CHAPTER **7**

LIQUEFIED PETROLEUM GAS

7.1 OVERVIEW

LPG is a by-product of both petroleum refining and natural gas processing plants. Approximately 60 percent of the LPG produced in North America comes from natural gas processing. Processing removes most of the ethane and heavier HCs as well as carbon dioxide, which may exist in the gas at the wellhead, to produce a pipeline gas with a relatively consistent heating value. In North America, LPG is formulated to consist mainly of propane with minor amounts of propylene, butane, and other light HCs. LPG is gaseous at room temperature and atmospheric pressure, but it liquefies at pressures greater than 120 psig. This property makes it convenient to store and transport LPG as a pressurized liquid. The stored liquid fuel is easily vaporized into a gas with clean-burning combustion properties similar to those of CNG.

From the comparative listing of chemical and physical properties of LPG and other fuels in Table 2, several key properties deserve special notice. Table 17 summarizes three key properties of LPG that affect its use as a transportation fuel.

Section 7.2 presents the current state of technology including the impacts of LPG fuel use on engine and vehicle performance and lists transit buses currently in operation using the technologies identified. Sections 7.3 and 7.4 discuss potential issues related to LPG use in fueling and maintenance facilities. Section 7.5 describes safety considerations. Section 7.6 identifies fuel availability and price issues. Section 7.7 evaluates potential cost implications including general capital and operating costs.

7.2 ENGINE AND VEHICLE TECHNOLOGY

7.2.1 Engine Technology

Like most other alternative fuels, LPG has a low cetane number, which makes it difficult to use in compression-ignition (diesel cycle) engines.

In all commercially available LPG engines and conversion kits, the fuel is vaporized and mixed with air before it is admitted to the combustion chamber. LPG prepared in this manner has combustion properties similar to those of CNG and LNG. Therefore, the fuel systems for LPG and natural gas are often quite similar; the major difference is that the CNG system must be calibrated for a higher volumetric fuel flow rate at a given load. Automotive fuel-grade CNG has a substantially higher octane rating than automotive LPG; therefore, to prevent combustion knock, a heavy-duty LPG engine is normally designed for lower peak combustion pressures than a similar CNG engine. This is accomplished by using a lower compression ratio or a lower turbocharger boost pressure. Because of this octane limitation, an LPG *engine* would be expected to have somewhat lower fuel efficiency than a CNG engine operating in similar service. Because the LPG *vehicle* would almost certainly have a lighter fuel storage system than a similar CNG vehicle, the LPG vehicle would perform less work, with the result that actual in-service fuel consumption (on a Btu/mi basis) probably would be quite similar to that of the CNG vehicle.

Direct injection of LPG into the combustion chamber as a liquid, with ignition assisted by glow plug or diesel pilot, has been demonstrated in laboratory engines. Direct injection of LPG could, theoretically, result in engines with fuel utilization efficiencies as high as those of diesel engines. However, no engine manufacturer currently has plans to develop direct injection of LPG for automotive engines.

A limited range of heavy-duty LPG engines, vehicles, and conversion systems is commercially available. Two LPG engine models derived from heavy-duty diesel engines are currently offered by North American engine manufacturers. These include Caterpillar's G3306 and Cummins B5.9-195 LPG engines.

The Cummins B5.9-195 LPG engine, which has been certified to the EPA 1999 Clean Fuel Fleet Vehicle Low Emission Vehicle standard, and CARB's optional low NO_x standard of 2.5 g/bhp-hour for heavy-duty engines, utilizes much of the existing fuel and ignition system components of the natural gas version of the B5.9. Although extensive recalibration of these systems was needed to adapt them to LPG, the ability to readily convert the existing natural gas engine allowed for substantial savings in the developmental costs of the LPG engine.

Warranted OEM LPG engines are now commercially available for buses up to 30 ft long. Use of LPG in larger transit buses is currently hindered by the lack of a suitable OEM engine. Detroit Diesel had been developing an LPG version of the Series 50G; however, this program has been discontinued.

TABLE 17 Summary of key properties of LPG versus diesel fuel

Property	Diesel Fuel	LPG	Implications for LPG Vehicle Use
Storage volume relative to diesel	100%	154%	Requires somewhat more storage volume for equivalent range
Cetane number	40 to 51	-5 to 0	Difficult to compression ignite
Reid Vapor Pressure Density of vapor, relative to air	0.02 to 0.2 400-600%	189 152%	LPG leaks and spills evaporate very rapidly. LPG vapor is heavier than air and tends to remain near ground level while spreading laterally from the leak source. LPG leaks present a significant fire hazard.

7.2.2 Vehicle Performance

The operating range of LPG buses may be less than that of diesel buses if LPG tanks are not sized to compensate for the lower energy density of the fuel. The performance considerations for natural gas generally apply to LPG, except that LPG has a somewhat lower octane rating, which may result in knock-limited torque ratings also being somewhat lower.

Size and placement of LPG tanks may be an issue for some buses. As pressure vessels, LPG tanks are necessarily cylindrical, which makes them difficult to effectively package. They are larger than energy-equivalent gasoline or diesel tanks because of the lower energy density of the fuel. The higher strength and larger size of LPG fuel tanks impose a moderate weight penalty compared with equivalent diesel tanks.

As with CNG buses using throttled and spark-ignited engines, LPG buses suffer a fuel economy penalty relative to diesel buses. For example, LPG buses operated at the Orange County Transportation Authority (OCTA) had an energy efficiency 26 percent lower than equivalent diesel buses.[31]

LPG bus engines generally have lower emissions than counterpart diesel engines, although generally not as low as natural gas or methanol. However, experimental LPG buses operated at OCTA underwent chassis dynamometer emissions tests that indicated very low NO_x emissions. It appears that proper optimization for lean combustion in spark-ignited LPG engines can yield excellent emissions performance.

7.2.3 Vehicles Currently in Use

Several transit agencies currently use full-sized LPG buses in their fleets (Table 18). Four agencies currently operate LPG buses, two of which have additional LPG vehicles on order. Although full-sized LPG transit buses are rare, LPG is used in several hundred paratransit vehicles (less than 30 ft long) with spark-ignited engines (e.g., at OCTA).

The availability of warranted OEM heavy-duty engines appears to have increased the interest of transit agencies in ordering LPG-fueled buses. For example, the Los Angeles Department of Transportation (LADOT) recently placed an order for 16 low-floor 30-ft LPG buses, plus 14 standard-floor 32-ft LPG buses. LADOT previously had been purchasing CNG buses in the 30-ft size range. The reasons cited by LADOT for moving to LPG include a lower vehicle purchase price (about $20,000 less per bus) and greater compatibility with their contract operations. LADOT awards bus operating contracts for periods of 3 to 5 years. If there is a change in contractors with a new contract award, LADOT is faced with the problem of finding, relocating, or constructing new CNG fueling facilities near the new contractor's operating base. LADOT has found it much easier and less costly to install or relocate LPG than CNG fueling facilities.[32] In 1993, VIA Metropolitan Transit, in San Antonio, Texas, formally selected LPG as their preferred alternative to diesel fuel. VIA recently ordered 66 30-ft low-floor LPG buses. Although VIA had solicited bids for 40-ft LPG buses, no manufacturer submitted a proposal.[33] The Corpus Christi Regional Transit Authority has also ordered five LPG buses as an add-on to the VIA procurement.

7.3 FUELING FACILITY IMPACTS

LPG requires that facilities originally designed for diesel fuel must be upgraded to different standards or a new facility must be constructed. NFPA details guidelines for LPG vehicular fuel systems in NFPA 58. This standard presents items such as the minimum distances required between storage or dispensing of LPG and buildings, adjoining property, streets, alleys, and underground tanks.

Automotive LPG fueling facilities are fairly commonplace. Design standards for these facilities are well developed

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[31] Unnasch, S., Klughers, S., and Reese, J., *Comparative Evaluation of Clean Fuels: Final Performance Evaluation.* Acurex Environmental, for Orange County Transportation Authority (Dec. 1994).

[32] Lawrence, E., Los Angeles Department of Transportation, personal communication with R. Remillard, ARCADIS Geraghty & Miller (Jan. 1998).

[33] Milam, J., General Manager, VIA Metropolitan Transit, memorandum to the VIA Board of Trustees (Oct. 28, 1997).

TABLE 18 LPG-fueled full-size transit buses in use and on order

Transit System	City	Units in Use	Units on Order	Vehicle Manufacturer	Model	Length (ft)	Engine
Corpus Christi Regional Transit Authority	Corpus Christi, TX	3		Chance Coach	RT-52	30	Cummins B5.9 modified to LPG by Vineyard Engine Systems. Will be repowered to OEM Cummins B5.9 LPG.
			5	Champion	SOLO (low-floor)	30	Cummins B5.9 LPG
Pasadena Department of Transportation	Pasadena, CA	2	0	Blue Bird	Q-bus	30	Cummins B5.9 LPG
West Contra Costa County Transit	Pinole, CA	2	0	Blue Bird	Q-bus	30	Cummins B5.9 LPG (prototype)
Los Angeles Department of Transportation	Los Angeles, CA	5		Blue Bird	Q-bus	30	General Motors
			16	El Dorado - National	EZ Rider (low-floor)	30	Cummins B5.9 LPG
			14	El Dorado - National	Transmark	32	Cummins B5.9 LPG
VIA Metropolitan Transit	San Antonio, TX		66	Champion	SOLO (low-floor)	30	Cummins B5.9 LPG
Total		12	101				

and are detailed in NFPA 58, Standard for the Storage and Handling of LPG.

LPG is typically stored in above-ground thick-gauge steel tanks at 120 psi and ambient temperature. Because the tanks are strong enough to support pressures of 250 to 300 psi, they can be supported by concrete or steel saddles without deforming. For protection from impacts with vehicles, tanks are surrounded by heavy upright steel barrier posts. LPG tanks can be placed underground but, to avoid excavation costs and corrosion, this usually is not done.

LPG fuel dispensers look much the same as standard diesel fuel dispensers and operate in a similar fashion. Fueling time is comparable to that of standard fuels. NFPA 58, Storage and Handling of LPG, requires that LPG fueling is performed outdoors. Because LPG vapors are heavier than air, a rain cover over the dispensing station is permitted. There is no danger of hazardous levels of fuel vapors accumulating under the canopy. LPG dispensers are also required to be located separately from other fuel tanks and dispensers.

A constant displacement pump is used for metering and to provide a constant flow rate of fuel to the vehicle's storage tanks. Pumping LPG into the vehicle's tanks condenses the vapor in the tank to make room for liquid. No vapor recovery system is necessary because the storage and dispensing system is sealed. Standard LPG dispensers are available to provide the 28 to 30 gpm needed to achieve diesel equivalent fill rates.

7.4 MAINTENANCE FACILITY IMPACTS

LPG vapor has fire properties similar to those of gasoline. Both are heavier than air and pool near ground level. A well-designed maintenance garage for LPG vehicles has explosionproof (classified) wiring and electrical equipment in low areas (0 to 18 in. above ground level) where LPG buses are maintained. Building ventilation rates must be sufficient to remove LPG gas from ground level. An alternative to explosion-proof devices and wiring is a strict policy of closing off vehicle LPG tanks and purging the fuel system before indoor maintenance activities are performed. Maintenance facilities should also be equipped with flammable gas detectors. These devices can detect concentrations of LPG before the vapors reach flammable levels. Routine maintenance activities can be performed outdoors as well.

There are no codes specifically governing the design of LPG maintenance facilities. Generally, LPG facilities are designed to meet the codes for maintenance garages for gasoline vehicles, per NFPA 88B, Standard for Repair Garages, and NFPA 70, the National Electric Code. As with the other widely used alternative fuels, the FTA has published a comprehensive reference on transit facility design requirements for LPG vehicles.[34] Transit agencies interested in converting to LPG, or agencies that are already operating LPG vehicles, should utilize this document to guide their planning process or operating procedures.

7.5 SAFETY

Operating and safety training is required for personnel operating and maintaining LPG vehicles. Because of the

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[34] Raj, P. K., Hathaway, W. T., and Kangas, R., *Design Guidelines for Bus Transit Systems Using Liquefied Petroleum Gas as an Alternative Fuel.* DOT-FTA-MA-26-7021-96-4. Technology & Management Systems, Inc., Burlington, Mass. (Sept. 1996). Available from the National Technical Information Service, Springfield, Va. 22161.

gaseous nature of LPG and the fact that it is stored under moderate pressure, handling characteristics are significantly different from more familiar liquid fuels.

Drivers must be aware of procedures to follow in the event of a leak, know what to do if they run out of fuel, and be alerted to any vehicle-specific peculiarities of the LPG vehicles. Drivers and mechanics should be made aware of the safety-related aspects of LPG. A training manual is available for LPG vehicle operators.

7.5.1 Fire Hazards

LPG is the only alternative fuel that is a heavier-than-air gas at ambient conditions. It will therefore descend from the location of a leak. Trained personnel must be aware of the ways to detect an LPG leak. Like natural gas, a small LPG leak may be detectable only by the smell of the odorant or with a combustible gas detector. Larger leaks may also be detected by their sound or by the appearance of frost.

As with all fuels, smoking is prohibited when LPG vehicles are being fueled or when work on their fuel systems is being done. Safe work practices and facility design can eliminate potential ignition sources where LPG is handled or where leaked gas may accumulate (e.g., at floor level, in pits, and in trenches). As with natural gas, any LPG leak is considered a fire hazard, because a flammable concentration exists at the interface between a gas plume and the surrounding air.

Specific firefighting practices apply to LPG. Properly used fire extinguishers can effectively starve a small LPG fire for oxygen and thus extinguish it.

Some LPG buses in demonstration projects are equipped with automatic fire suppression systems. These systems are desirable because LPG is more flammable than diesel.

7.5.2 Pressure

The storage pressure of LPG poses certain hazards that are minimized by proper equipment and training. A pressurized fitting, if loosened while under pressure, could become a missile. Skin contact with a pressure-fed gas jet could result in a gas embolism in the bloodstream. A more likely occurrence is a freeze burn caused by the drop in temperature at the point of a leak. Training that covers these hazards enables personnel to avoid them.

7.5.3 Other Hazards

Ingestion of LPG is unlikely because of the fuel's tendency to vaporize at ambient conditions. Although LPG is nontoxic, asphyxiation is possible in a closed environment because of displacement of oxygen. Absorption through the skin is not considered a problem.

7.6 FUEL AVAILABILITY AND COST

LPG is produced as a by-product of natural gas processing (approximately 60 percent) and petroleum refining (approximately 40 percent). Because so much propane production is associated with gasoline and diesel fuel production, some researchers and institutions do not classify LPG as an "alternative" fuel.

Oil and gas wells produce a spectrum of HCs, and part of this spectrum is referred to as "natural gas liquids." The various natural gas liquids, including propane, are separated out by a process called fractionation. From there, propane (plus the other light HCs contained in LPG) is transported by truck, railroad, or pipeline to propane sales and distribution centers. Propane has many uses in addition to its application as a motor vehicle fuel—e.g., for heating and cooking in rural areas where natural gas is not available, in recreational vehicle appliances, and in home barbecues.

LPG can be purchased wholesale from distribution centers by fleet users with their own refueling stations, it can be purchased by fleet users at discounted prices from public-access refueling stations, and it can be purchased by the general public at retail prices from public-access refueling stations. The number of public-access propane refueling stations in the United States is variously reported in the literature as between 5,000 and 10,000.

It is difficult to be precise about the price of LPG because its available purchase price depends on so many factors, such as whether the purchase is at the wholesale (e.g., fleet) or retail level, the quantity being purchased, the timing relative to yearly and seasonal propane market fluctuations, the location within the United States, and the state tax treatment.

Historically, the pretax wholesale price of propane has been somewhat less than (e.g., typically 75 percent of) the price of gasoline on an energy-equivalent basis (i.e., per Btu). Also, because a portion of propane production is associated with petroleum refining, propane's price fluctuations usually correlate with those of gasoline and diesel fuel. On the average, since the early 1990s, the energy-equivalent price of propane has been increasing relative to the price of gasoline and diesel fuel, so LPG is now nearly as expensive as gasoline and is more expensive than diesel fuel.

7.7 CURRENT CAPITAL AND OPERATING COSTS

Because of the limited availability of commercialized engines and vehicles from the OEMs, the incremental cost of a full-sized LPG bus cannot be determined with certainty. OCTA's experience indicates an approximate incremental cost of $30,000.[15] More recent procurements and price quotes from several bus manufacturers indicate an incremental cost of approximately $35,000 to $45,000.

VIA Transit's recent order for 30-ft low-floor LPG buses resulted in a price of $241,639 per bus.[35] The manufacturer estimates that this price is between $15,000 and $16,000 higher than that of a similarly equipped diesel model.

LPG fueling facilities and modifications to maintenance facilities entail additional capital costs. Although these costs vary substantially depending on the specific circumstances and equipment, a typical estimate for a 200-bus transit fleet is $300,000 for modifications to one maintenance garage and $700,000 for one LPG fueling facility.[15]

Operating costs for LPG buses, relative to diesel buses, depend primarily on fuel costs and maintenance costs. Fuel costs, as discussed in Section 7.6, should be slightly higher for LPG buses than for diesel buses based on current prices.

Maintenance costs for LPG buses are not well documented. LPG burns with less deposit formation than either gasoline or diesel fuel, which could result in less scheduled maintenance. LPG leaves no varnish or carbon deposits that can cause premature wear of pistons, rings, and valves. LPG's cold-starting characteristics prevent much of the wear and crankcase oil dilution associated with liquid motor fuel starting and warm-up periods.

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[35] Milam, J., General Manager, memorandum to the VIA Board of Trustees (Oct. 28, 1997).

CHAPTER **8**

HYBRID-ELECTRIC PROPULSION

8.1 OVERVIEW

Transit operators are seeking buses with reduced weight, improved fuel economy, lower emissions, and lower maintenance requirements to reduce operating expenses and to reduce the frequency of buses loaded beyond their gross vehicle weight requirements (GVWRs). In addition, low-floor designs are being introduced as a means of easing passenger boarding and off-loading and to eliminate the need for wheelchair lifts. Hybrid-electric drive systems are being aggressively investigated as a means of facilitating these important design goals.

Hybrid-electric vehicles (HEVs) use both an internal combustion engine and an electric driveline to provide propulsion energy. The combination of an internal combustion engine with an electric drivetrain provides certain advantages over pure battery-electric or internal combustion engine-driven power trains. As discussed in Chapter 9, battery-electric buses suffer from reduced performance and range, along with higher curb weights, compared with motor (internal combustion) buses because of the low specific energy capacity (e.g., in kW-hour per pound of battery weight) of commercially available batteries. On the other hand, motor buses, compared with battery-electric buses, are at a disadvantage in that battery-electric propulsion maintains high energy efficiency at low and part loads, whereas engines become inefficient at low loads. Because transit buses spend much of their time at low to moderate loads, this characteristic of internal combustion engine drive leads to comparatively poor fuel efficiency in transit bus service. In an HEV, a relatively small engine is used to power an alternator, which more or less continuously recharges the propulsion batteries.

The smaller engines of HEVs operate primarily at steady state, using batteries to store and discharge energy as needed under transient conditions. This can improve fuel economy and emissions over traditional internal combustion engines. HEVs have a longer range than pure electric vehicles (EVs) because they are not limited to stored battery energy. This also enables them to reduce the necessary battery weight on the vehicle, which further reduces overall energy consumption.

8.2 VEHICLE TECHNOLOGY

A conventional bus uses substantial amounts of kinetic energy while frequently accelerating from a standing start and then braking to a stop. The energy needed in one of these cycles is given by

$$E=1/2\ mv^2 \qquad (2)$$

where m = mass of the bus and v = maximum speed reached during the service cycle. For a 33,000-lb bus accelerating to 30 mph, this kinetic energy is equal to 0.50 hp-hour. A two-stroke diesel bus engine typically has a brake-specific fuel consumption (bsfc) rate of about 0.45 lb/bhp-hour, implying that each acceleration from standing start to 30 mph requires about 0.23 lb of fuel if rolling resistance and aerodynamic drag are ignored. This substantial amount of energy is then lost as heat when the bus is braked to a stop.

In a hybrid-electric drive system, the engine is used to drive a generator set, which in turn powers one or more propulsion motors. A potential advantage of electric drive is that the motor can easily function as a dynamic (electric) brake during deceleration, at which time it acts as a generator. This feature has been used for years in trolley buses and rail transit vehicles to extend the life of the service brakes. The braking power generated by dynamic braking in these vehicles is usually dissipated in an onboard resistance grid. Bus performance simulations have shown that if the kinetic energy converted by the motor could be efficiently stored and reused, it could dramatically reduce in-service fuel consumption. Emerging hybrid electric bus designs employ one or two pairs of wheel motors, with motors mounted directly to the hubs of the rear wheels. This configuration allows the mechanical transmission, driveshaft, and differential to be eliminated and the driven axles to be greatly shortened. As these components occupy a substantial amount of underfloor space in a conventional motor bus, their elimination greatly simplifies the design of low-floor buses.

Modern traction- and industrial-motor systems use AC motors controlled by inverters. The inverter synthesizes the correct AC frequency, voltage, and stator excitation needed to operate efficiently across various loads and speeds. The recent development of inverters based on insulated gate bipolar transistors (IGBTs) has resulted in AC traction motor systems that are lightweight, powerful, reliable, and durable. These electric motor drive systems operate over a wide range of rotational speeds, develop maximum torque near stall, and produce approximately constant power across the full range of motor speeds. These are ideal characteristics for driving heavy vehicles and, as a result, a multispeed mechanical transmission is not needed. Compared with a conventional motor bus drivetrain, this offers the potential for savings in both weight and maintenance.

By using the internal combustion engine in a generator set, the engine is mechanically decoupled from the drive train. This gives the control system much more latitude to maintain the engine near its most fuel efficient (and also usually its lowest emission) operating speed. Electric drive allows energy storage systems such as batteries, flywheels, and ultracapacitors to be easily incorporated for load leveling. Ideally, these systems would allow the engine to operate at a constant load at its most fuel-efficient operating point. The engine would charge the energy storage system while traction power demand is less than alternator output; conversely, the energy storage system would supplement engine power during periods of high power demand.

In fact, research is currently being conducted on a variety of hybrid-electric drive configurations. At one extreme are systems that are primarily battery-electric but that use a small engine-driven genset generator (roughly 7 kW) to reduce the battery output that otherwise would be needed, thereby extending the operating range between charges. At the other extreme are systems with gensets large enough (150 to 200 kW) to directly power the drive motors in all operating modes without being supplemented by a discharging energy storage device. With the small genset, the vehicle's batteries are externally recharged and constitute the primary energy source. With the large genset, the engine's fuel is the primary energy storage medium, and the vehicle is not equipped for external battery recharging. It remains the case that combustible fuels enjoy dramatically greater specific energies (measured as hp-hour/lb or kW-hour/kg) than batteries and that internal combustion engines achieve much higher specific power ratings (measured as hp/lb or kW/kg) than batteries. Given that the goals of much lighter weight and lower floor height are being sought by transit agencies for new bus designs, the large genset option appears to be the most feasible for general-purpose transit buses.

8.3 DEVELOPMENTAL STATUS

No full-sized 40-ft hybrid-electric buses are currently in transit service. However, several well-funded development programs are under way that will see the completion of prototype vehicles during the 1997-1998 period. Notable projects are listed in Table 19 and are summarized in the following subsections.

8.3.1 Advanced Technology Transit Bus (ATTB) Project

The ATTB program is ambitious and innovative. The objective is to develop an advanced lightweight, low-floor bus that has substantially lower energy consumption and emissions than current conventional designs, while being manufacturable at competitive cost. Northrop-Grumman, which is designing the bus and manufacturing the prototypes, has incorporated its aerospace manufacturing experience into the design of the bus. The project has moved through design to production of the first prototype. Six prototype buses are in production and are scheduled to undergo testing and demonstration at selected transit agencies in 1998.

The ATTB body consists of inner and outer fiberglass skins separated by a plastic foam core. The body, which was designed by extensive finite element analysis, is very strong and rigid and is also unusually lightweight. A low floor has been incorporated, which is of uniform height throughout the bus's interior. Although the prototypes of the ATTB will be CNG fueled, using roof-mounted tanks, a diesel option is envisioned for production vehicles. Power for all bus systems is provided by a Detroit Diesel Series 30 natural gas engine. This engine is based on the block of the widely used Navistar 7.3L medium-duty V-8 diesel engine bus and incorporates spark ignition, intake air throttle, and an electronically controlled gas mixer for operation on CNG. Rated engine output is 157 kW. The engine drives a Kaman Electromagnetics alternator, which is designed to

TABLE 19 Hybrid-electric bus development programs

Program	Sponsor(s)	Contractors
Advanced Technology Transit Bus (ATTB)	U.S. DOT/FTA	LACMTA, Houston Metro, Northrop
New York State Consortium	U.S. DOT/FTA, EPRI, NYSERDA	NYC MTA, General Electric, Orion Bus Industries
Demonstration of Universal Electric Transportation Subsystems (DUETS)	DARPA funding with FTA management	Novabus, Kaman Electromagnetics DOE/Sandia

produce an electrical output between 40 and 145 kW, as engine speed is varied from 900 to 2,600 rpm.

The AC output of the alternator is rectified to 360 V direct current (DC) for wheel motor power. Wheel motors located in each of the rear wheel hub areas provide vehicle propulsion. The permanent magnet AC motors used in the prototype buses are manufactured by Kaman Electromagnetics. The motors are controlled by IGBT inverters and incorporate dynamic braking. Initial prototype vehicles will not be equipped with energy storage devices to recover braking energy. The program's managers had planned to incorporate flywheel energy storage systems in the later prototypes. However, recent improvements in the performance and cost of ultracapacitors may lead to their incorporation instead.[36] The motor controller system is already designed to either dissipate braking energy to a resistance grid or direct it to a storage system when one is installed.

Performance simulations conducted by Northrop-Grumman indicate that the weight savings and drivetrain efficiencies achieved by the ATTB design will result in a 30 percent improvement in fuel consumption, compared with a conventional motor bus, even without an energy storage device.[36] A typical transit bus equipped with a diesel Detroit Diesel Series 50 engine travels about 4 mi per gallon in urban route service. If this projection for the ATTB holds, the ATTB would travel 5.2 mi per diesel-equivalent gallon on the same route.

Another analysis performed by Northrop-Grumman shows that the CNG-fueled ATTB achieves a 6,000-lb weight reduction compared with a diesel TMC RTS (Table 20). Note that, because of the reduction in fuel tank weight for diesel, this weight savings would likely increase to 7,500 lb for a diesel-powered ATTB compared with CNG.

8.3.2 New York State Consortium Project

The Intermodal Surface Transportation Efficiency Act of 1991 established a $12 million program for advanced transportation systems and EVs. The consortia program for advanced transportation technology was carried further under subsequent funding from the Defense Advanced Research Projects Agency. The New York State Consortium was one of four consortia competitively selected under the FTA Advanced Technology Transportation Program.

The New York State Consortium developed a prototype hybrid-electric bus based on a conventional Orion Bus Industries (OBI) Orion V (high floor) 40-ft chassis. General Electric was the supplier of electric drivetrain components. This bus used tandem axles driving a single wheel per axle end. All four of the rear wheels were driven by AC wheel motors using IGBT controllers. Compared with a conventional single rear axle with dual wheels at each end, this configuration reduced the intrusion of the wheel housings into the cabin and supports a similar load. Propulsion power was provided by a diesel Cummins B5.9, rated at 190 bhp, which drove a General Electric alternator rated at 100 kW. Nickel-cadmium (Ni-Cad) batteries manufactured by Saft were used to store regenerative braking energy and to increase transient power output (load leveling). Although they are much more expensive than conventional lead-acid batteries, Ni-Cad batteries offer higher energy storage capacity per unit weight and are also much more durable.

TABLE 20 Vehicle system weight: Conventional transit bus versus ATTB

Equipment System	Conventional Bus (TMC RTS) (lb)	ATTB Prototype (lb)
Body structure	6,851	6,129
Body equipment	5,102	4,082
Mechanical and propulsion	11,187	8,910
Electronics	80	1,623
Miscellaneous	3,250	—
Driver	150	150
Total	26,620	20,894

On the basis of measurements taken on a test track, OBI has presented fuel economy data for this prototype by using a transit bus driving cycle. Compared with a conventional Detroit Diesel Series 50-based drivetrain, 40 percent better fuel economy was observed for the hybrid-electric drivetrain, as shown in Table 21.[37] It will be quite impressive if this result can be duplicated in revenue service.

OBI reports that the hybrid electric bus prototype was able to follow FTA driving cycles during chassis emission testing better than a conventional bus. Emissions were reportedly reduced by 50 percent as well.

Orion Bus is moving toward commercial production of a hybrid-electric transit bus. In partnership with Lockheed Martin, an Orion VI low-floor, 40-ft transit bus with the Lockheed Martin electric drive system was completed in late 1997. The electric drive system will use a single AC induction traction motor in contrast to the General Electric wheel motors in the earlier prototype. New Jersey Transit procured four of the Orion VI hybrid-electric transit buses, which were delivered beginning in late 1997. MTA New York City Transit is also procuring 10 of these buses.

The New York Consortium project aims to integrate the electric propulsion and energy storage systems into an otherwise conventional steel-frame bus chassis. In an attempt to minimize the sources of uncertainty in the performance and durability of the resulting hybrid-electric bus, proven conventional components will be used wherever possible. This

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[36] Graham, B., ATTB Program Manager, Northrop-Grumman Corporation, personal communication (April 1996).

[37] Brager, M., *Hybrid Electric Bus Project Status Update.* Paper presented at the American Public Transit Association Bus Operations Conference (May 1996).

TABLE 21 Test track fuel economy data for OBI Orion V buses

Drive Train	Observed Fuel Economy (mpg)	Relative Fuel Economy
DDC 6V-92	4	-20%
DDC Series 50	5	Baseline
HEB Prototype	7	+40%

contrasts with the ATTB project, in which a completely new fiberglass chassis is being developed along with a hybrid-electric drivetrain.

8.3.3 Demonstration of Universal Electric Transportation Subsystems (DUETS) Project

Consistent with the goals of the Defense Advanced Research Projects Agency (DARPA), one of its principal sponsors, the DUETS project was concerned primarily with developing civilian applications for technologies originally developed for defense. The increasing power requirements of weapon systems on armored vehicles has prompted the development of designs using a single generator set to power weapons, auxiliary loads, and electric propulsion. Similarly, development of other military and high-technology subsystems, such as new control system technologies and better suspension technologies, resulted in a teaming arrangement between four companies to demonstrate their products in a commercial application. The FTA obligated DARPA funds and managed the DUETS bus program to address the commercial civilian application of these military technologies.

In support of their design and development responsibilities for the DUETS program, Kaman Electromagnetics had developed a permanent magnet traction motor for electric drive armored personnel carriers. This motor, model PA44, which is extremely powerful for its size and weight, was the basis for the two-wheel motors developed in the DUETS program and tailored for the transit bus application. Furthermore, Kaman developed a generator system that was mated to a CNG-fueled, rotary (Wankel) engine to serve as the genset for the DUETS' hybrid propulsion system. Finally, Kaman designed and produced a traction motor inverter and an auxiliary power supply inverter to control traction power and to provide electrical power for the onboard auxiliary systems, such as power steering and air conditioning.

Honeywell Technologies Center adapted technology developed for commercial flight control systems to serve as the vehicle management system for the DUETS bus. This system controlled all onboard equipment and communicated vehicle control information and vehicle diagnostics via a high-throughput, fault-tolerant fiberoptic digital communication system. This digital communication and control system will support the processing and communication needs anticipated for future intelligent transportation equipment.

David Technologies International designed and fabricated a semiactive suspension system to improve ride quality and to lessen any potential road damage due to the weight of the bus. This system incorporates a compressible fluid technology that allows control over the spring rates and damping coefficients to control roll, pitch, and heave characteristics of the vehicle.

These three companies worked with Nova Bus, Inc., to integrate these subsystems into an RTS 40-ft transit bus chassis. Energy storage for peak power and regenerative braking was supplied by a 270-V Saft Ni-Cad battery system with a capacity of 216 kW-hour.

Based on the experience gained in the development of the DUETS bus, Nova Bus plans to design and produce a demonstration fleet of diesel-fueled, hybrid-electric transit buses by 1999. Nova Bus is soliciting North American transit agencies to participate in the development and operation of these vehicles.[38]

8.4 FUELING FACILITY IMPACTS

For all of the hybrid-electric technologies being developed for full-sized transit buses, a diesel, LPG, or natural gas engine ultimately provides all the energy for propulsion. Therefore, the hybrid-electric bus would be fueled in a normal manner for one of these fuels. To the extent that hybrid-electric drive improves fuel economy in service, fuel fills and dispensing time would decrease, or lower dispensing rates could be used with unchanged dispensing times.

8.5 MAINTENANCE FACILITY IMPACTS

Maintenance facilities for HEVs will need a variety of new tools and equipment. This will include diagnostic equipment for propulsion control systems, high-voltage power electronic systems, and propulsion motors. If hybrid electric propulsion allows for significant reductions in transmission and brake maintenance, fewer service bays and maintenance spares may be needed than with a similar-sized fleet of motor buses. Provisions for storing and replacing propulsion batteries may be needed.

8.6 SAFETY

The electric motor drive systems in hybrid-electric buses typically use high DC voltages (360 V) with currents as high as several hundred amperes. These systems present shock and electrocution hazards to service personnel. Transit

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[38] McDowell, J., Director of Advanced Engineering, Nova Bus, personal communication (Aug. 1996).

agency personnel have safely serviced similar power systems in rail cars and trolley buses for some time; however, training in appropriate work practices is essential.

Hybrid-electric buses using alternative fuels will carry volatile fuels in the same vehicle as powerful electric propulsion systems. Careful system engineering will be called for to prevent electrical shorts or ground faults in the power system from presenting ignition sources for fuel leaks.

8.7 VEHICLE CAPITAL AND OPERATING COSTS

The development of full-sized hybrid-electric buses has now progressed to the advanced demonstration phase. However, bus manufacturers are only now planning product design and marketing strategies for commercialization. This makes it difficult to accurately project the capital and operating costs of production vehicles. New Jersey Transit is reportedly paying $550,000 per bus for its order of four low-floor Orion VI diesel hybrid-electric buses. Orion expects that fully commercialized diesel hybrids will be priced similarly to current CNG motor buses, at about $350,000.[39] In mid-1997, Foothill Transit in West Covina, California, placed an order with Gillig for a prototype CNG-fueled high-floor 40-ft hybrid-electric bus at a price of $600,000. The Foothill bus utilizes a conventional Gillig Phantom body and will be powered by a Cummins B5.9G engine driving a 125-kW alternator. The bus will be equipped with a hybrid-electric drivetrain designed by Siemens.[40]

The operating costs for hybrid-electric buses ultimately should be lower than those of conventional motor buses. Based on the performance of electric rail propulsion systems, mature, commercialized hybrid-electric drive systems should be quite reliable and durable. Operating data and performance simulations indicate that hybrids will consume approximately 30 percent less fuel than similar motor buses. The dynamic braking capabilities of the hybrid-electric bus should result in dramatically lower wear rates and extended repair intervals of the mechanical service brakes as well.

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[39] Garrick, L., Hybrids and Their Relatives Join the Fleets. *Mass Transit* (Sept.–Oct. 1997).

[40] Macleod, B., Vice President, Gillig Corporation, letter to J. Austin, Executive Director, Foothill Transit (May 28, 1997).

CHAPTER **9**

BATTERY-ELECTRIC PROPULSION

9.1 OVERVIEW

Battery-electric propulsion is being offered by several manufacturers for medium-duty buses between 22 and 30 ft long. These buses offer several attractive features, notably

- Lower noise levels than motor buses, especially at idle and low speeds;
- Zero tailpipe emissions, smoke, or exhaust odor; and
- Effortless cold starts.

Their principal drawbacks, compared with similar motor bus models, are reduced range and performance along with substantially higher purchase prices. Their battery packs require careful maintenance; otherwise, they may have to be replaced at 1- to 2-year intervals, also at substantial expense. State-of-the-art battery-electric buses incorporate the lightweight electric motors and chassis construction as well as the regenerative braking systems described for hybrid-electric buses. These systems promote extended range compared with earlier DC motor designs via lower energy consumption rates for propulsion. However, heating, air conditioning, and air compressor loads represent surprisingly and intractably large energy sinks in a transit bus. These loads must be considered when battery-electric bus performance is being evaluated.

9.2 DEVELOPMENTAL STATUS

Batteries, even those using advanced chemistries with the highest specific energies (i.e., W-hour/kg), have dramatically lower specific energies than combustible fuels. This is shown in Table 22, which compares the specific energies of the most prominent battery types with those of the leading combustible fuels. Forty-foot diesel transit buses are typically designed for a range of 400 mi. With a modern four-stroke engine averaging about 4 mi per gallon, this is equivalent to a tank capacity of 100 gallons (equal to 700 lb or 317 kg). The mass of the tank is about 100 kg, giving a total storage mass of 417 kg. As shown in Table 22, more than 15,000 kg (33,000 lb) of lead-acid batteries would be needed to store the same amount of usable energy as 100 gallons of diesel fuel, a weight 36 times as great, and greater than the weight of the bus itself. Even the most advanced lightweight zinc battery technologies entail storage weights 8.4 times as great as diesel fuel (Table 22). In contrast, CNG, the combustible fuel with the greatest storage weight of the fuels reviewed in Table 22, has a storage weight only 3.3 times that of diesel for equivalent energy storage. However, this is not a very representative comparison of actual vehicle performance, as it is not feasible to store 15,000 kg of batteries on a bus. Because vehicle weight affects the energy demand, adding more battery weight is beneficial only up to a maximum weight. Above that point, adding more battery weight has the opposite effect of reducing range and performance.

A more practical approach to comparing vehicle performance is to evaluate the vehicle ranges possible with storage capacities typical of vehicles currently in use. Table 23 shows this comparison. Typically a transit bus will store about 2,000 to 2,500 kg of lead-acid batteries and slightly less of the more advanced, lightweight batteries.[41] When vehicle ranges are compared it is less appropriate to compare thermal energy of a combustible fuel to electric energy of a battery, as the consumption rates are much higher for thermal energy than for electric energy. An electric transit bus, for example, will consume 1 to 2 DC kW-hour/mi, depending on the duty cycle and accessories operating (i.e., air conditioning, heating), whereas a diesel bus consumes an equivalent of 10 kW-hour/mi of thermal energy. Table 23 shows how vehicle ranges compare when electrical energy consumption is evaluated separately from thermal energy consumption.

Clearly, the ranges of electric buses are much less than those of conventional 40-ft diesel buses at this point. Because of its greater weight, a 40-ft bus requires about 25 percent more energy storage for a given operating range than a 30-ft bus, which then requires more battery weight to achieve, reducing payload by the same amount and possibly reducing the range. Although 40-ft battery-electric buses have been successfully operated in downtown shuttle routes with limited speeds and range, their performance limitations make them impractical for conventional route service but quite appropriate for niche routes requiring only 22- to 30-ft vehicles and ranges of 100 mi or less.

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[41] Based on battery-electric buses operating at the Santa Barbara Metropolitan Transit District.

TABLE 22 Energy storage weight for batteries versus combustible fuels

Energy Storage Medium	Usable Specific Energy (Wh/kg)[a]	Weight Equivalent to 100 Diesel Gallons Including Tank (kg)	Weight Relative to Diesel (Diesel = 1)
Batteries (80% DOD)			
Lead-acid	50[b]	15,070	36.1
Nickel-cadmium	50[c]	15,070	36.1
Nickel-metal hydride	80[b]	9,419	22.6
Zinc-air	215[d]	3,505	8.4
Sodium-sulfur	100[c]	7,535	18.1
Lithium-polymer	100[c]	7,535	18.1
Lithium-ion	100[b]	7,535	18.1
Combustible Fuels			
Diesel No. 2	2,377[e]	417	1.00
Natural gas	2,088[e]	1,361	3.26
LPG	2,057[e]	866	2.08
Methanol	1,111[e]	828	1.99
Ethanol	1,498[e]	633	1.52

[a] Battery-specific energy based on total weight of full battery pack.

[b] Kalhammer, F. R., Kozawa, A., Moyer, C. B., and Owens, B. B., *Performance and Availability of Batteries for Electric Vehicles: A Report of the Battery Technical Advisory Panel,* prepared for California Air Resources Board (Dec. 11, 1995).

[c] *Reclamation of Automotive Batteries: Assessment of Health Impacts and Recycling Technology,* prepared by Acurex Environmental Corporation for the California Air Resources Board (March 1995).

[d] Griffith, P., *Four-Year Report on Battery Electric Transit Vehicle Operation at the Santa Barbara Metropolitan Transit District,* prepared for the Federal Transit Administration (May 1995).

[e] Available energies for fuels based on lower heating value of fuel and assuming an overall vehicle efficiency of 20 percent for liquid fuels and 16 percent for gaseous fuels using an Otto cycle engine.

TABLE 23 Vehicle range comparison for EVs versus IC vehicles

Energy Storage Medium	Typical Energy Storage on Bus (kg)	Total Battery Available Energy (kWh)	Vehicle Energy Consumption (kWh/mi)	Estimated Vehicle Range (mi)	Range Relative to 100 Gallons Diesel (Diesel = 1)
Batteries (C/3)					
Lead-acid	2,500	125	1.7	74	0.19
Nickel-cadmium	2,200	110	1.5	73	0.18
Nickel-metal hydride	2,300	184	1.55	118	0.30
Zinc-air	1,000	215	1.3	165	0.41
	(gal)		(mpg)		
Combustible Fuels					
Diesel No. 2	100		4.0	400	1.00
Natural gas	10,000[a]		2.2[b]	220	0.55
LPG	100		2.0	200	0.50
Methanol	150		1.5	225	0.56
Ethanol	150		2.2	330	0.83

[a] Standard cubic feet (scf).

[b] Per 100 scf.

9.3 VEHICLES CURRENTLY IN USE

Table 24 lists transit agencies operating battery-electric buses. Note that these are predominantly 22- to 30-ft buses and not full-sized 40-ft buses.

9.4 CAPITAL AND OPERATING COSTS

The capital costs of battery-electric buses are substantially higher than those of similar-sized diesel transit buses. Some sample comparisons are presented in Table 25, which shows that a 25-ft battery-electric shuttle bus is slightly more than twice as expensive as a comparable diesel model when the battery-electric bus is equipped with a lead-acid battery pack. With the larger 33-ft buses, the cost premium for battery-electric falls to approximately 33 percent. A Ni-Cad battery option appears to be widely available. Specifying a Ni-Cad instead of a lead-acid battery pack yields greater range per battery charge and increases battery life from 3 to approximately 7 years. The Ni-Cad option is quite expensive, however, as it appears to add between $40,000 and $48,000 to the price of a battery-electric bus.

Operating costs for battery-electric buses that may differ from those of diesel motor buses include energy costs, maintenance costs, and costs or savings associated with lower or higher vehicle availability. Energy costs per mile reported for battery-electric buses are similar to those for similar-sized diesel buses. Examples are shown in Table 26. Note that the first entry for diesel bus energy costs in Table 26 uses a unit fuel cost of $0.76 per gallon, as reported by the Santa Barbara Municipal Transit District in 1995. The

TABLE 24 Battery-electric transit buses in use in the United States

City or Region	Transit System	Number in use	Chassis Manufacturer	Chassis Type	Length (ft)
Allentown, PA	Lehigh & Northampton Trans. Authority	1	AVS	Bus	22
Anderson, IN	City of Anderson	1	AVS	Bus	22
Atlanta, GA	Georgia Power Company	2 1	AVS Blue Bird	Bus Bus w/air cond.	22 32
Berkeley, CA	City of Berkeley University of California	3 4	Electricar Electricar	Bus Bus	22 22
Birmingham, AL	Birmingham-Jefferson Co. Transit Authority	3	AVS	Bus w/LPG air cond.	22
Burlington, VT	Chittenden County Trans. Authority	1	AVS	Bus	22
Cedar Rapids, IA	E. Central Iowa Transit	3	Blue Bird	Bus	34
Charlotte, NC	—	4	AVS	Bus w/LPG air cond.	22
Charlottesville, VA	—	3	AVS	Bus w/LPG air cond.	22
Chattanooga, TN	CARTA	2 4 2 6 1	SVMC AVS SVMC AVS AVS/SVMC	DC bus DC bus Bus AC bus Bus	22 22 31 22 31
Denver, CO	Regional Transportation District	6	BMI/Vetter	Mall shuttle bus	40
El Monte, CA	City of El Monte	2	SVMC	Bus	22
Farmingham, MA	—	3	SVMC	DC bus	22
Fresno, CA	Fresno Dept. of Transportation	1 1	EVI EVI	Bus Trolley	22 20
Grand Canyon NP, AZ	Visitor Transportation System	3	APS	AC bus	25
Honolulu, HI	Enoa Tours Hawaii Electric Co.	1 1	— Electricar	Classic Trolley Bus w/air cond.	35 22
Laguna Beach, CA	City of Laguna Beach	1	SVMC	Trolley	22
Los Angeles (San Pedro), CA	LADOT	3	SVMC	Trolley	22
Lowell, MA	University of Massachusetts	1	Electricar	Bus	22
Miami Beach, FL	Metro-Dade Transit Agency	9	AVS	AC bus w/air cond.	22
Nashville, TN	—	2	AVS	DC trolley	22
New York, NY	College of Staten Island	1	Electricar	Bus	21

Based on data provided by the Electric Transit Vehicle Institute, Chattanooga, Tennessee.
AVS = Advanced Vehicle Systems Manufacturing, Inc.; APS = APS Systems, Inc.; BMI = Bus Manufacturing, Inc.; SVMC = Specialty Vehicle Manufacturing Corporation.

TABLE 24 *(Continued)*

City or Region	Transit System	Number in use	Chassis Manufacturer	Chassis Type	Length (ft)
Palm Desert, CA	—	1	SVMC	Open-air bus	22
Phoenix, AZ	Phoenix Transit System	1	SVMC	Bus w/LPG air cond.	22
Pinellas Park, FL	—	1	AVS	Bus w/air cond.	22
Portland, ME	—	3	AVS	Bus	22
Providence, RI	Rhode Island Public Trans. Authority	2	AVS	Bus w/LPG air cond.	22
Redding, CA	Redding Area Bus Authority	1	SVMC	Bus w/air cond.	22
Richmond, VA	—	3	Blue Bird	Bus w/air cond.	32
Sacramento, CA	Sacramento Metro Airport Sacramento Municipal Utility Dist.	1 1 1 5	Electricar SVMC Electricar AVS	Bus Open-air trolley Bus Bus w/LPG air cond.	22 22 22 22
San Francisco, CA	San Francisco State University	1	Electricar	Bus	22
Santa Barbara, CA	Metropolitan Transit District	2 6 1 1 2 1	BMI SVMC APS BMI APS APS	Open-air bus Open-air bus Villager conversion Bus Open-air bus bus	22 22 30 22 22 35
Santa Barbara, CA	Metropolitan Transit District	5	APS	AC bus, 1 w/air cond.	26
Santa Monica, CA	Municipal Bus Lines	3	APS	AC bus w/air cond.	26
Savannah, GA	Chatham Area Transit	4	AVS	Bus w/LPG air cond.	22
Sheboygan, WI	Sheboygan Transit System	1	SVMC	Antique trolley	22
South Bend, IN	Public Transportation Corp.	4	AVS	Bus w/LPG air cond.	22
Torrance, CA	Torrance Transit	1	SVMC	Bus	31
Virginia Beach, VA	False Cape State Park	3	Tug Mfg.	Tram	—
Yosemite National Park, CA	Yosemite Transportation System	1 1	APS SVMC	Bus Bus	35 31
Total		**133**			

Based on data provided by the Electric Transit Vehicle Institute, Chattanooga, Tennessee.
AVS = Advanced Vehicle Systems Manufacturing, Inc.; APS = APS Systems, Inc.; BMI = Bus Manufacturing, Inc.; SVMC = Specialty Vehicle Manufacturing Corporation.

second entry is for the same bus using a more current cost for diesel fuel—$0.85 per gallon.

Very few maintenance cost data for battery-electric buses are reported in the literature. This may be because the power trains in many of the buses in service to date have been developmental and so have had maintenance requirements that are higher than would be expected in fully commercialized production vehicles and therefore are not comparable to production diesel vehicles. The Santa Barbara Metropolitan Transit District has pioneered the use of battery-electric buses in transit service, having introduced their first battery bus into service in 1991.[42] The *Four-Year Report on Battery-Electric Transit Vehicle Operation at the Santa Barbara Metropolitan Transit District* presents a maintenance cost comparison between 30-ft diesel buses and similar battery-electric buses made over a 4-year period. The battery-electric buses experienced 40 percent lower maintenance costs than the diesel buses on a dollars-per-day basis. However, the battery-electric buses had lower mileage accumulation rates than the diesel buses; when maintenance costs were calculated on a dollars-per-mile basis, maintenance costs for the battery-electric buses were 15 percent higher than those of the diesel fleet. The report states that "Nearly one-third of the cost of EV maintenance involves the traction battery. The majority of battery maintenance cost is related to the diagnosis and rectification of vehicle lowpower occurrences. Such events are invariably caused by premature cell degradation."[43]

In contrast, as of December 1997, Santa Monica Municipal Bus Lines had been operating their three-unit fleet

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[42] Fowler, T., and Euritt, M., "The Feasibility of Electric Bus Operations for the Austin Capital Metropolitan Transportation Authority," *Transportation Research Record 1496,* Transportation Research Board, Washington, DC (1995) pp. 112-119.

[43] Op. cit., p. ES-3.

TABLE 25 Capital costs of battery-electric buses versus similar diesel buses

Bus Type	Diesel	Price	Battery-Electric	Price
25-foot shuttle, ADA-compliant, equipped with air conditioning and heating	Blue Bird Transbus. Steel chassis & body, Cummins B5.9 engine, 10- year design life	$75,000–85,000, depending on options[a]	APS 25-foot. Fiberglass body & chassis, AC propulsion motor with regenerative braking. 8-year design life	$224,600, with Ni-Cad battery option; $175,900 with standard lead-acid battery pack[b]
33-foot bus, ADA-compliant, equipped with air conditioning and heating	Blue Bird Q-bus Cummins B5.9 engine, 12-year design life	$175,000-180,000, depending on options[c]	Blue Bird QEV, Westinghouse AC propulsion motor and controller with regenerative braking. Tubular cell lead-acid battery pack	$220,000 –245,000 with standard lead-acid battery pack. If Ni-Cad battery pack is specified, add $40,000[d]

[a]Mr. Dennis Costello, Commercial Sales Manager, A-Z Bus Sales, Inc., Colton, Calif., personal communication with Richard Remillard, ARCADIS Geraghty & Miller (Jan. 1998).

[b]Price bid in an order placed jointly by Santa Barbara Metropolitan Transit District and Santa Monica Municipal Bus Lines (Oct. 1996). Roy Neva, manager of vehicle and facility engineering, Santa Monica Municipal Bus Lines, personal communication with Richard Remillard, ARCADIS Geraghty & Miller (Nov. 1996).

[c]Mr. Stewart Pickett, Western Regional Sales Manager, Blue Bird Bus Company, personal communications with Richard Remillard, ARCADIS Geraghty & Miller (Jan. 1998).

[d]Ibid.

TABLE 26 Energy costs for battery-electric buses versus a similar-sized diesel bus model

Agency	Vehicle	Energy Consumption	Unit Energy Cost	Energy Cost per mile
SBMTD	30-ft diesel Villager	5.8 mpg	$0.76 per gallon	$0.131
SBMTD	30-ft diesel Villager	5.8 mpg	$0.85 per gallon	$0.147
SBMTD	30-ft electric Villager	1.906 kWh/mi	$0.085 per kWh	$0.162
SBMTD	22-ft electric shuttle	1.353 kWh/mi	$0.085 per kWh	$0.115
SMMBL	25-ft APS electric shuttle	1.67 kWh/mi	$0.125 per kwh	$0.209

Data for Santa Barbara Metropolitan Transit District are taken from Paul Griffith, Santa Barbara Metropolitan Transit District, *Four-Year Report on Battery-Electric Transit Vehicle Operation at the Santa Barbara Metropolitan Transit District,* U.S. Department of Transportation, Federal Transit Administration, FTA-CA-26-0019-95-1 (May 1995). SBMDT = Santa Barbara Metropolitan Transit District; SMMBL = Santa Monica Municipal Bus Lines.

of 25-ft battery-electric shuttle buses for 10 months and reported no failures or malperformance of traction batteries.[44]

Santa Monica ordered their buses with Saft Ni-Cad battery packs equipped with an automatic watering system; Santa Monica's better experience with battery maintenance than Santa Barbara's suggests that recent advances in propulsion battery design may result in lower battery maintenance requirements.

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[44] Neva, R., Manager of vehicle and facility engineering, Santa Monica Municipal Bus Lines, personal communication with R. Remillard, ARCADIS Geraghty & Miller (Dec. 1997).

CHAPTER **10**

FUEL CELLS

10.1 OVERVIEW

At the simplest level, fuel cells may be thought of as batteries that operate with hydrogen and oxygen. In fuel cells, the energy released by the oxidation of hydrogen to water is directly converted to an electric current. With this process, energy conversion efficiencies on the order of 80 percent are theoretically possible. In comparison, the energy conversion efficiency associated with burning fuels in heat engines to produce mechanical energy, and convert the mechanical energy to electric energy, is thermodynamically limited to less than 40 percent. Fuel cells either may be directly fueled by hydrogen or may use reformers to generate hydrogen from methanol, natural gas, or other HCs with water. Because the reforming and fuel oxidizing reactions take place continuously at relatively low temperatures, NO_x, CO, and unburned fuel emission rates from fuel cells are extremely low. Fuel cells' combination of very high efficiency and low emissions has excited researchers for some time.

10.2 FUEL CELL ENGINE TECHNOLOGY

The basic elements of a fuel cell are diagrammed in Figure 11. These include the anode, cathode, electrolyte, and electric load. The electrodes are commonly immersed in an electrolyte consisting of a strong acid or base. Hydrogen gas is admitted at the anode, and oxygen (or air) is admitted at the cathode. The electrodes are typically porous and coated with catalysts. (Increasing the porosity of the electrode increases its surface area and hence also increases the current that it can support at a given temperature. Rates of fuel cell reactions increase strongly with temperature. To promote high reaction rates at moderate temperatures, the electrodes are commonly coated with catalysts.)

The complete reaction of the fuel cell combines hydrogen with oxygen to produce water. Because the process can take place at low temperatures, the fuel cell may be viewed as a device that achieves cold combustion of hydrogen. The superior efficiency of a fuel cell arises from its ability to convert much of the energy released by the formation of water directly into an electric current. The energy associated with a unidirectional electron flow is almost completely available for conversion to work. In contrast, when fuel is burned to heat and expand a gas in a heat engine, the motion of the gas molecules is random and therefore is less available to accomplish useful work.[45]

Although the theoretical efficiency of hydrogen-oxygen fuel cells is as high as 85 percent, the maximum efficiency of practical cells is considerably less. The loss of efficiency arises from voltage losses that occur when the cell moves from an open circuit condition and begins to conduct a current as well as auxiliary loads such as water pumps, air compressors, and fans or other coolant pumps. Actual efficiencies of working fuel cells are in the range of 40 to 60 percent. Although this may not appear to be substantially better than that of a modern medium-speed diesel engine, it should be recalled that the efficiency of a diesel engine decreases markedly at low loads. This behavior compromises overall efficiency when the engine is operated over duty cycles with low average load factors, which is the case with a transit bus. For vehicles with low to moderate average loads, a significant advantage of fuel cells over internal combustion engines is that efficiency is highest at low to medium loads, and it remains fairly high over the entire load range.

10.2.1 Hydrogen Fueling

Despite the inherent advantages of fuel cell technology from the standpoints of efficiency and emissions, significant drawbacks for commercialization as a vehicle power source exist. Although fuel cells directly fueled with methanol are being investigated, hydrogen is currently the only practical fuel for fuel cells. The hydrogen may be stored onboard, or it may be generated from other fuels by a reformer. Directly fueling vehicles with hydrogen has a number of liabilities, however, notably

- High cost;
- Poorly developed supply infrastructure;
- Greater storage volume required than CNG; and
- Codes or standards for the design of electrical equipment, maintenance garages, and fueling facilities only now being developed.

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[45] Appleby, A. J., *Fuel Cell Handbook.* Van Nostrand Reinhold (1989).

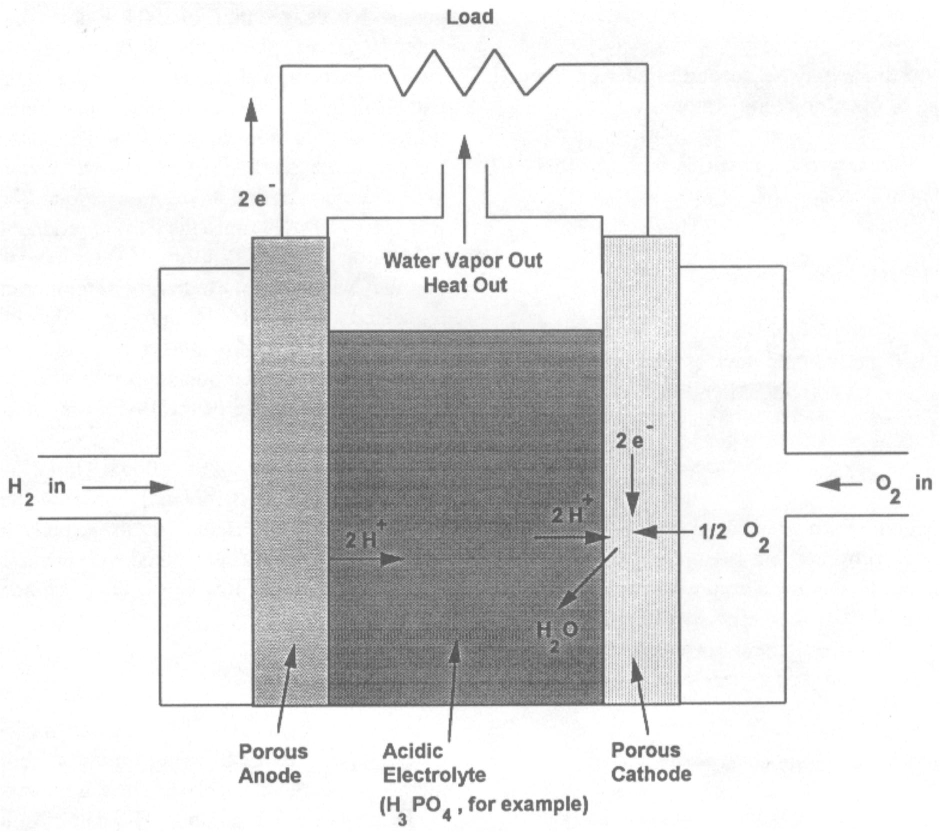

Figure 11. Elements of a fuel cell.

10.2.2 Fueling with Methanol or Methane

To avoid carrying large volumes of hydrogen, a reformer can be incorporated, which generates hydrogen from methanol or methane. Onboard reformers have been successfully developed and demonstrated. Water must be supplied along with the methanol or methane. In the reformer, they are broken down and converted to hydrogen gas, carbon dioxide, and small amounts of CO. Moderately high temperatures and suitable catalysts are needed to promote the reforming reactions; heat generated by a fuel cell can be used for this purpose, once the reformer is started up by a fuel-fired heater.

Adding a reformer increases the cost, bulk, and complexity of the fuel cell system. It also slows the cell's ability to respond to load transients, because the throughput of the reformer is limited by the heat provided by the fuel cell, which, in turn, is limited by the throughput of the reformer. Until recently, this thermal feedback mechanism was slow enough that the system had a minimum transient response time on the order of several seconds to minutes,[46] depending on the system design. As a result, the power needed for transients had to be provided by a large, heavy auxiliary battery.

Recent developmental work by Daimler-Benz, in partnership with Ballard Power Systems, however, appears to have led to dramatic improvements in hydrogen reformer performance for automotive fuel cells. In late 1997, Daimler-Benz announced they had engineered a compact methanol-fueled hydrogen reformer to work with a Ballard proton-exchange membrane (PEM) fuel cell that is capable of rapidly variable operation. The system has been installed in a small (A-class) Mercedes-Benz automobile chassis and given the name NECAR 3. Daimler-Benz states that the system can produce transients from idle to 90 percent of fuel power in just 2 seconds.[47] This performance is competitive with that of internal combustion engines and, if duplicated in a transit bus, would eliminate the need for an auxiliary propulsion battery.

Other fuel cell developmental issues remain to be resolved. These include the following:

- Cost and bulk per unit of output are much higher than those of diesel engines;

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[46] This value is derived from the 50-kW phosphoric acid fuel developed for the U.S. DOE fuel cell bus program.

[47] "Daimler-Benz Debuts New Fuel Cell System; No Tanks Required," news item reported by the World Wide Web site, http:/www.transit-center.com, operated by Metro Magazine (Sept. 12, 1997).

- Deterioration of electrodes occurs over time, resulting in a gradual loss of power; and
- Long start-up times may be needed to heat up the cell and reformer to operating temperature.

The severity of these problems varies with the fuel cell type, as discussed in Section 10.3.

10.2.3 Types of Fuel Cells

Three different types of fuel cells have been developed into commercially manufactured devices: alkaline fuel cells, phosphoric acid fuel cells, and PEM cells.

10.2.3.1 Alkaline Fuel Cells

Alkaline fuel cells have been used extensively in the United States space program, but they have properties that make them poor candidates for automotive use. Both phosphoric acid and PEM cells are being investigated in North American fuel cell bus development programs. The important characteristics of each type are reviewed below.

10.2.3.2 Phosphoric Acid Fuel Cells

Phosphoric acid fuel cells (PAFCs) were originally developed as natural gas-fueled electrical generating stations. The PAFC is so named because it uses hot concentrated phos-phoric acid as its electrolyte. PAFCs work well with reformers. Reformate gas normally contains some residual CO in addition to hydrogen and carbon dioxide. At low temperatures, CO strongly adsorbs onto the platinum catalysts on the fuel cell electrodes and deactivates them. However, CO adsorption decreases as temperature increases, enabling it to be controlled by using sufficiently high operating temperatures. In PAFCs, this is accomplished by using design temperatures in the region of 130° to 200°C. Among the strong acids, phosphoric acid is uniquely stable at these high temperatures, and it also has high ionic conductivity. These were the main reasons that phosphoric acid was chosen as the electrolyte for an acid fuel cell. A drawback of this choice is that phosphoric acid cells are inoperable at room temperature and must be preheated by some means. Ordinarily, a fuel burner is used for this purpose.

Working with the sponsorship of the Electric Power Research Institute (EPRI) and DOE, International Fuel Cell Corporation (IFC) is the principal developer of PAFCs in the United States. Pilot plants of 4.5 MW and, later, of 11 MW, operating on natural gas, were designed and built.[48] The PAFC technology developed by IFC is now in commercial production, with packaged units of 200 kW now commercially available. However, plant costs still are not competitive with those of conventional electric power-generating technologies. Establishing commercial viability now hinges on achieving substantial reductions in manufacturing costs. A recent study has concluded that PAFC fuel cells will become cost competitive when production increases to 200 to 300 MW per year, which is at least 10 times the current production rate.[49]

In automotive applications, PAFCs have the disadvantage that they cannot be started at room temperature but must be preheated to above 100°C before any current can be drawn. Further, the cells must always be maintained under partial load to prevent the carbon support of the catalyst from oxidizing. The ideal use of the PAFCs is, therefore, in steady operating modes.

The system functions as follows. Under steady-state operating conditions, methanol and purified water are mixed and pumped from their respective storage tanks to the vaporizer, where the mixture is evaporated with heat from the fuel cell. Mineral oil at about 190°C is used as the heat transfer fluid.

10.2.3.3 PEM Fuel Cells

Beginning in the early 1960s, General Electric developed a new type of fuel cell using a fluorocarbon ion-exchange membrane as the electrolyte. The membrane was developed by DuPont and is sold under the name Nafion. It is a solid material consisting of a Teflon matrix with side chains terminating in sulfuric acid groups. The PEM may be viewed as a solid-state acid electrolyte.

The PEM cell offers several advantages over phosphoric acid cells for automotive applications. The paramount advantage is that it may be started at room temperature without preheating. This eliminates both the delay and the complication associated with preheating systems. Unlike the case with cells using acid solutions, the acid anion (SO_4^{2-}) is firmly bound to the solid fluorocarbon polymer. It cannot be transported by water and so will not dissolve in water and corrode the electrodes or other cell components, and it does not create an acid hazard in case of accidental cell rupture. This property also results in extremely long electrode life (>10,000 hours). The solid polymer electrolyte is mechanically strong and can be fabricated into thin sheets with low ionic resistance.

In the PEM cell, the membrane must be saturated with water, because the proton (H^+) will transport efficiently only if it is attached to water [forming a hydronium ion (H_3O^+)]. Keeping the membrane saturated with water is accomplished by humidifying the fuel and air streams. Failure to maintain at least 400 mm Hg of water pressure results in a dehydration of the membrane, which leads to catastrophic increases in electrical resistance. The best way to maintain a high enough

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[48] Yolota, K., and Misono, T., 11 MW Fuel Cell Plant Operation Interim Report. *1992 Fuel Cell Seminar Program and Abstracts* (Nov. 1992).

[49] Teagan, P., *The Environmental Benefits of Fuel Cell Technology.* World Fuel Cell Council (July 1992).

partial pressure of water without overly diluting the hydrogen and oxygen is to pressurize the system.

An exciting advance in PEM technology was the development of a new membrane by Dow Chemical in the mid-1980s. Dow Chemical's membrane allows much higher ion diffusion rates (without voltage loss) than Nafion, allowing current density to be increased. Ballard Power Systems, of Vancouver, British Columbia, is using the Dow membrane to develop PEM cells. These cells are capable of remarkably high current densities, which makes them compact enough to be practical as automotive power plants.

Operating temperatures of PEMs are limited by the onset of membrane dehydration to a maximum of 80° to 100°C, depending on operating pressure. The negative consequence of having a relatively low operating temperature is extreme sensitivity of the electrocatalyst to CO poisoning. At 80°C the allowable concentration of CO in the fuel is only a few ppm.[50] This makes using a reformer to fuel PEM cells with methanol or methane more complicated than in a PAFC, because equipment must be added to remove the CO from the reformate gas before it enters the fuel cell.

Starting the PEM system is easier than starting the PAFC because the fuel cell can be operated at ambient temperature and does not need to be preheated. However, if the PEM is equipped with a reformer for methanol fueling, it will be necessary to heat the reformer to its normal operating temperature before hydrogen will become available. Start-up times for a methanol-fueled PEM vehicle will therefore be longer than for one fueled directly with hydrogen gas.

Recent research and development investigating the use of PEM cells for transportation has employed direct fueling with pure compressed or liquefied hydrogen. There are several advantages to this approach:

- Fueling with pure hydrogen eliminates the need for a reformer and a CO oxidizer. This substantially reduces the systems bulk, weight, and complexity, at the cost of higher fuel storage weight than with reformed methanol.
- The reformer is the major cause of slow response to power demand transients. Without a reformer, the PEM system responds very rapidly.
- The PEM's high efficiency goes a long way toward off-setting hydrogens high cost.
- Directly hydrogen-fueled PEM stacks are considered to be zero emission engines; reformer-related exhaust emissions preclude designation of reformate-fueled fuel cells as zero emission engines.

10.3 FUEL CELL BUS DEVELOPMENT PROGRAMS

Two major programs are under way in North America to develop and commercialize fuel cell buses for transit (Table 27). The longest-running project is being funded by the U.S. Department of Transportation (DOT), through the FTA. The prime contractor is Georgetown University. This project initially focused on the development of a methanol reformer-fueled PAFC in a 30-ft transit bus. PAFC/battery hybrid power trains were successfully installed and tested in three 30-ft test bed buses. The 50-kW Fuji PAFC stack plus reformer charges the onboard Saft Ni-Cad batteries, or it can power the motor directly at part loads. The batteries provide power for grades and acceleration. An elaborate control system monitors the battery's state of charge as well as traction power demand. When power is available from the fuel cell for charging and the battery is sufficiently discharged, the control system directs the fuel cell to charge the battery.[51] The batteries also provide energy storage for regenerative braking. The test bed buses are fully functional heavy-duty transit buses. They meet or exceed comparable diesel bus performance and comply with all Federal transit bus design standards, including those of the Americans with Disabilities Act (ADA).

The FTA fuel cell transit bus program is now moving into a new phase, which seeks to demonstrate methanol-fueled fuel cells in 40-ft transit buses. Initially, a 100-kW IFC PAFC stack will be engineered into a Nova Bus RTS chassis. As with the previous 30-ft bus prototypes, stored energy for load following and regenerative braking will be provided by batteries. Lockheed Martin is providing the electric drive system, which is based on the system they developed for the Orion VI hybrid bus. The Lockheed Martin system uses Electrosource lead-acid batteries for energy storage and load following. The 40-ft PAFC bus is scheduled to be completed in 1998.

The FTA fuel cell transit bus program is also developing a PEM fuel cell system for a 40-ft transit bus fueled with reformed methanol. The reformer technology is based on the Daimler-Benz and Ballard technology being used in the Mercedes-Benz NECAR 3. Ballard, under contract to Georgetown University, is scheduled to deliver a 100-kW PEM fuel cell system in June 1998. Integration of the system into a 40-ft transit bus is scheduled to be completed by the end of 1998.

The other project, performed by Ballard Power Systems of Vancouver, British Columbia, Canada, involves PEM fuel cell stacks directly fueled by compressed hydrogen. As reviewed above, direct hydrogen fueling eliminates the need for a reformer and allows the fuel cell engine to follow load transients well enough that supplemental batteries are not needed. A 32-ft prototype of the Ballard bus was completed and demonstrated in early 1993. Although this vehicle incorporated dynamic braking, lack of a suitable battery precludes storing and recovering dynamic braking energy.

The 32-ft Ballard prototype was powered by 24 5-kW PEM stacks. In the second phase of the Ballard project a more powerful 205-kW engine is being used, which is based

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[50] Krumpelt, M., and Christianson, C. C., *An Assessment and Comparison of Fuel Cells for Transportation Applications.* Argonne National Laboratory (1989).

[51] Roan, V., Energy and Power Management for Fuel Cell Vehicles. Presented at SAE Fuel Cells for Transportation, Toptec (March 1993).

TABLE 27 North American fuel cell bus development programs

Project	U.S. DOE Fuel Cell Bus Project	Ballard Fuel Cell Bus
Technology	• 40-foot prototypes will use a phosphoric acid fuel cell, methanol fueled through a reformer • Saft Ni-Cad batteries used for acceleration for braking energy recovery	•Ballard 205-kW proton exchange membrane fuel cell engine, directly fueled with compressed hydrogen, in a 40-foot low-floor New Flyer chassis. Bus uses roof-mounted all-composite tanks for compressed hydrogen storage.
Sponsors	• U.S. DOE • U.S. DOT/FTA	•Canadian Federal government •Province of British Columbia •BC Transit •South Coast Air Quality Management District (SCAQMD)
Prime Contractor	• Georgetown University	•Ballard Power Systems
Subcontractors	• IFC-PAFC: fuel cell stack and reformer • Ballard Power Systems: PEM stack and reformer • Lockheed Martin: propulsion motor and power controller • Booz-Allen & Hamilton — system integration • TMC (Novabus) — bus chassis	•Science Applications International (SAIC): system integration •New Flyer Industries: 40-foot low- floor bus chassis •EDO: composite tanks for compressed hydrogen fuel
Status	• Current phase promotes development of both PAFCs and PEM cells with reformers in methanol-fueled 40-foot buses • IFC will supply a 100-kW PAFC; Ballard was selected to be the PEM supplier	•32-foot prototype was completed and successfully road tested in 1993 •Phase II of project was recently completed, in which a 205-kW hydrogen-fueled Ballard PEM stack was installed in the engine compartment of a 40-foot low-floor bus •40-foot bus will soon be demonstrated, with 3 buses in Vancouver and 3 in Chicago

on a new generation PEM stack with 2.5 times the power density of that used in the prototype bus.[52] The more powerful stack has been engineered into a 40-ft New Flyer (D40LF) low-floor transit bus. This package is designed to meet White Book performance standards and achieve a range of 250 mi per hydrogen fill. Propulsion is provided by a Kaman Electromagnetics brushless permanent magnet motor controlled by IGBT inverters. The motor is attached to the chassis and is connected to a conventional MAN rear axle. Under a DOT Congestion Mitigation and Air Quality (CMAQ) grant, the Chicago Transit Authority (CTA) is undertaking a demonstration of three of these Ballard-New Flyer fuel cell buses. In September 1997, the CTA held an introduction ceremony for the fuel cell bus, and the bus was also exhibited at the American Public Transit Association (APTA) Annual Meeting in Chicago the same month. The two other buses were delivered in December 1997 and will begin a 2-year demonstration in Chicago. Three additional buses are scheduled for a similar demonstration at BC Transit in Vancouver.

Ballard has recently entered into partnerships with both Daimler-Benz and General Motors to develop PEM fuel cell passenger car prototypes.

10.4 FUELING FACILITY IMPACTS

Fueling facilities for fuel cell buses will be dramatically different depending on whether the bus uses an onboard reformer. Reformers in existing and planned fuel cell bus development programs are designed for methanol, although it is possible that a fuel cell engine using a natural gas reformer might be developed in the future. Conventional methanol bus fueling facilities, as described in Chapter 5, Section 5.3, would be suitable for fuel cell buses as well. Because fuel cell stacks are sensitive to contaminants, strict methanol fuel quality standards and transportation procedures may be needed. Because a fuel cell engine using a reformer does not store appreciable amounts of hydrogen, facilities would not have to be designed with hydrogen in mind.

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[52] Howard, P. F., Ballard Zero Emission Fuel Cell Bus Engine. *Proceedings of the 12th International Electric Vehicle Symposium* (Dec. 1994).

Fuel cell buses not using reformers are fueled directly with hydrogen. In the Ballard bus, hydrogen is stored as a compressed gas at 3,000 psi. In early demonstrations, it is likely that liquefied hydrogen from a remote plant will be trucked to a cryogenic storage tank at the fueling facility. Hydrogen would be compressed in the liquid state to 4,000 psi, vaporized to a gas, and then dispensed into the onboard storage tanks.

In full-scale fuel cell bus operations, synthesizing hydrogen from natural gas in a reforming plant at the bus's operating base may prove to be the most practical. This would avoid the cost and delivery scheduling associated with trucking in liquefied hydrogen. Steam reforming is currently used to make hydrogen at virtually all industrial facilities. The cost trade-offs between a local reforming station and trucking in hydrogen from a larger remote plant will depend on the extent to which there are economies of scale in the reforming process. A curbside reformer would be preferable for fire safety reasons: because the hydrogen could be synthesized continuously from pipeline natural gas, very little hydrogen storage would be needed.

10.5 CURRENT CAPITAL AND OPERATING COSTS

Fuel cell bus technology is in a developmental stage characterized by low production volumes and high unit costs. Firm cost data are hard to obtain. As with any new technology, unit costs will fall as production rates and manufacturing experience increase. The extent to which this will occur with fuel cells is a matter for discussion. Forty-foot Ballard bus prototypes to be operated by BC Transit and CTA reportedly cost $1.4 million each. Ballard has estimated that the price could fall to between $500,000 to $550,000 with mass production.[53]

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[53] Chicago Transit Unveils Ballard Hydrogen Fuel Cell Bus, Fleet Test to Start Next Year, *Hydrogen and Fuel Cell Letter*. Vol. X, No. 10 (Oct. 1995).

CHAPTER **11**

BIODIESEL

11.1 OVERVIEW

"Biodiesel" refers to fuels derived from vegetable oils that are suitable for compression-ignition engines. Biodiesel fuels are prepared by esterfication (insertion of an oxygen atom into the HC chain) of long-chain fatty acids.[54] One product, soy ester, is being promoted by the soy industry. Soy ester is a by-product of the process used to synthesize glycerin from soybean oil. Glycerin is widely used for pharmaceutical products and as a food additive. As soy ester is a surplus by-product, the soybean industry is interested in developing new markets for it.

Biodiesel is nontoxic and nonvolatile, and it will naturally degrade if spilled or otherwise exposed to the environment. It has a high cetane number (47 to 52) and excellent lubricity (the ability of a liquid coating a bearing surface to protect the surface from mechanical wear). It is typically blended with petroleum-distillate diesel fuel as 20 percent soy ester and 80 percent distillate. Biodiesel is readily attacked by microorganisms, and it is substantially more expensive than distillate. Blending with distillate tends to prevent microbial attack, thereby extending its storage life and also reducing its cost.

11.2 ENGINE AND VEHICLE TECHNOLOGY

11.2.1 Engine Technology

Biodiesel blends may be used in diesel engines with no change in calibration from those for petroleum distillate. When this is done, transient cycle emission testing with these blends consistently shows moderate reductions (10 to 20 percent) in PM, exhaust opacity, and CO, which may be accompanied by moderate increases in NO_x.[54,55] It appears likely that the biodiesel acts as a cetane additive, which has the effect of reducing ignition delay accompanied by emission impacts similar to advancing the injection timing. Indeed, when the beginning of injection was retarded by 3 degrees from standard calibration in a Cummins L-10 engine, PM rates from biodiesel blends returned to slightly below diesel baseline, and NO_x fell 8 percent below diesel baseline. However, with retarded injection timing, HC and CO rates for the blend remained essentially unchanged from those with standard injection timing. Therefore, using biodiesel along with moderately retarded injection timing could result in simultaneous moderate reductions in CO, NO_x, and PM.

As it is illegal for a transit agency to modify the calibration of an emission-certified engine, the engine manufacturer would be responsible for developing and certifying an engine calibration that is optimized for biodiesel blends, but apparently, no manufacturer has done this. The testing cited above used EPA-specification low-sulfur diesel fuel to establish diesel baseline emission rates. CARB diesel fuel specifications normally result in a higher cetane number than those of the EPA. Therefore, the emission benefit associated with biodiesel blends may be less significant relative to CARB-specification petroleum distillate fuel.

11.2.2 Vehicle Performance

Biodiesel has a somewhat lower energy content per unit volume than petroleum distillate. Diesel fuel systems meter fuel by volume, and no adjustment is normally available to increase maximum fuel rate to correct for fuel with a lower energy density. Therefore, a minor loss of full load torque and power could occur when fuel is being switched from distillate to biodiesel. Somewhat higher flow rates of biodiesel than distillate will be needed to maintain undiminished power at part load, which should cause a moderate increase in volumetric fuel consumption in service. Otherwise, biodiesel appears to perform like high-quality petroleum distillate.

11.2.3 Vehicles Currently in Use

According to APTA data, biodiesel fuels are being used in 33 buses at Sioux Falls (South Dakota) Transit System and in 1 bus at Owensboro (Kentucky) Transit System.

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[54] Marshall, W., Schumacher, L., and Howell, S., *Engine Exhaust Evaluation of a Cummins L10E When Fueled with a Biodiesel Blend.* Report No. 952363. Society of Automotive Engineers (1995).

[55] Schumacher, L. G., Biodiesel Emissions Data from Series 60 DDC Engines. Presented at the 1995 American Public Transit Association Bus Operations Conference (May 1995).

11.3 FUELING FACILITY IMPACTS

As biodiesel has mechanical and ignition properties very similar to petroleum distillate, conventional diesel fueling equipment may be used for biodiesel fuel. Biodiesel does have higher cloud-point and pour-point temperatures than distillate; these properties could affect fueling operations in very cold weather.

11.4 MAINTENANCE FACILITY IMPACTS AND SAFETY

Biodiesel is even less volatile than distillate and has a higher flash point. ("Flash point" is the lowest temperature for which enough vapor exists over the liquid to be ignitable when brought into momentary contact with a flame.) No modifications to maintenance garages or to safety procedures practiced with petroleum distillate are needed.

11.5 FUEL AVAILABILITY AND COST

Soy ester is produced at a number of plants located throughout the United States. Customers must be careful to specify highly purified product that is free of glycerin (glycerin will adversely affect engine performance). Current biodiesel prices are quite high—in the range of \$4.50 to \$5.00 per gallon. In 20 percent blends with petroleum distillate costing \$0.80 per gallon, the blended product would cost between \$1.54 and \$1.64 per gallon.

CHAPTER **12**

MARKET ASSESSMENT AND TRENDS

As discussed in previous chapters of this report, alternative fuels are at various stages of development. For comparative purposes, this chapter highlights some key indicators of the current market status of the alternative fuels in the transit industry and discusses current market trends. Section 12.1 discusses commercialized engines and vehicles available for each technology. Section 12.2 compares usage of alternative fuels in transit buses. Section 12.3 presents comparative emissions data for several alternative fuels.

12.1 AVAILABLE ENGINES AND VEHICLES

Table 28 lists OEM engines available for each of the major alternative fuels. This clearly illustrates that engine manufacturers are currently focusing their alternative-fuel engine offerings on natural gas. Cummins Engine Company has developed a number of heavy-duty natural gas engines. As of late 1997, Cummins was offering commercialized natural gas engine models suitable for different bus sizes (B-, C-, and L-series engines) (Table 28). Cummins also completed commercialization of the LPG version of their B5.9 engine in late 1997. If the market for the B5.9 LPG develops rapidly, Cummins has indicated that it will consider developing an LPG version of the larger C-series natural gas engine, the C8.3G, which would be suitable for full-sized (40-ft) transit buses.

The DDC Series 50 has become the successor to the DDC 6V-92 in the North American transit bus market. The diesel and natural gas versions of the Series 50 together had a collective market share of nearly 70 percent in 1995 (Figure 12). DDC had been developing an LPG version of the Series 50, with cost sharing by other organizations. However, the program was recently discontinued.

To summarize, despite some promising developments for LPG, natural gas is at present the only commercially significant alternative to diesel in the heavy-duty engine market.

Table 29 lists full-sized alternative-fuel buses available from OEM bus manufacturers. Again, although many manufacturers are selling alternative-fuel buses, the vast majority of these are CNG and LNG models.

12.2 TRENDS IN TRANSIT VEHICLE FUEL CHOICE AND ENGINE TECHNOLOGY

As recently as 1990, North American transit agencies were almost universally purchasing diesel buses, most of which were powered by the two-stroke engines. A methanol two-stroke engine was available as a warranted and certified product and was being ordered in limited numbers. Development of natural gas transit bus engines was just beginning but was being encouraged by natural gas's potential for lower operating costs and better engine durability than methanol. In 1991, Sacramento Regional Transit District (SRTD) was planning a bus procurement that would begin the District's conversion of its bus operations to an alternative fuel. The District had originally planned to convert to methanol but began to seriously consider CNG after staff's research and a consultant study[56] indicated that CNG would likely offer lower fuel costs and better vehicle maintain-ability than methanol. Natural gas bus engines being demonstrated at this time exhibited NO_x emission rates that were only somewhat lower than diesel rates and that were considerably higher than those of the methanol engine. In a presentation to the SRTD, an engine manufacturer committed to certify their natural gas engine at a NO_x rate under 2.5 g/bhp-hour for SRTD's pending bus procurement. In the opinion of SRTD managers, this commitment was sufficient to eliminate the one compelling advantage of methanol over CNG—lower NO_x emissions. SRTD subsequently ordered CNG buses.

The generally successful operating experience of SRTD and other transit agencies with CNG buses has led to the fuel becoming the preferred alternative to diesel in transit. For example, the latest available listing of transit buses in North American fleets shows CNG buses comprising nearly 2 percent of the fleet, whereas the alternative fuel with the next largest population (methanol, before LACMTA converted its fleet to ethanol) comprises only 0.8 percent of the fleet (Table 30). Records of orders for full-sized transit buses show that the market share for natural gas buses was between 12 and 22 percent during 1994–1996 (Table 31). (Almost all of these orders were for CNG buses.) Note that the fleet penetration by natural gas buses is considerably less than their market share over the past 3 years. The recent increase in CNG market share is not yet reflected in the entire transit bus fleet, the composition of which reflects all the purchases made over the past 12 to 15 years. In 1996, the full-sized

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[56] Kreeb, R., et al., Booz, Allen & Hamilton, Inc., *Alternative Fuel and Facility Evaluation Study for Sacramento Regional Transit District* (Feb. 1991).

TABLE 28 **Available alternative-fuel transit bus engines**

Engine Manufacturer and Model	Disp. (L)	Rated Power (hp)	Rated Torque (ft-lb)	Application	First Available	CNG	LNG	LPG
Caterpillar G3306	10.5	235 - 250	800 - 820	F	1995	X	X	X
Cummins B5.9G	5.9	150-195	375-420	S, M	1994	X	X	
Cummins B5.9LPG	5.9	195	420	S, M	1997			X
Cummins C8.3G	8.3	250	750	M, F	1996	X	X	
Cummins L-10G	10	240 - 300	750 - 850	F	1993	X	X	
Deere 6068H	6.8	225	640	S, M	1998	X		
Deere 6081H	8.1	250	800	M, F	1995	X		
DDC Series 50G	8.5	250 - 275	780 - 890	F	1994	X	X	
DDC Series 60G	12.7	350 - 400	1450	L	1996	(a)	(a)	

[a]Engines are being demonstrated, however, product may not be certified for commercial sale.

Applications: S=small bus, M=medium bus, F=full size transit bus, L=large suburban/intercity bus

Sources: U.S. Department of Energy Alternative Fuels Data Center, World Wide Web site (www.afdc.doe.gov), and C certification records

transit bus market could be summarized as being basically 80 percent diesel and 20 percent CNG. This situation will likely persist for the next few years.[57]

12.3 EMISSIONS FROM ALTERNATIVE-FUEL BUSES

Emission performance is a key driver for the alternativefuel bus market. Therefore, it is important to assess the extent to which each alternative fuel actually reduces emissions compared with current diesel buses. Because heavy-duty engines are emission tested and certified with an engine dynamometer, the effects of in-service duty cycle, vehicle weight, and power transmission on emission rates from a heavy-duty vehicle are not accounted for in the certification emission data. Fortunately, a fairly large body of chassis dynamometer emission testing data have been accumulated for transit buses. The comparability of these data is compromised to some degree by differences in testing and analytical procedures between facilities, which reflects the absence of a standardized federal chassis dynamometer emission test procedure for heavy-duty vehicles.

The DOE's NREL recently completed a project to evaluate and compare the performance of transit buses running on alternative fuels and diesel fuel. The buses operated at several sites across the country. This project generated an extensive body of chassis dynamometer emission testing data, which are quite comparable, as all emission testing was performed by West Virginia University over the central business district (CBD) cycle, using a portable chassis dynamometer laboratory. Results of the project have been published by Chandler et al.[58] All the methanol and ethanol buses monitored in the project were powered by Detroit Diesel 6V-92TA engines. All the CNG buses used Cummins L-10 engines. Diesel control vehicles were powered mainly by DDC 6V-92TA or Cummins L-10 engines. Limited data from diesel buses powered by the DDC Series 50 were also acquired late in the project. Engine model years ranging from 1988 through 1994 were emission tested.

As discussed in Chapter 2, diesel engines inherently emit HCs and CO at very low rates. This is generally true for heavy-duty alternative-fuel engines as well. HC and CO emissions result from incomplete combustion of the fuel; accordingly, high emission rates of HCs and CO are symptomatic of poor fuel utilization. Conversely, the low rates of HC and CO emissions shown by heavy-duty engines are the natural result of design optimization for high fuel efficiency.

Heavy-duty engines are significant sources of NO_x and PM, so the review of the chassis dynamometer emission data for transit buses is focused on these pollutants. Figures 13 and 14 show the emissions testing results for NO_x and PM, respectively. The data points represent average test results for each combination of engine model, fuel type, and model year tested. Each datum is the average of as many as 40 to 50 individual emission tests performed in the NREL project. Accordingly, the data are shown with error bars, which are equal to the standard deviation of these test data for each point.

In Figure 13, the trend in NO_x rate versus model year is plotted for the buses tested. Certification emission standards for NO_x over the same range of model years are also shown

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[57] Ahrens, C., Manager of Bus Sales, Cummins Engine Company, personal communication with R. Remillard (Oct. 1996).

[58] Chandler, K., et al. *Alternative Fuel Transit Bus Evaluation Program Results.* Report No. 961082. Society of Automotive Engineers (May 1996).

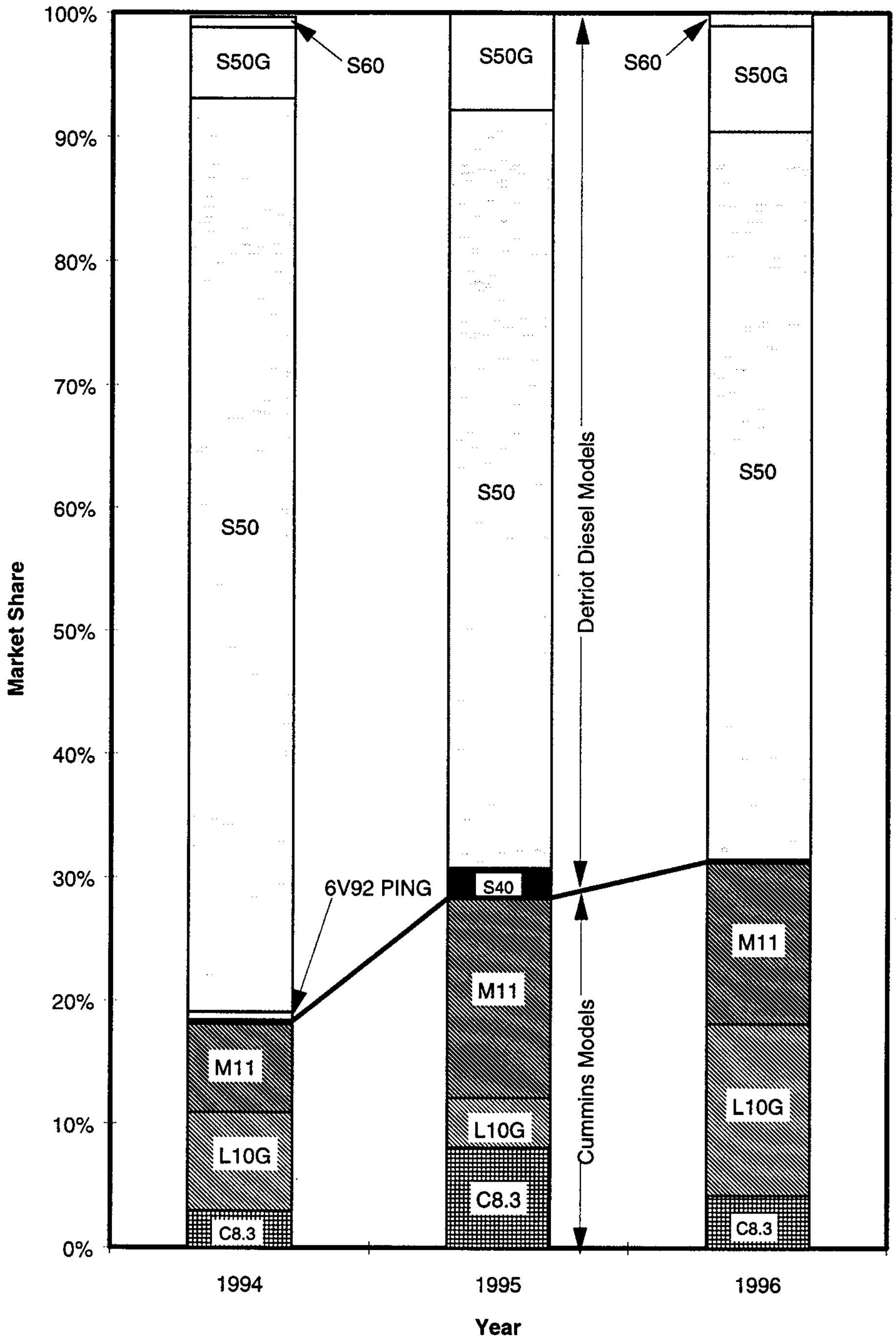

Figure 12. Transit bus engine market, based on numbers of units ordered. Data from Patrick J. Scully, Vice President, Bus and Coach Sales, DDC (Oct. 1996).

for comparison. The observed trend in average emission rates for the diesel buses clearly reflects the impact of the tightening of emission standards between 1989 and 1991. Over this time, the NO_x standard went from 10.7 g/bhp-hour to 5.0 g/bhp-hour. Observed chassis dynamometer emission rates decrease similarly: 1988 and 1989 model diesel buses produced NO_x at rates between 40 and 45 g/mi; for 1991–1993 model diesel buses, NO_x rates are clustered near 25 g/mi. Note that this 25-g/mi rate holds buses powered by either the two-stroke DDC 6V92 or the four-stroke Cummins L-10. The data also indicate that varying the type of diesel fuel used [Diesel No. 1 (D1), Diesel No. 2 (D2), and Jet-A] does not

TABLE 29 Available full-size alternative-fuel transit buses

Manufacturer	Model	Length (ft)	Fuel	Engine Used	Availability
Blue Bird	Q-Bus	35, 37	CNG or LNG	Deere 8.1L	1997
Gillig Corp.	Phantom	40	LNG	Cummins L10G Detroit Diesel Series 50G	1996
Neoplan USA	AN440 Transliner AN440L (low floor) Transliner	40	LNG or CNG	Cummins L10G Detroit Deisel Series 50G	1996
New Flyer Industries	D35 D40 D35LF (low floor) D35LF (low floor	35 40 35 40	LNG or CNG	Detroit Diesel Series 50G Cummins L10G	
Nova Bus	RTS	35, 40	CNG	Cummins L10G Detroit Diesel Series 50G	1996
North American Bus Industries (NABI)	Model 416 Model 40LFW (low floor)	40 40	LNG	Cummins C8.3G Cummins L10G Detroit Diesel Series 50G	1997
Orion Bus Industries	Orion 5 (high floor) Orion 6 (low floor)	30, 35 & 40	CNG	Cummins L10G Detroit Diesel Series 50G	1994 1997

Sources: U.S. Dept. of Energy Alternative Fuels Data Center, World Wide Web site, June 1998; World Wide Web sites of Blue Bird Corporation, Nova Bus, and North American Bus Industries; and Personal Communication with managers at all of the manufacturers listed.

TABLE 30 Population of buses, by power source, in the 1995 North American transit bus fleet

Power Source	Number in Fleet	Percent of Fleet
Diesel fuel	46,862	93.08
Diesel with particulate trap	1,188	2.36
Compressed natural gas	938	1.86
Methanol	396	0.79
Liquefied natural gas and diesel	283	0.56
Gasoline	234	0.46
Compressed natural gas and diesel	73	0.15
Liquefied natural gas	64	0.13
Ethanol and diesel	58	0.12
Jet fuel	52	0.10
Electric battery	39	0.08
Compressed natural gas and gasoline	34	0.07
Propane (liquefied petroleum gas)	29	0.06
Diesel and bio or soy fuel	25	0.05
Gasoline and compressed natural gas	23	0.05
Ethanol	19	0.04
Gasoline and propane	14	0.03
Diesel and compressed natural gas	6	0.01
Diesel and ethanol	5	0.01
Electric battery and propane	2	0.00
Totals	**50,344**	**100.00**

Source: *Transit Vehicle Data Book*, American Public Transit Association (1996).

significantly affect the NO_x rate. Note that the variation in NO_x rates from a particular model of diesel engine (as indicated by the standard deviation) also decreased substantially after 1990. This likely is due to tighter manufacturing and calibration tolerances needed to meet the 1991 5.0 g/bhp-hour NO_x standard.

The L10 240G was the earliest version of the natural gas L-10. It was offered with CARB certification at NO_x rates between 2.0 and 2.5 g/bhp-hour, which was approximately half the NO_x rate of comparable diesel engines. Nevertheless, as indicated in Figure 13, the 1991 and 1992 CNG L-10 buses exhibited rather variable NO_x rates, with average NO_x rates greater than those of diesel engines of the same model year. In fact, the LNG buses equipped with the 1993 L10-240G showed the highest NO_x rates of any of the buses tested in the program. These LNG buses most likely had excessively rich air/fuel mixtures. The L10 240G used a mechanical air/fuel mixer for mixture preparation, for which the air/fuel ratio was readily adjustable in service by mechanics. Mechanics tended to adjust the mixture excessively rich in order to maximize power, which also dramatically increases NO_x rates. The next generation of the natural gas L-10, the L10 260G, introduced in 1993, incorporated a mixture screw, which was set at the factory and then potted. This greatly reduced the incidence of maladjustments in the field. The L10 260G also incorporated other improvements, such as an electronically controlled turbocharger wastegate and other

TABLE 31 Transit bus orders by engine model and fuel type

Units Ordered

Engine Models			No. Units Ordered		
Mfr.	**Model**	**Type**	**1994**	**1995**	**1996**
Cummins	C8.3	Medium heavy-duty (MHD) diesel	136	479	122
	L10E	Heavy heavy-duty (HHD) diesel	6	0	0
	L10G	HHD spark-ignited natural gas	366	237	401
	M11	Heavy heavy-duty diesel	345	975	385
	All Models		853	1691	908
DDC	6V-92	Heavy heavy-duty 2-stroke diesel	9	0	0
	6V-92 PING	HHD diesel pilot-ignited natural gas	29	0	0
	S30G	MHD spark-ignited natural gas	0	5	0
	S40	Medium heavy-duty diesel	1	130	0
	S50	Heavy heavy-duty diesel	3401	3636	1701
	S50G	HHD spark-ignited natural gas	263	460	247
	S50P	HHD spark-ignited propane	0	2	0
	S60	HHD diesel for suburban/intercity buses	40	0	30
	All Models		3743	4233	1978

Market Share by Fuel Type

Engine Type	Units Ordered			Market Share (%)		
	1994	**1995**	**1996**	**1994**	**1995**	**1996**
MHD Diesel	137	609	122	3	10	4
HHD Diesel	3801	4611	2116	83	78	73
Natural Gas	658	702	648	14	12	22
Propane	0	2	0	0	0	0
All Types	4596	5922	2886	100	100	100

Based on data provided by Mr. Patrick J. Scully, Vice President, Bus and Coach Sales, Detroit Diesel Corporation (Oct. 1996).

Note: Data for 1996 apply to orders received during January-June.

calibration improvements. The success of these modifications is reflected in sharply reduced NO_x rates compared with the L10-240G (Figure 13). NO_x rates shown by the L10-260G are well below those of contemporaneous diesel engines, as would be expected from their respective certification data.

The alcohol engines showed significantly lower chassis dynamometer NO_x rates than comparable diesel engines. Methanol engines exhibited lower and less variable NO_x rates than ethanol. Buses equipped with the 1993 methanol 6V92 consistently produced the lowest NO_x rates of any of the buses tested in the program, with average NO_x rates of 6 g/mi—one-fourth that of contemporaneous diesel engines (Figure 13).

Chassis dynamometer PM emission data from the NREL testing program are compared in Figure 14. PM rates of 1988–1989 diesel buses were between 0.6 and 1.9 g/mi. In Model Year 1990, diesel PM rates were generally higher than those of the 1988–1989 models. Model Year 1990 diesel engine PM rates ranged from as little as 1.1 to as much as 3.3 g/mi. This increase from previous model years occurred despite the fact that the certification PM standard over 1988–1990 remained constant at 0.6 g/bhp-hour (Figure 14). Note that the NO_x standard was tightened substantially between 1989 and 1990 (Figure 13). Changes in engine calibration made in 1990 to meet the tighter NO_x standard (such as retarded fuel injection timing) appear to have resulted in increased PM emission rates in service. With both the DDC 6V92 and the Cummins L10, burning lighter diesel fuel (D1 versus D2) appears to offer no obvious PM benefit. The data show that buses fueled with D1 frequently have higher PM rates than those with the same engine model fueled with D2.

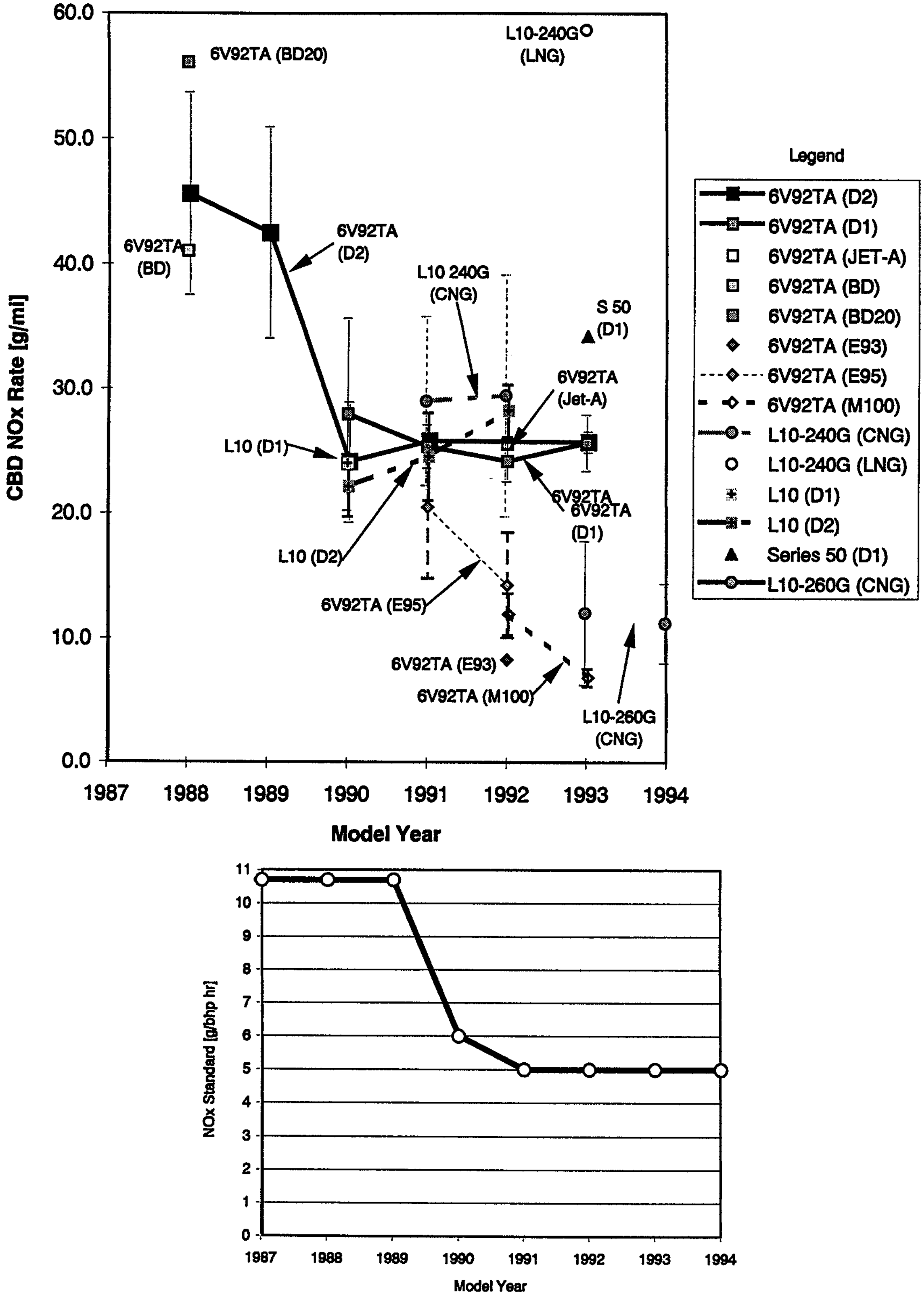

Figure 13. Chassis dynamometer NO_x rates using the CBD duty cycle—DOE/NREL program.

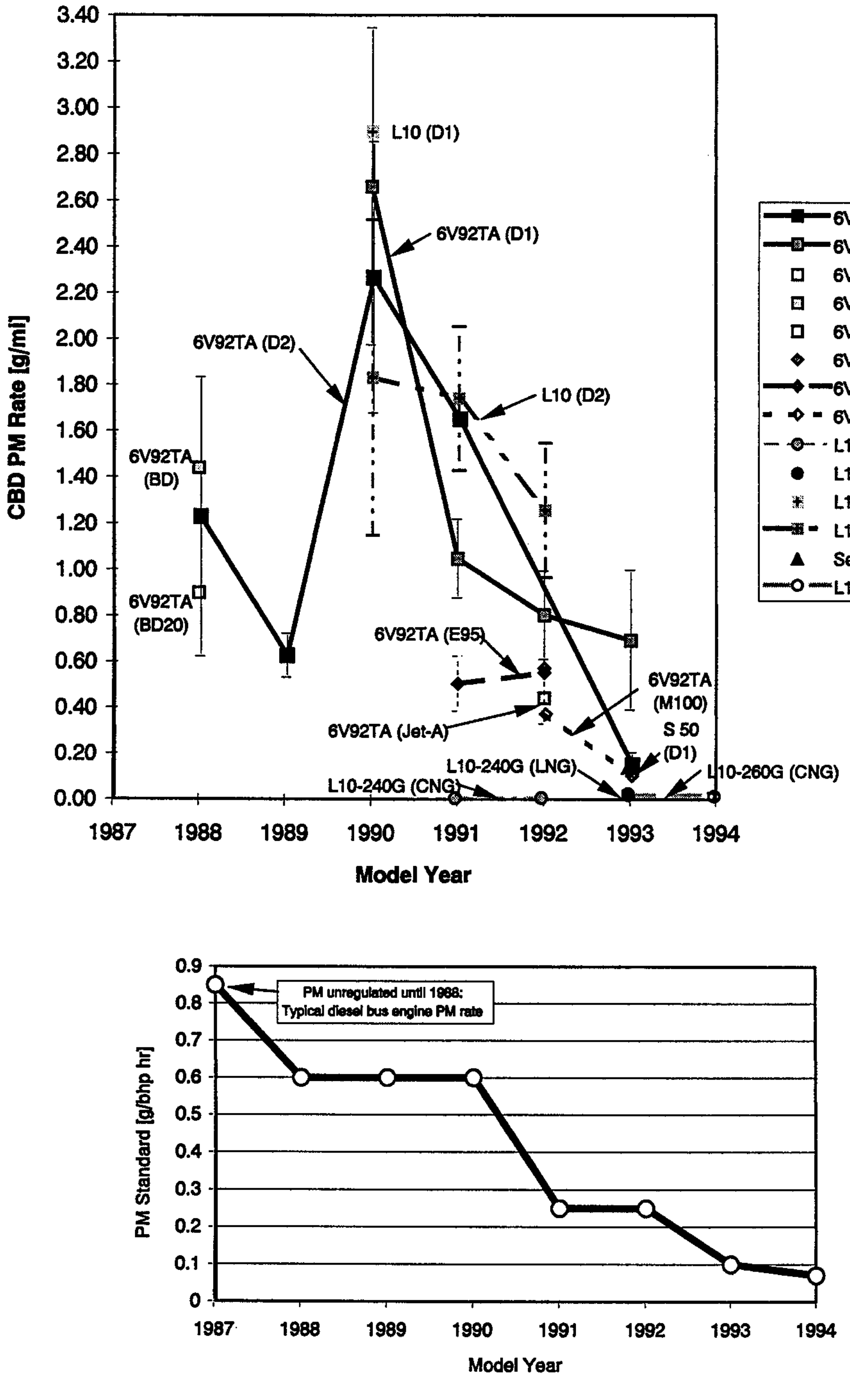

Figure 14. Chassis dynamometer PM rates using the CBD duty cycle—DOE/NREL Program.

The data show a trend of decreasing PM emissions by diesel buses between 1991 and 1993, which is likely due to better optimization for simultaneous reductions of NO_x and PM and the imposition of a PM standard of 0.10 g/bhp-hour in 1993. Both the ethanol and methanol versions of the 1991–1992 DDC 6V92 show somewhat lower PM rates than the diesel version. However, by Model Year 1993, the PM rates of four-stroke diesel engines (Cummins L-10 and DDC Series 50) had fallen below those of earlier-model two-stroke alcohol engines. All models of the natural gas Cummins L-10 show extremely low PM emission rates—typically below 0.03 g/mi.

Several conclusions may be derived from these emission test data:

- Emission rates of NO_x and PM from diesel buses have decreased significantly in response to increasingly stringent engine certification standards.
- Alcohol-fueled two-stroke engines can achieve NO_x rates that are consistently very low. Methanol appears to produce lower NO_x rates than ethanol. Fueling with either alcohol could produce PM reductions compared with the diesel version of the same engine. However, in recent-model four-stroke diesel engines engineered for very low PM rates, the PM reduction achieved by converting to alcohol could be small.
- Natural gas engines are capable of extremely low PM rates. They can achieve NO_x rates approximately 50 percent lower than diesel baseline when properly calibrated. However, the NO_x rate is quite sensitive to air/fuel ratio. The NO_x rates of natural gas engines can easily exceed diesel baseline in the event that the fuel systems are miscalibrated or given inadequate maintenance.

CHAPTER **13**

SELECTED CASE STUDIES

13.1 INTRODUCTION

In this chapter, three case studies of transit agencies are presented, each of which has a policy of converting all or a significant portion of bus operations to an alternative fuel and is well on the way to completing the conversion process. The following agencies were selected for study:

CNG and LNG are clearly the best established alternative fuels in public transit today. Sun Metro was the first transit agency in North America to commit to converting to dedicated LNG engines with pumpless onboard fuel systems. Although Houston Metro had begun demonstrating full-sized LNG transit buses before Sun Metro, Houston's buses used diesel pilot-ignited engines, which required onboard fuel systems equipped with high-pressure LNG fuel pumps. Dedicated engines and pumpless LNG fuel systems are now the standard design approach in OEM transit buses. Therefore Sun Metro was highlighted as an agency with extensive experience with commercially available LNG bus technology.

Indoor bus parking and indoor fueling are commonly practiced in regions with cold winter weather. Designing indoor parking, particularly indoor fueling facilities, for CNG bus operations entails costs and technical challenges that agencies operating in mild climates do not have to confront. Greater Cleveland Regional Transit Authority and Sacramento Regional Transit District are agencies that operate in cold and mild winter climates, respectively. Both agencies were pioneers in converting bus operations to CNG and have accumulated substantial operating experience with this fuel.

13.2 EL PASO MASS TRANSIT DEPARTMENT (SUN METRO): TRANSIT BUS OPERATIONS WITH LNG FUEL

13.2.1 Background

El Paso, nicknamed the Sun City, is a medium-sized border town located in westernmost Texas. The Rio Grande River divides it from Juarez, Mexico. El Paso has some very good trip generators. Military bases in the area, Fort Bliss and Biggs Airfield, have a high concentration of transit users. There is a fairly large population of poor to lower middle class people, as well as a large number of visitors from Mexico, who are also heavy users of the transit system. The year-round heat, aridity, and constant winds present an unusual climatic setting for transit bus operations.

13.2.2 Reasons for Converting to an Alternative Fuel

El Paso was motivated primarily by the passage of Texas Law requiring public transit fleets to convert to alternative fuels. The law was enacted in 1989. Public opinion did not enter into the decision; apparently there was little local pressure to convert. Management was also motivated to present an image of public transit as forward looking and progressive. The environmental benefits of alternative fuels were also a motivation for considering alternative fuels.

13.2.3 Planning Studies

Agency staff conducted a study of the available alternative fuels. This study was based on a combination of staff experience with CNG at another transit agency and a review of the limited literature available at the time. This analysis led to the conclusion that LNG could be a better alternative. Using LNG would result in substantially lower weight, greater range, and a much lower hazard because of fuel storage pressures, and it could be procured at low enough prices to be competitive with diesel. It is recommended that Sun Metro convert from diesel to LNG.

LNG engine options that were available during Sun Metro's fuel evaluation included dedicated, spark-ignited engines, and diesel pilot-ignited engines. While reviewing fuel options, management discussed the LNG engine alternatives with staff at other transit systems. Although the diesel pilot-ignition alternative would allow the bus to continue operating on diesel in the event of a malfunction involving the natural gas fuel system, Sun Metro decided against this option, fearing that drivers would prefer to operate the buses on diesel alone, even when the natural gas fuel system was working properly. Sun Metro therefore chose to purchase transit vehicles with *dedicated* LNG engines.

13.2.4 Operational Experience with LNG and CNG

Sun Metro's revenue bus fleet is listed in Table 32. In 1990, Sun Metro ordered their first LNG vehicles. These were van cutaways built on truck chassis. These were originally manufactured as gasoline vehicles and then converted to LNG. Sun Metro wanted full dealer warranties on the LNG fuel systems. The vehicle dealer therefore arranged for conversion of the fleet to LNG by a factory-qualified upfitter. The upfitter selected an LNG tank vendor providing a tank that was pumpless and used the LNG vapor pressure for fuel pressure. The tank was fairly complex, as it was equipped with heat exchangers and valves designed to warm the LNG fuel if tank pressure falls below the minimum pressure required by the engine. Problems were encountered with these tanks. The fuel gauges were very inaccurate and tended to overindicate fill level. Actual fills of as low as 50 percent registered as full. As a result, service personnel routinely underfilled the tanks, causing the buses to run out of fuel in service, which then had to be towed back to base. Piping from the tanks also vibrated excessively and failed frequently. As a result, Sun Metro replaced the tanks with tanks manufactured by another vendor. These tanks performed substantially better in service.

In 1993, Sun Metro ordered 18 CNG buses from Bus Industries of America (BIA), and 35 LNG buses from New Flyer Industries. The agency planned to compare the performance of CNG and LNG in service before making a final choice between them. The BIA Orion 5s were powered by Cummins L10 260Gs, and the New Flyers were powered by DDC Series 50Gs.

Sun Metro's CNG buses were 3,000 lb heavier than similar diesel buses, whereas their LNG buses were only 600 lb heavier than a diesel bus. The CNG buses were capable of 300 mi between fills; the LNG buses were capable of 400 mi.

Purchase prices for Sun Metro's natural gas and diesel buses are listed in Table 33. Note the higher price premium paid for the CNG bus versus the LNG bus compared with a similar diesel model.

Sun Metro has encountered very similar maintenance requirements among their diesel, CNG, and LNG transit buses. Road-call rates between the three technologies are virtually identical. Diesel road-call rates are 2.14 per 100,000 mi; those of the natural gas buses are 2.15 per 100,000 mi. Maintenance staff performed teardowns on a Cummins L-10G and a DDC Series 50G at 100,000 mi; both engines were in excellent condition and did not exhibit any premature wear. Spark plugs are replaced every 36,000 mi, and the onboard gas leak detection system requires periodic recalibration. These were the only areas of additional maintenance reported for the natural gas buses.

13.2.4.1 Fuel Costs at Sun Metro

At the time of this writing, Sun Metro paid $0.90 per gallon for diesel fuel, with the price fixed over a 1-year contract. The agency was supplied LNG at $0.38 per gallon, with the price fixed for 3 years. Sun Metro's fuel quality specification calls for a minimum methane content of 97 percent. An outside laboratory periodically analyzes LNG samples to verify fuel quality. This comparatively low price for LNG reflects the fact that Sun Metro is a large consumer (monthly LNG consumption is now 110,000 gallons) and that they are close to major sources of LNG located on the Gulf Coast.

Fuel economy and fuel costs per mile reported by Sun Metro for their diesel and LNG buses are shown in Table 34. The data show that LNG buses achieve substantial fuel cost savings compared with Sun Metro's diesel fleet. The relative fuel economies between LNG and diesel buses are biased somewhat in favor of LNG because the diesel fleet is powered

TABLE 32 City of El Paso's (Sun Metro) transit bus fleet

Model Year	Bus Model	Engine	Fuel	No. in Fleet
1997	Chance AH-28 Trolley	Cummins B5.9-195G	LNG	25
1997	Bluebird 25'	Cummins B5.9-195G	LNG	30
1997	Superior/GMC GP30 Van Cutaways	GMC 454 CID V-8	LNG	24
1994	BIA Orion 5.501	Cummins L-10	CNG	18
1994	New Flyer D40	DDC Series 50G	LNG	35
1993	TMC T80 206	Cummins L-10	CNG	2
1991	TMC T80 208	DDC 6V-92	Diesel	79

Total CNG Fleet	20
Total LNG Fleet	114
Total Diesel Fleet	79

TABLE 33 Transit vehicle purchase prices at Sun Metro

Vehicle	Cost	Cost of Similar Diesel Vehicle
1997 Superior/GMC GP30 Van Cutaways (LNG)	$73,000 each	Unknown
1997 Chance AH-28 Trolley (LNG)	NA	NA
1997 Blue Bird 25' (LNG)	$122,760 each	NA
1994 New Flyer D40 (LNG)	$256,000 each	$219,000 each, quoted by New Flyer Industries
1994 BIA Orion 5.501 (CNG)	$319,000 each	$215,000 — $218,000 each

Note: NA=not available.

by two-stroke engines. These engines are substantially less fuel efficient than current-model four-stroke diesel models. Numerous data indicate that buses powered by four-stroke diesel engines achieve fuel economies at least 20 percent higher than those of two-stroke engines in similar service. Because Sun Metro has no diesel buses with four-stroke engines, we have estimated that the likely fuel economy of a four-stroke diesel engine bus operating at El Paso is 4.2 mi per gallon, on the basis of a 20 percent differential (Table 34). Sun Metro's data indicate that they are achieving a 34 percent fuel cost savings with LNG compared with their two-stroke diesel fleet and that they would achieve a 21 percent fuel cost savings compared with a diesel fleet powered by a four-stroke diesel engine (Table 34).

13.2.4.2 Facility Modifications for LNG Fueling

L/CNG fueling station. In 1994, Sun Metro completed construction of a large permanent fueling station for LNG and CNG. Sun Metro staff developed the general design specifications, which were then incorporated into an RFP for detailed design and construction services. The facility was built on time and within budget. The station is very unusual in that it combines the capability for fast fueling of both LNG and CNG buses from stored LNG. Table 35 describes the facility and its installed cost.

Shortly after start-up, the triplex pumps used for generating CNG began failing at a rate of one every 11 days. Each pump cost $40,000. A total of 16 pumps failed and were replaced before the manufacturer was able to incorporate design modifications that made the pumps durable. Since this problem was solved, the station has performed reliably and has required little maintenance.

Sun Metro is planning to install a standby power generator that will allow the fueling station to operate during extended power outages.

An FTA capital grant paid for 80 percent of the cost of constructing the fueling station. Local funds and CMAQ funds provided the remaining 20 percent. Vehicle procurement costs have been paid for largely by FTA capital grants and FTA alternative-fuel program funds. Sun Metro has been very successful in obtaining FTA and CMAQ funding for its LNG conversion program.

Maintenance facility modifications. Sun Metro has not yet modified their maintenance garage for LNG vehicles. Handheld methane detectors are used to check for leaks from LNG buses before they are parked in the garage for repairs. Agency staff have evaluated facility modification requirements in consultation with the local fire department. The planned modifications are modeled after those made at Austin Capital Metro for CNG buses. These include installation of methane detectors linked to the fire protection system,

TABLE 34 Fuel costs at Sun Metro

Fuel/Engine	Purchase Price ($/gal)	Fuel Economy (mi/gal)	Fuel Cost ($/mi)	Fuel Cost/mi 2-stroke Diesel	Fuel Cost/mi 4-stroke Diesel
Diesel DDC 6V-92 (two stroke)	$ 0.90	3.50	$0.257	100%	120 %
LNG — DDC Series 50G (four stroke)	$ 0.38	2.24	$0.170	66%	79%
Diesel — DDC Series 50 (four stroke)	$ 0.90.	4.20 (est.)	$0.214	83%	100%

Note: Fuel economy of bus powered by a diesel Series 50 was estimated by assuming that it achieves 20 percent better fuel economy than El Paso's diesel 6V-92 powered fleet.

TABLE 35 L/CNG fueling facility cost at Sun Metro

Facility Description	Total Installed Cost in 1994
Three 20,000-gallon vertical LNG tanks supply three LNG dispensers and three CNG dispensers. 300-gallon batch conditioning tanks are located just upstream from the LNG dispensers. LNG Dispensers deliver product at 50 gal/min, and are equipped with vibrating tube mass flow meters for flow totalizing. Two high-pressure triplex LNG pumps work in parallel to supply LNG at 4,500 psi, which is then vaporized and fed to a CNG storage cascade. The CNG storage cascade supplies three CNG dispensers. Methane boiled off from the LNG storage tanks is used as burner fuel to supply heat for the LNG vaporizer. The facility can simultaneously fuel three LNG vehicles plus three CNG vehicles.	$2,219,500

enhanced ventilation to dilute LNG fuel leaks to below the lower flammability limit, and elimination of ignition sources in areas where LNG leaks are likely to accumulate. The estimated cost of these modifications is $1,850,000. The agency had recently released an RFP to have the garage modifications performed at the time of this writing.

13.2.5 Conclusion

Based on their positive experience operating LNG transit vehicles, Sun Metro is now purchasing LNG buses exclusively. Maintenance costs and vehicle availability have been approximately equal to those of their diesel vehicles. They are able to procure LNG at a low enough price that fuel costs are below diesel baseline.

13.3 GREATER CLEVELAND REGIONAL TRANSIT AUTHORITY (GCRTA) TRANSIT BUS OPERATIONS WITH CNG FUEL IN AN AREA WITH A COLD WINTER CLIMATE[59]

13.3.1 Background

Downtown Cleveland is an older industrial center and a moderate nonattainment area for ozone. RTA's large motor bus fleet operates out of four garages. Table 36 summarizes GCRTA's operation. Public awareness of the air pollution problem and a general consensus that steps should be taken to improve the city's air quality created a political climate that was conducive to the introduction of alternative-fueled transit buses. The FTA made funding available to GCRTA to offset the incremental costs of converting bus operations to an alternative fuel. The transit agency's decision to convert to CNG was influenced by the local gas company, which offered financial assistance for constructing CNG fueling facilities.

Operating in an area with cold, humid winter weather, GCRTA uses indoor bus parking and indoor fueling. The indoor parking areas are moderately heated, which greatly facilitates cold starting in the morning. Fueling and servicing are performed indoors for the comfort of personnel. However, conducting these operations indoors with natural gas buses is complicated by the fire hazard posed by potentially confining leaks of natural gas from the onboard fuel systems and during fueling. GCRTA had to develop suitable fire protection techniques and get them approved by code officials during the process of converting to CNG.

13.3.2 Operational Experience with CNG

GCRTA began its investigation of natural gas for bus fueling in 1989 when one bus, powered by an early version of a CNG engine, was delivered. The bus was demonstrated in revenue service for approximately 1 year. Its performance was promising enough that the agency ordered 20 more units of the same model during 1991–1992. The Board of Directors subsequently committed the Authority to a major conversion of its bus operations to CNG. GCRTA has since constructed a new garage (Harvard Garage) that was designed from its inception for CNG bus operations. Harvard Garage houses one of the largest CNG compressor stations in the world and is one of the first CNG fueling facilities in North America designed for indoor fueling.

TABLE 36 Operational profile of the GCRTA

General Information	
Service Area	515 square miles
Population	1.6 million
Annual Ridership (1995)	58.3 million
Annual Operating Budget	$169.2 million
Number of Bus Operators	1,040
Total number of employees	2,750

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[59] This review is based on interviews with, and information provided by, Win L. Terrentine, Director of Bus Equipment, and Anthony J. Russo, General Supervisor of Garages, of GCRTA (April 1997).

Cleveland's revenue bus fleet consists of 710 40-ft buses, of which 166 are CNG fueled, and 544 are diesel fueled. This number includes 65 new CNG buses and 15 new diesel buses that were scheduled to be delivered in October 1997. The planned fleet makeup with the delivery of the new buses is shown in Table 37. Each of Cleveland's pre-1997 CNG buses is equipped with six fiber-reinforced aluminum fuel tanks, which provide a total capacity of 16,000 scf at a settled pressure of 3,600 psi. This storage capacity gives the buses an operating range of 230 to 240 mi per fill. This is insufficient for the buses to serve all of Cleveland's routes on a single fill per shift; midday fueling would be needed on some routes. CNG buses are currently limited to those routes that can operate over a full shift on a single fill. These are mainly routes that serve the downtown.

GCRTA operated some of the earliest versions of several natural gas bus engines. The fuel and ignition system design was not fully worked out in these engines, and quite a bit of servicing was required to perform adjustments and upgrades. For example, early ignition systems frequently malfunctioned, especially in damp weather. This problem has largely been solved with improved ignition coils and insulator materials. However, GCRTA is still replacing spark plugs fairly frequently—every 18,000 mi. Approximately six engines were replaced on warranty because of damage to the exhaust valves and piston crowns attributable to excessively high combustion temperatures. The engine damage occurred in the winter when peakshaving by the utility can result in the gas being off-specification. With gas containing too much ethane and propane, the octane rating (knock resistance) falls, and the heating value (btu/scf) increases, leading to engine damage. GCRTA was unable to determine whether the cause of the engine damage was off-specification fuel or miscalibration of the fuel system that led to excessively rich fuel/air mixtures.

Seventeen or 18 of the CNG tanks in the fleet have been replaced because of mechanical damage. Impacts by road debris apparently pitted or otherwise deformed the tank's surfaces. Replacing the damaged tanks is complicated by the fact that the original manufacturer no longer produces these tanks. The manufacturing tools and fixtures for these tanks were sold to another company. Whereas the original price of the tanks was $3,000 each, the new company is now asking $6,000 for replacement tanks. CNG fuel lines onboard the buses have also been damaged by road debris. It appears that better shielding is needed to protect the fuel storage system from these impacts.

13.3.3 Facility Modifications for CNG Fueling

CNG buses are based at two of GCRTA's four bus garages. An existing garage was first retrofitted to safely house CNG buses. Harvard Garage is entirely new and was built specifically to house CNG buses. The local fire marshall was deeply involved in planning and designing

TABLE 37 GCRTA's motor bus fleet

Model Year	Bus Model	Engine	Fuel	No. in Fleet
1997	Novabus RTS	DDC Series 50G	CNG	65
1997	Novabus RTS	DDC Series 50	Diesel	15
1995	Flxible Metro 40102-4D-1	DDC Series 50G	CNG	31
1994	Flxible Metro 40102-4C-1	Cummins L-10	Diesel	5
1994	Flxible Metro 40102-4D-1	DDC Series 50G	CNG	49
1992	Flxible Metro 35102-6C-1	Cummins L-10	CNG	5
1991	Flxible Metro 30102-6C-1	Cummins L-10	CNG	15
1991	Flxible Metro 40102-6-1	DDC 6V-92	Diesel	58
1990	Flxible Metro 40102-6C-1	Cummins L-10	Diesel	150
1989	Flxible Metro 40102-6C-1	Cummins L-10	CNG	1
1989	TMC T80 206	DDC 6V-92	Diesel	77
1988	Flxible Metro 40102-6C-1	Cummins L-10	Diesel	77
1985	Flxible Metro 40102-6-1	DDC 6V-92	Diesel	105
1984	Flxible Metro 40102-6-1	DDA 6V-92	Diesel	57
Total CNG Fleet				166
Total Diesel Fleet				544
Total Bus Fleet				710

the facility. The fire protection system for CNG leaks encompasses the indoor bus parking areas and the repair bays. Methane detectors are located near the roof and in the pits. Detection of a leak will automatically trigger an increase in ventilation. If the methane concentration continues to increase, the doors are automatically opened, and non-safety-critical electrical systems are shut off to minimize ignition sources.

At the time of its construction, the CNG compressor station at Harvard Garage was the largest natural gas vehicle fueling station in the United States. It is capable of fueling 200 natural gas buses in 8 hours.[60] The CNG station is equipped with four compressors, each having a capacity of 1,300 (scf/min). The compressors do not use compressor oil, which eliminates the need to filter out compressor oil mist before fueling. All four compressors can work in parallel to supply 6,200 scf/min of gas to the buffer tanks. Total buffer storage capacity is 60,000 scf at 3,600 psi. The buffer tanks supply three dispensers in the fuel island area. Each dispenser has a maximum capacity of 2,300 scf/min. The total installed cost of the compressor station and dispensers was $3 million.

GCRTA pioneered indoor fueling of CNG buses with this installation. RTA staff and the consulting architectural and engineering firm worked closely with local fire officials to develop appropriate safety measures. All electrical conduit in the dispensing area is rigid, sealed, and explosion proof. Electrical cabinets for the dispenser's control system are ventilated with outside air at higher than ambient pressure. This prevents the entry of gas leaks into the cabinets, thereby preventing contact with the ignition sources within. Methane detectors are located above the fueling islands, which automatically shut off the dispensers in the event of a large leak. Indoor fueling has been performed at the facility routinely since 1995. Figure 15 shows a bus at a CNG fueling island at Harvard Garage.

13.3.4 Operating Costs with CNG Fueling

GCRTA currently pays $0.362 per therm of uncompressed gas. The compressor suction pressure at Harvard Garage is between 65 and 80 psi. Electric motors are used for compressor drive. Electrical energy costs for compression are $0.08 per therm of gas delivered.[61] GCRTA maintenance staff perform routine adjustments of the CNG compressor station, and major maintenance is contracted out.

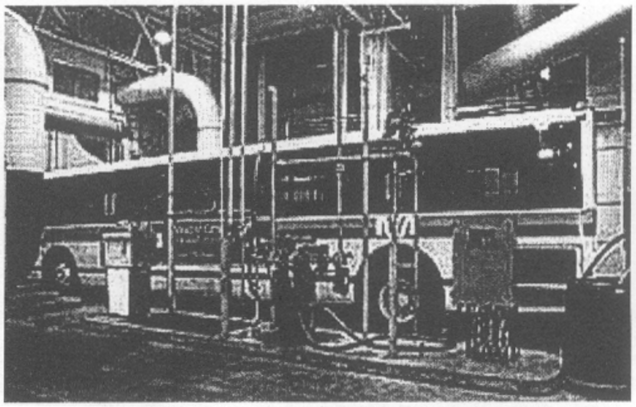

Figure 15. GCRTA bus at indoor CNG fueling island at Harvard Garage.

13.4 SACRAMENTO REGIONAL TRANSIT DISTRICT (SRTD): WARM CLIMATE OPERATION WITH CNG[62]

13.4.1 Background

Along with GCRTA, SRTD was one of the first public transit agencies in the United States to commit to a major conversion of its fleet to CNG. California's capital, Sacramento, is situated in the Great Central Valley. The Great Valley is bordered on the west by the Coast Ranges and on the east by the Sierra Nevada. This geographic setting produces stagnant air capped by strong inversions in the summer. Sacramento is currently classified as a serious nonattainment area for ozone. Because of its geographic setting, Sacramento has the potential for much higher levels of ozone (like Southern California), if the inventory of ozone-precursor pollutants is allowed to increase. Air quality is an important policy driver in Sacramento, and the Sacramento Metropolitan Air Quality Management District plays an influential role in the region.

Sacramento has a mild climate year-round. Buses operate out of a single garage located downtown and are parked and fueled outdoors. The SRTD was chosen for study as an example of a successful conversion to CNG in a warm climate.

13.4.2 Reasons for Converting to Alternative Fuels

By 1990, transit bus demonstrations with methanol two-stroke engines had established that methanol fueling could produce substantial reductions in NO_x and PM compared with diesel. SRTD staff was planning a 75-bus procurement to replace an aging diesel fleet. The SRTD Board had estab-

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[60] *Nation's Largest NGV Fueling Station Opens in Cleveland,* Consolidated Natural Gas Company, World Wide Web page: http://www.cng.com.

[61] Russo, A., General Supervisor of Garages, Greater Cleveland Regional Transit Authority, letter to S. Barsony (Sept. 16, 1997).

[62] This information is based on interviews with Cameron Beach, Chief Operating Officer, and Michael Cook, Maintenance Manager, on April 17, 1997.

lished a policy that the District would purchase only "clean fuel" buses. Clean fuel was understood to mean that the bus emitted NO_x at a rate less than one-half that of a conventional diesel bus. At the time this policy was established, methanol-fueled two-stroke engines were the only transit bus engines that had clearly demonstrated this capability. However, CNG engine prototypes had also demonstrated low NO_x rates, with proper calibration. LNG was emerging as a possible alternative to CNG.

13.4.3 Planning Studies

To assist SRTD's planning effort to choose a fuel for the pending bus procurement, in 1990, the agency retained a consultant to conduct a study that compared the relative knowledge about alternative fuels at that time. The study compared the emission, performance, and cost impacts of methanol, CNG, LNG, and clean diesel fuel. There was a spirited debate between methanol and CNG supporters about the relative merits of the two fuels. Staff from the Southern California Rapid Transit District (now LACMTA) were brought in to share their experiences with the Board of Directors. SRTD staff issued a request for proposals for new buses with three different fuels—CNG, LNG, and methanol. As a result of this procurement process, staff recommended a CNG bus to the Board of Directors because they thought it had the best overall cost-effectiveness. After discussion, the Board of Directors agreed with the staff recommendation.

13.4.4 Operational Experience with CNG

SRTD operates out of one facility for its bus operations. They currently operate 211 buses in revenue service, with 136 powered by CNG. The balance of their fleet consists of 75 40-ft diesel buses (Table 38). The diesel buses are used primarily for tripper service, and base runs are covered by the CNG buses. The average fleet age is 4.9 years.

The CNG buses are powered by Cummins L10 240Gs (Phase I version developing 240 hp) and L10 280Gs (Phase II version developing 280 hp). SRTD has a normal pull out of 173 buses, so they are operating with about an 18 percent spare factor. The replacement of diesel buses powered by two-stroke engines with CNG buses powered by four-stroke engines has greatly reduced engine oil leakage in the bus storage yard. (Oil consumption rates are compared in Table 39.) This has had the beneficial result of noticeably lower worker's compensation claims due to slips and falls.

SRTD experienced numerous PRD failures early in the life of their 1993 model CNG. This was a widespread problem at the time. The PRDs are designed to melt or burst if the onboard tanks experience excessive heat or pressure. The GRI led an extensive investigation of the problem, which revealed that the PRD's fusible metal disks were failing because of the heat of compression during tank filling. The PRD manufacturer solved the problem by modifying the composition of the metal alloy to have a higher melting temperature. Despite several episodes of CNG tanks venting in the maintenance garage, SRTD never experienced a fire or explosion during the event. SRTD had eliminated its open flame heaters and other ignition sources near the ceiling as part of the modification of the garage for CNG.

The most recent (1996) model buses at SRTD are equipped with CNG tanks that have plastic liners fully supported by fiber-reinforced composite. These tanks are quite light. As has occurred with other fleets using these tanks, SRTD maintenance personnel have observed gas seeping out the ends of some of the tanks. The tanks operate at 3,000 psi. The problem has shown up on about 10 of the approximately 400 tanks that are in service.

TABLE 38 SRTD's revenue bus fleet

Model Year	Bus Model	Engine	Fuel	No. in Fleet
1996	OBI Orion 5 (31 ft), EDO Light Ryder tanks	Cummins L10-280G	CNG	15
1996	OBI Orion 5 (40 ft), EDO Light Ryder tanks	Cummins L10-280G	CNG	26
1994	BIA Orion 5.501 (40 ft), SCI tanks	Cummins L10-240G	CNG	20
1993	BIA Orion 5.501 (40 ft), SCI tanks	Cummins L10-240G	CNG	75
1990	Gillig Phantom 40TB102	DDC 6V-92TA	Diesel	50
1985	Gillig Phantom 40TB102	DDC 6V-92TA	Diesel	25

Total CNG Fleet	136
Total Diesel Fleet	75
Total Revenue Fleet	211

TABLE 39 Fluid consumption rates reported at SRTD during March 1997

	CNG		Diesel	
Mileage	542,679	—	146,401	—
Fuel	232,935 thm	2.33 mi/thm	40,371 gal	3.63 mi/gal
Energy [LHV][a]	2.17E+10 Btu	39,919 Btu/mi	5.196E+09 Btu	35,490 Btu/mi
Engine oil[b]	1,410 qt	385 mi/qt	506 qt	289 mi/qt
Transmission fluid	53 qt	10,239 mi/qt	31 qt	4,723 mi/qt

[a] Assuming lower heating values of 93,000 btu/thm for CNG and 128,700 btu/gal for diesel fuel.

[b] Includes make-up oil only, not oil changes.

The electronic fuel control systems on the earlier CNG engines had some problems. However, the manufacturer has worked with the SRTD to eliminate or reduce the problems.

The SRTD has found that the CNG buses are cheaper to operate than their older diesel buses. Road-call rates for the CNG fleet have been moderately higher than those for the diesel fleet. Road-call rates reported for March 1997 are as follows: diesel buses, one call every 9,150 mi; CNG buses, one call every 7,865 mi.

Before the arrival of the CNG buses, road-call rates were on the order of one call every 5,000 mi. For the past 4 years, the combined fleet road-call rate has been approximately one call every 7,500 mi.

Both the engines and transmissions of the CNG buses are considerably more oil tight than those of the diesel buses. The fuel consumption data indicate that the two-stroke engines powering SRTD's diesel fleet are about 10 percent more energy efficient than the CNG engines.

SRTD uses oil analysis and has been able to raise the change interval on the CNG buses from 6,000 to 8,000 mi on the basis of the analyses. They use a low-ash, 15W40 weight oil. They now use the same oil with their diesel buses to simplify operations. The only modification made to their road-call trucks for CNG operations was the addition of low-ash oil.

SRTD has not had to rebuild any engines for the CNG buses. They plan to do the work in-house when they start. A number of their CNG engines have over 200,000 mi and are still going strong. They plan to send their first engine over 250,000 mi to the manufacturer for an analytical teardown so they can properly forecast their rebuild workload. This is in contrast to the two-stroke diesel engines that normally were overhauled in the 170,000-mi range.

Like many transit agencies, SRTD buses exceed legal weight limits with high passenger loads. Because of their higher curb weight, the problem is more severe with CNG than with diesel buses. Operationally, this has not presented a problem because enforcement of weight limits is currently suspended.

The greatest benefits from the conversion to CNG have been reduced cost of operation and the enhanced image for the SRTD as a low-emission fleet. Table 40 shows that the operating cost savings have been considerable. Maintenance costs of the CNG buses have been below diesel baseline while under warranty and have not really changed since they went out of warranty. Fuel costs with CNG are substantially lower than diesel baseline because of the attractive pricing that is available to SRTD. Data provided by SRTD indicate that the agency paid $0.284 per therm for natural gas and $0.81 per gallon for diesel between July 1996 and March 1997. SRTD buys gas directly from a wholesaler, who injects into the local gas company's pipeline system in Bakersfield. The gas is delivered at a pressure of 300 psi. This very high compressor inlet pressure yields a substantially lower cost of compression compared with facilities supplied with gas at normal distribution system pressures. Note that the operating cost savings compared with diesel would be less dramatic if the baseline diesel buses were powered by modern fuel-efficient four-stroke engines.

The most difficult problem associated with the conversion to CNG has been the constant training required for mechanics. All new technology is heading toward computer control, which requires new skills for the average mechanic. There is also a strong need for the ability to read and interpret schematic drawings.

13.4.5 Facility Modifications for CNG Fueling

13.4.5.1 CNG Compressor Station

SRTD's fueling station uses three compressors rated at 750 scf/min to supply four dispensers. The fill cycle is fully controlled by a microprocessor. It cost approximately $1.8 million to build. The local gas company provided substantial technical assistance to SRTD in specifying the station design and managing its construction. The company also provided SRTD with high-capacity (6-in. line), 300-psi gas service at no cost to the transit agency and paid $600,000 to offset the capital cost of the fueling station. The Sacramento Metropolitan Air Quality Management District granted SRTD $1,000,000 for fueling station construction and maintenance garage modification costs.

TABLE 40 Comparative operating costs for CNG versus diesel fleets for the period July 1, 1996, through March 31, 1997

	CNG Fleet			Diesel Fleet		
Mileage	4,284,327			1,754,314		
Cost Element	**Absolute $**	**Per Mile $**	**% of Total**	**Absolute $**	**Per Mile $**	**% of Total**
Oil[a]	25,000	0.0058	1.7	13,000	0.0074	1.4
Parts	376,000	0.0878	25.1	192,000	0.1094	20.6
Labor	374,000	0.0873	25.0	281,000	0.1602	30.1
Compression	128,000	0.0299	8.5	—	—	0.0
Fuel	523,000	0.1221	34.9	392,000	0.2234	42.0
Indirect	72,000	0.0168	4.8	56,000	0.0319	6.0
Total	1,498,000	0.350	100.0	934,000	0.532	100.0

[a] This figure includes oil changes.

SRTD has never failed to make a rollout because of mechanical breakdown of the fueling station, fuel contamination, or electric power outage. In the future, the SRTD would like to have a backup fueling capability using standby power generation, if funds can be made available.

13.4.5.2 Maintenance Garage Modifications

An engineering firm specializing in fire safety-related building design was retained to develop detailed recommendations for modifying the maintenance garage for CNG. Methane detectors connected to audible and visible alarms were installed, along with upgraded ventilation, replacement of open flame heaters, and installation of explosion-proof electrical equipment in selected locations. The cost of these modifications totaled approximately $800,000. All facilities are maintained in-house. This has been facilitated by good training and low turnover of maintenance staff.

13.4.6 Vehicle Procurement Practices

To procure CNG buses, SRTD begins with their standard bus specification and adds specifications for CNG fueling, an onboard fire suppression system, and emission test data documenting compliance with the District's low-emission bus policy. SRTD does not use onboard gas leak detection systems. All buses are equipped with wheelchair lifts and air conditioning. The minimum range specified for 40-ft buses is 400 mi, and for 31-ft buses it is 300 mi. SRTD conducts its vehicle procurement process, including bus inspections at the factory, with their own staff.

The following prices were paid by SRTD for their most recent CNG bus purchases: 40-ft bus, $330,000 ($298,788 bid plus 7.75 percent sales tax and delivery charges); 31-ft bus, $320,000.

SRTD operates in a low-corrosion area. They plan to keep their buses at least 12 years and hope they will last up to 20 years. They plan to run the buses as long as it is economical to do so.

13.4.7 Conclusion

The performance of the CNG buses has exceeded the expectations of the SRTD staff. Operating costs have been lower, and vehicle reliability has been better than originally forecast. The public strongly supports the CNG operation as a way of improving air quality.

CHAPTER **14**

SUMMARY AND CONSIDERATIONS FOR EVALUATING FUELS AND VEHICLE TECHNOLOGIES

14.1 SOME CONCLUSIONS REGARDING FUEL CHOICES

14.1.1 Diesel Engines

Diesel will remain the standard fuel for transit for at least another decade. Diesel engines offer superior fuel efficiency, which will not likely be exceeded until direct hydrogen fuel cell buses are commercialized. Advances in diesel engine emission control technology will ensure that diesel engines will be commercially available at least through the year 2010. Post-2004 diesel engines will emit NO_x below 2.5 g/bhp-hour (50 percent of the 1997 standard) with PM at 0.05 g/bhp-hour (current standard). Diesel fuel offers the lowest fire hazard of any of the fuels considered here for transit buses. Fire protection systems in vehicles, fueling facilities, and maintenance garages can therefore be considerably less elaborate and less costly than those needed with other, more volatile, fuels.

14.1.2 Hybrid-Electric Propulsion

Hybrid electric is a very promising technology for the next generation of transit buses. Suitable propulsion motor and power control system designs are becoming increasingly available. Modern AC propulsion motors controlled by electronic inverters are inherently reliable and durable and allow most of the vehicle braking to be accomplished dynamically (electrically), with no mechanical wear. Maintenance costs for transmission and brake repairs in conventional transit bus fleets are substantial and could be greatly reduced by converting to electric-drive trains. With a suitable energy storage device for capturing braking energy and augmenting engine power during acceleration, a substantially smaller engine may be used. A compact, lightweight energy storage device that will charge and discharge with the necessary power has not yet been perfected. Batteries may be used in the near term. Using a properly rated diesel engine in a hybrid-electric bus, energy consumption and emissions will be 30 to 40 percent lower than current baseline. Additional NO_x and PM emission reductions could be realized by using alternative-fuel engines in hybrid-electric buses, instead of diesel.

14.1.3 Methanol and Ethanol

The available emission data show that alcohol-fueled buses generally exhibit substantially and consistently lower NO_x emissions than diesel buses. However, no alcohol engine is currently certified for heavy-duty vehicles. The only commercialized alcohol engine, the 6V-92, is no longer offered as an automotive engine, even for diesel fuel. The LACMTA, the transit agency operating the largest fleet of methanol (and subsequently, ethanol) buses, has experienced significantly higher maintenance costs and reduced engine life with their alcohol-fueled buses compared with diesel baseline. Fuel cost per unit of heating value for both methanol and ethanol have remained substantially higher than that of diesel over the past decade (readers should refer to the cost model, *FuelCost 1.0,* for illustrations). The Energy Information Agency projects that diesel fuel supplies and price should remain stable for at least another decade; there appears to be little reason to believe that the price competitiveness of alcohol fuels will improve any time soon. This fundamentally limits the market potential for alcohol fuels at present and effectively prevents the investment needed to engineer a current engine model to alcohol.

14.1.4 CNG

CNG is the best-established alternative fuel for transit. Vehicles and fueling stations are commercially available from numerous vendors. Compared with diesel, CNG fuel offers significant NO_x reductions and moderate PM reductions. However, the emission performance of CNG buses is quite sensitive to fuel system calibration. Chassis-dynamometer emission data document many instances of excessively high NO_x emission rates from CNG buses. This problem will likely be substantially eliminated with emerging electronic fuel metering systems. These systems use sensors and feedback controls to reliably maintain lean air/fuel mixtures and can clearly achieve NO_x rates as low as 1.5 g/bhp-hour. In many regions, using CNG will yield savings in fuel bills of 30 to 35 percent, compared with diesel. However, other operating costs exist with CNG that more than offset the savings in fuel costs. These include electric power and maintenance costs for the compressor station and higher vehicle maintenance costs. Total operating costs for CNG buses will usually moderately exceed those for diesel. For a typical 200-bus transit division, it is estimated that median fuel-related operating costs will be $0.66 per mi with CNG and $0.62 per mi with diesel. Incremental capital costs for CNG buses are substantial, and there is no evidence to indicate that these will decrease in the future. Two major factors account for CNG buses' inherently higher cost: (1) the high precision needed to engineer and manufacture light, durable, and reliable onboard CNG tanks as well as the liability cost associated with defects in tank design and manufacture; and (2) the need for onboard fire protection systems. Whereas fueling station installation and garage modifications for CNG represent substantial up-front costs, the long life of these investments greatly reduces their life-cycle cost impact compared with incremental vehicle replacement costs. (Refer to the cost scenarios appearing in *FuelCost 1.0 User's Guide* for examples.)

14.1.5 LNG

LNG is emerging as a nice alternative to CNG. It offers more consistent fuel quality than pipeline gas, lower onboard storage weight and volume, and a substantially lower pressure hazard. Although LNG tanks are extremely well insulated, heat transfer into the tanks is unavoidable. Operationally, this means that fuel vaporization and weathering limit fuel storage time onboard the vehicle, which makes LNG operationally more rigorous than CNG. LNG fuel system designs are also not as mature as those for CNG. In most parts of the country, LNG fuel is more costly than CNG, even if the cost of compression work is included with that of procuring CNG.

14.1.6 LPG

LPG buses have demonstrated reliable operating performance and good safety records in the past. For example, the CTA operated much of its bus fleet on LPG for many years. Chicago's LPG operations were ultimately ended by the lack of a suitable commercially available engine. The recent certification of the LPG version of the Cummins B5.9 engine, however, makes LPG a much more practical option for small- to medium-sized transit buses; however, a commercialized OEM heavy-duty 8- to 10-L LPG engine must become available for LPG to make any significant inroads into the full-sized transit bus market.

The fuel storage weight and volume associated with LPG are only somewhat greater than those associated with diesel. LPG fuel tanks are designed for the same working pressures as LNG; pressure hazards are accordingly similar. However, because LPG is stored at ambient temperature, it can be stored onboard indefinitely without venting or weathering. Being designed for moderate storage pressures and having no need for insulated tanks, LPG fuel systems are substantially less expensive than CNG and LNG fuel systems. Limited vehicle procurement experience indicates that this results in bus purchase prices $10,000 to $20,000 lower than those of similar CNG or LNG models. On the other hand, LPG has a lower octane rating than natural gas. Therefore, the brake-specific fuel consumption will be poorer than with CNG/LNG because of the reduced compression ratio needed to prevent combustion knock. Also, LPG fuel costs are typically higher than those for CNG and LNG and are subject to greater seasonal and regional price fluctuations. However, the cost of LPG fueling facilities is moderate, and facility design standards are well established. Maintenance and operating costs for LPG fueling facilities are similar to those for diesel fuel. The emissions performance of LPG engines should be comparable to those of CNG/LNG engines. LPG presents an arguably greater fire hazard than CNG or LNG. Like gasoline, LPG fuel leaks produce vapor that is heavier than air. The dense vapor remains concentrated near ground level and tends to spread laterally over a large area where it may encounter ignition sources. This contrasts with LNG or CNG leaks, which are buoyant in air once they have warmed up to ambient temperatures, and thereby mix with air more readily, and more quickly become diluted to subflammable concentrations. Numerous LPG fleets have documented years of safe operations, but managers need to know and enforce appropriately rigorous facility design standards and operating procedures.

In summary, LPG offers a potential emissions performance similar to that of CNG and LNG but with operational characteristics more similar to those associated with conventional liquid fuels and with lower vehicle and fueling facility costs.

14.1.7 Fuel Cells

The first commercialized fuel cell bus will most likely use PEM fuel cells directly fueled with compressed hydrogen gas. Such a bus will be a true zero-emission vehicle with excellent performance, acceptable range, and good maintainability and will have superior fuel utilization efficiency. It will probably be offered at twice the price of a similar diesel bus. The introduction of fuel cell engines will be facilitated by the prior commercialization of hybrid-electric motor buses, because the electric propulsion motors and power control and distribution systems for hybrid electric buses are very similar to those for fuel cell buses. Onboard reformers are now being developed that appear to be practical for operating fuel cells with methanol but that will have nonzero emissions. Currently, the distribution system for hydrogen fuel is quite limited. Compressed hydrogen has substantially lower energy density than CNG. The hydrogen molecule is quite small, giving the fuel a remarkable propensity to leak through fittings and seals. These properties add cost and complexity to the distribution and storage of hydrogen as compressed or liquefied hydrogen gas. *Fuel island* *reformers* could be developed, which would allow stored diesel or methanol, or pipeline natural gas, to be used as a feedstock for hydrogen gas and may offer a more practical fuel supply scenario than distribution and bulk storage of compressed or liquefied hydrogen gas. Hydrogen leaks are a serious concern, as the gas is quite buoyant and explosive; appropriate design standards for maintenance garage fueling facilities do not yet exist.

14.2 CONSIDERATIONS FOR EVALUATING FUEL OPTIONS AND CONVERTING A TRANSIT BUS OPERATION TO ALTERNATIVE FUELS

As evidenced by the case studies presented in Chapter 13, a number of transit agencies are successfully operating on alternative fuels. Some conversion programs have been much more difficult than their planners envisioned. From these experiences, it is clear that much can be done during the process of planning and executing the conversion to alternative fuels to facilitate success.

1. Evaluate the local situation candidly and thoroughly. Converting to an alternative fuel will entail costs and operational changes that do not have to be borne with continued operation on diesel. What benefits will be realized in converting to the alternative? Emission reductions and fuel-source diversification are the most commonly cited reasons for considering alternatives to diesel. What is the nature of local air quality problems? Although alternative fuels clearly yield NO_x reductions compared with diesel, they do not offer benefits in terms of lower CO or significantly lower PM. Because the primary effect of NO_x on air quality is its contribution to ozone formation, NO_x reductions have the most meaningful benefit in ozone nonattainment areas. In areas that are in attainment of ozone standards, but nonattainment for CO, the benefits of alternative fuels are not as great. Is the community willing to bear additional costs to convert to alternative fuels? Do local opinion leaders clearly understand both the costs and the benefits? What funding sources are available? Would implementation costs adversely affect service? The planning process for converting to alternative fuels should begin with a comprehensive study of the issues involved. It may be desirable to have an outside firm conduct the study, as the firm will (ideally) be disinterested, objective, and well informed.

The planning study should address a number of relevant issues:

- **Evaluating the air-quality benefits of alternative fuels in the context of the local air quality.**
- **Identifying sources of supply for the fuels under consideration.** How reliable are they? How distant? How much competition exists? Is the available fuel quality acceptably and uniformly high? (For example, does the gas utility employ wintertime peakshaving with LPG?) In certain areas, a particular fuel will be largely available from local sources (such as CNG, LNG, and LPG in the Gulf Coast area, and ethanol in the Midwest). A community may wish to support local industries through the transit agency's choice of fuel.
- **Determining the extent to which facility modifications are needed.** Appropriately qualified professional engineers should evaluate facility modifications that will be needed for alternative fuels and estimate the associated costs. Code provisions stipulate minimum setbacks for fueling stations from buildings and property lines. Is enough space available at the existing garage(s) to accommodate fueling facilities for the alternative fuel? Will land have to be acquired? Is suitably located real estate available for sale or long-term lease? Would local building and fire officials impose any unusual design requirements? For CNG, does the existing gas pipeline have sufficient capacity to meet the large additional demand? If not, how much line must be upgraded, and who will bear the cost? Will electrical service to the garage have to be upgraded for compressor motors? To what design standards was the existing maintenance facility built: Diesel vehicles? Gasoline vehicles? Are existing ventilating rates high enough, or will ventilation have to be upgraded? Are there particular hazards, such as ceiling construction tending to trap gas leaks or open-flame heaters? How extensively will the fire protection system have to be upgraded?

2. Carefully evaluate the technological risks associated with the fuel options. A number of risks exist for transit agencies that are considering conversion to alternative fuels or other advanced, unconventional bus-propulsion technologies. These include the following:

- **Unanticipated safety hazards;**
- **Market obsolescence caused by the principal vendors no longer offering the product; and**
- **Adopting a technology before it is fully developed.**

Unanticipated safety hazards. During the commercialization of CNG, safety hazards have arisen that were not anticipated. These include the frequent failure of PRDs because of the effects of compression heating and the recent instances of leakage and failure of the Type IV (lightweight, all-composite) cylinders. Often, when a new technology is introduced, some of its properties or operating characteristics that potentially affect safety are not fully understood. The transit agency contemplating the introduction of a new fuel or propulsion technology should evaluate the level of such uncertainty that exists with the technology and candidly assess the organization's tolerance of mishaps that may result from this uncertainty.

Market obsolescence. New technologies are usually pioneered by one or two companies that have a vision that the new technology offers compelling advantages over existing products. If their new product is not commercially successful, small, entrepreneurial companies will likely stop offering warranty and technical support to existing owners of the product. For example, a company marketed a lightweight fiberglass-reinforced aluminum CNG tank in the early to mid-1990s. The company then left the market and sold the rights to the tank design to another company. This company offers support, such as repairs of damaged tanks, at much higher prices. As another example, a manufacturer of onboard LNG tanks, has since left this market, leaving the owners of the tanks virtually without product support. Such a prospect is possible for customers of battery-electric buses that are currently being sold by small entrepreneurial companies. Transit agencies contemplating purchasing innovative vehicles or components from such companies should do so with the understanding and acceptance of these risks.

Adopting a technology before it is fully developed. Modern diesel engine and drivetrain component designs are the culmination of decades of service experience. When properly integrated into a vehicle, they are remarkably reli-

TABLE 41 Summary of capital costs for transit bus fuel options

Fuel	Capital Cost Element		
	Vehicle Replacement	**Fueling Facilities[a]**	**Maintenance Garage Modifications**
Diesel	Lowest of any of the alternatives. $250,000 ea., low floor or lift equipped, w/ air conditioning, HHD engine, electronic fare box & destination sign.	Costs are moderate and generally predictable. However, failing to contain leaks from underground storage tanks can lead to high remediation costs.	None. Existing garages are designed for diesel buses.
CNG	Most expensive except for hydrogen fuel cell. $320,000 each, w/400 mi range. Equipped as with diesel, except that fire suppression system is normally specified.	Approximately $1.7M for 200 bus facility. Design for high mechanical loads, high pressure, plus need for drying & filtration makes cost high.	Methane detection, increased ventilation, classified (explosion proof) electrical service in selected locations, and fire protection control system upgrades. $600,000 median cost.
LNG	Somewhat less expensive than CNG, due to lower fuel tank cost. $305,000 each, with fire suppression system and methane leak detection system.	Approximately $1.8M for 200 bus facility — similar to CNG. Materials and designs for storing pumping and metering cryogenic fuels are costly. Mechanical and pressure loads are much lower than with CNG.	Same as CNG.
LPG	$290,000 each. Vehicle cost is similar to, or somewhat less than LNG. LPG tanks are not insulated, making them less expensive than LNG tanks. LPG buses should be equipped with fire suppression systems.	Approximately $700k. Design standards are quite mature; costs are predictable. Tanks must be strong enough to support moderate (250 psi) pressures. Fuel is non-toxic liquid at room temperature; material requirements are moderate.	None if garage is designed for gasoline vehicles. If not, increased ventilation, classified electrical service in low areas, and fire protection control system upgrades will be needed. Modifications should be less costly than for CNG or LNG, since LPG fuel leaks remain near the floor. $340,000 median cost.
Methanol	Somewhat higher than diesel ($280,000), due to larger fuel tank, higher engine cost and need for corrosion resistant materials in the fuel system. Fire suppression system is normally specified.	Somewhat higher than with diesel: Approximately $440k. Wetted materials must be selected carefully to resist corrosiveness of the fuel; vapor recovery system must be added. 2x storage tank volume needed re diesel.	Similar to LPG.
Ethanol	Similar to methanol.	Similar to methanol.	Similar to LPG.
Hydrogen	Most expensive, likely to be $500,000 ea. Would be used only in a fuel cell bus w/ CH$_2$ storage. Fire suppression system would be specified.	Designs are in conceptual stage. L-CH$_2$ is a possibility, as is curb-side reforming from methanol. Likely to be more expensive than with CNG.	Need to mitigate very buoyant, potentially explosive fuel leaks. Design standards and costs are not yet established.

[a] Facility costs are for a 200-bus garage.

able and durable. During the 1990s, transit bus fleets are being converted from two-stroke diesel engines with mechanical fuel systems to four-stroke engines with improved lubrication, metallurgy, and electronic controls. As a result, expected engine durability has increased from 150,000 to 250,000 mi. In comparison, emerging technologies, such as hybrid-electric, battery electric, and fuel-cell propulsion, and to a lesser degree gaseous fueling, lack the benefit of such experience. Either rigorous (and expensive) preproduction testing or several years in revenue service are needed to discover and rectify unexpected design weaknesses. Therefore, it is reasonable to assume that new propulsion technologies may suffer from comparatively poor reliability and durability for some time after their introduction.

The market problems of the methanol engine were due, in part, to an underestimation of the engineering effort needed to make the engine competitive with diesel or natural gas engines in reliability and durability. The engine was arguably

TABLE 42 Summary of operating costs for transit bus fuel options

Fuel	**Operating Cost Element**			
	Vehicle Operating	**Vehicle Maintenance**	**Fueling Facility O&M**	**Maintenance Garage O&M**
Diesel	Fueling cost = ($0.87/gal)/(4 mi/gal) = $.22/mi	Lowest except possibly for hydrogen fuel cell. New electronically-controlled four stroke diesel engines are significantly more durable and maintainable than earlier 2-stroke engines.	Low operating and maintenance costs. These include electric energy to pump fuel, annual tank pressure testing and operating permit renewal; and occasional servicing of dispensers and pumps.	Moderate HVAC energy costs: Ventilating rates must be high enough in repair bays to adequately dilute vehicle exhaust.
CNG	Fueling cost = ($0.326/thm gas + 0.08/ thm compression)/(2.14 mi/thm) = $.19/mi Bus is 35% less energy efficient than diesel bus.	Agencies report similar or moderately higher maintenance costs than with diesel buses. Greater engine complexity, design immaturity, and vehicle weight suggest that moderately higher maintenance costs will continue.	Highest, except possibly for hydrogen. High mechanical loads, vibration and fatigue wear potential exist with gas compressors. Gas dryers and filters need to be periodically serviced. Compression energy cost is significant.	Slightly higher maintenance costs exist re diesel for periodically testing and calibrating methane leak detectors.
LNG	Fueling cost = ($0.48/gal)/(1.83 mi/gal) = $.26/mi Bus is 30% less energy efficient than diesel bus.	Similar to CNG, except that rigorous inspection & maintenance programs in place for on-board CNG tanks at some agencies, could be avoided: LNG uses rugged moderate pressure tanks.	Lower than hydrogen or CNG, but higher than the other fuels. Mechanical and pressure loads are much lower than with CNG. Components are subjected to severe thermal cycling. Pumps, valve packings and gaskets may have to be frequently serviced or replaced.	Same as CNG.
LPG	Fueling cost = ($0.65/gal)/(1.92mi/gal) = $.34/mi Bus is 35% less energy efficient than diesel bus.	Similar to CNG.	Similar to diesel.	Similar to CNG, since fire protection system may also incorporate combustible gas detectors.
Methanol	Fueling cost = ($0.59/gal)/(1.54mi/gal) = $.38/mi Bus is 15% less energy efficient than diesel bus.	Transit agencies have experienced very high maintenance costs due to frequent premature engine failures involving injectors, liners and bearings. Operating life between rebuilds is often 1/2 to 1/3 of diesel baseline.	With properly designed facility, operating and maintenance costs should be similar to diesel facilities. Improper material selection can lead to elevated costs for replacing hoses, product filters and gaskets and seals.	Similar to LPG.
Ethanol	Fueling cost = ($1.08/gal)/(2.06 mi/gal) = $.52/mi Bus is 15% less energy efficient than diesel bus.	Similar to methanol.	Similar to methanol.	Similar to LPG.
Hydrogen	Not yet established; several fuel supply scenarios are possible.	Could yield lowest power train maintenance cost of any propulsion mode, due to extreme mechanical simplicity of the PEM fuel cell engine.	Fuel-island reformer designs are in conceptual stage, so no actual data exist. High system complexity and CNG-equivalent storage pressure suggest that operating and maintenance costs will be higher than with CNG.	No data exist, but likely to be higher than for CNG.

introduced prematurely, resulting in problems with reliability and durability in service.

CNG and LNG motor bus technology has benefited from a lengthy development effort and a high level of commitment by several engine manufacturers, gas utilities, research organizations, and other equipment vendors. Transit agencies may now evaluate and select CNG and LNG vehicles with reasonable confidence that the equipment involved is proven, serviceable, and durable. Technologies such as hybrid-electric propulsion and fuel cells are now in the advanced prototype stage of development and show great promise. The developers of these technologies usually say that they will ultimately offer better durability and maintainability than diesel or CNG motor buses, along with lower overall life-cycle costs. However, it would be premature for transit agencies to begin ordering hybrid-electric or fuel-cell buses now on the *assumption* that these goals will be realized. Before adopting a new fuel or propulsion technology for large-scale revenue operations, transit agencies should carefully evaluate its development status, assess how much further effort is needed to fully develop the technology, and evaluate the commitment and resources of the product's developers.

In most cases, it is advisable to demonstrate a candidate technology in several vehicles for at least a year before making a greater commitment. This enables the performance of the technology to be measured and evaluated in the agency's own operation over a long enough period that trends in fuel consumption, maintenance requirements, and durability can be established with some degree of certainty.

3. Conduct a thorough cost analysis of the candidate fuels or technologies. In the past, transit agencies have tended to focus on the operating cost impacts of alternative fuels and propulsion technologies and gave less attention to capital cost impacts. This has followed from the availability of outside funding for capital acquisitions. However, moving to an alternative fuel involves costly investments in fueling facilities and maintenance garage modifications that are long-lived. Alternative-fuel vehicles may entail a substantial replacement cost premium that may never go away. Capital subsidies from outside sources may decrease in the future or even become completely unavailable. For example, with the deregulation of the gas utility industry in many states, utility companies are no longer able to "rate base" or pass onto their customers the costs associated with subsidizing compressor station construction projects. As a result, gas utility cost sharing for compressor stations, which used to be reasonably available to transit agencies, is becoming much less available.

An evaluation of fuel or vehicle technology options should include a full life-cycle cost analysis of each option being considered over a period of at least 12 years. This should also include annualized budgets needed to meet anticipated capital expenditures as well as likely operating costs. The cost model developed for this study, *FuelCost 1.0*, provides a good starting point for this process. The relative capital and operating costs of the fuel and propulsion technology options considered in this study are summarized in Tables 41 and 42, respectively.