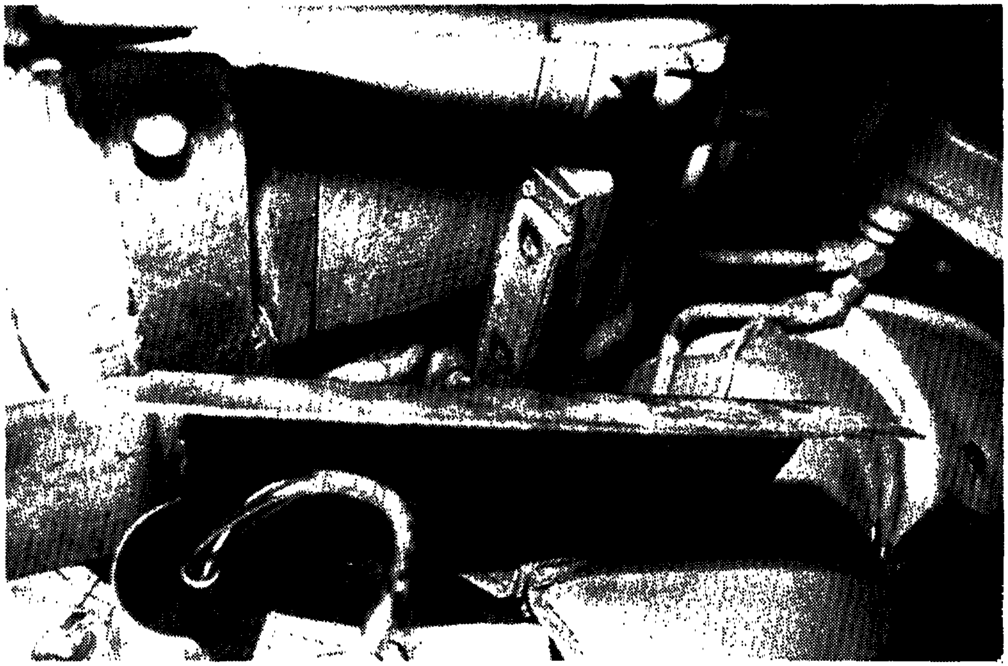


Figure 4-10. Final exhaust bracket configuration

timing at rated power was 17° BTDC, when it should have been 24° BTDC. Caterpillar investigated the cause and traced it to the personality module installed when the governor was reprogrammed. Caterpillar supplied an updated personality module to correct the problem. However, the new module, when installed, did not allow calibration of the installed oxygen sensor. The cause of this was not discovered. Caterpillar supplied an identically configured new module, which restored the oxygen sensor calibration capability.

4.3.2.6 Magneto Interface Box

Investigation of the misfire and personality module problems revealed a third unrelated problem with the MIB. During attempts to set the ignition timing with the updated personality module, it was observed that the timing was advancing to 35°. It was determined that the MIB was not receiving a clock signal from the ECM, putting the MIB into an override mode that advanced the timing fully. Caterpillar supplied a new MIB, which functioned correctly. The malfunctioning unit was returned to Caterpillar for investigation of the failure. Caterpillar determined that water had entered the unit through an unpotted Amphenol bulkhead connector, probably during pressure-washing of the engine. The new MIB had this connector sealed with RTV silicone. Vons and Power Systems were advised to avoid directing water spray toward the MIB when washing the engine.

4.3.2.7 Pressure Regulator

On June 14, 1993, Vons noted that the relief valve adjacent to the pressure regulator was venting natural gas at a low flowrate when the CNG tractor was parked. There should normally be no flow through the regulator under static conditions. Investigating this problem, Acurex Environmental determined that gas was leaking through the regulator when the engine was stopped. This caused pressure to build up above the regulator's setpoint of 1,172 kPa (170 psi). Pressure continued to build up until the relief valve's setpoint of 1,724 kPa (250 psi) was reached, at which point the valve vented gas as intended. A new regulator was supplied by Tescom Corporation (Tescom), the manufacturer, and the original unit was returned to Tescom for analysis. Tescom dismantled the returned regulator and reported that the failure was caused by a buildup of contamination on the regulator seat. Figure 4-11 shows a magnified view of deterioration on the regulator pintle caused by the contamination. The contamination observed inside the regulator inlet, shown in Figure 4-12, and on the seat was a fine, dark, oily grit of unknown origin. The new unit, installed on June 18, incorporated a 40-μm inlet filter intended to protect against contamination. The second regulator experienced a similar failure in September 1993, and was replaced by Acurex Environmental on September 24.

4.3.2.8 Solenoid Valve

In March 1993, it was observed that the solenoid shut-off valve was no longer completely stopping the flow of gas when de-energized. As a result, the manual shutoff valve was closed whenever the vehicle was parked until the solenoid valve could be repaired. Acurex Environmental obtained the repair kit for overhauling the valve, including a new plunger. When the valve was

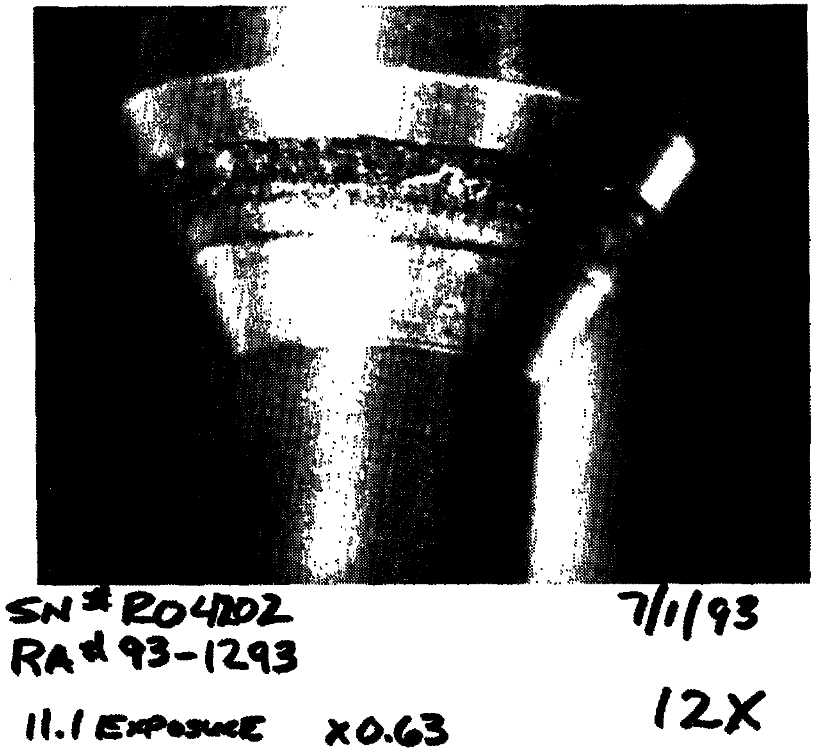


Figure 4-11. Damage to regulator pintle caused by contamination

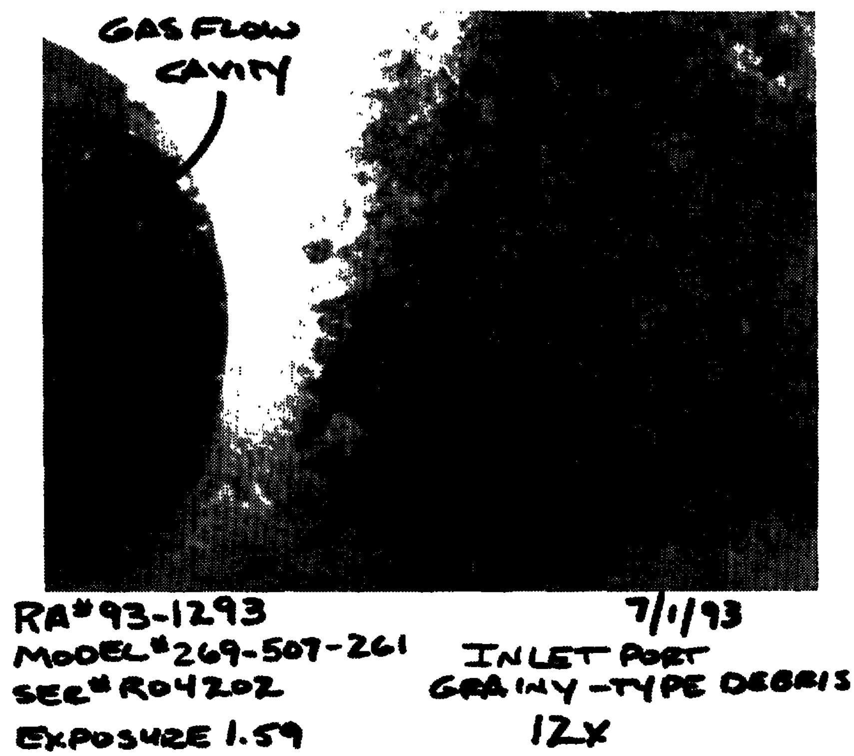


Figure 4-12. Buildup of contamination inside regulator inlet (magnified)

disassembled, it was observed that a contaminant like that found in the failed regulator had accumulated inside the valve. Contamination inside the solenoid valve inlet is shown in Figure 4-13. The rubber seal on the plunger was permanently indented where it contacted the seat. The valve was cleaned, then reassembled with the new parts provided in the repair kit. The overhauled valve worked correctly and gave a positive shutoff when installed on the vehicle.

4.3.2.9 Turbocharger Wastegate

In October 1993, during dynamometer testing of the truck following repair of an exhaust leak at Power Systems, excessively high horsepower and severe detonation were observed, which led to the discovery of a problem with the turbocharger wastegate. An attempt was underway to adjust the A/F ratio to the correct value when these observations were made. As the A/F ratio was being adjusted, the horsepower increased beyond the rated value, and it was later speculated that the inlet manifold pressure was significantly higher than the desired wastegate setpoint of

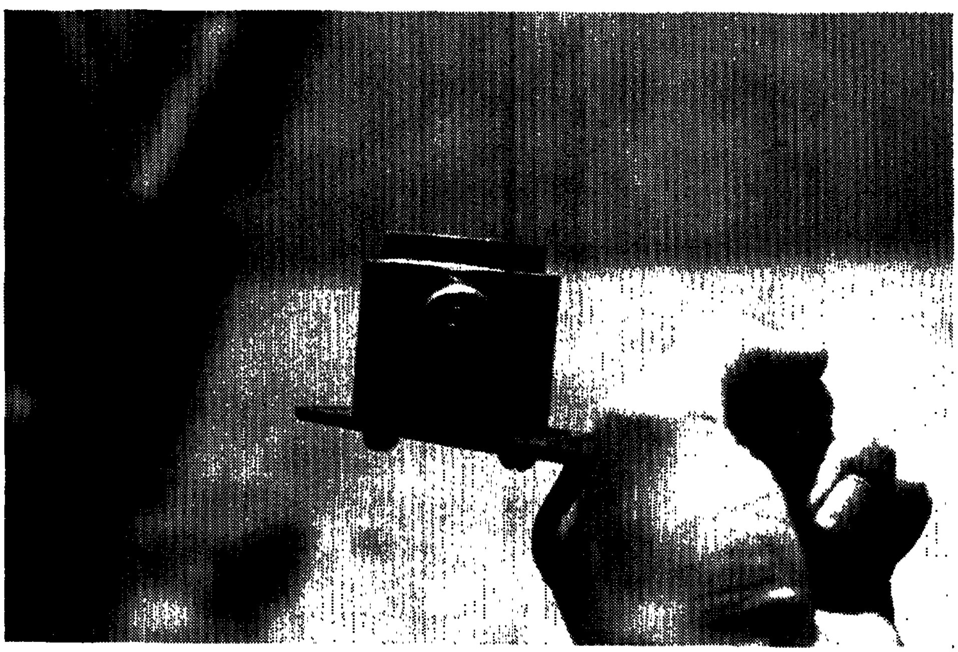


Figure 4-13. Contamination inside solenoid valve inlet

103 kPa (15 psi). Power Systems later determined that the turbocharger wastegate valve was stuck in the closed position, causing the engine to operate on uncontrolled boost pressure. Upon the wastegate's disassembly, the wastegate valve stem was found to have excessive wear on one side, possibly causing it to stick. Figure 4-14 is an illustration of the worn valve.

The wear could have resulted from the horizontal installation of the valve assembly and the high temperatures that the turbocharger encountered in this application, versus the stationary gas engine upon which this engine is based.

As a further consequence of the malfunction, the exhaust heat shields were severely scorched. The inner shield material is rated to a maximum temperature of 593°C (1,100°F) and the outer material is rated to a maximum temperature of 204°C (400°F).

A new wastegate was installed and the heat shields replaced. Because of the excursion beyond rated boost pressure and horsepower, Caterpillar recommended that all cylinders be bore-scoped to check for possible engine damage. This was done by Power Systems, and no indications of damage were found.

4.3.2.10 Oxygen Sensor

An attempt was made to set the A/F ratio following repair of the turbocharger wastegate. A/F ratio is inferred from the voltage signal provided by the oxygen sensor mounted in the exhaust. This signal is displayed as percentages of oxygen on Caterpillar's digital diagnostic tool (DDT). The

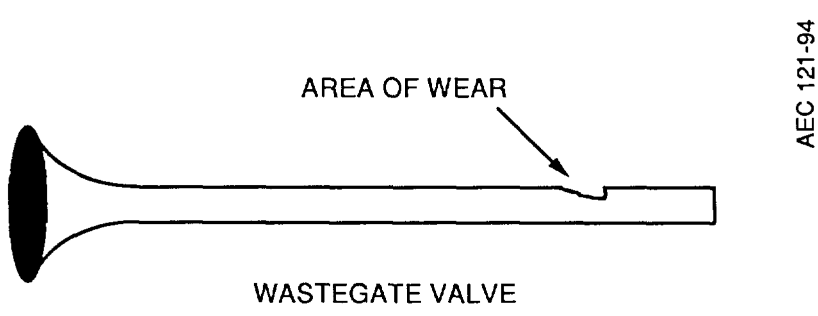


Figure 4-14. Wear on wastegate valve

desired setting for this engine is 7 percent exhaust gas oxygen (EGO) (wet) (λ = 1.51). In this attempt, the DDT initially indicated approximately 7.6 percent EGO (wet) (λ = 1.57); enriching the A/F ratio to the adjustment limit yielded a reading of 7.4 percent, still too lean. The vehicle was returned to service pending further investigation of this matter.

In December 1993, Caterpillar attempted to calibrate the CNG vehicle's oxygen sensor. In several attempts, the same result occurred: the sensor read the ambient oxygen content as approximately 10 percent while under calibration, while the true ambient oxygen is approximately 20.9 percent. The ECM was unable to complete the calibration in the 7 minutes allowed for this routine, and instead displayed fault code 27, "Oxygen sensor calculated slope out of range." Caterpillar installed a new oxygen sensor that calibrated correctly.

On the Power Systems' dynamometer, the truck's EGO was approximately 3 percent according to the new sensor. The fuel control was adjusted to yield 7-percent EGO (wet) (λ = 1.51) at rated condition (full throttle, 2,000 rpm). With this setting, power was down noticeably, and boost pressure was found to be too low. Several iterations of adjusting the wastegate spring and checking the result at rated condition yielded the desired 200-kPa boost pressure with the wastegate adjusting screw adjusted to its limit. The fuel control was then adjusted to yield approximately 7-percent EGO (wet) (λ = 1.51) at rated conditions. Ignition timing was adjusted to specification.

Dynamometer torque measurements were performed at discrete rpm intervals. Power was lower than expected, and at 1,400 rpm detonation, indicated by the DDT, increased to unacceptable levels. Several efforts to limit detonation were made by retarding the timing in successive stages to 17° BTDC and then by leaning the mixture slightly, to 7.2 percent EGO (wet) (λ = 1.53) at rated conditions. Detonation levels indicated by the DDT remained unacceptable at 1,400 rpm, yet lean misfire was perceived. Power had dropped sharply, to under 149 kW (200 hp) at rated rpm. All instrumentation was checked and found to be working correctly. These observations were reported to Caterpillar.

Caterpillar advised Acurex Environmental and Power Systems that the DDT was probably indicating "false" detonation, and that the engine should be tuned to the specified A/F and spark timing, notwithstanding indications from the DDT. This was done, and engine performance returned to normal in all respects.

4.3.3 CNG Cylinder Damage

Early in 1994, following reports of two separate incidents of CNG cylinders bursting on natural gas vehicles, an intensive inspection of the CNG fuel cylinders aboard the Vons tractor was conducted. The entire surface area of each of the 10 cylinders was thoroughly inspected for any signs of damage. All of the mounting brackets and rubber insulators were found to be in good condition, with no signs of wear. All cylinders showed no inherent problems with respect to their mounting, i.e., rubbing or contacting of cylinders with fuel lines, brackets, chassis, etc.

However, significant damage was discovered on two of the cylinders. The manual *Guidelines for Visual Inspection & Requalification of Fiber Reinforced High Pressure Cylinders,* Compressed Gas Association, Inc., 1988 edition, provides criteria for evaluating cylinder damage. A gouge, shown in Figure 4-15, was found on the rear inner side of the driver's side upper outboard cylinder. The damage was circular, approximately 1.27 cm (0.5 in) in diameter, and was visually estimated to be 1.5 mm (0.06 in) in depth. The gouge was thought to be the result of abrasion caused by a hard object wedged between the chassis frame rail and the cylinder. There was nothing wedged there at the time of inspection, but a coinciding wear mark found on the chassis, running parallel approximately 1.9 cm (0.75 in) away, supports this conclusion.

An area of burn damage, and several gouges, were found on the middle inner side of the passenger-side lower inboard cylinder. Two of the gouges are considered severe based upon the criteria in *Guidelines*. Both are approximately 2.54 cm (1 in) long and transverse to the fiber direction. The larger of the two gouges was visually estimated to be at least 1.65 mm (0.065 in) deep, and the smaller 1.5 mm (0.06 in) deep. A discolored area measuring 10.2 by 3.8 cm (4 by 1.5 in), apparently caused by heat, is near the gouges. Figure 4-16 shows the damaged area. The

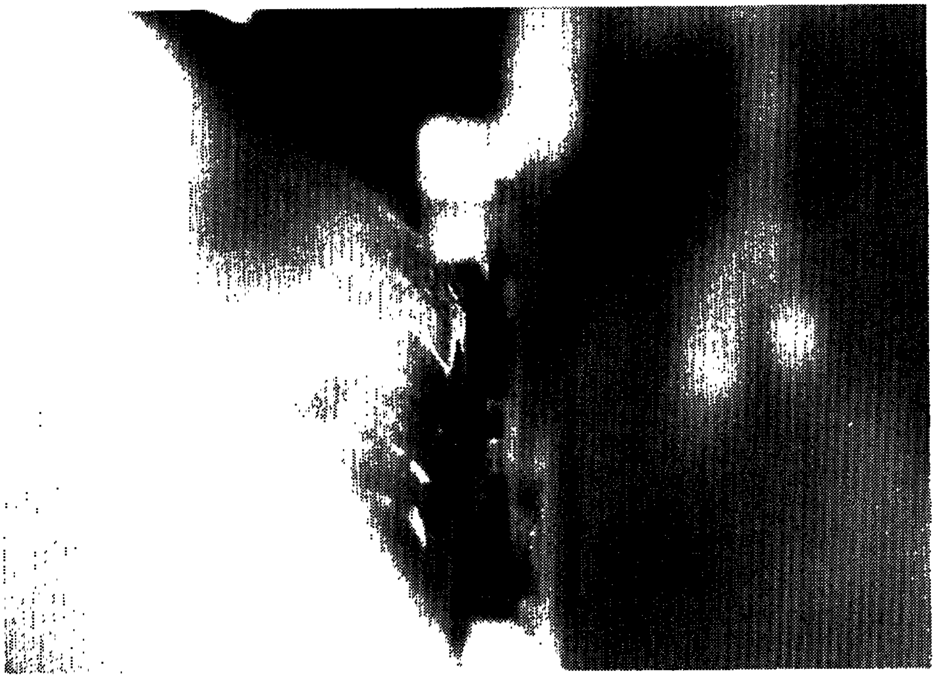


Figure 4-15. Circular gouge in CNG cylinder

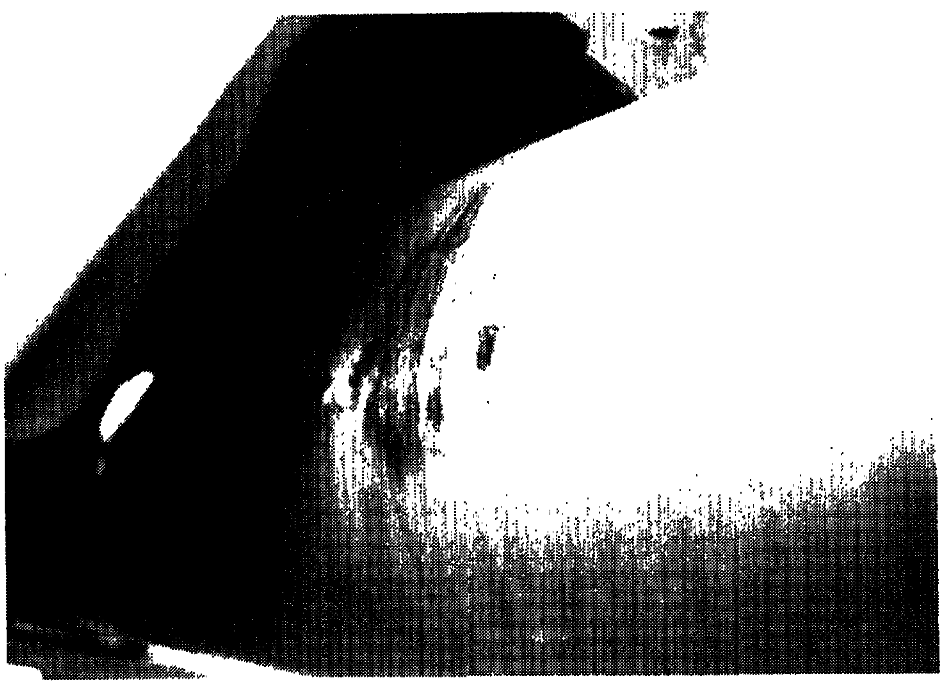


Figure 4-16. Abraded and scorched area of CNG cylinder

discolored fiber overwrap does not appear to be charred. This damage was possibly the result of an undocumented failure of a joint in the exhaust pipe that runs approximately 15.2 cm (6 in) below the damaged cylinder. Early in the demonstration, according to an anecdotal report, the exhaust system had become loose during a night run to Bakersfield and was reconnected by PG&E personnel. The pipe probably made violent contact with the nearby cylinder while the truck was operating, causing the gouges, and the escaping exhaust may have caused the burn damage. At the time of this inspection, the exhaust pipe was fully wrapped in an insulating cover in the area of the cylinder damage. Damage to the cylinder would not be likely without noticeable damage to the cover. A new insulating cover was installed during the vehicle's conversion to the dual-exhaust configuration in April 1993. This suggests that the damage occurred prior to that conversion. However, no prior reports of damage to the CNG cylinders occurred while work was performed underneath the tractor during the demonstration.

According to *Guidelines*, the cuts and abrasions on the two damaged cylinders correspond to Level 2 Damages (Rejectable — additional inspection or repairs required). The heat-damaged cylinder corresponds to Level 3 (Condemned — not repairable). Copies of this manual were distributed to Power Systems and Vons, as well as to all program participants, including the project sponsors.

As a result of the inspection, the tractor was grounded pending repair or replacement of the damaged cylinders. In addition, their shutoff valves were closed to isolate them from the remainder of the fuel system, in order to prevent any unauthorized refueling of potentially hazardous cylinders. This step was taken as a precaution until the damaged cylinders could be depressurized and removed. Pressure aboard the vehicle was approximately 9,653 kPa (1,400 psi) at that time, less than half the working pressure of the cylinders. The tractor was sold to SoCalGas, and the cylinders were inspected by NGV Systems, Inc., the manufacturer of the cylinders. All of the cylinders except for the heat-damaged one were recertified by NGV Systems at that time.

4.4 TOTAL OPERATING COSTS

All available operating costs were recorded and compiled during the field evaluation, including those for fuel usage, and service labor and parts required by the CNG and diesel control tractors. This enabled the calculation of total operating cost for both vehicles, so that the cost-effectiveness of using CNG could be evaluated. The results of this project can be used only as a guide because of:

- The small sample size of one experimental and one control vehicle
- The short period of field evaluation
- The CNG engine and systems being prototypes

The results of the cost comparison are summarized in Table 4-4.

Because of the interruption in accurate fuel metering at MTA during most of the demonstration, the total fuel cost for the CNG demonstration vehicle could only be estimated, as follows:

- Aggregate fuel economy (from periods of accurate fuel metering): 5.65 km/therm (3.51 mi/therm) (higher heating value [HHV])

Table 4-4. CNG and diesel operating cost comparison

Vehicle	CNG Tractor 9207		Diesel Tractor 9200	
Expenditure	Material ($)	Labor (hr)	Material ($)	Labor (hr)
Fuel	5,018	NA[a]	18,824	NA
Fuel system maintenance	361	16	137	17
Engine maintenance	5,103	238	462	22
Collision repair	1,698	10	NA	1
Tires	3,028	5	3,208	7
All other maintenance	1,401	42	1,645	88
Miles driven	32,022		118,326	

[a]NA = Not applicable.

- Nominal fuel price (charged to Vons): $0.55/therm (HHV)
- Estimated operating cost: $0.098/km ($0.157/mi)
- Estimated fuel cost: $5,017.69

Similarly, the total fuel cost for the diesel control vehicle was estimated, as follows:

- Aggregate fuel economy (on Bakersfield route): 35.4 L/100 km (6.63 mi/gal)
- Nominal fuel price (average for period): $0.279/L ($1.056/gal)
- Estimated operating cost: $0.099/km ($0.159/mi)
- Estimated fuel cost: $18,843.89

The CNG and diesel fuel costs per mile were roughly equivalent ($0.157 versus $0.159). The lower energy price of CNG — $5.21 per GJ ($0.55 per 100,000 Btu) (HHV) of CNG versus $7.30 per GJ ($0.77 per 100,000 Btu) (HHV) of diesel — is offset by the lower fuel efficiency of the CNG tractor. As expected, much higher expenditures were incurred on the CNG tractor's engine than on the diesel's. Included in the engine maintenance of the CNG tractor are its conversion to dual exhaust and other field upgrades. Also included are labor and parts expended on troubleshooting unfamiliar problems for which diagnostic procedures had not been developed. Expenditures on fuel system maintenance for the CNG tractor were also higher than those for the diesel. These expenditures are mainly the result of replacing the CNG regulator and solenoid because of contamination. Each tractor received one new set of tires at approximately the same odometer mileage. The question of increased tire wear caused by the added weight of the CNG cylinders, approximately 680 kg (1,500 lb), cannot be addressed using the available data.

Tables containing details of specific maintenance actions performed on each vehicle during the field evaluation are included in Appendix B.

SECTION 5

EMISSION TESTING

5.1 TEST FACILITY

Emission tests of the CNG tractor were conducted on the chassis dynamometer at the MTA Emissions Testing Facility (ETF), located in Los Angeles, California; the facility is pictured in Figure 5-1. Whereas there is no Federal Test Procedure (FTP) for measuring the emissions of a heavy-duty vehicle in a chassis dynamometer test, the ETF is configured to follow Code of Federal Regulations (CFR) Title 40, Part 86, Subpart N, which governs emission testing of heavy-duty engines for emissions certification. All specified procedures and quality control checks are done as required under these regulations.

The ETF features a computer-controlled 477-kW (600-hp) DC motor/absorber. Torque is transferred to the twin 183-cm (72-in) rolls via a planetary gearset. The assembly is mounted on axial bearings; torque is supported by a load arm fitted with a load cell for torque measurement. Collection and measurement of exhaust emissions according to the constant volume sampling (CVS) principle begins in the dilution tunnel, which can be configured for flowrates from 28 m^3/min to 113 m^3/min (1,000 to 4,000 cfm). Ambient air is drawn through a filter bank into the dilution tunnel; full exhaust flow from the test vehicle enters the dilution tunnel immediately downstream of the filters. Total gas flow is controlled at a constant flowrate governed by the critical flow venturi (CFV) system; flowrate is manually selected prior to the test. The diluted exhaust sample is drawn from the center of the dilution tunnel, approximately 10 tunnel diameters downstream of the point where raw exhaust enters the tunnel. The dilute sample is drawn from the sampling probe through a temperature-controlled sampling line and sample oven. The sample flow is then split into several

Figure 5-1. MTA Emissions Testing Facility

streams, which are individually pumped to the emissions analyzers and the sample collection bags. The analytical system incorporates six separate instruments for the measurement of HC, NO_x, CO (one analyzer each for low and high concentrations), and CO_2 (one analyzer each for low and high concentrations). In addition, an oxygen analyzer is provided for the measurement of oxygen content when raw exhaust is sampled.

A particulate sampling system draws exhaust from the dilution tunnel, from a point adjacent to the gaseous sample probe, and passes it to a secondary dilution tunnel, where it is further diluted, ensuring that the temperature never exceeds 51.7°C (125°F). The cooled, diluted gas then passes through primary and secondary particulate filters, which are weighed before and after the test to determine the deposited particulate mass.

The ETF also has equipment for recovering formaldehyde from the dilute exhaust. A sample of dilute exhaust is drawn from the dilution tunnel, from a point near the gaseous sample probe, and is passed through a cartridge containing a 2,4-dinitrophenyl hydrazine (DNPH) solution. A DNPH-formaldehyde derivative forms when DNPH is exposed to formaldehyde. Following the test, the quantity of formaldehyde recovered in the cartridge is determined by an analytical laboratory. Data recorded for the test, including sample volume, are used to convert the reported formaldehyde mass to g/mi units.

Control of the emission testing process is provided by a computerized system that interfaces with the dynamometer and the sampling and analysis systems. The computer provides actuation of solenoid valves and pumps for directing calibration and sample gases to the analyzers, controls dynamometer loading during a test, and displays the vehicle driving trace on video monitors in the control room and in the test cell. The video monitors also display test parameters, including elapsed time, speed, horsepower, ambient temperature and pressure, and vehicle parameters for which the test has been instrumented. Instrument data, including emissions, are recorded at 1-second intervals during the test.

5.2 TEST PROTOCOL

A test plan for emission-testing the CNG tractor was developed and circulated to the participants as a memorandum. Covered in the test plan were preparation of the engine (tuning), coast-down testing and determination of road load, and schedule of tests to be conducted. A copy of the test plan is provided in Appendix C. Figure 5-2 shows an emission test in progress.

Testing was performed on January 27 and 28, 1994. Emissions of the CNG tractor were determined from bag samples collected during each test or test phase, as specified in 40 CFR 86.1309-90, covering measurement of spark-ignition engine emissions. Particulate sampling was used in all driving test cycles, but not in the idle test. The test cycles specified in the test plan included the following:

- Federal Transit Administration (FTA) Central Business District (CBD) Cycle (the CBD phase of the FTA Advanced Design Bus Test Cycle)

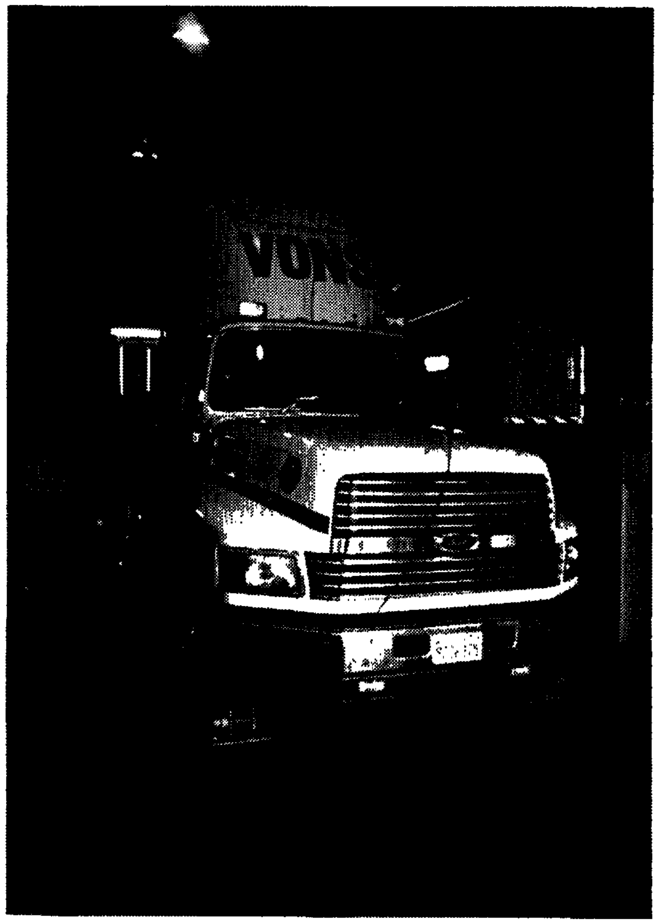


Figure 5-2. Emission test in progress

- FTA Commuter Cycle (the Commuter phase of the FTA Advanced Design Bus Test Cycle)
- EPA Schedule (d) Cycle (the EPA Urban Dynamometer Driving Schedule for Heavy-duty Vehicles)

Formaldehyde samples were collected in all but two tests for subsequent analysis at the California Air Resources Board (ARB) analytical laboratory in El Monte, California. In addition, HC speciation of the dilute exhaust sample from one EPA Schedule (d) test was determined by ARB.

All of the standardized test cycles used in testing the CNG tractor called for acceleration that exceeded the vehicle's acceleration capability at the 31,457-kg (69,350-lb) inertia weight. The issue of how a vehicle's ability to follow various test driving cycles affects the validity of emission test results has not been resolved as yet. Figure 5-3 shows an actual acceleration event on the dynamometer monitor during an EPA Schedule (d) test. The required speed is denoted by a red line that scrolls down the screen as the test proceeds. The actual speed is traced out in green by the cursor (white crosshairs), which the driver attempts to keep over the red trace. Vertical lines represent speed in 16-kph (10-mph) increments, with 0 kph (0 mph) on the left and 96 kph (60 mph) on the right.

A memorandum detailing the emission testing of this vehicle was circulated following the event, and is included in Appendix C.

Figure 5-3. EPA Schedule (d) driving trace

5.3 RESULTS

Results of the CNG truck emission tests are presented in Table 5-1. Fuel economy is reported in diesel-equivalent mpg. PM and formaldehyde measurements were not made in the idle test. The idle test was performed for a cycle emissions prediction technique under development by Acurex Environmental.

The data show good repeatability of the HC, CO, NO_x and CO_2 results among successive iterations of the EPA Schedule (d) and FTA Commuter tests.

Speciated HC results are available from one bag sample drawn during an EPA Schedule (d) test. The analysis showed that approximately 90 percent of the total HC emissions were methane, which EPA and ARB consider to be nonreactive in terms of photochemical ozone production.

5.4 DISCUSSION

The averaged emissions of the CNG tractor are shown in Table 5-2 with those of other vehicles tested on the MTA chassis dynamometer. None of the vehicles in this population is directly comparable to the CNG tractor due to inertia weight differences and excessive "driver error" associated with the CNG tractor. However, the data permit some general observations. The test cycles refer to the FTA CBD, EPA Schedule (d) transient, and FTA Commuter cycles. It is apparent that the total HC emissions of the CNG tractor, although mostly methane, are relatively high. The HC emissions of Orange County Transportation Authority (OCTA) CNG bus 4267, which is powered by a Cummins L10 240G natural gas engine with an exhaust catalyst, show the potential for low total HC with a catalyst-equipped natural gas engine. It may be concluded from this comparison that the CNG tractor's engine-out methane emissions were significant, and that its catalyst had a limited effect on the oxidation of methane. As with OCTA bus 4267, the CNG tractor's CO emissions are essentially zero; the conclusion can be drawn that the tractor's catalyst was very effective at oxidizing CO. Taking the inertia weight of the vehicles into account, the NO_x emissions of the CNG tractor appear to be relatively lower than those of OCTA diesel bus 4219 and Caterpillar's 3306 methanol-powered refuse hauler, but somewhat higher than the DDC 6V-92

Table 5-1. CNG tractor emissions

Test No.	Test Cycle[a]	Inertia Weight, kg (lb)	HC, g/km (g/mi)	CO, g/km (g/mi)	NO_x, g/km (g/mi)	CO_2, g/km (g/mi)	Fuel Economy, L/100 km (mpg)[b]	HCHO, g/km (g/mi)	PM, g/km (g/mi)	Driver Error, S[c]
823	CBD	31,457 (69,350)	71.4 (114.9)	0.16 (0.25)	19.3 (31.1)	2,775 (4,465)	199 (1.18)	NM[d]	0.0229 (0.0369)	171.5
824	EPA	31,457 (69,350)	26.2 (42.2)	0.16 (0.25)	12.6 (20.2)	1,482 (2,385)	104 (2.25)	0.006 (0.01)	0.0413 (0.0665)	102.4
825	EPA	31,457 (69,350)	25.0 (40.3)	0.17 (0.28)	12.4 (20.0)	1,459 (2,347)	103 (2.29)	0.006 (0.01)	0.0234 (0.0376)	86.6
826	EPA	31,457 (69,350)	24.7 (39.8)	0.12 (0.19)	11.5 (18.5)	1,460 (2,348)	103 (2.29)	ND[e]	0.0431 (0.0694)	80.0
827	COM	31,457 (69,350)	8.0 (12.9)	0.075 (0.12)	10.7 (17.2)	1,096 (1,764)	75 (3.12)	0.012 (0.02)	0.007 (0.0110)	66.7
828	COM	31,457 (69,350)	10.7 (17.2)	0.044 (0.07)	10.3 (16.6)	1,098 (1,767)	76 (3.10)	0.006 (0.01)	0.0119 (0.0191)	65.8
829[f]	Idle	31,457 (69,350)	17.2 (27.7)	0.44 (0.71)	1.5 (2.4)	658 (1,058)	NA[g]	NM	NM	NA
830	EPA	31,457 (69,350)	24.1 (38.8)	0.13 (0.21)	12.1 (19.5)	1,492 (2,398)	105 (2.24)	0.006 (0.01)	0.0406 (0.0654)	107.3
831	COM	20,412 (45,000)	10.6 (17.1)	0.068 (0.11)	10.4 (16.7)	1,016 (1,635)	71 (3.31)	NM	0.0073 (0.0118)	0

[a]CBD = Central Business District, EPA = U.S. Environmental Protection Agency, COM = Commuter.
[b]Diesel-equivalent mi/gal.
[c]Excessive "driver error" is an indication that the driving cycle did not represent normal vehicle operation. Comparison to test results without driver error may be inappropriate.
[d]NM = Not measured.
[e]ND = Not detected.
[f]Emission results reported as total grams for test.
[g]NA = Not applicable.

Table 5-2. Emissions comparison

Vehicle	Engine/Fuel	Test Cycle[a]	Inertia Weight, kg (lb)	HC, g/km (g/mi)	CO, g/km (g/mi)	NO_x, g/km (g/mi)	Fuel Economy, L/100 km (mpg)[b]	HCHO, g/km (g/mi)	PM, g/km (g/mi)	Driver Error, S[c]
CNG tractor	Caterpillar G3406LE/CNG	CBD	31,457 (69,350)	71.40 (114.90)	0.16 (0.25)	19.30 (31.10)	199 (1.18)	NM[d]	0.0229 (0.0369)	1.71
Sludge hauler	DDC 6V-92TA/methanol	CBD	22,208 (48,960)	5.13 (8.25)	41.25 (66.38)	8.37 (13.47)	104 (2.27)	1.03 (1.65)	0.7714 (1.2412)	86.6
Refuse hauler	Caterpillar 3306B/methanol	CBD	13,535 (29,840)	5.03 (8.10)	12.93 (20.80)	17.60 (28.30)	63 (3.74)	0.59 (0.95)	0.0746 (0.1200)	0
OCTA[e] bus 4267	Cummins L10 240G/CNG	CBD	15,060 (33,200)	2.56 (4.12)	0.00 (0.00)	3.76 (6.05)	101 (2.32)	0.019 (0.03)	0.0266 (0.0428)	0
OCTA bus 4269	Cummins L10/LPG	CBD	14,225 (31,360)	1.92 (3.09)	0.012 (0.02)	1.89 (3.04)	93 (2.54)	0.019 (0.03)	0.0224 (0.0360)	0
OCTA bus 4219	Cummins L10/diesel	CBD	14,161 (31,220)	0.69 (1.11)	9.22 (14.83)	19.32 (31.08)	56 (4.22)	0.044 (0.07)	0.3344 (0.5380)	0
CNG tractor	Caterpillar G3406LE/CNG	EPA	31,457 (69,350)	25.00 (40.30)	0.14 (0.23)	12.17 (19.58)	104 (2.27)	0.006 (0.01)	0.0371 (0.0597)	89.7
FedEx tractor	DDC 6L-71/methanol	EPA	13,880 (30,600)	ND[f]	2.88 (4.64)	6.50 (10.45)	90 (2.62)	0.06 (0.10)	0.155 (0.2500)	107.2
Sludge hauler	DDC 6V-92/methanol	EPA	22,208 (48,960)	1.95 (3.14)	11.83 (19.04)	5.36 (8.62)	53 (4.42)	0.66 (1.06)	0.264 (0.4248)	68.2
CNG tractor	Caterpillar G3406LE/CNG	COM	31,457 (69,350)	9.32 (15.00)	0.062 (0.10)	10.50 (16.90)	76 (3.11)	0.009 (0.015)	0.007 (0.0110)	66.3
CNG tractor	Caterpillar G3406LE/CNG	COM	20,412 (45,000)	10.63 (17.10)	0.068 (0.11)	10.40 (16.70)	71 (3.31)	NM	0.007 (0.0118)	0
FedEx tractor	DDC 6L-71/methanol	COM	13,880 (30,600)	ND	0.80 (1.29)	6.76 (10.88)	73 (3.24)	NM	0.114 (0.2150)	79.1
OCTA bus 4269	Cummins L10/LPG	COM	14,225 (31,360)	0.068 (0.11)	0.00 (0.00)	0.14 (0.22)	45 (5.24)	NM	0.009 (0.0142)	0

[a]CBD = Central Business District, EPA = Environmental Protection Agency, COM = Commuter.
[b]Diesel-equivalent mi/gal.
[c]Excessive "driver error" is an indication that the driving cycle did not represent normal vehicle operation. Comparison to test results without driver error may be inappropriate.
[d]NM = Not measured.
[e]OCTA = Orange County Transportation Authority.

methanol sludge hauler and the OCTA CNG and LPG buses. It can be concluded that the Vons CNG tractor's engine has realized some of the potential of natural gas to lower heavy-duty engine NO_x emissions, but that additional developmental work is needed to reduce emissions to a level competitive with other alternative-fueled-engine designs.

SECTION 6

PUBLIC AND INDUSTRY AWARENESS

The public and industry awareness campaign was an important element of this project. Activities included the appearance of the CNG tractor in press events and in trade and trucking shows, as well as coverage of the tractor in newspapers, trade magazines, and technical publications. These activities are described in the subsections that follow.

6.1 PRESS EVENTS

On April 13, 1993, the CNG tractor made its public debut in back-to-back press events held at Vons supermarkets in Burbank and Bakersfield. Figure 6-1 shows the Bakersfield press event.

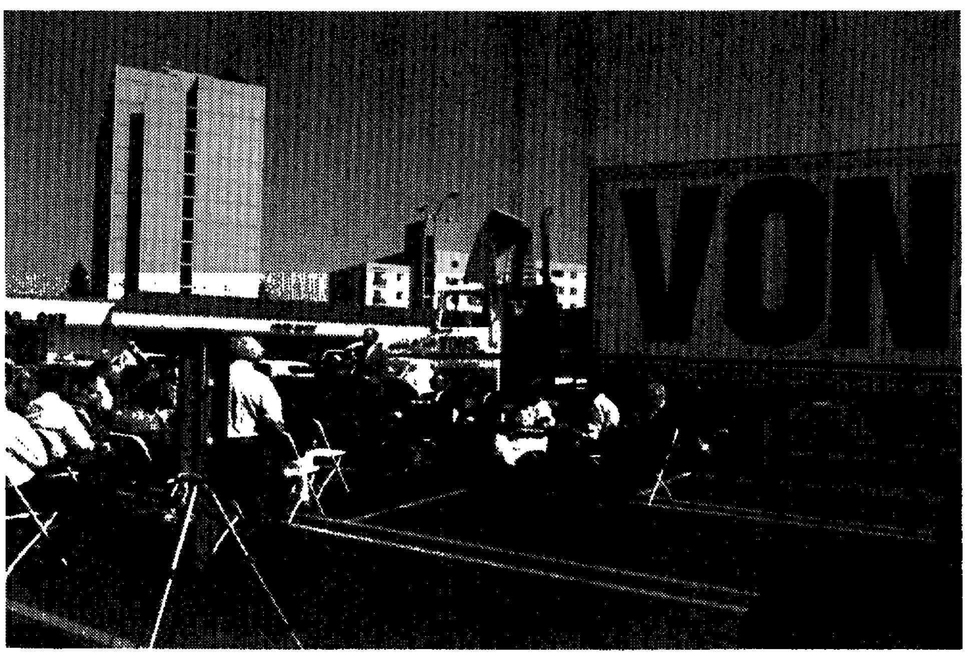


Figure 6-1. Bakersfield press event, April 13, 1993

Presentations were made by the CEC, SCAQMD, SoCalGas, PG&E, and Vons. The events received coverage from local television stations and newspapers, and were successful in raising public awareness of the CNG tractor and the broader issues driving alternative-fuel programs.

6.2 TRADE AND TRUCKING SHOWS

The CNG tractor appeared in a number of trade and trucking shows. The participants took pride in exhibiting the vehicle, and were gratified by the positive publicity it generated. The events at which the tractor was displayed are summarized in Table 6-1.

6.3 PRINT COVERAGE

Several newspaper articles publicizing the CNG tractor resulted from the press events. Articles and briefs about the project also appeared in trade journals in the months following the events. Table 6-2 summarizes print coverage of the vehicle. An article from the Ford truck trade journal *SalesPro* is reproduced in Figure 6-2.

For project documentation and reporting purposes, the following three internal technical publications were generated prior to this final report:

- *Conversion of a Ford LTLA-9000 Tractor to Compressed Natural Gas Operation*
- *Caterpillar G3406 Mobile, Low Emission Engine for the Vons Companies, Inc. of El Monte, CA*
- *Vons Natural Gas Tractor Fuel Metering*

In addition, a technical paper presentation related to this project was presented at NGV '94, the Fourth Biennial Conference and Exhibition on Natural Gas Vehicles, held in Toronto, Canada, October 3-6, 1994.

Table 6-1. Trade and trucking shows exhibiting the Vons CNG tractor

Date	Event	Location	Presenter
July 23, 1992	International Truck Show	Anaheim, CA	Ford
Sept. 16, 1992	Photo session	Pico Rivera, CA	SoCalGas
Sept. 28, 1992	Pacific Equipment Technology Exposition	Costa Mesa, CA	CEC
Nov. 18, 1992	Photo session	Sun Valley, CA	SCRTD[a]
May 10-11, 1993	NGV West Exposition	Newport Beach, CA	CEC
May 19, 1993	Private Fleet Council monthly meeting	Commerce, CA	Vons
May 23, 1993	Anaheim Truck Show	Anaheim, CA	Vons
Oct. 6-10, 1993	Ridgecrest Exposition	Ridgecrest, CA	Vons
Oct. 14, 1993	Advanced Engine Technology Task Force Seminar	Bakersfield, CA	PG&E

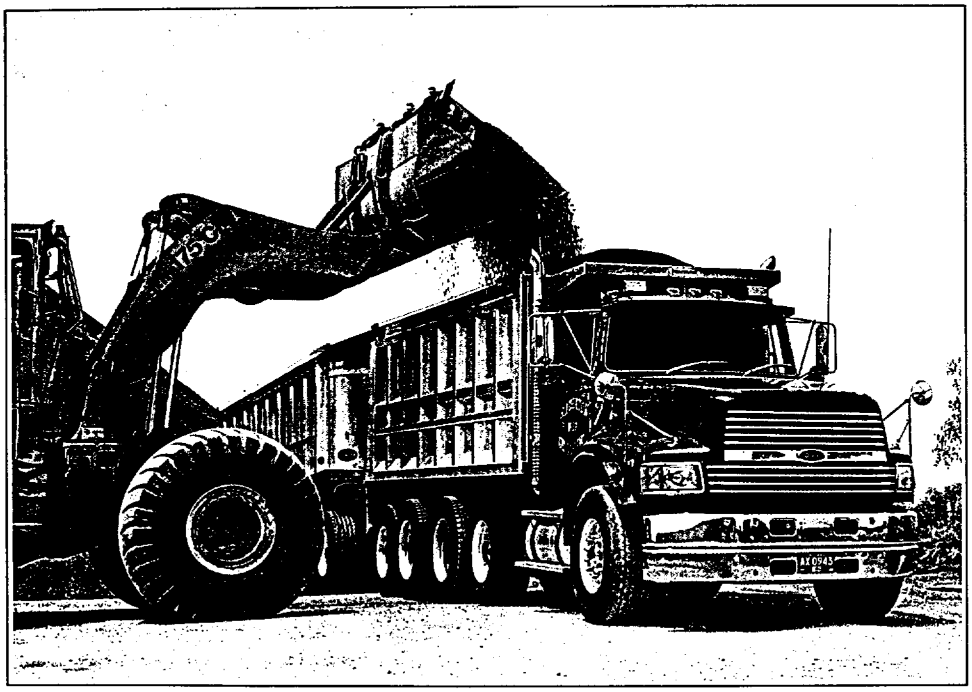
[a]Now MTA.

Table 6-2. Print coverage of the Vons CNG tractor

Date	Publication	Title or Headline
September 1992	*Heavy Duty Trucking*	"Heavy Truck Meets Natural Gas in Grocery Fleet's Real-World Test"
September 1992	Vons Employee Newsletter	"Vons unveils country's first tractor trailer rig to run on natural gas"
April 13, 1993	*Los Angeles Times*	"Big Rig, Small Emissions: Vons 'Pleased' With Early Tests of Natural Gas-Powered Truck"
April 14, 1993	*Los Angeles Daily News*	"Alternative-fuel test"
April 14, 1993	*Californian*	"Food delivery a natural gas with Vons rig"
April 14, 1994	*Pasadena Star News*	"Vons tests first clean-fuel big rig: Firm's use of natural-gas powered truck may signal new era"
June 1993	*American Gas*	"NATURAL GAS POWERS LONG-HAUL 18-WHEELER"
July 1993	*Heavy Duty Trucking*	"Natural Gas: The Race Moves Forward"
August 1993	*SalesPro: Journal of Ford Heavy Truck Sales Professionals*	"ALTERNATIVE FUELS: Moving to the Fast Track"

JOURNAL OF FORD HEAVY TRUCK SALES PROFESSIONALS

SalesPRO



Alternative Fuels Move to Fast Track

Sleeper Upgrades Add Advantages

Exhaust Systems Examined

Vol. 9 No. 4 August 1993

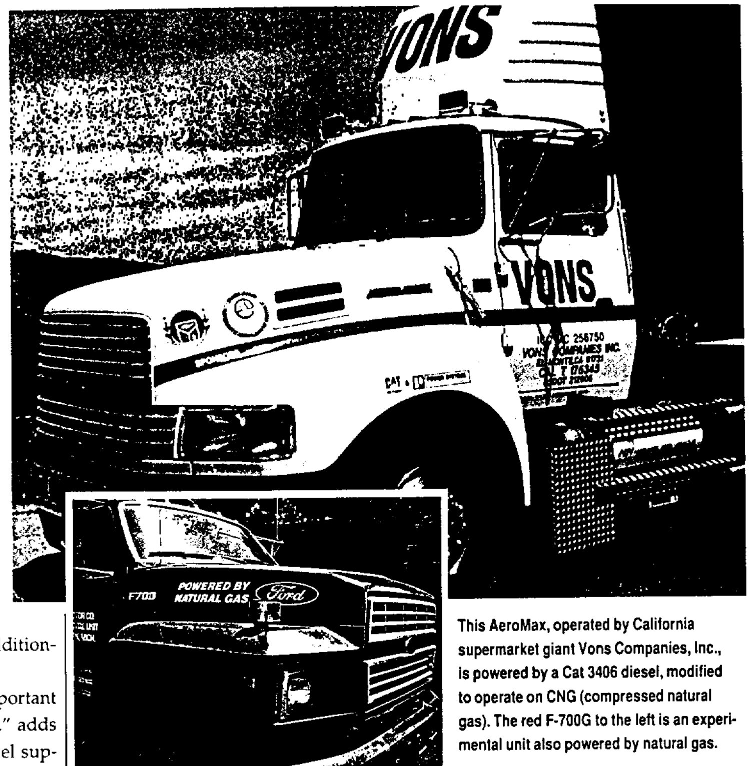
Figure 6-2. *SalesPro* article on the Vons CNG tractor

Earn 25-percent LPG Tax Break

Beginning July 1, 1993, buyers accepting delivery of an LPG-fueled F-600G or F-700G could gain a first-year tax break that equals 25 percent of the cab-chassis price. That could amount to an additional $5,000 tax deduction in the year of purchase.

"Because Ford is the first and only U.S. automaker to offer a warranted, factory-built LPG truck, the new ruling allows Ford buyers to gain the greatest tax advantage," says Medium Duty Marketing Plans Manager **Tom Steckel**. "That's a substantially larger depreciation than after-market, add-on LPG systems. They normally cost about $1,000, so you can only deduct that amount [cost of conversion]. With Ford LPG, you can get an additional $4,000 tax break.

"LPG fuel offers some important advantages at this point in time," adds Tom. "It's a readily available fuel supply, it gets good fuel mileage, and it's fairly easy to reengineer gasoline engines into LPG engines. We expect this vehicle to have significant sales this year and next." (See sidebar on page 4 for more details about LPG truck benefits.)



This AeroMax, operated by California supermarket giant Vons Companies, Inc., is powered by a Cat 3406 diesel, modified to operate on CNG (compressed natural gas). The red F-700G to the left is an experimental unit also powered by natural gas.

Ford CNG Programs

Ford Truck has several alternative-fuel test programs going on now that could lead to future production vehicles. "We're putting 14 F-700G trucks with 7.0-liter compressed-natural-gas engines into several fleets around the country," says Pete Hubbard, Ford powertrain planning supervisor. "Four are already in place in California and Kansas.

"The modifications for CNG are very similar to LPG," explains Pete. "We use different fuel-metering in the carburetor, and the tanks are different, but the performance is very similar." The CNG pilot trucks will be slowly produced and tested for an indefinite period, and might lead to full production vehicles.

Ford Heavy Truck has been working with Caterpillar for about a year on a demonstration project involving a Cat 3406 diesel modified to operate on natural gas. The engine is mounted in an AeroMax 120, and has been in daily service with the **Vons Companies, Inc.**, the largest retail supermarket chain in Southern California. (*SalesPro* offered a "Satisfied User" article on this fleet in November, 1990.) "The truck has been running well," says **E.J. Geiger**, principal powertrain specialist for Ford Heavy Truck. "It makes a 250-mile roundtrip run daily between Vons' distribution center in El Monte, California and its retail grocery outlets in the Bakersfield area, and there have been very few problems."

Industry Activity Visible

Converting diesel engines to burn alternative fuels presents several problems. Because LPG and CNG are harder to ignite than diesel, compression-type ignition of fuel can be difficult. Many diesel-engine manufacturers add an electric ignition and spark-plug system to their engines to help burn those fuels.

Caterpillar has been building CNG-powered stationary engines with spark plugs for half a century, but has done little with truck engines. The Vons 3406 and a few spark-plug 3306s run-

Figure 6-2. *SalesPro* article on the Vons CNG tractor (concluded)

SECTION 7

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 SUMMARY

The Caterpillar G3406LE mobile natural gas engine was developed and successfully demonstrated in a Class 8 CNG-fueled line-haul tractor. The technical feasibility of the CNG tractor was demonstrated in a demanding service application, hauling groceries daily for Vons over a 400- to 450-km (250- to 280-mi) round trip between El Monte and Bakersfield, California. When operating in service, the tractor performed well and experienced few problems. Several developmental issues that had not been resolved when the tractor entered service caused the vehicle to be unavailable for service for significant periods during the field evaluation phase. In 14 months of field operation, the vehicle accumulated 829 engine hours and 52,082 km (32,369 mi). Its overall availability was 49 percent, while its natural-gas-specific availability was 63 percent.

Caterpillar's goals for fuel efficiency, peak torque, lug range, and steady-state emissions were met in the engine development phase, as discussed in Section 3. The engine and natural gas fuel system combined into a visually clean installation in a 1992 Ford AeroMax LTLA-9000 tractor, originally powered by a Caterpillar 3406B ATAAC diesel engine. The CNG storage cylinders added approximately 635 kg (1,400 lb) to the tractor's weight. Some equipment, including the air cleaner and exhaust system, had to be relocated and/or reconfigured to accommodate the natural gas engine and fuel system. A 13-speed transmission was substituted for the original 9-speed unit, to better suit the torque output of the natural gas engine. Performance of the CNG tractor was measured against its diesel counterpart, and was found to be comparable in all respects. Operational experience indicated that the rear axle ratio, unchanged in the conversion process, was numerically lower than ideal for the CNG engine, which is rated at 200 rpm higher than the diesel engine it replaced.

The maximum range of the CNG tractor met the target of 400 km (250 mi). However, the target underestimated the actual round trip distance, because multiple stops in the Bakersfield area were not included in the estimate. The typical round trip distance was between 400 and 450 km (250 and 280 mi), so it was necessary to refuel twice per trip. Refueling times were about 10 to 20 minutes. Of more significance to the user was that the tractor had to deviate from its route to refuel with CNG, whereas diesel trucks are refueled at the El Monte base after returning from a trip.

The CNG tractor was limited to a range of about 400 km (250 mi) due to an approximately 30-percent loss in engine efficiency and the use of fiberglass-reinforced aluminum cylinder technology. Improvements in engine/drivetrain efficiency and CNG cylinder technology, as well as vehicle configurations with more available space for storage cylinders, could improve the range of CNG vehicles to make them more competitive with diesel vehicles, which typically have a 1,600-km (1,000-mi) range.

Several improvements to the engine and vehicle configuration were indicated and implemented during the field evaluation phase. Improvement of the governor strategy resulted in full driver acceptance of the natural gas engine. Exhaust backpressure was reduced to within specifications, from 1,422 to 3.56 mmH_2O (56 to 14 in H_2O), through the addition of a second, parallel flow muffler/catalyst unit. Parasitic losses from operation of the cooling fan were reduced through hardware and programming changes that optimized use of the fan to enhance aftercooler effectiveness. These improvements resulted in an increase in fuel economy from 54.7 to 50.6 diesel-equivalent L/100 km (4.3 to 4.64 mi/diesel-equivalent gal).

A few unforeseen difficulties were experienced during the field evaluation. A recurring full-load misfire problem was eventually traced to spark plug gap sensitivity of the ignition system combined with spark plug gap spreading in service. The specified spark plug gap is 0.38 mm

(0.015 in); when gaps spread beyond 0.4 mm (0.016 in), full-load misfire became a problem. Contamination from an unknown source necessitated overhaul of the CNG solenoid shutoff valve and replacement of the primary regulator twice. The custom-installed exhaust ducting from the engine repeatedly loosened and leaked in service. In a detailed inspection of the CNG storage cylinders following completion of the field evaluation, previously unknown, potentially serious damage to the composite wrap was discovered on two cylinders.

Comparison of the maintenance of the CNG tractor and a diesel control vehicle showed significantly higher expenditures on parts and labor for the prototype CNG tractor. Fuel consumption and costs indicated that the fuel cost-per-mile of the CNG tractor was approximately 5 percent lower than that of the diesel control vehicle. Oil sampling and analysis, performed regularly throughout the field evaluation, indicated no need for an oil change in more than 800 engine operating hours. The regular oil change interval of the Caterpillar 3406 diesel engine is 250 hours.

Emissions were measured through chassis dynamometer testing following the field evaluation's completion. Emissions of CO were very low. In addition, emissions of NO_x, PM, and NMHC showed that the engine should meet the ARB heavy-duty engine certification standards on the EPA engine dynamometer transient cycle.

In the wake of this successful single-engine demonstration, Caterpillar is planning a second-generation G3406 natural gas heavy-duty engine, to be certified in 1995. In addition, DDC has designed a natural gas Series 60 truck engine and will produce several for demonstration projects in California.

7.2 CONCLUSIONS

- Natural gas is a technically viable fuel for Class 8 truck engines, because the technology used gives the Caterpillar G3406LE engine competitive performance and is applicable to other engines in the class

- Although minor reliability and durability issues remain to be resolved, a natural gas trucking engine can potentially equal or exceed diesel engine reliability and durability levels, with sufficient R&D
- Contamination in the natural gas appears to have caused problems with the on-board CNG pressure regulator and shutoff solenoid valve. Additional work is required to determine the source of the contamination (compressor lubrication is suspected).
- While the energy consumption of the natural gas engine in this project was significantly higher than that of the diesel engine it replaced, the overall fuel cost differential was 5 percent in favor of the natural gas engine. Future improvements in natural gas engine efficiency, higher petroleum prices, and higher diesel fuel refining costs would make the relative cost of natural gas more attractive.
- CNG may not be the best choice for fuel storage on Class 8 tractors in applications where distances of more than 644 km (400 mi) are traveled between refuelings
- A CNG Class 8 truck engine replacing a diesel engine can significantly reduce emissions
- Engine manufacturers are taking steps toward producing certified natural gas Class 8 trucking engines

7.3 RECOMMENDATIONS

- Continue to fund demonstrations that encourage and support heavy-duty engine manufacturers in making less-polluting Class 8 truck engines widely available and competitive with diesel engines in all respects
- Study the cost-effectiveness versus range of CNG and LNG fuel storage options for Class 8 trucks, to help users determine which method is appropriate for a given application
- Determine the sources of, and appropriate remedies for, contamination in CNG

- Make CNG fueling as convenient to the user as possible by establishing CNG fueling facilities at or near existing diesel fueling facilities, and by making CNG refueling times comparable to those for liquid fuels
- Seek further reductions in fuel consumption and NO_x emissions through the application of advanced technologies such as lean-burn closed-loop control
- Minimize packaging differences between natural gas engines and their diesel counterparts

APPENDIX A

OPERATOR-MECHANIC-MANAGEMENT SURVEY SUMMARY

Acurex Environmental

CORPORATION

A Geraghty & Miller Company

MEMORANDUM

To: Distribution

From: Henry Modetz HKM

Date: January 20, 1994

Subject: Survey Results

I have enclosed a summary of the results of a survey made in late 1993 of the operator, mechanics, and management associated with the demonstration of the Caterpillar G3406LE natural gas engine by The Vons Companies Inc. Completed questionnaires were received from the following personnel at Vons and at Power Systems Associates, who did the conversion and provided field support:

•	Rick Webb	Operator	Vons
•	Alan Yamamoto	Mechanic	Vons
•	Cliff Sheridan	Supervisor	Vons
•	Paul Wolkow	Mechanic	Power Systems
•	Frank Rtych	Lead mechanic	Power Systems
•	Bill Turner	Truck Shop Foreman	Power Systems
•	Kevin Campbell	Truck Service Manager	Power Systems

On the summary, the number of responses to each question were tabulated and any written comments were transposed beneath the tabulation. In a few instances, there were no responses to a particular question.

In general, the survey results were what we expected, e.g., fuel economy and range were major issues. However, there were some interesting observations as well, e.g., the importance of trouble-shooting documentation for the mechanics and the generally positive recommendations about buying additional natural gas-fueled vehicles.

If you desire copies of the individual surveys, or if you have any questions, please do not hesitate to call me at (415) 961-5700, extension 3348.

555 Clyde Avenue, P.O. Box 7044 • Mountain View, California 94039 • (415) 961-5700 • FAX: (415) 964-5145/6523

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Mark Riechers, National Renewable Energy Laboratory
Cindy Sullivan, South Coast Air Quality Management District
Jerry Wiens, CEC

ALTERNATIVE FUELED TRUCK DEMONSTRATION
NATURAL GAS PROGRAM

Operator-Mechanic-Management Survey

Summary

The purpose of this survey was to obtain the opinions of the operators, mechanics, and management of demonstration vehicles in the California Alternative-Fueled Truck Demonstration Natural Gas Program. Each interviewee was asked to circle the description which most closely reflects the interviewee's opinion.

Much worse = Much worse than comparable diesel vehicle/engine
Worse = Worse than comparable diesel vehicle/engine
Same = Same as comparable diesel vehicle/engine
Better = Better than comparable diesel vehicle/engine
Much better = Much better than comparable diesel vehicle/engine

If the interviewee had no knowledge or opinion, the interviewee was asked to circle **N/A**.

Operation: How do you rate the operation of the natural gas-fueled truck compared to the comparable diesel-fueled truck in the same application for the following categories?

Reliability

Much worse	Worse	Same	Better	Much Better	N/A
1	1	6			

- Starts when needed
- Still working out bugs because of being new
- Not apple to apple; worse because of downtime; engine ok
- 77% less usage compared to like year diesel trucks

Ease of operation

Much worse	Worse	Same	Better	Much Better	N/A
1	2	4	1		

- Fueling a pain; could be improved
- RPM range different
- Feels more like a car than truck
- Takes special driver (mainly for refueling)

Route flexibility

Much worse	Worse	Same	Better	Much Better	N/A
4	4				

- Fueling location
- Limited range; refueling
- Mileage a problem
- Have to base on refueling station locations due to limited range

Scheduling flexibility

Much worse	Worse	Same	Better	Much Better	N/A
	5	3			

- Have to work around refueling station basis

Re-fueling station(s) location

Much worse	Worse	Same	Better	Much Better	N/A
5	3				

- Need more

Re-fueling dispenser(s) accessibility

Much worse	Worse	Same	Better	Much Better	N/A
	2	2	1		3

Re-fueling time

Much worse	Worse	Same	Better	Much Better	N/A
1	2	3	1		1

- CNG 30 minutes; diesel 5-10 minutes

Re-fueling procedure

Much worse	Worse	Same	Better	Much Better	N/A
1		4	1		2

- No effort after hookup
- At Pico Rivera, switching between cascade banks required

Range

Much worse	Worse	Same	Better	Much Better	N/A
8					

- Diesel 1100-1200 mile range vs 200
- 78% less than diesel

Performance: How do you rate the performance of the natural gas-fueled truck compared to the comparable diesel-fueled truck in the same application for the following categories?

Uptime

Much worse	Worse	Same	Better	Much Better	N/A
1	4	2	1		

- Not this truck but future truck(s)
- But fine tuning, working out bugs makes worse

Drive-ability

Much worse	Worse	Same	Better	Much Better	N/A
		7	1		

- No difference
- Maybe lacking torque
- Driver input

Acceleration (from a stop)

Much worse	Worse	Same	Better	Much Better	N/A
	1	4	3		

- Little bit worse
- Driver input

Acceleration (city driving)

Much worse	Worse	Same	Better	Much Better	N/A
		4	3		1

Acceleration (freeway driving)

Much worse	Worse	Same	Better	Much Better	N/A
	1	3	3		1

Hill climbing

Much worse	Worse	Same	Better	Much Better	N/A
		5	1	1	1

- After getting used to transmission shifting requirements
- No experience but probably same

Lug down

Much worse	Worse	Same	Better	Much Better	N/A
1	2	3			2

- Shift gears to achieve diesel lug down performance

Fuel economy

Much worse	Worse	Same	Better	Much Better	N/A
4	3				1

- Can't make round trip to Bakersfield
- Seems worse; can't easily compare pressure to gals
- Getting 4.5

Maintenance: How do you rate the maintenance requirements for the natural gas-fueled truck compared to the comparable diesel-fueled truck in the same application for the following categories?

Engine preventive maintenance requirements

Much worse	Worse	Same	Better	Much Better	N/A
	2	6			

- Spark plugs, but oil changes better
- Oil samples needed to be taken too frequently because of new technology
- Oil samples

Fuel system preventive maintenance requirements

Much worse	Worse	Same	Better	Much Better	N/A
	2	1	3	1	1

- No filters
- Tank inspection
- No fuel filters; only worry about leaks

Engine corrective maintenance (repair) history

Much worse	Worse	Same	Better	Much Better	N/A
	5	2			1

- Ignition system
- Neglecting little bugs in system

Fuel system corrective maintenance (repair) history

Much worse	Worse	Same	Better	Much Better	N/A
	3	3	2		

- Engine miss

Ease of working on engine

Much worse	Worse	Same	Better	Much Better	N/A
	2	5	1		

- Everything seems reasonably accessible
- More electrical wires, sensors, exhaust shields
- Maybe worse if needed to remove valves and regulators to work behind or around the starter, air compressor

Ease of working on fuel system

Much worse	Worse	Same	Better	Much Better	N/A
		4	3		1

- Tanks would be a problem if work required

Safety: How do you rate the safety of the natural gas-fueled truck compared to the comparable diesel-fueled truck in the same application for the following categories?

Re-fueling safety

Much worse	Worse	Same	Better	Much Better	N/A
	4	2	2		

- High pressure
- More caution

Re-fueling safety training requirements

Much worse	Worse	Same	Better	Much Better	N/A
	2	2	1		3

- Probably same

Driving safety

Much worse	Worse	Same	Better	Much Better	N/A
		4	3	1	

- Fuel release less likely in accident
- Diesel - worry about slipping, puddling; CNG dissipates
- Diesel fuel tanks more vulnerable to puncture; CNG less hazardous if punctured

Driving safety training requirements

Much worse	Worse	Same	Better	Much Better	N/A
	1	5	1		1

Crash-worthiness

Much worse	Worse	Same	Better	Much Better	N/A
1		2	4	1	

- Fuel system integrity
- Tanks less likely to rupture
- Fuel lines and tank valves vulnerable
- No spillage

Economics: How do you rate the cost of operating and maintaining the natural gas-fueled truck compared to the comparable diesel-fueled truck in the same application for the following categories?

Fuel cost

Much worse	Worse	Same	Better	Much Better	N/A
	2		3	2	1

Lube oil cost

Much worse	Worse	Same	Better	Much Better	N/A
		3	2	1	2

- Low ash oil is being used; 1/3 more [costly] but less oil changes

Preventive maintenance cost

Much worse	Worse	Same	Better	Much Better	N/A
		6	1		1

- No fuel filters; less dilution

Corrective maintenance (repair) cost

Much worse	Worse	Same	Better	Much Better	N/A
		6	2		

- Injectors = spark plugs
- Not much info available
- Guessing - parts are parts
- No injection pump
- 500,000 warranty on new engines

Operator training cost

Much worse	Worse	Same	Better	Much Better	N/A
	3	3			2

- Not much worse

Mechanic training cost

Much worse	Worse	Same	Better	Much Better	N/A
	3	4			1

Downtime cost

Much worse	Worse	Same	Better	Much Better	N/A
1	3	4			

- Downtime is downtime
- Hasn't "broken down" - a lot of tinkering
- Waiting to go to P.S. to get bugs out

Acceptance: How do you rate the acceptance of the natural gas-fueled truck compared to the comparable diesel-fueled truck in the same application by the following personnel?

Operators

Much worse	Worse	Same	Better	Much Better	N/A
	5	1	2		

- Rick Webb is very keen about truck
- Much worse in beginning; truck has gained respect by staying with other trucks on hill; lower fuel cost
- Probably
- Except for Rick, skeptical of safety

Mechanics

Much worse	Worse	Same	Better	Much Better	N/A
	3	2	1		1

- Worse in beginning
- Other mechanics are skeptical also

Management

Much worse	Worse	Same	Better	Much Better	N/A
	5	3			

- Because of added costs
- A lot of downtime
- Some like, some don't; Overall worse. If whole fleet with easier fueling & better range, acceptance would be better

What do you like best regarding the natural gas-fueled truck?

- Cleaner emissions; engine cleaner inside
- Cleaner exhaust
- Low emissions
- Simpler fuel system - no diesel mess
- Oddity, newness
- Emission
- Low emissions

What else do you like regarding the natural gas-fueled truck?

- Interesting to work on
- Interesting to work on
- Domestic fuel supply; nice to drive - like diesel
- "Burns real clean"
- Clean burning; seeing other companies getting together to work on it, i.e., CAT, Ford
- Ease of maintenance, especially fuel system; Driveability

What do you dislike the most regarding the natural gas-fueled truck?

- Not having trouble-shooting information available
- Lack of fuel stations
- Range
- Lack of training, maintenance information, specifications
- Fuel tanks setting so low to ground makes it difficult to work on
- Downtime
- Refueling time and location
- Short range

What else do you dislike regarding the natural gas-fueled truck?

- Short range
- Not enough fuel stations
- Shortage of fuel stations; fuel tank arrangement, plumbing; rigid fuel lines
- Difficulty in fueling

If you could make changes to the natural gas engine, what would they be?

- Better self-diagnostics
- Improve efficiency
- Make torque curve like a diesel's
- Make exhaust system easier to work on
- Nothing; fuel system: raise tanks
- None
- More reliable

If you could make changes to the natural gas fuel system, what would they be?

- None
- Reduce weight of fuel tanks; reduce number of tanks
- Increase amount of fuel storage
- No changes
- Use flexible fuel lines; reduce number of cylinders; raise tanks to improve access underneath
- Raise tanks; tanks are too bulky - make one big oblong tank out of the way
- Faster fueling

Based on what you know now, would you recommend that your company purchase additional natural gas-fueled vehicles for its fleet?

- Yes for city driving; not for long distance
- Yes
- For city use only
- Not at present - too new - let someone else be guinea pig
- Yes if bugs were worked out; would be good for around town, not for long trips; need more fueling sites and maintenance facilities
- Yes
- Not in class 8 at this time

Additional comments

Survey favors established diesel types over prototype CNG truck

If CNG engine truck had same development time as diesel, would do better in survey

Truck receives a lot of attention from management, especially when down.

APPENDIX B

FIELD EVALUATION DATA

ACCELERATION TEST OF VONS CNG TRACTOR AND DIESEL CONTROL TRACTOR

ACCELERATION TEST OF VONS CNG TRACTOR AND DIESEL CONTROL TRACTOR

TRACTOR	CNG TRACTOR #9207	DIESEL TRACTOR #9333
ENGINE	CATERPILLAR G3406LE 350 BHP	CATERPILLAR 3406C 350 BHP
TEST WT	69,530	73,490
LOCATION	UNION AVE, WEST OF ARVIN	VALLEY BLVD, WEST OF POMONA
DATE	JULY 8, 1993	JULY 27, 1993

DATA

	ACCEL. TIME, S DIRECTION (SEC)			ACCEL. TIME, NE DIRECTION (SEC)		
SPEED	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 1	TRIAL 2	TRIAL 3
0	0.00	0.00	0.00	0.00	0.00	0.00
10	8.02	7.61	8.11	7.12	8.58	8.05
20	18.30	17.86	18.36	17.43	18.58	--------
30	31.08	30.61	31.48	30.21	31.71	31.52
40	48.77	48.36	49.61	51.12	53.39	52.05
50	73.53	71.50	72.75	91.77	94.77	93.30

	ACCEL. TIME, N DIRECTION (SEC)			ACCEL. TIME, SW DIRECTION (SEC)		
SPEED	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 1	TRIAL 2	TRIAL 3
0	0.00	0.00	0.00	0.00	0.00	0.00
10	7.21	8.39	8.87	7.55	6.83	7.24
20	19.53	19.61	20.52	16.43	15.24	17.15
30	32.56	33.52	35.37	27.02	25.64	27.81
40	51.02	52.64	54.52	39.96	38.52	41.24
50	78.99	78.84	80.77	55.37	56.20	--------

	ACCEL. RATE, S DIRECTION (FT/SEC**2)			ACCEL. RATE, S DIRECTION (FT/SEC**2)		
SPEED	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 1	TRIAL 2	TRIAL 3
5	1.829	1.927	1.808	2.060	1.709	1.822
15	1.427	1.431	1.431	1.423	1.467	--------
25	1.148	1.150	1.118	1.148	1.117	--------
35	0.829	0.826	0.809	0.701	0.677	0.714
45	0.592	0.634	0.634	0.361	0.354	0.356

	ACCEL. RATE, S DIRECTION (FT/SEC**2)			ACCEL. RATE, S DIRECTION (FT/SEC**2)		
SPEED	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 1	TRIAL 2	TRIAL 3
5	2.034	1.748	1.654	1.943	2.147	2.026
15	1.190	1.307	1.259	1.652	1.744	1.480
25	1.126	1.054	0.988	1.385	1.410	1.376
35	0.795	0.767	0.766	1.133	1.139	1.092
45	0.524	0.560	0.559	0.952	0.830	--------

	COMPOSITE ACCELERATION (FT/SEC**2)	COMPOSITE ACCELERATION (FT/SEC**2)
SPEED	AVG	AVG
5	1.833	1.951
15	1.340	1.294
25	1.097	1.072
35	0.798	0.909
45	0.583	0.475

	COMPOSITE ACCELERATION TIMES	COMPOSITE ACCELERATION TIMES
SPEED	AVG	AVG
0	0.00	0.00
10	8.00	7.52
20	18.94	18.85
30	32.30	32.52
40	50.67	48.65
50	75.79	79.51

HILL-CLIMB TEST OF VONS CNG TRACTOR AND DIESEL CONTROL TRACTOR

HILL–CLIMB TEST OF VONS CNG TRACTOR AND DIESEL CONTROL TRACTOR

TRACTOR	CNG TRACTOR #9207	DIESEL TRACTOR #9287
ENGINE	CATERPILLAR G3406LE 350 BHP	CATERPILLAR 3406C 350 BHP
TEST WT	72,860	70,850
LOCATION	KELLOGG HILL, EAST OF COVINA	KELLOGG HILL, EAST OF COVINA
DATE	JULY 20, 1993	JULY 20, 1993

DATA

ENTRY SPEED	55 MPH	55 MPH
ELAPSED TIME	120 SEC	112 SEC
TERMINAL SPEED	29 MPH	32 MPH

MAINTENANCE OF CNG TRACTOR

CNG TRACTOR M9207 MAINTENANCE

LINE NO.	ODOMETER	RO_NUM	DATE_OF_REPAIR	TYPE	PARTS_CODE	PARTS_COST	PARTS_DESC	WORK_DONE_CODE	LABOR_HOURS
1	71955	831909	03-Oct-92	S				09	0.7
2	71955	831909	03-Oct-92	S	43	$142.19	EXHAUST HEAT SHIELDS, CLAMPS	13	3.2
3	71955	831909	04-Oct-92	U	3	$17.67	AIR GOVERNOR	04	0.5
4	71955	831909	04-Oct-92	S				01	2
5	71955	831909	04-Oct-92	S				01	5.8
6	71955	831909	05-Oct-92	CC	44			13	5
7	71955	831909	07-Oct-92	U	42.003	$412.75	FAN HUB & BELTS	03	2.8
8	71955	831909	07-Oct-92	U	35.004	$27.00	T/M EXTRACTOR CORD	03	0.5
9	71955	831909	10-Oct-92	U				13	1.5
10	72584	832027	14-Oct-92	U	41			01	0.5
11	72997	832108	15-Oct-92	U	71	$53.76	REAR WINDOW RUBBER SEAL	03	
12	73302	832396	17-Oct-92	S	44			06	1
13	73938	832139	20-Oct-92	U	45.011	$34.49	ENGINE OIL & FILTER	03	0.5
14	74214	832042	21-Oct-92	S				06	
15	74217	832140	21-Oct-92	U	45.011	$2.19	ENGINE OIL	06	0.2
16	74796	832497	23-Oct-92	S				09	1.5
17	74796	832497	23-Oct-92	U				06	1
18	74796	832497	23-Oct-92	U	2	$29.15	DOOR KEY SET	03	1.5
19	74796	832497	23-Oct-92	U	34	$317.19	LIGHT BULB	13	1
20	74796	832497	23-Oct-92	U	35.004	$198.54	SPEEDO HEADSET, SENSOR	03	
21	74796	832496	23-Oct-92	S				09	0.5
22	74796	832497	28-Oct-92	CC	43	$34.62	HEAT DEFLECTORS	13	9.5
23	74796	832497	04-Nov-92	U	16	$658.20	FRT SPRING ASSEMBLY AND HARDWARE	03	10.2
24	74796	832497	06-Nov-92	U	3	$10.12	OIL SENDER ASSEMBLY	03	1.3
25	0		10-Nov-92	U	24			13	
26	79621	834209	19-Dec-92	S				09	0.5
27	79621	834209	19-Dec-92	U	41			01	1.4
28	79621	834209	19-Dec-92	S				02	0.5
29	79621	834185	19-Dec-92	S				09	0.5
30	79621	834209	21-Dec-92	U	41			13	0.5
31		N/A	08-Jan-93	CC	41			01	12
32		N/A	23-Jan-93	CC	41	$0.00	NEW STYLE AIR CLEANER & DUCTING	13	20
33	81129	834539	02-Feb-93	CC	43	$10.16	EXHAUST BRACKET AND CLAMPS	13	4.8
34	81129	834539	02-Feb-93	U	41			06	0.5
35	0	834570	02-Feb-93	CC	44			13	3
36	83115	41092	26-Feb-93	U	35	$6.98	DIRECTIONAL FLASHER	03	1.5
37	83845	41135	02-Mar-93	RC				13	
LINE NO.	ODOMETER	RO_NUM	DATE_OF_REPAIR	TYPE	PARTS_CODE	PARTS_COST	PARTS_DESC	WORK_DONE_CODE	LABOR_HOURS

LINE NO.	LABOR_DESC	REMOVED	RETURNED
1	PMD INSPECTION (RESULTING WORK FOLLOWS)	3-Oct	10-Oct
2	EXCHANGE EXHAUST STACKS, INSTALL HEAT SHIELDS	3-Oct	10-Oct
3	REPLACE AIR GOVERNOR	3-Oct	10-Oct
4	RETORQUE STEER BOX, U-BOLTS. SECURE WIRING	3-Oct	10-Oct
5	CHECK & ADJUST: RR AXLE ALIGN, FRT TOE-IN, CLUTCH, KING PIN, T/M MILEAGE, TIRE AIR	3-Oct	10-Oct
6	REPOSITION AIR CLEANER, FABRICATE AIR INTAKE BRKT, INSTALL FIRE & REFL. KIT, MOVE AIR LINES OFF TANK	3-Oct	10-Oct
7	R&R FAN HUB & AC BELTS	3-Oct	10-Oct
8	REPLACE EXTRACTOR CORD	3-Oct	10-Oct
9	R&R 5TH WHEEL INST KIT	3-Oct	10-Oct
10	ADJUST FAN, ALT, AC BELTS	14-Oct	14-Oct
11	INSTALL SEAL (OUTSIDE VENDOR LABOR $25.00)	15-Oct	15-Oct
12	CHECK FUEL SYSTEM FOR LEAKS	17-Oct	17-Oct
13	UNSCHEDUALED OIL CHECK	20-Oct	20-Oct
14	CHECK AND ADJUST ODOMETER (OUTSIDE VENDOR LABOR $65.00)	21-Oct	23-Oct
15	CHECK ENGINE OIL	21-Oct	23-Oct
16	PMA INSPECTION	23-Oct	6-Nov
17	KEY PAD INSPECTION, TIRE PLUG	23-Oct	6-Nov
18	REPLACE DOOR KEY SET	23-Oct	6-Nov
19	REPLACE DEFECTIVE LIGHT	23-Oct	6-Nov
20	REPLACE SPEEDO HEADSET AND SENSOR (OUTSIDE VENDOR LABOR $80.00)	23-Oct	6-Nov
21	PMD INSPECTION	23-Oct	23-Oct
22	INSTALL HEAT DEFLECTORS, FABRICATE MTG BRKT FOR AIR TANK	23-Oct	6-Nov
23	R&R FRT SPRINGS, SHACKLES, BUSHINGS	23-Oct	6-Nov
24	REPLACE OIL SENDER	23-Oct	6-Nov
25	LABOR COST TO CUT DRIVE SHAFT $106.64	10-Nov	11-Nov
26	PMA INSPECTION	19-Dec	21-Dec
27	ADJUST: 5TH WHEEL JAWS AND SLIDER, RESET AIR GOV., TIGHTEN AIR COMPRESSOR MAGNETO	19-Dec	21-Dec
28	STEAM CLEAN ENGINE	19-Dec	21-Dec
29	PMD INSPECTION	19-Dec	19-Dec
30	REPAIR EXHAUST LEAK, INSTALL STUD IN PS PUMP	19-Dec	21-Dec
31	TEST DIFFERENT GOVERNOR STRATEGIES AND RECONFIGURE GOVERNOR TO MIN\MAX STRATEGY	8-Jan	9-Jan
32	INSTALL CUSTOM FABRICATED AIR PLENUM AND DUCTING	23-Jan	26-Jan
33	REINSTALL LOOSE EXHAUST PIPE, FABRICATE NEW BRACKET FOR EXHAUST PIPE, MODIFY EXISTING BRACKET	2-Feb	2-Feb
34	INSPECT OPERATION OF TEMPERATURE SENDER	2-Feb	2-Feb
35	ALTER BRACKET SO GAS LINES DO NOT RUB	2-Feb	2-Feb
36	DIAGNOSE INOPERABLE DIRECTIONAL AND REPLACE FLASHER	26-Feb	26-Feb
37	TOWING CHARGE $315.00	2-Mar	13-Mar
LINE NO.	LABOR_DESC	REMOVED	RETURNED

38	44798	305167	05-Mar-93	S				09	0.5
39	83845	41135	11-Mar-93	U	3	$29.23	HOUR METER	03	1
40	83845	41135	13-Mar-93	U	44			13	0.7
41	87391	41648	26-Mar-93	S				09	1
42	88775	41902	06-Apr-93	U	41			06	2.4
43	90061	20182	10-Apr-93	U	17	$608.98	FRONT TIRES	03	2
44	86338	T29252	19-Mar-93	U	43	$66.87	Ring Seals for turbo outlet and waste gate	13	7.75
45	86338	T29252	19-Mar-93	U	41			06	5
46	90651	T29489	21-Apr-93	CC	43	$1,422.63	exhaust tubing, elbows, brackets, & accessories	13	62.13
47	90651	T29449	27-Apr-93	U	33.003	$515.62	spark plugs	13	20.25
48	91184	T29641	14-May-93	U	33.003	$1,707.31	spark plug "extenders", coils	03	14.5
49	91561	20749	15-May-93	U	71	$1,697.96	BUMPER, GRILL, LAMPS, AIRFOIL, PAINT	13	9.5
50	91561	21046	19-May-93	U	17	$2,419.04	8 NEW DRIVE TIRES	03	2
51	92874	21893	15-Jun-93	U	44			13	2
52	92891	N/A	19-Jun-93	U	44	$0.00	First stage regulator, mfrs design upgrade	03	2
53	92874	21893	21-Jun-93	S				06	1.9
54	93475	N/A	26-Jun-93	U	44	$55.00	Solenoid Valve overhaul kit	08	2
55	93475	22135	26-Jun-93	S				06	1.7
56	93475	22175	29-Jun-93	U	1	$8.00	FREON	13	1.5
57	95262	22688	16-Jul-93	CC	3.001	$45.00	PRESSURE RECEIVER IN-DASH DISPLAY	03	2
58	95262	22688	16-Jul-93	U	41			13	2.5
59	96676	T30208	27-Jul-93	U	41			01	5.05
60	96676	T30208	29-Jul-93	U	41			01	3.25
61	96676	T30208	30-Jul-93	U	41			13	4.55
62	100237	T30480	01-Sep-93	U	43	$14.24	LOCKNUT, GASKET	13	1.75
63	100237	T30523	08-Sep-93	U	43			06	1.75
64	100265	32446	19-Sep-93	S				09	1
65	100603	T20021	05-Oct-93	U	43			06	5
66	101081	32990	12-Oct-93	RC	44	$306.40		13	
67	101081	32990	12-Oct-93	U	71			13	2
68	100603	T20021	14-Oct-93	U	43		EXHAUST BRACKET	03	5.5
69	100603	T20021	28-Oct-93	U	43.004	$739.52	TURBOCHARGER	04	14
70	100603	T20021	03-Nov-93	U	43		EXHAUST PIPE SPACER	13	10.25
71	104474	T20556	17-Dec-93	U	35.004		Exhaust Oxygen Sensor	03	2
72	104474	T20556	17-Dec-93	U	43			06	4
73	104547	T20676	06-Jan-94	U	33.003			06	2
74	104547	T20676	13-Jan-94	U	45.006			13	6.25
75	104547	T20676	13-Jan-94	U	41.002			06	2

38	PMD INSPECTION	5-Mar	6-Mar
39	REPLACE HOUR METER	2-Mar	13-Mar
40	REPAIR AIR INTAKE	2-Mar	13-Mar
41	PMD INSPECTION	26-Mar	26-Mar
42	INSPECT: TURBO NOISE, AIR FILTER, EXHAUST LEAK	6-Apr	6-Apr
43	R&R STEER TIRES	10-Apr	10-Apr
44	Repair exhaust leak.	17-Mar	24-Mar
45	T/S ENGINE MISS: R&R SPARK PLUGS, INSPECT, DYNO TEST	17-Mar	24-Mar
46	Replumb CNG for space, install Y-pipe & dual exhaust	20-Apr	27-Apr
47	T/S misfire, personality module problems, install new plugs	27-Apr	11-May
48	Install new personality module, calibrate, dyno test	14-May	15-May
49	REPLACE DAMAGED BODYWORK, PAINTING BY OUTSIDE VENDOR $125	15-May	21-May
50	INSTALL 8 NEW DRIVE TIRES	19-May	19-May
51	T/S GAS LEAK, CLOSE CNG CYLINDERS	15-Jun	21-Jun
52	Exchange regulator due to contamination, DYNO TEST WITH NEW REGULATOR	15-Jun	19-Jun
53	90 DAY INSPECTION	21-Jun	21-Jun
54	overhaul leaking solenoid valve	26-Jun	26-Jun
55	PMA	26-Jun	26-Jun
56	RECHARGE A/C TO SPEC, TEST	29-Jun	29-Jun
57	REMOVE FUEL GAUGE, INSTALL AND CONNECT PRESSURE RECEIVER	16-Jul	16-Jul
58	INSTALL THERMOCOUPLES, TEST COOLING FAN OPERATION	16-Jul	23-Jul
59	R&R SPARK PLUGS, REGAP, CHECK F/A RATIO, SPARK TIMING, DYNO TEST	27-Jul	30-Jul
60	INSTALL THERMOCOUPLES, TEST COOLING FAN OPERATION	27-Jul	30-Jul
61	T/S EXHAUST LEAK, REPLACE RING SEALS @ TURBO, FABRICATE CLAMP	27-Jul	30-Jul
62	REPLACE GASKET TO FIX EXHAUST LEAK; STEAM CLEAN	1-Sep	1-Sep
63	CHECK ALL EXHAUST JOINTS FOR LEAKS	8-Sep	9-Sep
64	PM-D 90 DAY INSPECTION	19-Sep	19-Sep
65	TROUBLESHOOT ENGINE BACKFIRE ON DECELERATION	5-Oct	5-Oct
66	A.V. PUMPS OUT. TRUCK RAN OUT OF FUEL; TOWED IN	12-Oct	13-Oct
67	REMOVE SLIP JOINT, REASSEMBLE DRIVELINE, INSTALL FRONT BUMPER	12-Oct	13-Oct
68	FABRICATE EXHAUST BRACKET	28-Oct	9-Nov
69	REBUILD TURBOCHARGER	28-Oct	9-Nov
70	FABRICATE EXHAUST SPACER TO CHANGE ANGLE OF FLANGE AT TURBO END	28-Oct	9-Nov
71	Replace O2 sensor, retune engine to specifications	17-Dec	18-Dec
72	Troubleshoot exhaust leak	17-Dec	1-Jan
73	Remove and inspect spark plug gap	6-Jan	20-Jan
74	Remove spark plugs and perform air cylinder test	6-Jan	20-Jan
75	Check intake manifold for leaks	6-Jan	20-Jan

MAINTENANCE OF DIESEL TRACTOR

DIESEL TRACTOR 9200 MAINTENANCE

LINE NO.	ODOMETER	RO_NUM	REPAIR DATE	TYPE	PARTS_CODE	PARTS_COST	PARTS_DESC	WORK_DONE_CODE	LABOR_HOURS
1	75258	832175	19-Oct-92	S	13	$134.21	PNEUMATICE QUICK-RELEASE VALVE	03	3.5
2	91697	833099	28-Nov-92	S				09	0.7
3	91697	833108	02-Dec-92	S				09	2.8
4	91697	833108	02-Dec-92	S				09	1
5	91697	833108	02-Dec-92	U	32.001	$44.00	BATTERIES	03	2.8
6	91697	833108	02-Dec-92	U	42.007	$8.42	WATER FILTER	09	1.5
7	91697	833108	02-Dec-92	U	44.002	$9.50	FUEL FILTERS	09	1
8	91697	833108	03-Dec-92	U	45.011	$34.49	OIL & FILTERS, LUBED TRACTOR	09	2.2
9	101939	833574	25-Dec-92	U	35	$19.00	HEADLIGHT SWITCH	03	0.9
10	101939	833574	25-Dec-92	U				01	0.5
11	102856	833838	06-Jan-93	S	17	$3,208.02	TIRES	03	6.9
12	102856	833838	06-Jan-93	S				01	2.9
13	102856	833838	06-Jan-93	S				06	2.7
14	103623	833867	08-Jan-93	U				01	2.3
15	104354	833898	09-Jan-93	U	3	$27.00	T/M CORD	03	0.5
16	104942	833936	10-Jan-93	S				09	1.7
17	104942	833936	11-Jan-93	S	45.011	$34.49	OIL & FILTERS	09	1
18	104942	833936	11-Jan-93	S	42.007	$8.42	WATER FILTER	09	1
19	104942	833936	12-Jan-93	S	44.002	$9.50	FUEL FILTERS	09	1.2
20	104942	833936	12-Jan-93	S				06	1
21	104942	833923	11-Jan-93	S				09	1
22	0	834334	26-Jan-93	U	3	$9.05	POWER STEERING DIP STICK GAUGE	03	0.3
23	0	834334	26-Jan-93	S	18	$2.24	NUT	02	4.5
24	120094	834518	29-Jan-93	U	26	$61.94	TRANSMISSION OIL	09	1
25	113785	834620	31-Jan-93	U	35.004	$0.00	MOUNTING BRACKET (FABRICATED)	08	1.5
26	113785	834620	31-Jan-93	U	34	$0.25	LIGHT BULB	06	0.7
27	116837	835022	20-Feb-93	U				13	0.8
28	118440	41065	25-Feb-93	U	43	$70.19	EXHAUST PIPE FLANGE	03	2.5
29	118442	836041	02-Mar-93	S	35.004	$37.00	T/M BATTERY AND SENSOR	03	0.4
30	119543	41224	05-Mar-93	S				09	0.5
31	119543	41226	05-Mar-93	S	45.011	$34.49	OIL & FILTER	09	3
32	119543	41226	05-Mar-93	S				06	1.4
33	119543	41226	05-Mar-93	S				02	2
34	134539	20046	11-Apr-93	U				06	0.5
35	134539	20046	11-Apr-93	U				06	0.5
36	134539	20046	11-Apr-93	U	43	$10.16	EXHAUST ADAPTER AND CLAMP	03	1
37	134539	20046	11-Apr-93	U				01	2
38	134934	20090	14-Apr-93	S	44.002	$34.49	OIL FILTER & OIL	06	3

DIESEL TRACTOR 9200 MAINTENANCE

LINE NO.	LABOR_DESC	REMOVED	RETURNED
1	R&R VALVE, CHECK BRAKES	19-Oct	20-Oct
2	90 DAY INSPECTION	30-Nov	3-Dec
3	CHECK & ADJUST; ALT, U-BOLTS, CLUTCH, STARTING SYSTEM, TIRE TOE-IN	28-Nov	20-Nov
4	PMA INSPECTION	28-Nov	4-Dec
5	WON'T START; CHANGED BATTERIES	28-Nov	4-Dec
6	CHANGED WATER FILTER	28-Nov	4-Dec
7	CHANGED FUEL FILTER	28-Nov	4-Dec
8	CHANGED OIL & FILTER, LUBED TRACTOR	28-Nov	4-Dec
9	REPLACE HEADLIGHT SWITCH	25-Dec	25-Dec
10	ADJUST CLUTCH	25-Dec	25-Dec
11	REPLACE ALL TIRES	6-Jan	6-Jan
12	ALIGN DRIVE AXLES, TIGHTEN U-BOLTS, SET FRNT TOE-IN, TIGHTEN ALT & AC BELTS	6-Jan	6-Jan
13	CHECK WATER LEAK, FILL RADIATOR, CHECK LIGHTS	6-Jan	6-Jan
14	RESET PARS.IN T/M	8-Jan	8-Jan
15	R/R T/M CORD	9-Jan	9-Jan
16	PMA INSPECTION	10-Jan	12-Jan
17	CHANGE OIL & FILTER	10-Jan	12-Jan
18	CHANGE WATER FILTERS, SERVICE ALL HOSES	10-Jan	12-Jan
19	CHANGE FUEL FILTERS	10-Jan	12-Jan
20	CHECK AND ADJUST: BATTERY CABLES, CLUTCH	10-Jan	12-Jan
21	PMD 90 DAY INSPECTION	10-Jan	11-Jan
22	REPLACE DIP STICK GAUGE	26-Jan	27-Jan
23	CLEAN & PAINT WHEELS, REPLACE 2 NUTS	26-Jan	27-Jan
24	CHANGE TRANSMISSION OIL	29-Jan	29-Jan
25	REPAIRED EXTRACTOR CORD FOR T/M, MADE T/M MOUNTING BRKT	31-Jan	31-Jan
26	CHECK ALL LIGHTS, R&R RT TAIL LIGHT BULB	31-Jan	31-Jan
27	CLEANED AND LUBED REAR TAIL LIGHTS TO REPAIR AS A RESULT OF ACCIDENT	20-Feb	20-Feb
28	REPLACED EXHAUST PIPE FLANGE BEHIND TURBO	24-Feb	28-Feb
29	REPLACE T/M PARTS, PME INSPECTION	2-Mar	2-Mar
30	PMD INSPECTION	5-Mar	5-Mar
31	PMB INSPECTION	5-Mar	5-Mar
32	CLEAN BATTERY TERMINALS, TEST BATTERY SYSTEM	5-Mar	5-Mar
33	STEAM CLEAN FRAME & ENGINE	5-Mar	5-Mar
34	CHECK TRIPMASTER	11-Apr	13-Apr
35	CHECK FOR AIR LOSS	11-Apr	13-Apr
36	REPAIR EXHAUST FLANGE, REPLACE CLAMPS	11-Apr	13-Apr
37	ADJUST CLUTCH	11-Apr	13-Apr
38	PMA	14-Apr	14-Apr

39	ODOMETER	RO_NUM	REPAIR DATE	TYPE	PARTS_CODE	PARTS_COST	PARTS_DESC	WORK_DONE_CODE	LABOR_HOURS
40	134934	20090	14-Apr-93	U				01	1
41	134934	20090	14-Apr-93	S				06	1
42	139404	20383	26-Apr-93	U	35.004	$95.00	TRIP RECORDER	04	1.2
43	139404	20383	26-Apr-93	U				06	0.6
44	139676	20421	28-Apr-93	U				13	1.7
45	139676	20421	28-Apr-93	U				08	2.3
46	149044	21225	25-May-93	S				06	1
47	149044	21225	25-May-93	S	44.002	$34.49	OIL AND FILTERS	06	8
48	149044	21225	25-May-93	S				01	0.7
49	149044	21225	25-May-93	S				02	0.5
50	149044	21225	25-May-93	U	71	$7.88	HOOD SAFETY CABLE	03	0.5
51	149044	21226	25-May-93	U	13	$690.90	BRAKE LININGS, DRUMS & FITTINGS	08	3
52	149044	21226	25-May-93	U	14	$202.18	YOKE AND FITTINGS	04	2.5
53	158453	22207	30-Jun-93	U				06	1.3
54	158453	22207	30-Jun-93	U	34	$2.00	LEFT SIDE MARKER LIGHT LENS	03	1.5
55	159187	22310	02-Jul-93	U	22	$2.00	DIFFERENTIAL FLANGE GASKETS	03	2.1
56	159187	22310	02-Jul-93	U				01	2.3
57	164500	22871	21-Jul-93	S				06	1
58	164500	22872	21-Jul-93	S	44.002	$34.49	OIL AND FILTERS	06	2.3
59	164500	22872	21-Jul-93	S				02	0.3
60	164500	22872	21-Jul-93	U				13	1
61	165144	22941	25-Jul-93	U	1	$40.00	A/C BLOWER MOTOR	03	1.7
62	177093	32226	12-Sep-93	S				09	1
63	177093	32225	12-Sep-93	S				09	2
64	177093	32225	12-Sep-93	U	44.011	$14.36	CRUISE CONTROL SWITCH	03	1.8
65	177093	32225	12-Sep-93	S				02	0.4
66	177093	32225	13-Sep-93	U	14			01	1
67	177093	32225	13-Sep-93	U	32.001		BATTERY CABLE	03	1
68	182273	T20055	07-Oct-93	U	35	$225.10	LABOR (OUTSIDE CONTRACTOR)	01	3.7
69	182273	T20055	07-Oct-93	U	42	$261.80	WATER PUMP	01	1.3
70	182264	32870	05-Oct-93	U	3	$32.50		01	0.5
71	182264	32870	05-Oct-93	U				06	1.6
72	183312	33089	14-Oct-93	U	3			01	1
73	183312	33089	14-Oct-93	U	71			13	2
74	183312	33089	14-Oct-93	U				06	2.7
75	189160	33616	30-Oct-93	U	3	$13.03	SHUTDOWN SWITCH	03	2
76	193584	33849	12-Nov-93	S				09	0.75

39	LABOR_DESC	REMOVED	RETURNED
40	FIX OIL LEAK AT DIFF.	14-Apr	14-Apr
41	PMD	14-Apr	14-Apr
42	R&R T/M	26-Apr	26-Apr
43	CHECK LIGHTS, BRAKES, TIRE AIR PRESSURE	26-Apr	26-Apr
44	REPAIR FAULTY CONNECTION ON TACHOMETER	28-Apr	28-Apr
45	R&R CLUTCH ADJUSTMENT MECHANISM	28-Apr	28-Apr
46	PM-D	25-May	3-Jun
47	PM-A	25-May	3-Jun
48	CHECK A/C CLUTCH, ADJUST BELTS	25-May	3-Jun
49	STEAM CLEAN TIRES & HUBS	25-May	3-Jun
50	R&R HOOD SAFETY CABLE	25-May	3-Jun
51	BRAKE JOB, OUTSIDE VENDOR LABOR $175	25-May	3-Jun
52	R&R TRAILER YOKE	25-May	3-Jun
53	CHECK A/C	30-Jun	30-Jun
54	R&R LENS	30-Jun	30-Jun
55	R&R DIFFERENTIAL FLANGE GASKETS	2-Jul	2-Jul
56	MODIFY FRONT MUD FLAP STIFFENERS	2-Jul	2-Jul
57	PM-D	21-Jul	22-Jul
58	PM-A	21-Jul	22-Jul
59	STEAM CLEAN TRACTOR	21-Jul	22-Jul
60	T/S COOLING FAN, REPAIR WIRING, TEST COOLING FAN OPERATION	21-Jul	22-Jul
61	T/S A/C, R&R BLOWER MOTOR	25-Jul	25-Jul
62	PM-D 90 DAY INSPECTION	12-Sep	12-Sep
63	PM-B INSPECTION; LUBE TRACTOR	12-Sep	14-Sep
64	DIAGNOSE AND REPLACE CRUISE SWITCH	12-Sep	14-Sep
65	STEAM CLEAN TRACTOR	12-Sep	14-Sep
66	CHECK AND ADJUST COUPLING SYSTEM	12-Sep	14-Sep
67	MAKE NEW BATTERY CABLE	12-Sep	14-Sep
68	CHECKED AND ADJUST TIMING SENSOR	7-Oct	8-Oct
69	R&I WATER PUMP	7-Oct	8-Oct
70	CALIBRATE SPEEDOMETER	5-Oct	8-Oct
71	INSPECT WATER PUMP FOR LEAK, INSPECT TIRE AIR, LIGHTS, BRAKES	5-Oct	8-Oct
72	CALIBRATE SPEEDOMETER AND TRIPMASTER	14-Oct	14-Oct
73	WELD BROKEN AIR FOIL BRACKET	14-Oct	14-Oct
74	INSPECT TIRE AIR, CLUTCH ADJUSTMENT, RESET TOE-IN, RETORQUE FRONT U-BOLTS	14-Oct	14-Oct
75	TROUBLESHOOT, REPLACE AND TEST SHUTDOWN SWITCH	30-Oct	30-Oct
76	CHP 90-DAY INSPECTION	12-Nov	13-Nov

APPENDIX C

EMISSION TEST PLAN AND RESULTS

Acurex
Environmental
CORPORATION
A Geraghty & Miller Company

MEMORANDUM

To: Distribution

From: Geoff Hemsley

Date: February 1, 1994

Subject: Vons Truck Emission Testing and Results

Emission testing of the Vons/Caterpillar CNG tractor took place on January 27 and 28, 1994, at the Los Angeles County Metropolitan Transportation Authority (LACMTA) emission test facility. No unusual incidents or difficulties occurred during testing. A memorandum presenting the test plan was distributed in September prior to the first attempted emission test of this vehicle; this plan served as the basis for the emission testing performed on January 27 and 28. A copy the September memo, less attachments, is included with this memo as Attachment A.

On January 27, following LACMTA's usual practice, a pre-test was run on the Federal Transit Administration (FTA) Central Business District (CBD) cycle (i.e., the CBD phase of the FTA Advanced Design Bus Test Cycle). The pre-test assures that the vehicle and dynamometer are properly warmed up, and affords the staff an opportunity to review their equipment and procedures. During the pre-test, it quickly became apparent that the acceleration performance of the truck at the inertia weight setting of 69,350 lb. (the actual vehicle weight during coastdown testing) did not enable it to follow the speed trace of the CBD cycle. The truck's inability to follow the CBD cycle is not unusual, as loaded Class 8 tractors typically cannot match the low-speed acceleration of a bus. As a result, the decision was taken to reduce the number of CBD tests to be run from a minimum of two, as called out in the test plan, to one. The rationale for the change was that, since the results would not provide a meaningful comparison with CBD test results of other vehicles, effort would be better spent on tests that place less emphasis on acceleration. Mr. Gary Yowell of the California Energy Commission (CEC), who was present, participated in this discussion, and concurred with the decision. It was observed during the pre-test that the left and right exhaust stack temperatures differed by approximately 60°F throughout the test. Furthermore, exhaust hydrocarbon concentrations were quite high. These observations may be an indication that one of the catalysts has deteriorated since last July, when a dynamometer test at Power Systems Associates in Industry, CA, showed that left and right exhaust stack temperatures differed by less than 3 degrees under most conditions. A call was made to Mr. Jeff Headean of Caterpillar, Inc., notifying him of this via voice mail. A response to this message was not received. While the exhaust temperature disparity and high hydrocarbons might ordinarily be cause to delay or cancel testing pending investigation of the engine, the situation with this vehicle did not permit testing to be delayed. That is because Vons had already indicated their intention to discontinue the demonstration; a future opportunity to emission test this vehicle might not occur.

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Testing proceeded, with one CBD test, followed by three Environmental Protection Agency (EPA) Schedule (d) tests (i.e., the EPA Urban Dynamometer Driving Schedule for Heavy-duty Vehicles), and two FTA Commuter tests (i.e., the Commuter phase of the FTA Advanced Design Bus Test Cycle). The exhaust stack temperature disparity continued, and exhaust backfires were heard occasionally during deceleration (once per test, on average). High peak concentrations of exhaust hydrocarbons were seen during deceleration and transient conditions. Another voice mail message was left for Mr. Headean regarding the high hydrocarbons and backfiring. All test results are summarized in a table at the end of this memo.

Modal type testing was reduced to one steady-state idle test, since the significance of 0-20 acceleration and 20 mph cruise tests (called for in the test plan) was diminished by the fact that the CBD cycle was not considered to be valid for this vehicle. Data from the steady state idle test and the FTA Commuter tests will enable a prediction of EPA Schedule (d) emissions, which can be compared to actual EPA Schedule (d) test results.

On January 28, a final EPA Schedule (d) test was run, for the purpose of having a speciation of exhaust hydrocarbons performed by the California Air Resources Board (ARB). One exhaust backfire was heard during this test. On completion of the test, quantities of Phase 1 and Phase 2 exhaust were transferred into separate sample bags provided by ARB for the purpose. The samples were transported by Mr. Michael O'Connor to the ARB laboratory in El Monte for speciation by gas chromatagraph. Following this test, a call was received from Mr. Yowell, from his office in Sacramento. He requested that an additional test be performed using a lower inertia weight representing partially loaded operation, as on a return trip. I cautioned Mr. Yowell that simply changing the inertia weight did not affect the frictional loading of the road load model; however the frictional loading does decrease in the real life case, since 16 of the truck's 18 wheels carry less weight when the trailer is unloaded. No information was available to us to enable revision of the road load model to reflect a lower test weight, since coastdown testing was done at only one weight, i.e., 69,350 lb. This fact is apparent in the coastdown test data attached to the test plan memo that was originally circulated in September. While acknowledging this, it was agreed that an FTA Commuter test would neverthless be performed at a lower inertia weight, with the frictional loading unchanged. The FTA Commuter phase contains elements of the truck's driving pattern in actual use; namely steady acceleration to 55 mph, and cruise at 55 mph. Emissions for this test would be expected to be different only in the acceleration portion, since the loading by the dynamometer at a steady speed is not affected by changes in inertia weight setting. With input from Vons regarding typical return loads, an inertia weight setting of 45,000 lb was selected for this test. Three exhaust backfires were heard during the test. At the end of testing, the CNG engine had accumulated 32,369 miles and 829 hours in service (these figures correspond to an odometer reading of 104,689 miles and an hourmeter reading of 511.7 hours). Table 1 contains available test results, which are unofficial until confirmed by LACMTA. Particulate, formaldehyde, and hydrocarbon speciation results will be reported when available.

Table 1. Preliminary Emission Test Results
Do Not Quote or Cite

Test No.	Test Type	Inertia Weight	HC (g/mi)	CO (g/mi)	NOx (g/mi)	CO2 (g/mi)	Econ. (mpg)	HCHO sample	Specia-tion
823	CBD	69,350	129.5	0.25	35.15	4465	1.16	Yes	No
824	EPA	69,350	50.46	0.25	23.17	2385	2.23	Yes	No
825	EPA	69,350	49.77	0.28	23.56	2347	2.26	Yes	No
826	EPA	69,350	49.11	0.20	21.64	2348	2.26	Yes	No
827	COM	69,350	20.84	0.12	19.78	1764	3.08	Yes	No
828	COM	69,350	21.02	0.07	18.36	1767	3.08	Yes	No
829	Idle	69,350	N/A	N/A	N/A	N/A	N/A	No	No
830	EPA	69,350	48.23	0.21	23.25	2398	2.22	Yes	Yes
831	COM	45,000	20.64	0.11	18.57	1635	3.32	No	No

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