6.3.1 Fuel Systems

It is clear for both lean-burn and stoichiometric engines that maintaining the proper A/F is critical. With stoichiometric engines, the acceptable range of A/F is very narrow due to the requirements of TWC systems. Air/fuel control, however, is equally important in lean-burn engines which must operate near the lean limit. In each case, improper A/F can lead to poor combustion and the production of unacceptable emissions. Conventional carbureted systems provide superior gas/air mixing in comparison with electronic injectors. It is important to separate fuel metering and air/fuel mixing. Electronic fuel metering provides many benefits associated with flexible control, particularly for lean-burn engines. Single point injection (conventionally called throttle body injection (TBI) but injection point will not always be at the throttle) gives flexible control and the induction system can be engineered to give good gas/air mixing. Multi point (MPI) injection may give additional benefits in terms of faster transient control (though this has yet to be successfully demonstrated on a heavy-duty NG engine) but provides inferior gas/air mixing. Heavy-duty NG engines are likely to produce best results when using TBI. Lean misfire limit is a function of combustion system.

6.3.2 Combustion Systems

Very few problems are experienced in developing satisfactory combustion systems for NG engines. All engine types are developed to maximize the benefits from available fuel properties, hence SI engines are designed to run as close to the knock limit (or lean limit) as possible. NG engine durability will probably be equal or superior to diesel engines.

Pre-chamber designs are very successful when used in large bore engines, allowing the use of leaner mixtures and providing higher efficiency than open chambers. Prechambers are designed to burn a small portion of the fuel near stoichiometric conditions. The resulting burning constituents expand out of the prechamber nozzle into the main chamber containing a very lean mixture. This torch ignition source exiting the prechamber allows much leaner mixtures to be ignited. Prechambers increase efficiency, widen the acceptable A/F band, decrease exhaust temperature, provide good torque and allow higher compression ratios to be used. However, they are difficult to control, may increase part load HC emissions, and have complex designs. Most manufacturers have abandoned prechamber designs. Pre-chamber designs become desirable in large bore sizes but are not preferred for automotive NG engines.

Open combustion chambers are therefore being optimized to maximize burning rate and minimize flame travel. Present work on high turbulence swirl systems and compact combustion chambers is proceeding to define their benefits with respect to performance and reducing emissions. By increasing the burning rate or reducing the flame travel distance, the spark timing can be retarded resulting in lower NO_x emissions and better thermal efficiency. The Ricardo "Nebula" combustion chamber is such a design. It is a well developed high turbulence combustion chamber used in many prototype applications (Co-Nordic Saab and Navistar engines are examples) and has been shown to improve the important NG engine NO_x/HC trade-off compared to simple open chambers (Reference 60).

Exhaust gas recirculation (EGR) systems are also being developed to reduce NO_x. These systems must be optimized with respect to the engine speed, combustion chamber, and ignition system to properly reduce NO_x without increasing HC emissions. Fast burn combustion chambers are more tolerant to high levels of EGR before reaching misfire and rough running conditions. Air dilution is preferred to EGR for lean-burn applications since it is cooler. EGR is useful for stoichiometric applications to improve knock-limited bmep and reduce catalyst NO_x conversion efficiency requirement.

Variable geometry turbochargers are being developed to increase power output to acceptable levels over extended engine operating ranges. These turbochargers provide higher torque and decreased NO_x when compared with typical wastegated turbocharging. Variable geometry turbochargers provide benefits to all engine types but particularly lean-burn NG engines.

6.3.3 Ignition Systems

NG's resistance to ignition requires that a strong spark or ignition source be present for complete and even combustion to occur. Table 6-3 provides the conditions for autoignition for various fuels.

Typically, spark plugs are used to cause ignition in natural gas engines. This technique has proven effective for the short term, but has also left questions with respect to spark plug durability and ability to overcome the low flame speed of NG.

Stratified charge engines provide a fuel-rich mixture near the spark source to provide rapid flame growth that will then spread to the remaining leaner mixture. Research continues on ensuring that the fuel mixture remains stratified when inducted through the intake manifold, however, it is doubtful that an organized and stratified mixture will be maintained through the compression process to the time of ignition. It is not expected that stratified charge will be used in automotive NG engines in the short or medium term.

6.3.4 Exhaust Aftertreatment

Both lean-burn and stoichiometric engines use additional exhaust aftertreatment to meet the current and future emission standards. Lean-burn engines often require an oxidizing catalyst to oxidize HC, formaldehyde and CO emissions. Stoichiometric engines make use of a TWC to oxidize HC and CO while reducing NO_x. Surplus amounts of methane reduce the reduction efficiency of NO_x in a TWC. Methane also does not oxidize efficiently. These systems currently use palladium and platinum/rhodium precious metals as catalyst. Work has continued in developing catalysts by identifying materials and optimizing reactions to increase efficiency.

Research in this area includes selective catalytic reduction (SCR) which uses ammonia or cyanuric acid to convert HC and NO_x into nitrogen, carbon dioxide, and water in exhaust gas containing oxygen. SCR catalysts based on zeolite materials are promising.

SCR operates most efficiently at temperatures that are above lean-burn operating temperatures. SCR work includes system simplification, miniaturization, and further controls development. Development for both systems include optimizing efficiency with respect to engine operating temperatures. ORTECH is experimenting with an SCR system using an ammonia (NH_3) reductant. They are testing the system on a natural gas fueled Cummins L10 with the ORTECH GFI system. ORTECH is using a lubricating oil with low sulfur and phosphorus content to minimize catalyst poisoning. As in the case of diesel NO_x catalysts, efficiency drops with temperature. ORTECH estimates that an 85 percent overall efficiency is possible on the FTP cycle. On a 6 g/bhp-hr NO_x engine, NO_x emissions are 324 g/hr requiring 184 g/hr of NH_3 to be used. A computer controlled mixer delivers NH_3 at the appropriate levels. Preliminary test results show a reduction in NO_x from 6.3 to 1.3 g/bhp-hr with this system (Reference 61).

6.3.5 Closed-Loop Feedback Control

As stated above, the A/F in both lean-burn and stoichiometric engines is important for their proper operation, both with respect to performance and emissions. The wide range of gas composition currently available from pipeline natural gas can dramatically affect the stoichiometric A/F of the fuel. Fluctuations in these parameters adversely affect the efficiencies of both types of engines, particularly the stoichiometric engine which must be operated over a very narrow range of A/Fs. In order to overcome these difficulties, research has focused on developing a reliable feedback control system that will utilize either an oxygen sensor (lambda sensor) to constantly measure exhaust composition or a knock sensor to detect knocking. Since many engines run close to the knock limit, sensing the onset of knock and correcting engine conditions to prevent knock can produce more power and lower emissions than uncontrolled engines. In addition, several Japanese manufacturers have developed lean oxygen sensors to provide feedback control in very lean mixtures. Careful control of A/F can increase efficiency and reduce emissions. A feedback control system will be necessary for very low emission NG engines.

6.3.6 Development of a Natural Gas Transportation Sector

The adoption of NGVs will only occur if both vehicles and fuel supplies are accessible. The foundations for dedicated NGVs already exist in the form of a natural gas distribution infrastructure (compressors are needed, however, to supply pressurized gas to vehicles). Demonstration programs, as well as dual-fuel engine technology, will promote transition to the commercialization of NGVs. While NG is significantly cheaper than diesel fuels, the cost of compressing or liquefying natural gas must also be added into the cost of operation. Presently, use of natural gas in vehicles is limited to fleets that are centrally fueled, however, commercial CNG stations are beginning to appear.

6.4 GASEOUS ENGINE TECHNOLOGY SUMMARY

Gaseous fueled engines have demonstrated much promise in reducing both NO_x and PM emissions. Referring to Figure 6-3, it can be seen that current natural gas and LPG engine development has already begun to yield benefits. Table 6-4 lists a high number of lean-burn and stoichiometric engines which have emissions levels well within Scenario 1 emission goals. Several stoichiometric engines emit NO_x below 1.5 g/bhp-hr and lean-burn engines also exhibit the potential

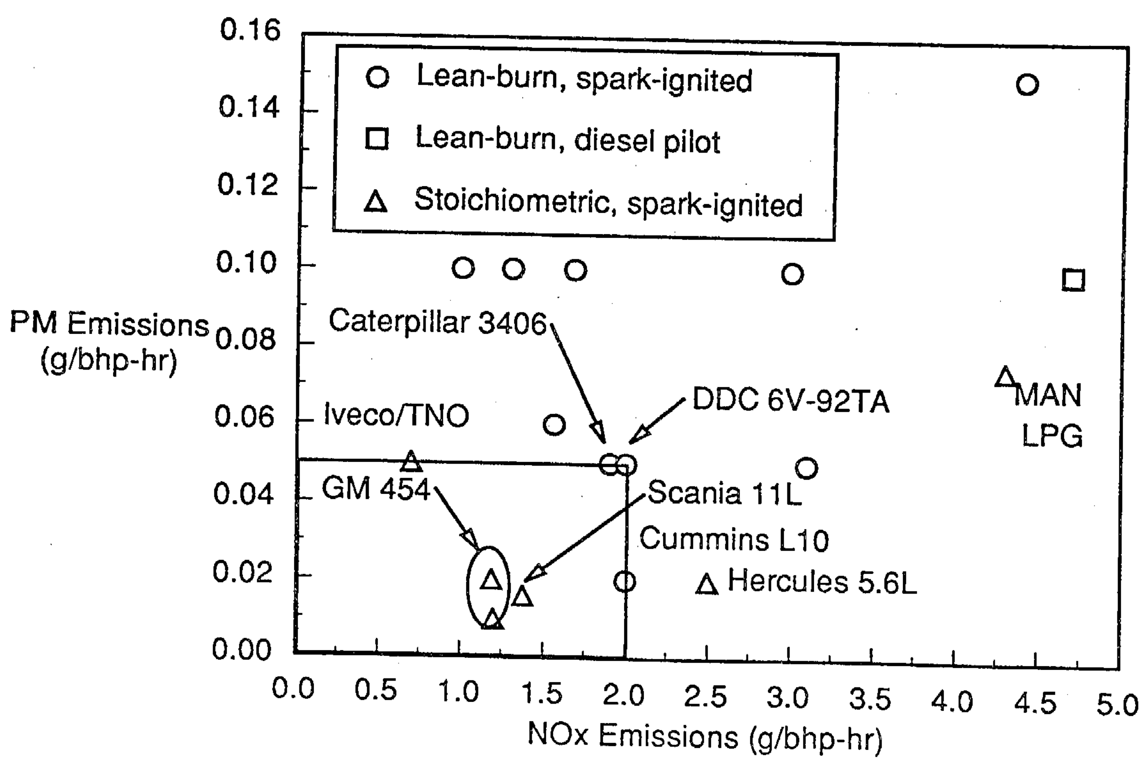

Figure 6-3. PM versus NO_x emissions for gaseous fueled engines

Table 6-4. Survey of heavy-duty gaseous engines

Sponsor	Data Year	Model	HP	A/F[2]	Ignition[3]	Catalyst[4]	Test[5]	Emissions (g/bhp-hr)			
								PM	NO_x	CO	NMHC (HC)
Navistar/Ricardo	1992	7.3L (Demo)	190	LB	SI	No	FTP	0.1	3.38	2.84	0.5 (5.14)
BC Research	1990	Caterpillar 3406 PEEC	350	LB	Pi	No	FTP		1-9	2.5-5.75	8-13
Caterpillar	1992	Caterpillar 3406	350	LB	SI	Ox	FTP	0.05	1.9	2	(3.5)
Ortech	1992	Cummins L10	240	LB	SI	SCR	FTP	<0.1	1.3	2.1	3.50
Cummins	1992	Cummins L10	270	LB	SI	No	FTP	0.1	3.00	1.85	0.4
Cummins	1992	Cummins L10	240	LB	SI	Yes	FTP	0.02	2.0	0.4	0.6
SwRI	1990	Cummins L10	270	LB	SI	No	FTP	0.15	4.40	4.9	55
Detroit Diesel	1992	DDC 6V-92TA	277	LB	Pi	Ox	FTP	0.10	4.7	0.5	(1.0)
Detroit Diesel	1992	DDC 6V-92TA	277	LB	CI	No	FTP	0.05	2	0.5	(1)
GM/Acurex	1992	GM 4.3 L	140	LB	SI	Ox	Otto FTP	—	1.91	4.21	17.83
GM	1992	GM 8.2 L	175	LB	SI	No			5.00	3.000	6
SwRI	1991	GM 8.2 L	175	LB	SI	No		0.100	<1		
Hercules	1992	Hercules-3.7 L	130	LB	SI	No	FTP	0.100	1.68	3.550	1.3 (13.7)
Hercules	1992	Hercules-5.6 L	190	LB	SI	No	FTP	0.06	1.56	2.09	0.76 (3.97)
Cummins	1992	NTC-400	350	LB	SI	No			2.20		
Co-Nordic(SwRI)	1991	THD102	230	LB	SI	Ox	FTP est.	0.115	1.15	0.75	1.66
BC Research	1992	Cat-3306	240	Stoich	SI	TWC	FTP	0.02	2.50	3	0.6 (6)
BUG	1988	Chevy 454 ci	230	Stoich	SI	TWC	FTP	0.010	1.20	6.600	1.00
GM/Acurex	1991	GM 4.3 L	140	Stoich	SI	TWC	FTP	—	1.52	7.67	0.29 (2.23)
GM/Tecogen	1992	GM 427	213	Stoich	SI	TWC	FTP		1.4	14.5	0.3
TNO	1988	GM 454 ci	240	Stoich	SI	TWC		0.020	1.19	6.320	0.97
Co-Nordic(Ricardo)	1991	Scania 11 L	240	Stoich	SI	TWC	FTP	0.016	1.38	1.26	(0.73)
Deltec	1992	Iveco 8469-21	220	Stoich	SI	TWC	ECE 49	<0.05	0.7	0.35	(0.35)
Deltec	1988	MAN G2866 LPG	237	Stoich	SI	TWC	ECE 49	0.08	4.3	0.4	(0.08)

[1]CNG unless otherwise noted.
[2]A/F = Air/Fuel Ratio; LB = lean burn; Stoich = stoichiometric.
[3]CI = Compression Ignition; Pi = Pilot Ignition; SI = spark ignition
[4]TWC = three-way catalyst; SCR = ammonia selective catalytic reduction; Ox = oxidation catalyst; No = no catalyst.
[5]FTP = Transient Federal Test Procedure; 8M = ARB 8-mode test; 13M = 13-mode test; Otto FTP = Otto cycle transient Federal Test Procedure.

for low NO_x. Engine efficiencies and vehicle fuel economy are currently 20 to 30 percent worse than those of diesel counterparts.

NG engine development is still in its infancy in relation to diesel and gasoline engines. NG shows excellent potential for low emissions. While several technical problems still need to be overcome to produce ultra low emissions, it is conceivable that closed-loop controlled stoichiometric/TWC engines could produce NO_x emissions well below 1 g/bhp-hr. Fuel economy of stoichiometric engines is fairly poor, but with the low cost of natural gas, this still may be very cost effective.

Lean-burn engines also show much promise as low or ultra low emission engines. Fuel economy and engine-out emissions are significantly better in these engines. Sophisticated fast-burn combustion chambers coupled with high energy ignition systems will be needed to produce low NO_x levels.

Two-stroke direct-injection natural gas engines can also produce very low emissions. DDC has shattered the myth that natural gas cannot be used in compression-ignition engines. With further development, these engines may well have the best fuel economy of any natural gas engine.

Even though non-methane hydrocarbon emissions of natural gas engines are low, total hydrocarbon emissions can be high due to the fact that methane does not oxidize effectively in exhaust catalysts. As methane is a prominent greenhouse gas, it seems prudent to require some level of methane control that is both feasible and does not allow for substantial increases in greenhouse gas emissions. Methane is about 20 times as effective a greenhouse gas as carbon dioxide; however, the estimates for this value vary considerably and depend on specific emission scenarios. Higher methane emissions from natural gas engines will be offset to some extent by the lower carbon dioxide emissions associated with natural gas production and combustion. High methane emissions can be encountered with three-way catalyst-equipped engines that are operating close to stoichiometry as well as lean-burn engines that are operating near the misfire limit. As engines are optimized for lower NO_x emissions, methane emissions will tend to increase unless controlled by a catalyst. However, methane is chemically stable and does not react readily in most catalysts. A total hydrocarbon standard of 6 g/bhp-hr should allow for sufficient flexibility in controlling NO_x emissions while also providing some level of methane control. A catalyst would probably be required to meet this levels and also achieve lowest NO_x.

SECTION 7

ELECTRIC AND HYBRID ELECTRIC TECHNOLOGIES

From an air quality perspective, the most attractive alternative to gasoline- and diesel-powered vehicles are electric-powered vehicles (EV). EVs produce no evaporative or tailpipe emissions. Although emissions from power plants that provide energy for the EVs must be considered, the overall net emissions are small on a weighted grams per mile basis.

The potential market for EVs may exceed that of vehicles powered by other fuel alternatives, if technological improvements can make EVs viable for more heavy-duty vehicle applications. EVs, unlike other alternative fueled vehicles, are not constrained to fueling locations because they can be recharged at night by using either a standard 110-V or 220-V outlet. It is expected that standard recharging outlets will be 220-V three-phase outlets. Vehicle maintenance costs are significantly reduced with electric engines, compared with IC engines. Although batteries will require replacement at regular intervals in strictly battery-powered vehicles, vehicle life is expected to be extended with electric power.

7.1 CURRENTLY AVAILABLE TRANSIT AND TRUCK APPLICATIONS

7.1.1 Transit Vehicles

Electric power has been used for public transit applications for more than a century in the form of fixed guideway "catenary" power wire systems and, more recently, through third-rail applications. While electricity has been used as a power source for transit vehicles, EVs not requiring capital-intensive and rigid fixed guideway systems have only recently been seriously considered. Electric trolley buses (ETB) are a proven technology that is currently available and provides viable clean replacement for existing heavy-duty diesel transit vehicles. These buses, powered electrically via overhead catenaries, are an available and a cost-competitive option for meeting air quality and mass transit goals. Since they are powered by catenaries incorporated in the local electrical supply system, these vehicles have no fuel supply problems. ETBs are a readily available technology, and, as zero emission vehicles, would provide the largest emissions reduction of all alternative technologies.

Silent and nearly pollution-free battery-powered EVs have advanced far beyond the "golf cart" type vehicle application. Due to advancements in battery and vehicle technology, electric vehicles are being offered in the marketplace for transit and truck fleets. Most impressive of these new offerings are the small transit vehicles available from Specialty Vehicle Manufacturing Corporation of Downey, California.

The vehicles offered by this manufacturer are described in detail below. Table 7-1 summarizes the characteristics of vehicles currently available for transit applications.

7.1.1.1 Specialty Vehicle Manufacturing Corporation

The vehicles currently being marketed by Specialty Vehicle Manufacturing Corporation, of Downey, California, originated from their partnership with Southern California Edison and Santa Barbara Transit District to design a battery-powered shuttle vehicle for Santa Barbara's downtown waterfront shuttle system. As a result of this effort, six vehicles are presently operating in Santa Barbara, and 4 additional vehicles have been delivered to a number of other transit operators and utilities (including Sacramento Municipal Utility District) for use in similar shuttle applications.

The Specialty Vehicle Manufacturing Corporation shuttle vehicles are 22 ft long, and offer capacity for 16 to 22 seated passengers depending upon the model. The shuttles are powered by tubular lead/acid (Pb/acid) batteries. The on-board battery pack contains 108 battery cells. Total battery weight is estimated at 4,104 lb with the total gross vehicle weight being between 9,000 lb and 17,000 lb. The battery pack has a 70.2 kilowatt-hour (kWh) nominal capacity with a 5-hr discharge rate at a nominal voltage of 216 volts.

Table 7-1. Electric bus summary

Characteristics	Specialty Vehicle Manufacturing Corporation Model Number				
	3122 T	4122 S	5122 S	5122 B	5130 B
Vehicle Type	Trolley	Shuttle	Shuttle	Bus	Bus
Length (ft)	22	22	22	22	30
Width (in)	81	80	92	92	96
Height (in)	103	98	99	99	104
Wheelbase (in)	115	145	147	147	192
Ground clearance (in)	6	8	8	8	8
Passengers (seated)	21	16	22	22	28
Maximum standees	7	2	7	7	9
Top speed (mph)	35	30	35	35	40
Gross vehicle weight (lb)	16,000	9,000	17,000	17,000	19,200
Battery technology	Pb/acid[a]	Pb/acid	Pb/acid	Pb/acid	Pb/acid
Regenerative braking	Yes	Yes	Yes	Yes	Yes
Battery weight (lb)	4,104	4,104	4,104	Unknown	Unknown
Range/charge (mi)	50 to 75	50 to 75	50 to 75	50 to 75	50 to 75

[a]Pb/acid = lead/acid.

The vehicles in Santa Barbara can operate up to 10 hours between recharges. This duration was possible, in part, through the optimization of regenerative braking, in which the traction motor operates as a generator producing electrical energy that is returned to the battery.

The manufacturer estimates the vehicle range to be 50 to 75 miles per charge. The shuttles' top speed is approximately 35 mph, although local shuttle operations rarely require speeds in excess of 20 mph.

The shuttles come in a 21 passenger trolley, a 16 passenger shuttle and a 22 passenger shuttle with current prices for these shuttles estimated at between $109,000 for the 16 passenger shuttle to $140,000 for the antique trolley design.

Specialty Vehicle Manufacturing Corporation also is offering two passenger buses, a 22 foot bus holding 22 seated passengers and a 30 foot bus holding 28 seated passengers. Both bus designs are totally enclosed. The bus prices start at $140,000 for the 22 foot bus.

Hughes Power Control Systems have devised an AC drive and controller to work with the larger buses. Hughes system uses two drive motors instead of one, yielding 130 horsepower in comparison to the 50 horsepower from one motor. The AC drive provides better speed-torque curves than the DC drives in the smaller shuttles.

7.1.2 Truck Applications

Current battery technology is easily applied to transit operations, where slow speeds, little need for "freeway" acceleration levels, and frequent stops are the norm. Applying current technologies to truck applications, however, is more difficult.

The first production run model of an EV of this type is a 1-ton van, the G-Van, produced by General Motors, Vehma International, and Chloride EV Systems. The other major American automobile manufacturers are also working on electric van applications. The G-Van is powered by Pb/acid batteries. The vehicle has a 50 to 60 mile range between recharges, and a top speed of approximately 55 mph.

The Chrysler TEVan, a 1/2-ton van, was expected to enter into production in 1991, but has been delayed. The TEVan will use a DC motor with a nickel/iron (Ni/Fe) battery. As shown in Table 7-2, this battery offers better range and performance than do the Pb/acid batteries used by the G-Van. The TEVan also offers an automatic battery watering system, an on-board charger, and an electronic instrument cluster that displays remaining range and battery state-of-charge. One of the drawbacks of the TEVan compared with the G-Van is the reduction in cargo space and payload capacity in the updated model.

Using existing battery technology, it is difficult to achieve the acceleration and power characteristics of the internal combustion engine. In addition, the long recharge time needed in current EVs does not lend itself to long-range travel. Neither the G-Van nor the TEVan can

Table 7-2. Comparison of G-Van and TEVan operation

Characteristic	G-Van	TEVan
Top speed (mph)	52	70
Urban range (mi)	60	110
0 to 30 mi acceleration (s)	12.9	7
Payload capacity (lb)	1,640	1,200
Cargo space (ft^3)	231	120
Power train	DC	DC
Mi/kWh from battery	1.2	Unknown

therefore be considered an entry into the heavy-duty truck arena. Moreover, no existing product has been marketed that can serve the needs of heavy-duty vehicle operators.

However, two parallel research efforts may allow EVs to overcome their limitations and capture a significant share of the heavy-duty vehicle market, including transit bus and truck applications. These developments are:

- Improvements in battery technology
- Development of fuel-cell and hybrid-electric technology

Many of the vehicle developments underway with these technologies are considered proprietary, and details about them are consequently unavailable. The information presented below was derived from existing literature. Discussions with vehicle developers indicate that improved battery technology will appear in light- and medium-duty vehicles within the next 12 months, and that fuel-cell technology will be available within the next 2 to 4 years.

7.2 NEAR-TERM DEVELOPMENTS IN ELECTRIC VEHICLES

The present commercial Pb/acid battery, used in virtually every EV on the road today, is essentially unchanged since the late 1800s; it is large, heavy, and expensive. EVs with Pb/acid batteries generally have a range of under 100 miles. If battery-powered EVs are to find a place in the heavy-duty vehicle market, better batteries must become available.

In the near-term (1 to 3 years), the successor to the standard Pb/acid battery appears to be either an improved Pb/acid or the nickel/iron (Ni/Fe) battery. These near-term developments offer modest improvements over conventional lead/acid batteries.

7.2.1 Nickel/Iron Battery

The near term successor to the Pb/acid battery appears to be the nickel/iron (Ni/Fe) battery. Nickel/iron batteries are lighter and more powerful than lead/acid batteries, on an equal energy basis and thus deliver better performance. Unfortunately, Ni/Fe batteries are expensive due to the high cost of nickel and produce relatively large amounts of hydrogen gas. These batteries are available today but are not generally used commercially due to their high initial cost. In addition, the Ni/Fe batteries require frequent additions of water and are therefore considered "high maintenance." Nickel/cadmium (Ni/Cd) batteries are also near term solutions, however, there are potentially serious disposal issues due to the toxicity of cadmium.

7.3 MID-TERM DEVELOPMENTS IN ELECTRIC VEHICLES

In the slightly longer term (3 to 10 years), at least four major battery technologies are being explored. They include zinc/bromide (Zn/Br), sodium/sulfur (Na/S), and lithium-metal/iron-sulfide (Li-me/Fe-S). The most promising of these appear to be the Na/S and Li-me/Fe-S batteries. Metal-air batteries also offer promise, and present a major deviation from current technologies. Advantages and disadvantages of various battery technologies are listed in Table 7-3 (Reference 62). Battery performance comparisons are listed in Table 7-4 (Reference 63).

7.3.1 Sodium/Sulfur Battery

The Na/S battery is quite different from other batteries. It has a solid ceramic electrolyte, rather than a liquid electrolyte as in conventional batteries, and liquid, not solid, reactants. In order to keep the reactants liquid, the battery must be maintained at a temperature of about 300°C. When energy is being drawn from the battery, it produces enough heat to maintain this temperature, but when it is idle, it does not. Consequently, the battery must be well insulated to

Table 7-3. Advantages and disadvantages of batteries

Battery	Advantages	Disadvantages/R&D Issues
Pb/acid	Proven, commercially-available technology	Low specific energy and power due to great weight of lead, decrease in voltage and performance as battery discharges
Ni/Fe	Durable, high cycle-life, good energy density	High initial cost of nickel, excessive hydrogen gassing, high water consumption, low efficiency
Zn/Br	High power, inexpensive	Bulky, complex, short life, corrosion, difficulty of containing bromine
Li-me/Fe-S	High specific energy and power, compact	High temperature, high cost and insulation weight, high cost of current collectors, unstable cell components
Na/S	High specific energy and power, inexpensive, widely available materials	High temperature, high cost and weight insulation, corrosion of seals and casing, safety concerns
Zn/air	High specific energy and power, mechanically rechargeable	Complex, low-cell efficiency, CO_2 scrubber needed, problems with air electrode and management
Al/air	Very high specific energy, high power, mechanically rechargeable	Complex and bulky, short life of air electrode, CO_2 scrubber needed, high cost of aluminum, low-cell efficiency

Table 7-4. Performance characteristics of several battery technologies

Battery Description	Model	Type	Module Weight (kg)	Module Capacity 3-h Rate (Ah)	Specific Energy 3-h Rate (Wh/kg)	Volumetric Energy Density (Wh/L)	Peak Pwr. for 15s 50% DOD (W/kg)	Battery Columbic Efficiency (%)	Battery Energy Efficiency (%)	IDSEP Van SFUDS Range (miles)
Chloride	3ET205	Lead-Acid	32.8	185	33	78	92	87	68	47
Eagle-Picher	NIF200	Nickel-Iron	25	203	51	118	112	74	58	87
SEA	ZBB-5/48	Zinc-Bromide	81	126	75	56	53	93	75	93
Ovonics	H-cell	Nickel-Metal	0.628	28	55	152	183	90	80	97
SAFT-America	R&D Cells	Litium-Iron Monosulfide	3.675	203	66	133	83	95	81	95
CSPL	PB-MK3	Sodium-Sulfur	29.2	292	79	123	94	100	88	150
ABB	B-11	Sodium-Sulfur	253	238	81	83	151	100	91	154

retain heat. The insulation maintains battery temperature for about 2 weeks, after which external heat must be applied.

This battery offers several advantages over current technologies, as shown in Table 7-3. The high performance battery offers considerably greater energy and power density than the conventional Pb/acid battery and somewhat greater than the Ni/Fe battery. Unlike conventional batteries, the Na/S battery does not require watering, is essentially maintenance-free, and does not create gases when charged. Moreover, the two reactants are relatively inexpensive, abundant, and widely available.

Some technical issues still need to be resolved for this battery. Most important are the need for more durable electrodes, and for containers and seals that are resistant to the corrosive compounds developed during discharge. Another problem is the weight of battery insulation required to maintain battery temperature.

7.3.2 Lithium-Metal/Iron-Sulfide Battery

Like the Na/S battery, the Li-me/Fe-S battery is a high performance and maintenance-free battery. It is relatively compact, light, and safe. Simulations and preliminary vehicle tests have demonstrated that the Li-me/Fe-S battery holds great promise. In one simulation, for example, a van powered by Li-me/Fe-S batteries drove 200 miles in stop-and-go traffic between charges. In an actual road test in which the Chrysler TEVan was powered by Li-me/Fe-S batteries, a 109-mile range consumed only 0.56 kWh/mi from the charger.

This battery has both advantages and disadvantages when compared to the Na/S battery. Corrosion of seals and casings is not a problem, and the lithium-based battery will be more compact and safer than the Na/S battery. However, lithium is more expensive and less abundant than sodium.

7.3.3 Metal/Air Batteries

Metal/air batteries have a metal anode of aluminum (Al), zinc (Zn), or iron (Fe), and a cathode that uses atmospheric oxygen. All metal/air batteries offer high power and energy density.

The main advantage of this technology is the possibility of fast mechanical recharging. In conventional batteries, charging requires either very large current flows or long recharging times. With the Al/air or Zn/air battery, however, the metal anode can be recharged simply by replacing the consumed metal with fresh metal; in addition, the air produces an essentially inexhaustible source of fresh oxygen for the cathode. This makes recharging comparable in time and ease to refueling gasoline vehicles. Metal/air batteries are still in the developmental stage, however, and technical difficulties must be overcome before they are available for vehicles.

7.3.4 Fuel Cell Developments

The fuel cell is a device that produces electricity by catalytically causing hydrogen and oxygen to react and form water. The reaction is continuous, so long as the fuel and oxidant are supplied. The energy source for the cell can be any of a number of fuels, including natural gas, methanol, heavy hydrocarbons, diesel oil, and hydrogen. Much research and development is now underway using fuel cells powered by methanol, natural gas, and hydrogen.

Most fuel cells that are currently applicable for vehicle applications produce electricity from the electrochemical reaction of hydrogen and oxygen to form water vapor. Therefore, hydrogen must be stored on the vehicle or produced from fuel on-board the vehicle. Limitations on hydrogen storage and distribution systems will probably require the use of carrier fuels such as methanol or natural gas. These fuels are reacted with water vapor to produce hydrogen in a reformer. In the case of methanol,

$$CH_3OH + H_2O => 3H_2 + CO_2$$

and with natural gas or methane,

$$CH_4 + 2H_2O => 4H_2 + CO_2$$

Reformers must operate at temperatures of 200 to 1000°C, depending on the reformer feedstock and catalysts used in the reformer. Emissions from reformers must also be controlled as CO can be produced if the above reactions do not proceed to completion.

It is estimated that an electric/fuel cell powered bus will be commercially available within the next 3 to 4 years. No known development is currently underway that would apply this technology to heavy-duty trucks, however, and such applications would be expected to lag.

The Fuel Cell/Battery Bus Program, sponsored jointly by the Department of Transportation and Department of Energy, has conducted simulations of a fuel cell bus using a phosphoric acid fuel cell powered by methanol. The system was simulated for three typical transit service routes, including a Georgetown commuter route a composite route; run in Indianapolis, Indiana; and the Santa Barbara State Street Shuttle. Performance data under these conditions are show in Table 7-5 (Reference 64). TMC plans to produce fifty 40 ft buses with fuel cells for demonstration in 1995 and put these buses in production in 1996 (Reference 65).

Although fuel cell technology offers promise in the transit bus market, there are some problems still to be resolved. These include the size, weight, and high cost of present fuel cell systems.

7.4 HYBRID INTERNAL COMBUSTION ENGINE/BATTERY-POWERED VEHICLES

The hybrid electric vehicle consists of an internal combustion (IC) engine that drives a generator which, in conjunction with storage batteries, supplies power to the vehicle's traction motors. Published data are available on a 25-ft natural gas hybrid electric bus developed by Ontario Bus Industries of Ontario, Canada. Many other ongoing projects will feature hybrid engines powered by natural gas, methanol, and hydrogen. The details of these projects are considered proprietary, and data were consequently unavailable. However, in all cases, the developers indicated that large (40-ft) transit buses would be commercially available within the next 2 to 4 years, with truck applications lagging behind bus development by approximately 3 to 5 years.

In the Ontario Bus Industries project, a 25-ft Orion II bus was equipped with a 4.3-L V-6 engine rated at 90 bhp at 3,000 rpm, converted to operate on compressed natural gas (CNG). The engine is controlled by an engine management system (EMS) that allows engine speed and power output to vary with load conditions. The EMS monitors the load conditions, and signals the engine

Table 7-5. Fuel cell performance

Parameters	Georgetown	Indianapolis	Santa Barbara
1. Route Characteristics			
Route length (mi)	8.20	14.0	5.5
Stops/mi	4.0	4.0	6.9
Maximum speed (mph)	35	40	30
Loops/day	17	11	11
mi/day	140	154	61
Bus size (ft)	26.9	26.9	26.9
Bus weight (lb)	21,444	20,794	20,172
2. Performance Simulation			
FC size (hp)	67	67	67
Battery size (kWh)[a]	38	21	10
Route time (min)	32	60	45
Dwell time (min)	7	17	26
Time/loop (min)	58	70	46
Energy/loop	23.76	38.92	19.31
Route speed (mph)	8.7	22.5	11.75
Energy consumption (kWh/mi)	2.90	2.79	3.49
Fuel consumption (mpg)	2.12	2.05	1.50
3. Emissions Estimates (FTP)[b]			
HC—0.0016 g/mi			
CO—Not detected			
NO_x—0.00037 g/mi			

[a]The battery size is selected to result in the same state of charge at the completion of the route as at the beginning.
[b]Chasis dynamometer estimates

to increase speed and power output at a slow rate to minimize transients, thereby increasing fuel economy and decreasing emissions. An emission control system further decreases overall emissions.

The hybrid electric vehicle operates in three modes:

1. **Operation on IC Engine Power Alone**—Steady-state operation on power produced by the IC engine only. In this mode, the engine supplies all the power to propel the vehicle. The present configuration allows the bus to operate at 37 mph without requiring power from the storage batteries.

2. **Operation on IC Engine and Battery Power**—During this mode, the IC engine provides power to the accessories only, and power produced by regenerative braking is delivered to the battery for storage. By reducing or eliminating accessories, such as air conditioning, the need for IC engine power is minimized during this phase of operation.

3. **Operation on Storage Batteries**—The storage batteries are the primary power source for acceleration, grade climbing, and high-speed cruising. The batteries tested were 12 V with a capacity of 160 amp-hr and a weight of 141 lb each. Fifteen batteries were connected in series. Two groups of batteries were connected in parallel to yield a system of 189 V and 320 amp-hr capacity. The battery pack is also used to store energy that is recovered during regenerative braking. This increases usable on-board energy as well as brake life.

Preliminary testing of this vehicle shows reduced energy consumption per mile in all phases of operation compared to diesel operation. Only limited research has been done with regard to engine emissions; however, there is an indication that by running the engine at a steady-state condition, and allowing the batteries to supply the energy for the peak loads, the engine emissions may be significantly reduced compared to either conventional diesel or conventional CNG applications. Fuel economy is also improved by relying on battery power for part of the range. This reduces the weight requirement for longer-range CNG tanks on-board the vehicle. Dependence on the IC engine will be further reduced in future generations as accessories are made to operate more efficiently.

7.5 ELECTRIC AND HYBRID ELECTRIC VEHICLE TECHNOLOGY SUMMARY

From an air quality perspective, EVs offer the greatest potential of any alternative-fueled transportation vehicles. Improvements in battery, fuel cell, and hybrid electric technologies will eventually make large-scale applications of electric powered heavy-duty vehicles a reality. At present, electric power is not widely available for heavy-duty vehicle applications. However, a growing "niche market" exists for smaller transit vehicles, such as downtown circulators or employee shuttles, that provide essentially local service. These vehicles are limited in capacity and somewhat limited in range, although current technology can provide sufficient range to cover the basic services of many shuttle operations.

The future of electric power for heavy-duty vehicle applications may lie with the fuel cell and hybrid electric applications that eliminate the need for frequent charging and battery replacement. These technologies are 4 to 6 years from the production marketplace for large transit bus applications, and somewhat farther off for other heavy-duty vehicles, but will offer very low emissions as well as improved acceleration, higher speed, and increased payload capacity over current EV technologies.

SECTION 8

LIFE CYCLE COSTS

8.1 INTRODUCTION

8.1.1 Overview

The analysis of life cycle costs for heavy-duty vehicles is limited to those fuels and engine technologies which we expect to be commercially available and have potential to meet the required emission standards. The analysis is limited to the four "sample" vehicle types which were selected to be representative of one of the four classes of heavy-duty vehicles. The analysis begins with an overview of cost assumptions/methodologies which are common to all of the samples, discusses baseline cost data for standard diesel and gasoline vehicles, and then develops detailed cost data for one sample vehicle type in each of four heavy-duty vehicle classes.

The analysis projects costs for each of the four classes of vehicle types using both "low" and "high" estimates.

8.1.2 Approach

This analysis evaluates the user costs of owning and operating a gasoline, diesel, or alternatively-fueled heavy-duty vehicle. Summary data for each vehicle/technology is reported in cents per mile and is listed in Table 8-1. These cost per mile comparisons take into account differences in vehicle life, and the average miles per year that the vehicle is operated over its useful life. The assumptions about vehicle life and annual miles are summarized in the following section. These assumptions are used in the more detailed vehicle type cost analysis included in the later sections of this report.

Table 8-1. Vehicle and technology scenarios considered in cost analysis (1992 Dollars)

Fuel	Vehicle/Technology	Cost (cents/mile) Low	High
	HHD Transfer Truck		
1993 Diesel	Baseline 1998 DI diesel	40	42
Diesel	DI diesel with EGR and catalytic trap	44	47
Diesel	DI diesel with DE-NO_x catalyst	43	46
M100	DI compression ignition 2-stroke	44	48
M100	DI glow plug ignition 4-stroke	44	47
CNG	Lean burn spark-ignition	42	46
LNG	Lean burn spark-ignition	44	50
LPG	Lean burn spark-ignition	45	47
	Urban Transit Bus		
1993 Diesel	Baseline 1998 DI diesel	142	147
Diesel	DI diesel with EGR and catalytic trap	148	158
Diesel	DI diesel with DE-NO_x catalyst	146	152
M100	DI compression ignition 2-stroke	155	164
M100	DI glow plug ignition 4-stroke	154	162
CNG	Lean burn spark-ignition	150	167
LNG	Lean burn spark-ignition	157	174
LPG	Lean burn spark-ignition	136	150
	MHD Delivery Truck		
1993 Diesel	Baseline 1998 DI diesel	44	53
Diesel	DI diesel with EGR and catalytic trap	47	57
M100	DI compression ignition 4-stroke	47	59
CNG	Lean burn spark-ignition	43	54
LNG	Lean burn spark-ignition	47	60
LPG	Lean burn spark-ignition	47	57
	LHD Delivery Truck		
Phase 2 gasoline	Stoichiometric spark-ignition with TWC	29	31
M85	Stoichiometric spark-ignition with TWC	29	33
CNG	Stoichiometric spark-ignition with TWC	27	32
LNG	Stoichiometric spark-ignition with TWC	28	34
LPG	Stoichiometric spark-ignition with TWC	28	32
Electric	Battery powered electric	27	30
	Small Transit		
1993 Diesel	Baseline 1998 DI diesel	216	216
Electric	Battery powered electric	235	256

Three general types of costs are developed. These include one time costs associated with vehicle purchase, recurring annual costs associated with the routine use of the vehicle, and periodic costs for major component repair/replacement which do not occur on an annual basis.

The costs of acquiring the vehicle are limited to those one-time costs associated with the actual purchase of the vehicle. This includes the sales tax applied to the purchase price. For alternatively fueled vehicles such as heavy-duty natural gas vehicles, the report does not consider the economies of scale associated with mass-production which would reduce the price for these vehicles. The life cycle costs of the vehicle purchase are also affected by the number of years during which the vehicle is used, and the salvage value.

The annual operating costs include those items which can be expected to be on-going regular expenditures over the life of the vehicle. These include the fuel used to power the vehicle as well as preventive maintenance and routine repair parts and labor, annual registration and license fees, and vehicle insurance. Vehicle fuel costs are determined from our assessment of engine efficiency as well as on-road fuel economy data, combined with fuel price, and the miles traveled per year.

The periodic expenditures are generally for major vehicle components that are preplanned, or rebuilt on a recurring basis which can be anticipated. These expenditures include engine rebuilds, and tire and other major component replacement. Expenditures such as repairs associated with damage that occurs from a collision accident, routine preventive maintenance, or minor repairs are included in the annual maintenance costs.

8.2 COMMON COST FACTORS AND CONVENTIONS

A number of cost factors and assumptions affect each of the sample vehicle analyses. This section summarizes the key factors and assumptions.

8.2.1 Cost Basis

Detailed baseline cost data was determined from estimates prepared by Acurex Environmental based upon manufacturer input. All data have been developed and reported in 1992 dollars. The "low" and "high" projections are given in 1992 dollars. Annual and periodic costs are also presented in 1992 dollars. These costs are calculated over the lifetime of the vehicle and a present value is calculated. For the present value calculations, we have used a discount rate of 10 percent for private fleets and 7 percent for public fleets.

It is assumed that the light heavy-duty delivery truck, medium heavy-duty delivery truck, and heavy heavy-duty transfer truck are all owned and operated privately. These users are subject to all relevant Federal, State, and local taxes. The urban transit bus and small transit bus are assumed to be operated by public transit agencies. These vehicle types will therefore have reduced tax liabilities.

8.2.2 Cost Values

Cost values were developed using actual bid prices as available, manufacturer's price estimates, and projections from knowledgeable industry resource persons.

8.2.3 Initial Purchase Price

The life cycle purchase cost of a vehicle is the sum of the initial purchase price and sales taxes, less the salvage value. The initial purchase price of the vehicle distinguishes the key component systems which are expected to be impacted by the alternative technologies. While this report does not address every cost item that will be affected, it includes those which are considered to be the most significant. In some cases offsetting cost savings, such as the elimination of the need for pollution control equipment for some of the technologies, will result. These items will be reviewed in the vehicle type discussion.

The life cycle cost of the vehicle purchase price is reduced by the salvage value. The representative vehicles used are generally specialty items with long lives. As a result, salvage value is estimated as 5 percent of the initial purchase price.

8.2.4 Vehicle License and Registration Fees

Annual California vehicle license and registration fees for the HDVs were determined using the California Department of Motor Vehicles (DMV) Vehicle License Fee Rate Tables. Federal, state and local government agencies are exempt from license and registration fees. In this study, urban buses are assumed to be owned and/or operated by such an agency, therefore, license and registration fees are not included in the cost discussions of this vehicle type.

License fees are based on the vehicle purchase price. License fees are currently reduced as the vehicle ages and has reduced resale value. For the purposes of this analysis, the average annual license fee was developed which incorporates the declining costs over the life of the vehicle. This figure is based on a 1992 purchase of a new vehicle, and a 12 year life. The California Department of Motor Vehicles (DMV) currently charges the annual license fee as 2.5 percent of the "Book Value" plus an additional 2 percent of that sum. "Book Value" is determined by depreciating the purchase price of the vehicle over eleven years, from 100 percent the initial year, to 15 percent the last. The depreciation schedule and rates are set by the California State Legislature, and are politically determined, precluding estimates of future rate increases.

Registration fees may vary up to $11.00 by county of registration. Fees include a fixed charge of $29.00 per vehicle and a weight based fee of ranging from $8.00 to $560.00 for two-axle commercial vehicles. This study assumes an average base registration fee of $34.00, with weight charges of $560.00 based on a gross vehicle weight greater than 18,000 lb for 2 axle heavy heavy-duty trucks and medium heavy-duty trucks, and $284.00 for a two-axle light heavy-duty step van with a gross vehicle weight of 8,500 lb. Buses owned by public agencies are exempt. Raising registration fees for older vehicles is being considered in order to reduce the use of older vehicles, which generally produce more pollutants. This analysis does not include such a change.

8.2.5 California Sales Taxes for Vehicles

California sales tax varies by county from 6.25 to 8.75 percent. An assumed average of 6.5 percent has been applied to the purchase price of the vehicle. Vehicles purchased by government agencies are exempt.

8.2.6 Vehicle Insurance

Vehicle insurance premiums were estimated from data supplied by fleet operators, a survey of insurers, and insurance industry representatives. We have found no distinction in insurance premiums based on the application of technology or alternative fuels. Insurance premiums were found to vary based on vehicle cost. Fleet operators also tend to reduce insurance costs for older vehicles by dropping collision coverage. The insurance costs assume that the first five years of the vehicle include both liability and collision coverage, but that for the remaining years of the vehicle only liability coverage is provided. These insurance premium costs are averaged over the life of the vehicle.

8.2.7 Fuel Costs

Fuel costs include the base price, distribution and handling costs, federal and state excise taxes, and California sales tax.

Gasoline price projections are developed every two years as part of the CEC's 1987 Fuels Report (Reference 66). Price projections assume a continued stable economic and political situation. These projections are based on the CEC's Fossil Fuels Office using the Delhi IV survey results published in Appendix E of the 1987 Fuels Report. These costs have been adjusted using the California CPI average for the period 1987 to 1992. Ranges in prices for alternative fuels were also based on previous assessments performed by Acurex Environmental.

The projections do not consider future environmental regulations which may impact the fuel processing costs, with the exception of the Reid vapor pressure (RVP) and benzene standards. The cost of these standards was estimated as 4 cents per gallon.

Table 8-2 summarizes the estimated fuel prices.

8.2.8 Diesel Fuel Prices

Diesel fuel prices have stabilized in recent years. Current prices are now close to those for unleaded gasoline. Baseline diesel fuel projections are based on the CEC's 1987 Fuels report (Reference 66). The projections assume that, in order to address fuel quality issues, the cost of diesel fuel is likely to escalate faster than gasoline.

ARB testimony at the AB 234 Environmental Health and Safety Workshop indicated that the incremental cost of low-sulfur/low aromatic diesel would be approximately 11 to 12 cents per

Table 8-2. Summary of fuel prices (1992 Dollars)

Fuel	Wholesale	State Tax	Federal Tax	Subtotal	Markup	Sales Tax	Total	Units
Public Fleet		0	0		0.00%	7.50%		
1993 diesel	81	0	0	81	0.00	6.08	87.08	¢/gal
Diesel, 0.01%S	83	0	0	83	0.00	6.23	89.23	¢/gal
Diesel, 2% oxy	90	0	0	90	0.00	6.75	96.75	¢/gal
M100 low	40	0	0	40	0.00	3.00	43.00	¢/gal
M100 high	45	0	0	45	0.00	3.38	48.38	¢/gal
CNG low	38	0	0	38	0.00	2.85	40.85	¢/100 scf
CNG high	40	0	0	50	0.00	3.75	53.75	¢/100 scf
LNG low	48	0	0	48	0.00	3.60	51.60	¢/gal
LNG high	58	0	0	58	0.00	4.35	62.35	¢/gal
LPG	56	0	0	56	0.00	4.20	60.20	¢/gal
Electricity							8.00	¢/kWh
Private fleet					5.00%	7.50%		
1993 diesel	81	16	20.1	117.1	5.86	9.22	132	¢/gal
Diesel, 0.01%S	83	16	20.1	119.1	5.96	9.38	134.43	¢/gal
Diesel, 2% oxy	90	16	20.1	126.1	6.31	9.93	142.34	¢/gal
M100 low	40	8	7.1	55.1	2.76	4.34	62.19	¢/gal
M100 high	45	8	8.05	61.05	3.05	4.81	68.91	¢/gal
M85	49.2	8	7.1	64.3	3.22	5.06	72.58	¢/gal
CNG low	38	7	0	45	2.25	3.54	50.79	¢/100 scf
CNG high	50	7	8	65	3.25	5.12	73.37	¢/100 scf
LNG low	48	6	0	54	2.70	4.25	60.95	¢/gal
LNG high	58	6	8	72	3.60	5.67	81.27	¢/gal
LPG	56	6	8	70	3.50	5.51	79.01	¢/gal
Phase 2 gasoline	100	16	14.1	120.1	6.01	9.46	135.56	¢/gal
Electricity							8.00	¢/kWh

gallon (Reference 67). The ARB approved "equivalent emissions" option is expected to be considerably less expensive. For the purposes of this study, the incremental cost of clean diesel fuel will be 5 cents per gallon. However, by the year 2000, it is assumed that refiners are not able to satisfy the "equivalent emissions" option and the costs will increase to 16 cents per gallon.

Fuel Tax

The vehicle fuel taxes are based on current Federal and California sales and excise taxes. For gasoline and diesel, these taxes are applied at the fuel pump and are charged based on gallons of use. For alternative fuels, the tax basis varies. For example, sales tax is levied on natural gas as a vehicle fuel only when sold by a non-utility entity. Fuel taxes are included in the total fuel price shown in Table 8-2.

Fuel use tax is levied on natural gas as a vehicle fuel in one of two ways: either at the rate of 7 cents per one hundred cubic feet purchased or as a sticker fee based on gross vehicle weight. However, this tax is levied on the purchaser of the fuel and/or the vehicle owner, not the distributor.

Fuel Consumption

Fuel consumption is a function of the efficiency of the engine/fuel system technology as well as the energy content of the fuel. It is assumed that improvements in diesel fuel will be made without adversely effecting the energy content. Fuel consumption estimates are based on available data from a limited number of test vehicles which have been revised, based on projections of the effects of technology modifications which are expected to appear. The fuel consumption for the technologies considered in this analysis is shown in Table 8-3. Ranges in fuel economy are shown for some of the technologies where we had sufficient information to project a range or where a significant range in fuel consumption might be expected.

Maintenance Costs

Annual maintenance costs include those items associated with normal use of the vehicle. These include the following functions:

Table 8-3. Comparison of fuel consumption for HD vehicles

Fuel	Technology	Fuel Economy (mi/gal, mi/100 scf)		LHV[a] (Btu/gal, Btu/100 scf, Btu/kWh)	Relative Energy Efficiency[b]	
		Best	Worst		Best	Worst
HHD Truck						
1998 diesel	Base	9.6		128,000	1.000	
Diesel	EGR	9.4	9.1	128,000	1.021	1.055
Diesel	DE-NOx	9.1	8.7	128,000	1.055	1.103
M100	2-stroke	4		57,000	1.069	
M100	2-stroke	4.1		57,000	1.043	
CNG	Lean burn	6.3		97,000	1.155	
LNG	Lean burn	4.8		73,000	1.141	
LPG	Lean burn	5.5		84,000	1.145	
Transit bus						
1998 diesel	Base	3.5		128,000	1.000	
Diesel	EGR	3.4	3.3	128,000	1.029	1.061
Diesel	DE-NOx	3.3	3.2	128,000	1.061	1.094
M100	2-stroke	1.4	1.3	57,000	1.113	1.199
M100	4-stroke	1.45	1.4	57,000	1.075	1.113
CNG	Lean burn	2.3	2.1	97,000	1.153	1.263
LNG	Lean burn	1.75	1.6	73,000	1.141	1.248
LPG	Lean burn	2	1.85	84,000	1.148	1.242
MHD truck						
1998 diesel	Base	12		128,000	1.000	
Diesel	EGR	11.6		128,000	1.034	
M100	4-stroke	5		57,000	1.069	
CNG	Lean burn	7.5		97,000	1.213	
LNG	Lean burn	5.7		73,000	1.201	
LPG	Lean burn	6.6		84,000	1.200	
LHD truck						
Gasoline	Stoich/TWC	12		115,500	1.000	
M85	Stoich/TWC	7		65,776	0.976	
CNG	Stoich/TWC	10.1	9.8	97,000	0.998	1.028
LNG	Stoich/TWC	7.6		73,000	0.998	
LPG	Stoich/TWC	8.8		84,000	0.992	
Electricity	Battery	1.43		3,412	0.248	
Small transit						
Gasoline	Stoich/TWC	10		115,500	1.00	
Electricity	Battery	1.0		3,412	0.29	

[a]LHV = lower heating value in Btu/100 scf for CNG, Btu/kWh for Electricity, all others in Btu/gallon
[b]Btu/mi for alternative technology divided by base technology Btu/mi.

Servicing

Activities associated with fueling, checking fluid levels and cleaning.

Preventive Maintenance

Activities include statutorily required inspections (either by state or local authority or directed by the operating policies of the fleet operator), safety inspections, and minor and major inspections conducted at specified mileage or time intervals.

8.2.9 Running Repairs

Day-to-day light maintenance and repairs include diagnosis, repair, component removal and replacement whether performed on a prescheduled or unscheduled basis. The costs include both the labor and parts associated with each of these functions. Parts costs include consumable and non-consumable items, except for fuel which is addressed separately.

8.2.10 Periodic Repairs

These include major components which are rebuilt and/or replaced, usually on given mileage intervals. The two key components in the category include tires and the vehicle engine. Costs for these are developed by estimating the life of the component, determining the average cost for the rebuild/replacement and then calculating the number of such replacements which will occur during the life of the vehicle. For example, an urban transit bus has an engine life of 250,000 miles, a vehicle working life of 12 years, and operates 40,000 miles per year. It is assumed that the engine is rebuilt only once, in the sixth year, after 250,000 miles. The newly rebuilt engine will last until the vehicle is retired at 480,000 miles.

These costs also include both the labor and parts associated with the component rebuild/replacement.

Table 8-4 presents expected component replacement intervals for a gasoline powered vehicle. For the purposes of this study all components except tires and engines are included in the "Other" category.

Table 8-4. Expected component life for gasoline vehicles

Component	Expected Life (Miles)
FUEL SYSTEM	
Fuel pump	60,000 - 70,000
Intake and exhaust manifold gaskets	100,000 - 110,000
Carburetor, adjust	10,000 - 15,000
Carburetor	40,000 - 50,000
EMISSION CONTROLS	
Crankcase Emissions:	
Positive crankcase ventilation valve	50,000 - 60,000
Crankcase vent filter	50,000 - 60,000
Air Injection Reactor types:	
Air pump cleaner	80,000 - 100,000
Air pump	80,000 - 100,000
Air pump relief valve	50,000 - 80,000
Gulp valve	60,000 - 70,000
Check valve	60,000 - 70,000
Controlled Combustion type:	
Air cleaner vacuum motor	60,000 - 70,000
Air cleaner temperature sensor	60,000 - 70,000
Thermal vacuum switch	60,000 - 70,000
Evaporative Emission type:	
Charcoal cannister	80,000 - 100,000
Cannister purge thermal vacuum switch	60,000 - 70,000
Exhaust Gas Recirculation	
EGR valve	60,000 - 70,000
ALTERNATOR OR REGULATOR	
Alternator	60,000 - 75,000
Voltage regulator	60,000 - 75,000
STARTING SYSTEM	
Starter	40,000 - 50,000
Starter solenoid	40,000 - 50,000
BRAKE SYSTEM	
Brake shoes/or pads	30,000 - 40,000
Wheel cylinder	80,000 - 100,000
Master cylinder	80,000 - 100,000
Power brake booster	80,000 - 100,000
Power brake booster brake valve	80,000 - 100,000

Component	Expected Life (Miles)
COOLING SYSTEM	
Radiator	125,000 - 150,000
Radiator hoses	60,000 - 70,000
Fan belt	25,000 - 30,000
Water pump	70,000 - 80,000
Temperature gauge	- 100,000
Heater hoses	60,000 - 70,000
Hot water shut off valve	60,000 - 70,000
Heater core	125,000 - 150,000
EXHAUST SYSTEM	
Muffler	40,000 - 50,000
Tail pipe	40,000 - 50,000
Catalytic converter	70,000 - 70,000
Front exhaust pipe	40,000 - 50,000
Rear exhaust pipe	40,000 - 50,000
FRONT SUSPENSION	
Alignment	20,000 - 30,000
Front wheel bearings, repack	125,000 - 150,000
Front wheel grease seals	40,000 - 50,000
Front shock absorbers	30,000 - 40,000
Steering arm and knuckle	60,000 - 70,000
Lower control arm assy	60,000 - 70,000
Lower control arm bushings	60,000 - 70,000
Upper control arm bushings	60,000 - 70,000
Ball joints	60,000 - 70,000
Front spring	60,000 - 150,000
Front stabilizer shaft bushings	60,000 - 70,000
STEERING LINKAGE	
Tie rod ends	60,000 - 70,000
HEATER AND AIR CONDITIONING	
Blower motor	40,000 - 50,000
Heater core	90,000 - 100,000
Purge & recharge	25,000 - 30,000
A/C compressor/clutch	40,000 - 50,000

Component	Expected Life (Miles)
STEERING GEAR	
Upper mast jacket bearing	80,000 - 100,000
Tilt column bearing housing	80,000 - 100,000
Steering shaft lower coupling	80,000 - 100,000
Steering gear	125,000 - 150,000
Pitman shaft seal	80,000 - 100,000
Power steering belt	30,000 - 40,000
Power steering gear box	80,000 - 100,000
Valve body	80,000 - 100,000
Power steering pump	60,000 - 70,000
Pump flow control valve	80,000 - 100,000
Power steering hose	60,000 - 70,000
ENGINE	
Cylinder head	80,000 - 100,000
Valves, adjust	50,000 - 60,000
Valve cover gasket, each	25,000 - 30,000
Valve lifters	80,000 - 100,000
Engine assembly	125,000 - 150,000
Engine mounts	125,000 - 150,000
Timing cover oil seal	70,000 - 80,000
Timing cover gasket	70,000 - 80,000
Oil pan and gasket	80,000 - 100,000
Oil pump	80,000 - 100,000
TRANSMISSION (Turbo Hydro matic 400)	
Transmission	60,000 - 80,000
Front oil pump	60,000 - 80,000
TRANSMISSION (AT-540)	
Transmission	60,000 - 80,000
Throttle lever oil sheals	60,000 - 80,000
Oil pan gasket	20,000 - 24,000
Adjust shift linkage	20,000 - 24,000
Retarder linkage	20,000 - 24,000

8.3 ANALYSIS OF COSTS BY VEHICLE TYPE

8.3.1 Overview

Five representative vehicle types are used in the comparative analysis. The first four specific vehicles were selected as representative of each class of heavy-duty vehicles. The last one is a special case which was developed in order to provide a base of comparison with electric vehicles. This case has a different duty cycle than vehicles typical of the class and is likely to represent only a small percentage of the overall vehicle population.

The heavy heavy-duty vehicle (HHD) group are those with a GVW greater than 33,000 lb. The selected transfer truck is an over-the-road vehicle intended for long distance freight hauling between urban areas.

The urban transit bus group is represented by a standard 40 ft long diesel-powered transit bus configured for urban use. The use pattern includes frequent stops and heavy passenger loads.

The medium heavy-duty (MHD) vehicles have gross vehicle weights between 14,000 and 33,000 pounds. The selected representative vehicle is a single unit truck used within an urban area, hauling moderate loads over relatively short distances. It has two axles with double rear tires.

The light heavy-duty (LHD) vehicles have gross vehicle weights between 8,500 and 14,000 pounds. The selected vehicle is a specialty vehicle built on a van chassis. It has two axles, with double tires on the rear axle. The use pattern consists of frequent stops transporting light loads over short distances.

The baseline small transit vehicle is a 22 ft gasoline-powered vehicle that seats 22 seated passengers. It is used as an urban area shuttle with slow speeds, frequent stops, and a maximum daily range of 75 miles.

Table 8-5 summarizes the baseline vehicle data for these five vehicle types.

Table 8-5. Summary of baseline vehicle data for HDV user cost analysis (1992 Dollars)

Vehicle Class/Baseline Vehicle	Baseline Fuel	Vehicle Cost ($)	Vehicle Life (yr)	Gross Vehicle Weight (lb)	Annual Mileage	Average Fuel Use (mpg)
Heavy heavy-duty/ Transfer truck	Diesel	90,000	12	80,000	40,000	9.6
Urban transit bus/ Standard bus	Diesel	200,000	12	27,000	40,000	3.5
Medium heavy-duty/ Delivery truck	Diesel	70,000	12	30,000	25,000	12.0
Light heavy-duty/ Delivery truck	Gasoline	35,000	20	10,500	15,000	12.0
Small transit bus/ 22 ft bus	Gasoline	55,000	4	11,000	12,000	10.0

8.3.2 Heavy Heavy-Duty Transport Truck

Baseline Vehicle

The baseline vehicle uses diesel fuel meeting 1998 standards, in a direct-injection diesel engine. The initial purchase price is based on manufacturer's price quotes. We have selected $90,000 as the base vehicle cost. The base vehicle has an additional $3,000 added on the high side for engine modifications.

The annual costs for the baseline vehicle assume a fuel consumption rate of 9.6 miles per gallon (mpg).

The periodic costs will increase for the rebuilding of the exhaust system and engine. Based on manufacturer's estimates, this is expected to be about a 20 percent over the current engine rebuild costs of $9,250.

Table 8-6 presents the projected costs for the baseline vehicle for both "high" and "low" cases.

Table 8-6. Baseline heavy heavy-duty transfer truck vehicle costs (1992 Dollars)

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE	$90,000	$90,000
DIFFERENTIAL COST		
ENGINE	$0	$3,000
FUEL SYSTEM	$0	$0
EXHAUST SYSTEM	$0	$0
FIRE SUPPRESSION SYSTEM	$0	$0
SUB-TOTAL	$90,000	$93,000
SALES TAX AT 6.5%	$5,895	$6,092
SALVAGE AT 5% OF PRICE (1)	$4,500	$4,650
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	80,000	80,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$91,395	$94,442
.......ANNUAL.......		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/GAL)	9.6	9.6
FUEL COST PER GALLON	$1.32	$1.42
ANNUAL FUEL COST	$5,508	$5,917
APRX. ANNUAL LICENSE (3)	$958	$1,000
REGISTRATION FEES PER YEAR (3)	$958	$958
INSURANCE/YR (5)		
INCL COLLISION	$5,468	$5,711
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$3,615	$3,776
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$4,387	$4,582
ROUTINE MAINTENANCE COST/YEAR (6)	$1,125	$1,350
TOTAL ANNUAL COSTS/YEAR	$12,936	$13,807
NPV ANNUAL COSTS (4)	$88,139	$94,076
.....PERIODIC.....		
TIRE REPLACEMENT MILES	100,000	100,000
TIRE REPLACEMENT COST EA SET	$3,917	$3,917
LIFETIME TIRE REPLACMENTS	4	4
ENGINE REBUILD MILES	375,000	375,000
ENGINE REBUILD COST EA	$9,250	$11,100 (7)
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (4)	$12,731	$13,488
TOTAL VEHICLE NPV	$192,265	$202,005
TOTAL COSTS PER MILE	$0.40	$0.42

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) BASED ON CA DMV 1992
(4) ASSUMES A DISCOUNT RATE OF 10%
(5) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(6) BASED ON RYDER TRUCK LEASE'S MAINTENANCE SCHEDULE AND COSTS
(7) 20% INCREASE

Alternative Technologies

DI Diesel With EGR and Catalytic Trap

Table 8-7 presents projected costs for a heavy heavy-duty vehicle equipped with a catalytic trap and fueled with diesel meeting the 1998 standards, in a direct-injection diesel engine. Differential costs for this technology include $10,000 to $12,000 for the engine, and $4,500 to $5,700 for the catalytic trap system.

The annual costs assume a fuel consumption rate of 9.1 to 9.4 mpg.

The maintenance costs assume a 20 percent increase over current maintenance costs for the engine, exhaust, and fuel systems. This is assumed to increase an additional 20 percent with the "high" case technology.

DI Diesel With DE-NO_x

Table 8-8 presents projected costs for this alternative. Differential costs for this technology include $7,500 to $10,000 for the engine, $500 to $1,000 for fuel system improvements and $1,000 to $1,500 for the DE-$NO_x$ catalyst system.

The annual costs assume a fuel consumption rate of 8.7 to 9.1 mpg.

The maintenance costs assume a 20 percent increase over current maintenance costs for the engine, exhaust, and fuel systems. This is assumed to increase an additional 20 percent with the "high" case technology.

M100 DI Compression Ignition 2-Stroke

Table 8-9 presents projected costs for a methanol-fueled heavy heavy-duty vehicle with a 2-Stroke engine. Differential costs for this technology include $5,000 to $10,000 for the engine, $5,000 for the fueling system, and $500 to $1,000 for an oxidation catalyst.

The annual costs assume a fuel consumption rate of 4 mpg.

The maintenance costs assume a 20 percent increase over current maintenance costs for the engine, exhaust, and fuel systems. This is assumed to increase an additional 20 percent with the "high" case technology.

Table 8-7. DI diesel with EGR and catalytic trap HHD transfer truck costs (1992 Dollars)

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE	$90,000	$90,000
DIFFERENTIAL COST		
ENGINE	$10,000	$12,000
FUEL SYSTEM	$0	$0
EXHAUST SYSTEM	$4,500	$5,700
FIRE SUPPRESSION SYSTEM	$0	$0
SUB-TOTAL	$104,500	$107,700
SALES TAX AT 6.5%	$6,845	$7,054
SALVAGE AT 5% OF PRICE (1)	$5,225	$5,385
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	80,000	80,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$106,120	$109,369
.......ANNUAL.......		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/GAL)	9.4	9.1
FUEL COST PER GALLON	$1.34	$1.42
ANNUAL FUEL COST	$5,702	$6,242
APRX. ANNUAL LICENSE (3)	$1,059	$1,092
REGISTRATION FEES PER YEAR (3)	$958	$958
INSURANCE/YR (4)		
INCL COLLISION	$6,047	$6,232
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$3,998	$4,120
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$4,852	$5,000
ROUTINE MAINTENANCE COST/YEAR (5)	$1,204	$1,539
TOTAL ANNUAL COSTS/YEAR	$13,775	$14,831
NPV ANNUAL COSTS (6)	$93,858	$101,052
.....PERIODIC.....		
TIRE REPLACEMENT MILES	100,000	100,000
TIRE REPLACEMENT COST EA SET	$3,917	$3,917
LIFETIME TIRE REPLACMENTS	4	4
ENGINE REBUILD MILES	375,000	375,000
ENGINE REBUILD COST EA	$9,250	$11,100 (7)
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (6)	$12,731	$13,488
TOTAL VEHICLE NPV	$212,708	$223,909
TOTAL COSTS PER MILE	$0.44	$0.47

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) BASED ON CA DMV 1992
(4) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(5) ASSUMES 20% to 40% INCREASE IN ENGINE/FUEL SYSTEM MAINTENANCE COSTS
(6) ASSUMES A DISCOUNT RATE OF 10%
(7) 20% INCREASE

Table 8-8. DI diesel with DE-NO_x catalyst HHD transfer truck costs (1992 Dollars)

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE	$90,000	$90,000
DIFFERENTIAL COST		
ENGINE	$7,500	$10,000
FUEL SYSTEM	$500	$1,000
EXHAUST SYSTEM	$1,000	$1,500
FIRE SUPPRESSION SYSTEM	$0	$0
SUB-TOTAL	$99,000	$102,500
SALES TAX AT 6.5%	$6,485	$6,714
SALVAGE AT 5% OF PRICE (1)	$4,950	$5,125
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	80,000	80,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$100,535	$104,089
.......ANNUAL........		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/GAL)	9.1	8.7
FUEL COST PER GALLON	$1.34	$1.42
ANNUAL FUEL COST	$5,890	$6,529
APRX. ANNUAL LICENSE (3)	$1,013	$1,049
REGISTRATION FEES PER YEAR (3)	$958	$958
INSURANCE/YR (4)		
INCL COLLISION	$5,787	$5,989
NO OF YEARS	5	5
INSURANCE/YR		
NO COLISSION	$3,826	$3,960
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$4,643	$4,805
ROUTINE MAINTENANCE COST/YEAR (5)	$1,204	$1,539
TOTAL ANNUAL COSTS/YEAR	$13,708	$14,880
NPV ANNUAL COSTS (6)	$93,403	$101,389
.....PERIODIC.....		
TIRE REPLACEMENT MILES	100,000	100,000
TIRE REPLACEMENT COST EA SET	$3,917	$3,917
LIFETIME TIRE REPLACMENTS	4	4
ENGINE REBUILD MILES	375,000	375,000
ENGINE REBUILD COST EA	$9,250	$11,100 (7)
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (6)	$12,731	$13,488
TOTAL VEHICLE NPV	$206,668	$218,965
TOTAL COSTS PER MILE	$0.43	$0.46

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION

(2) EPA TEST DATA,HEAVENRICH ET AL

(3) BASED ON CA DMV 1992

(4) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION

(5) ASSUMES 20% to 40% INCREASE IN ENGINE/FUEL SYSTEM MAINTENANCE COSTS

(6) ASSUMES A DISCOUNT RATE OF 10%

Table 8-9. M100 DI compression ignition 2-stroke HHD transfer truck costs (1992 Dollars)

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE	$90,000	$90,000
DIFFERENTIAL COST		
ENGINE	$5,000	$10,000
FUEL SYSTEM	$5,000	$5,000
EXHAUST SYSTEM	$500	$1,000
FIRE SUPPRESSION SYSTEM	$0	$0
SUB-TOTAL	$100,500	$106,000
SALES TAX AT 6.5%	$6,583	$6,943
SALVAGE AT 5% OF PRICE (1)	$5,025	$5,300
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	80,000	80,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$102,058	$107,643
.......ANNUAL........		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/GAL)	4	4
FUEL COST PER GALLON (3)	$0.62	$0.69
ANNUAL FUEL COST	$6,219	$6,891
APRX. ANNUAL LICENSE (4)	$1,019	$1,074
REGISTRATION FEES PER YEAR (4)	$958	$958
INSURANCE/YR (5)		
INCL COLLISION	$5,816	$6,134
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$3,845	$4,056
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$4,666	$4,922
ROUTINE MAINTENANCE COST/YEAR (6)	$1,204	$1,539
TOTAL ANNUAL COSTS/YEAR	$14,066	$15,384
NPV ANNUAL COSTS (7)	$95,843	$104,821
.....PERIODIC.....		
TIRE REPLACEMENT MILES	100,000	100,000
TIRE REPLACEMENT COST EA SET	$3,917	$3,917
LIFETIME TIRE REPLACMENTS	4	4
ENGINE REBUILD MILES	375,000	375,000
ENGINE REBUILD COST EA	$13,412	$16,418 (8)
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (7)	$14,433	$15,664
TOTAL VEHICLE NPV	$212,334	$228,127
TOTAL COSTS PER MILE	$0.44	$0.48

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) 1998 PRICE BASED ON PROJECTED HIGH, 2004 ON PROJECTED LOW
(4) BASED ON CA DMV 1992
(5) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(6) ASSUMES 20% to 40% INCREASE IN ENGINE/FUEL SYSTEM MAINTENANCE COSTS
(7) ASSUMES A DISCOUNT RATE OF 10%
(8) 20% INCREASE

M100 DI Glow Plug Ignition 4-Stroke

Table 8-10 presents projected costs for a methanol-fueled heavy heavy-duty vehicle with a 4-stroke engine. Differential costs for this technology include $5,000 to $10,000 for the engine, $5,000 for the fueling system, and $500 to $1,000 for an oxidation catalyst.

The annual costs assume a fuel consumption rate of 4.1 mpg.

Maintenance costs assume a 20 percent increase over current maintenance costs for the engine, exhaust, and fuel systems.

CNG Lean Burn Spark-Ignition

Table 8-11 presents projected costs for a heavy heavy-duty vehicle fueled with compressed natural gas. Differential costs for this technology include $10,000 to $15,000 for the engine, $5,000 for changes in the fuel system, and $500 to $1,000 for an oxidation catalyst.

The annual costs assume a fuel consumption rate of 6.3 miles per 100 standard cubic feet (scf) of natural gas.

The maintenance costs assume a 20 percent increase over current maintenance costs for the engine, exhaust, and fuel systems. This is assumed to increase an additional 20 percent with the "high" case technology.

LPG Lean Burn Spark-Ignition

Table 8-12 presents projected costs for an LPG fueled heavy heavy-duty vehicle. Differential costs for this technology include $10,000 to $15,000 for the engine, $5,000 for changes in the fuel system, and $500 to $1,000 for an oxidation catalyst.

The annual costs assume a fuel consumption rate of 5.5 mpg.

Since propane is an older technology, propane fleet operators generally have more experience with the fuel than operators of the other alternative fueled fleets. Propane fleet operators also report few problems, long engine life, and less frequent spark plug and oil changes. The L.A. Times reported some vans had achieved over 500,000 miles (Reference 68).

Table 8-10. M100 DI glow plug ignition 4-stroke HHD transfer truck costs (1992 Dollars)

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE	$90,000	$90,000
DIFFERENTIAL COST		
ENGINE	$5,000	$10,000
FUEL SYSTEM	$5,000	$5,000
EXHAUST SYSTEM	$500	$1,000
FIRE SUPPRESSION SYSTEM	$0	$0
SUB-TOTAL	$100,500	$106,000
SALES TAX AT 6.5%	$6,583	$6,943
SALVAGE AT 5% OF PRICE (1)	$5,025	$5,300
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	80,000	80,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$102,058	$107,643
.......ANNUAL........		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/GAL)	4.1	4.1
FUEL COST PER GALLON (3)	$0.62	$0.69
ANNUAL FUEL COST	$6,067	$6,723
APRX. ANNUAL LICENSE (4)	$1,019	$1,074
REGISTRATION FEES PER YEAR (4)	$958	$958
INSURANCE/YR (5)		
INCL COLLISION	$5,816	$6,134
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$3,845	$4,056
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$4,666	$4,922
ROUTINE MAINTENANCE COST/YEAR (6)	$1,204	$1,539
TOTAL ANNUAL COSTS/YEAR	$13,915	$15,216
NPV ANNUAL COSTS (7)	$94,810	$103,676
.....PERIODIC.....		
TIRE REPLACEMENT MILES	100,000	100,000
TIRE REPLACEMENT COST EA SET	$3,917	$3,917
LIFETIME TIRE REPLACMENTS	4	4
ENGINE REBUILD MILES	375,000	375,000
ENGINE REBUILD COST EA	$13,412	$16,418 (8)
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (7)	$14,433	$15,664
TOTAL VEHICLE NPV	$211,301	$226,982
TOTAL COSTS PER MILE	$0.44	$0.47

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) 1998 PRICE BASED ON PROJECTED HIGH, 2004 ON PROJECTED LOW
(4) BASED ON CA DMV 1992
(5) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(6) ASSUMES 20% to 40% INCREASE IN ENGINE/FUEL SYSTEM MAINTENANCE COSTS
(7) ASSUMES A DISCOUNT RATE OF 10%

Table 8-11 **CNG lean burn spark-ignition HHD transfer truck costs (1992 Dollars)**

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE	$90,000	$90,000
DIFFERENTIAL COST		
ENGINE	$10,000	$15,000
FUEL SYSTEM	$5,000	$5,000
EXHAUST SYSTEM	$500	$1,000
FIRE SUPPRESSION SYSTEM	$0	$0
SUB-TOTAL	$105,500	$111,000
SALES TAX AT 6.5%	$6,910	$7,271
SALVAGE AT 5% OF PRICE (1)	$5,275	$5,550
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	80,000	80,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$107,135	$112,721
.......ANNUAL........		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/100 SCF)	6.3	6.3
FUEL COST PER 100 SCF (3)	$0.51	$0.73
ANNUAL FUEL COST	$3,225	$4,658
APRX. ANNUAL LICENSE (4)	$1,100	$1,173
REGISTRATION FEES PER YEAR (4)	$958	$958
INSURANCE/YR (5)		
INCL COLLISION	$6,336	$6,695
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$4,189	$4,426
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$5,084	$5,371
ROUTINE MAINTENANCE COST/YEAR (6)	$1,103	$1,418
TOTAL ANNUAL COSTS/YEAR	$11,469	$13,579
NPV ANNUAL COSTS (7)	$78,149	$92,522
.....PERIODIC.....		
TIRE REPLACEMENT MILES	80,000	80,000
TIRE REPLACEMENT COST EA SET	$3,917	$3,917
LIFETIME TIRE REPLACMENTS	6	6
ENGINE REBUILD MILES	375,000	375,000
ENGINE REBUILD COST EA	$9,250	$11,100 (8)
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (7)	$16,494	$17,251
TOTAL VEHICLE NPV	$201,778	$222,494
TOTAL COSTS PER MILE	$0.42	$0.46

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) 1998 PRICE BASED ON PROJECTED HIGH, 2004 ON PROJECTED LOW
(4) BASED ON CA DMV 1992
(5) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(6) ASSUMES MAINTENANCE COST DIFFERENTIAL RANGING FROM -2% TO +5%
(7) ASSUMES A DISCOUNT RATE OF 10%
(8) 20% INCREASE

Table 8-12. LPG lean burn spark-ignition HHD transfer truck costs (1992 Dollars)

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE	$90,000	$90,000
DIFFERENTIAL COST		
ENGINE	$10,000	$15,000
FUEL SYSTEM	$5,000	$5,000
EXHAUST SYSTEM	$500	$1,000
FIRE SUPPRESSION SYSTEM	$0	$0
SUB-TOTAL	$105,500	$111,000
SALES TAX AT 6.5%	$6,910	$7,271
SALVAGE AT 5% OF PRICE (1)	$5,275	$5,550
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	80,000	80,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$107,135	$112,721
.......ANNUAL........		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/GAL)	5.5	5.5
FUEL COST PER GALLON	$0.79	$0.79
ANNUAL FUEL COST	$5,745	$5,745
APRX. ANNUAL LICENSE (3)	$1,100	$1,173
REGISTRATION FEES PER YEAR (3)	$958	$958
INSURANCE/YR (4)		
INCL COLLISION	$6,336	$6,695
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$4,189	$4,426
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$5,084	$5,371
ROUTINE MAINTENANCE COST/YEAR (5)	$1,103	$1,350
TOTAL ANNUAL COSTS/YEAR	$13,990	$14,598
NPV ANNUAL COSTS (6)	$95,324	$99,465
.....PERIODIC.....		
TIRE REPLACEMENT MILES	90,000	90,000
TIRE REPLACEMENT COST EA SET	$3,917	$3,917
LIFETIME TIRE REPLACMENTS	5	5
ENGINE REBUILD MILES	375,000	375,000
ENGINE REBUILD COST EA	$9,250	$11,100 (7)
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (6)	$14,557	$15,314
TOTAL VEHICLE NPV	$217,016	$227,500
TOTAL COSTS PER MILE	$0.45	$0.47

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) BASED ON CA DMV 1992
(4) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(5) ASSUMES 5% SAVINGS IN ENGINE/FUEL SYSTEM MAINTENANCE COSTS
(6) ASSUMES A DISCOUNT RATE OF 10%
(7) 20% INCREASE

The Colorado Task Force predicted slightly lower maintenance costs for light-duty gasoline engines operated on LPG through extended engine life and less engine deposits. Reduced preventive maintenance costs are possible, but are not likely to be realized because of warranty implications. They projected heavy-duty vehicle costs to be slightly less to the same (Reference 69).

LNG Lean Burn Spark-Ignition

Table 8-13 presents projected costs for a heavy heavy-duty vehicle fueled with liquified natural gas. Differential costs for this technology include $10,000 to $15,000 for the engine, $5,000 to $10,000 for changes in the fuel system, and $500 to $1,000 for an oxidation catalyst.

The annual costs assume a fuel consumption rate of 4.8 miles per gallon.

The maintenance costs assume a 20 percent increase over current maintenance costs for the engine, exhaust, and fuel systems. This is assumed to increase an additional 20 percent with the "high" case technology.

Heavy Heavy-Duty Transfer Truck Cost Summary

A summary of the heavy heavy-duty transfer truck life cycle costs for all technologies costed above is shown in Table 8-14. Life cycle costs vary from $0.40 per mile for the low baseline diesel to $0.50 per mile for the high LNG lean-burn spark-ignited transfer truck estimates.

8.3.3 Urban Bus

Baseline Data

The baseline vehicle is a standard 40 ft transit bus using a direct-injection diesel engine. The basic cost data for this vehicle is from "Public Transportation Alternative Fuels—A Perspective For Small Operators" (Reference 70).

Initial purchase price estimates are based on an average of recent bus bid prices. A baseline price of $200,000 to $210,000 is used in this analysis.

Transit buses report wide variations of fuel consumption. This is a function of variations in duty-cycle from express routes that operate at high speed with few stops to more typical urban

Table 8-13. LNG lean burn spark-ignition HHD transfer truck costs (1992 Dollars)

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE	$90,000	$90,000
DIFFERENTIAL COST		
ENGINE	$10,000	$15,000
FUEL SYSTEM	$5,000	$10,000
EXHAUST SYSTEM	$500	$1,000
FIRE SUPPRESSION SYSTEM	$0	$0
SUB-TOTAL	$105,500	$116,000
SALES TAX AT 6.5%	$6,910	$7,598
SALVAGE AT 5% OF PRICE (1)	$5,275	$5,800
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	80,000	80,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$107,135	$117,798
.......ANNUAL........		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/GAL)	4.8	4.8
FUEL COST PER GALLON (3)	$0.61	$0.81
ANNUAL FUEL COST	$5,083	$6,750
APRX. ANNUAL LICENSE (4)	$1,100	$1,223
REGISTRATION FEES PER YEAR (4)	$958	$958
INSURANCE/YR (5)		
INCL COLLISION	$6,336	$6,984
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$4,189	$4,618
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$5,084	$5,604
ROUTINE MAINTENANCE COST/YEAR (6)	$1,103	$1,418
TOTAL ANNUAL COSTS/YEAR	$13,328	$15,953
NPV ANNUAL COSTS (7)	$90,812	$108,698
.....PERIODIC.....		
TIRE REPLACEMENT MILES	90,000	90,000
TIRE REPLACEMENT COST EA SET	$3,917	$3,917
LIFETIME TIRE REPLACMENTS	5	5
ENGINE REBUILD MILES	375,000	375,000
ENGINE REBUILD COST EA	$9,250	$11,100 (8)
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (7)	$14,557	$15,314
TOTAL VEHICLE NPV	$212,505	$241,810
TOTAL COSTS PER MILE	$0.44	$0.50

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) 1998 PRICE BASED ON PROJECTED HIGH, 2004 ON PROJECTED LOW
(4) BASED ON CA DMV 1992
(5) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(6) ASSUMES 5% SAVINGS TO 15% INCREASE IN ENGINE/FUEL SYSTEM MAINTENANCE COST
(7) ASSUMES A DISCOUNT RATE OF 10%
(8) 20% INCREASE

Table 8-14. Heavy heavy-duty transfer truck life cycle cost summary (1992 Dollars)

CONFIGURATION	COST RANGE	PURCHASE PRICE	LIFETIME (YEARS)	GVW (LBS)	REG WGT (LBS)	NO OF AXLES	NO OF TIRES	MILES PER YEAR	COST PER MILE
BASELINE	LOW	$90,000	12	80,000	15,000	3	10	40,000	$0.40
	HIGH	$93,000	12	80,000	16,000	3	10	40,000	$0.42
DI DIESEL WITH TRAP	LOW	$104,500	12	80,000	15,000	3	10	40,000	$0.44
	HIGH	$107,700	12	80,000	16,000	3	10	40,000	$0.47
DI DIESEL WITH DE-NOx	LOW	$99,000	12	80,000	15,000	3	10	40,000	$0.43
	HIGH	$102,500	12	80,000	16,000	3	10	40,000	$0.46
M100 2 STROKE	LOW	$100,500	12	80,000	16,000	3	10	40,000	$0.44
	HIGH	$106,000	12	80,000	17,000	3	10	40,000	$0.48
M100 GLOW PLUG 4 STROKE	LOW	$100,500	12	80,000	16,000	3	10	40,000	$0.44
	HIGH	$106,000	12	80,000	17,000	3	10	40,000	$0.47
CNG LEAN BURN SPARK	LOW	$105,500	12	80,000	17,000	3	10	40,000	$0.42
	HIGH	$111,000	12	80,000	18,000	3	10	40,000	$0.46
LPG LEAN BURN SPARK	LOW	$105,500	12	80,000	17,000	3	10	40,000	$0.45
	HIGH	$111,000	12	80,000	18,000	3	10	40,000	$0.47
LNG LEAN BURN SPARK	LOW	$105,500	12	80,000	17,000	3	10	40,000	$0.44
	HIGH	$116,000	12	80,000	18,000	3	10	40,000	$0.50

operations with frequent stops and slow speed operation. For the purposes of this study we have assumed the typical urban duty cycle. The fuel consumption rate for the baseline vehicle is 3.5 mpg.

Maintenance costs for the transit bus include both the annual and periodic costs. Other studies of transit vehicle maintenance costs have combined the annual and periodic costs into a total maintenance cost per mile. APTA's 1991 Operating and Financial Statistics shows an average maintenance cost per mile of $1.00 for transit systems operating primarily 35 and 40 foot coaches. Tires are typically leased by the transit operator so that this becomes an annual rather than a periodic expense. We have used a cost of $1.00 per mile as the total maintenance cost of the baseline vehicle.

Studies of maintenance practices at transit agencies have found that maintenance of the engines, exhaust systems, and fuel systems account for 35 percent of total fleet maintenance costs, or about $0.35 per vehicle mile.

Table 8-15 identifies the basic cost factors for the baseline transit bus.

Alternative Technologies

Insurance industry representatives and fleet operators of alternative-fueled and advanced diesel vehicles report no change in insurance premiums as a result of the change to new fuel systems. There will be some impact if collision coverage is provided because of the increased initial purchase prices. These increased costs will be less than proportional to the price differential in the purchase price. Since many fleet operators do not carry collision insurance, and public fleet operators are often self insured, the overall impacts of this are expected to be minimal and have not been included in the cost analysis for the baseline urban bus or alternative technologies.

DI With EGR and Catalytic Trap

The DDC 6V-92TA engine with the Donaldson dual trap system and the Cummins L10 engine with the Donaldson dual trap system were both certified in 1992. These engines are about 1.8 times the cost of the equivalent standard diesel engine. Manufacturer's verbal price quotes for the engines used in standard 40 foot transit buses were twice the cost of the standard diesel engine

Table 8-15. Baseline urban bus costs (1992 Dollars)

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE (1)	$200,000	$210,000
DIFFERENTIAL COST		
ENGINE	$0	$0
FUEL SYSTEM	$0	$0
EXHAUST SYSTEM	$0	$0
FIRE SUPPRESSION SYSTEM	$0	$0
OTHER	0	0
SUB-TOTAL	$200,000	$210,000
SALES TAX AT 6.5%	$13,100	$13,755
SALVAGE AT 5% OF PRICE (2)	$10,000	$10,500
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	27,000	27,000
NPV VEHICLE CAPITAL COST	$203,100	$213,255
.......ANNUAL........		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/GAL) (3)	3.5	3.5
FUEL COST PER GALLON (3)	$0.87	$0.97
ANNUAL FUEL COST	$9,943	$11,086
APRX ANNUAL LICENSE (4)	0	0
REGISTRATION FEES PER YEAR (4)	0	0
CLAIMS COSTS (10% LESS THAN INSURANCE)	$10,416	$10,936
MAINTENANCE COST/MILE	$1.00	$1.00
TOTAL ANNUAL COSTS/YEAR	$60,359	$62,022
NPV ANNUAL COSTS (5)	$479,411	$492,619
TOTAL VEHICLE NPV	$682,511	$705,874
TOTAL COSTS PER MILE	$1.42	$1.47

(1) FROM "PUBLIC TRANSPORTATION ALTERNATIVE FUELS" 1992 DATA
(2) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(3) ACUREX ESTIMATES
(4) PUBLIC AGENCIES EXEMPT FROM LICENSE & REGISTRATION FEES
(5) ASSUMES A DISCOUNT RATE OF 7%

by Cummins, and an additional $10,000 to $18,000 for the Donaldson trap system. Actual bids for coaches provided to the Southern California Rapid Transit District had a cost differential of $20,000. (Standard Flexible coach without trap was $204,000, with trap $224,000.)

The cost increase includes the cost of the trap system as well as vehicle engineering and installation.

Based on these data, we estimate the cost increment for a particulate trap equipped vehicle over the cost of a standard vehicle to be $10,000 to $20,000. The estimated incremental cost of the EGR system was $5,000 to $10,000.

NYCTA and the S.E. Pennsylvania Transit Authority reported a 3 to 5 percent loss in fuel efficiency, Orange County reported an 8 percent loss (Reference 68). We have assumed a 5 percent loss. This will reduce the mpg by .17 from 3.5 to 3.33.

Early demonstration transit buses have experienced a high rate of failure. SCRTD has been testing several alternative versions of the Donaldson system. The wall flow system had a high failure of the combustion air blowers due to stress being placed on the bearings, metal hoses that deliver the combustion air were prone to splitting due to stress from installation and operation, and seal leaks occurred in the valves. The ceramic fiber retrofit system allowed too much heat to dissipate away from the filter which led to a plugged filter element (Reference 71).

In their status report on particulate trap developments for the transit industry, Battelle concluded that early trap failure rates seem to be a function of the newness and complexity of the technologies which are not understood by the transit systems repair staff. Including staff training in the procurement process is expected to address most of these issues. Of greater concern was the impact of the trap system on the ability to maintain other bus system components. The size of the trap, controls, and associated wiring obscures other components and requires removal or disconnection in order to provide routine maintenance. This impact on maintenance staff time, as well as the increased time to maintain the new components associated with the trap system itself were of concern (Reference 72).

The maintenance costs for the trap equipped vehicle are expected to be slightly higher than those of the baseline bus, but less than those for the alternative-fueled buses. While the exhaust system is more complex, there is no change in the fueling system and no need for adding a fire suppression system. We have assumed an increase of half that of the alternative fuels, or about \$0.02 per mile. The cost analysis is shown in Table 8-16. Cost analyses for a DI diesel bus with DE-NO_x catalyst is shown in Table 8-17.

M100 Direct Injection Glow Plug Ignition 2-Stroke

The increased costs for a methanol bus include an engine at about twice the cost of a diesel: a fuel system with stainless steel fuel tanks, new filters, liners, electric fuel pump and cooler; and a fire protection system. Bids received on January 10, 1992 for SCRTD's order of 75 methanol coaches were \$221,000 by New Flyer Industries, and \$248,000 by Motor coach Industries. We have assumed that the changes result in an additional cost of about \$20,000 over the price of the baseline bus.

Fuel economy data for the three transit operators with the highest numbers of demonstration vehicles indicate only about one third the efficiency of the diesel fleets. This is consistent with the theoretical energy equivalent ratio of 2.25:1 indicating approximately equal efficiency between the two versions of the DDC 6V-92 engine that are in use. The DDC Methanol engines have shown improvements in fuel economy. We have assumed that the average diesel/ methanol fuel economy ratio of 2.5:1 will be achieved. This results in a rate of 1.4 mpg (3.5 mpg of diesel engine divided by 2.5).

Vehicle maintenance costs for methanol vehicles are higher than the baseline diesel coach. These costs would come from additional parts to be maintained such as glow plugs and glow plug controllers, new systems such as fire suppression, increased fuel injector wear, and possible accelerated bearing, liner, and ring wear. Fuel contamination by water has been a problem with some of the demonstration fleets. This has resulted in a need for more frequent fuel filter changes which has resulted in increased costs.

Table 8-16. DI diesel with EGR and catalytic trap bus costs (1992 Dollars)

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE (1)	$200,000	$210,000
DIFFERENTIAL COST		
ENGINE	$5,000	$10,000
FUEL SYSTEM	$0	$0
EXHAUST SYSTEM	$10,000	$20,000
FIRE SUPPRESSION SYSTEM	$0	$0
OTHER	$0	$0
SUB-TOTAL	$215,000	$240,000
SALES TAX AT 6.5%	$14,083	$15,720
SALVAGE AT 5% OF PRICE (2)	$10,750	$12,000
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	27,000	27,000
NPV VEHICLE CAPITAL COST	$218,333	$243,720
.......ANNUAL.......		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/GAL)	3.4	3.3
FUEL COST PER GALLON	$0.89	$0.97
ANNUAL FUEL COST	$10,471	$11,758
APRX ANNUAL LICENSE (3)	0	0
REGISTRATION FEES PER YEAR (3)	0	0
CLAIMS COSTS (10% LESS THAN INSURANCE)	$10,936	$11,978
MAINTENANCE COST/MILE	$1.02	$1.02
TOTAL ANNUAL COSTS/YEAR	$62,207	$64,536
NPV ANNUAL COSTS (4)	$494,087	$512,586
TOTAL VEHICLE NPV	$712,420	$756,306
TOTAL COSTS PER MILE	$1.48	$1.58

(1) FROM "PUBLIC TRANSPORTATION ALTERNATIVE FUELS" 1992 DATA
(2) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(3) PUBLIC AGENCIES EXEMPT FROM LICENSE & REGISTRATION FEES
(4) ASSUMES A DISCOUNT RATE OF 7%

Table 8-17. DI diesel with DE-NO_x catalyst bus costs (1992 Dollars)

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE (1)	$200,000	$210,000
DIFFERENTIAL COST		
ENGINE	$5,000	$10,000
FUEL SYSTEM	$0	$0
EXHAUST SYSTEM	$1,000	$1,500
FIRE SUPPRESSION SYSTEM	$0	$0
OTHER	$0	$0
SUB-TOTAL	$206,000	$221,500
SALES TAX AT 6.5%	$13,493	$14,508
SALVAGE AT 5% OF PRICE (2)	$10,300	$11,075
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	27,000	27,000
NPV VEHICLE CAPITAL COST	$209,193	$224,933
.......ANNUAL........		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/GAL)	3.3	3.2
FUEL COST PER GALLON	$0.89	$0.97
ANNUAL FUEL COST	$10,788	$12,125
APRX ANNUAL LICENSE (3)	0	0
REGISTRATION FEES PER YEAR (3)	0	0
CLAIMS COSTS (10% LESS THAN INSURANCE)	$11,327	$11,640
MAINTENANCE COST/MILE	$1.00	$1.00
TOTAL ANNUAL COSTS/YEAR	$62,115	$63,765
NPV ANNUAL COSTS (4)	$493,359	$506,465
TOTAL VEHICLE NPV	$702,552	$731,399
TOTAL COSTS PER MILE	$1.46	$1.52

(1) FROM "PUBLIC TRANSPORTATION ALTERNATIVE FUELS" 1992 DATA
(2) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(3) PUBLIC AGENCIES EXEMPT FROM LICENSE & REGISTRATION FEES
(4) ASSUMES A DISCOUNT RATE OF 7%

Methanol operators have reported high parts costs associated with the limited market. There have also been high failure rates with early fleets from fuel injectors and glow plugs.

Actual operating maintenance cost data for 40 ft transit buses was available from two operators who had established diesel control fleets and is shown in Table 8-18.

The vehicle manufacturers recommend a more extensive preventive maintenance program. Table 8-19 shows the recommended engine maintenance schedule for the DDC 6V-92 methanol engine.

It is estimated that the engine, fueling and exhaust system maintenance will cost 5 to 20 percent more than the baseline transit bus. This results in a cost per mile increase of $0.0175 to $0.07. We have assumed an average increase of $0.04 per mile.

The demonstration fleets have not accumulated sufficient miles in order to assess the long term effects on engine durability. However, it is reasonable to assume there will be some reduction in vehicle life because of the corrosive nature of the fuel. We have assumed a 10 percent reduction in engine life. Because it is expected that emissions will continue to meet the EPA standards until the 250,000 mile rebuild time frame, this reduction in durability does not result in any cost increases in our cost model. However, over a large fleet, it is likely that this would result in further cost increases. Cost analyses of an M100 2-stroke bus is shown in Table 8-20. Cost analyses of an M100 4-stroke bus is estimated in Table 8-21.

CNG Lean Burn Spark-Ignition

CNG buses will include increased costs for the engine, on-board fuel delivery system, fire protection system, and structural modifications. The engine is expected to cost about twice that of the baseline bus. Recent bid prices for CNG buses ranged from $247,975 for Austin Metro to $260,300 for Sacramento RTD. It is estimated that the cost increase will from $40,00 to $50,000 over the standard diesel bus.

Several of the transit properties operating CNG demonstration fleets have established a diesel coach control group and have comparative data on fuel efficiency for similar duty cycles.

Table 8-18. Average operating maintenance costs (1992 Dollars)

Agency	Maintenance Cost Per Mile			Total ($)
	Fuel ($)	Parts ($)	Labor ($)	
SCRTD[a]				
Methanol	0.44	0.50	0.40	1.34
Diesel	0.17	0.38	0.34	0.89
Seattle Metro[b]				
Methanol	0.38	0.10	0.03	0.51
Diesel	0.19	0.10	0.02	0.31

[a]Alternative Fuel Project Fourth Quarter Report 1991
[b]Methanol Project Data Report December 1991

Table 8-19. Manufacturer's recommended methanol bus engine maintenance schedule

Component	Schedule	
	Miles	Months
Glow plus—replace	50,000	12
Injectors		
Clean tips	50,000	12
Change out[a]	100,000	24
Bypass control components		
PWM solenoid valve—replace	50,000	12
Feedback potentiometer—replace	100,000	24
Air pressure regulator filter—clean	Per manufacturers' recommendation[b]	
Change oil and filter[c]	6,000	—
Change fuel filters		
First change	1,000	—
Thereafter	6,000	—

[a]A manufacturing exchange program will be established.
[b]This component is supplied by the bus manufacturer.
[c]Engine oil must be changed if contaminated with fuel from injector leak.

Table 8-20. M100 DI compression ignition 2-stroke bus costs (1992 Dollars)

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE (1)	$200,000	$210,000
DIFFERENTIAL COST		
ENGINE	$12,000	$12,000
FUEL SYSTEM	$1,000	$1,000
EXHAUST SYSTEM	$500	$1,000
FIRE SUPPRESSION SYSTEM	$7,000	$7,000
OTHER	$0	$0
SUB-TOTAL	$220,500	$231,000
SALES TAX AT 6.5%	$14,443	$15,131
SALVAGE AT 5% OF PRICE (2)	$11,025	$11,550
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	28,000	28,000
NPV VEHICLE CAPITAL COST	$223,918	$234,581
.......ANNUAL........		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/GAL)	1.4	1.3
FUEL COST PER GALLON (3)	$0.43	$0.48
ANNUAL FUEL COST	$12,286	$14,769
APRX ANNUAL LICENSE (4)	$0	$0
REGISTRATION FEES PER YEAR (4)	$0	$0
CLAIMS COSTS (10% LESS THAN INSURANCE)	$11,457	$11,978
MAINTENANCE COST/MILE	$1.04	$1.07
TOTAL ANNUAL COSTS/YEAR	$65,343	$69,547
NPV ANNUAL COSTS (5)	$518,997	$552,392
TOTAL VEHICLE NPV	$742,914	$786,972
TOTAL COSTS PER MILE	$1.55	$1.64

(1) FROM "PUBLIC TRANSPORTATION ALTERNATIVE FUELS" 1992 DATA
(2) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(3) ACUREX ESTIMATES
(4) PUBLIC AGENCIES EXEMPT FROM LICENSE & REGISTRATION FEES
(5) ASSUMES A DISCOUNT RATE OF 7%

Table 8-21. M100 DI compression ignition 4-stroke bus costs (1992 Dollars)

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE (1)	$200,000	$210,000
DIFFERENTIAL COST		
ENGINE	$12,000	$12,000
FUEL SYSTEM	$1,000	$1,000
EXHAUST SYSTEM	$500	$1,000
FIRE SUPPRESSION SYSTEM	$7,000	$7,000
OTHER	$0	$0
SUB-TOTAL	$220,500	$231,000
SALES TAX AT 6.5%	$14,443	$15,131
SALVAGE AT 5% OF PRICE (2)	$11,025	$11,550
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	28,000	28,000
NPV VEHICLE CAPITAL COST	$223,918	$234,581
.......ANNUAL........		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/GAL)	1.45	1.4
FUEL COST PER GALLON (3)	$0.43	$0.48
ANNUAL FUEL COST	$11,862	$13,714
APRX ANNUAL LICENSE (4)	$0	$0
REGISTRATION FEES PER YEAR (4)	$0	$0
CLAIMS COSTS (10% LESS THAN INSURANCE)	$11,457	$11,978
MAINTENANCE COST/MILE	$1.04	$1.07
TOTAL ANNUAL COSTS/YEAR	$64,919	$68,492
NPV ANNUAL COSTS (5)	$515,632	$544,013
TOTAL VEHICLE NPV	$739,550	$778,593
TOTAL COSTS PER MILE	$1.54	$1.62

(1) FROM "PUBLIC TRANSPORTATION ALTERNATIVE FUELS" 1992 DATA
(2) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(3) ACUREX ESTIMATES
(4) PUBLIC AGENCIES EXEMPT FROM LICENSE & REGISTRATION FEES
(5) ASSUMES A DISCOUNT RATE OF 7%

Although the early comparisons found CNG to be about 32 percent less efficient, it is projected that as the technology develops CNG will achieve comparable efficiency, or about 2.1 miles per 100 standard cubic feet of natural gas.

It is estimated that the engine, fueling and exhaust system maintenance will cost 5 to 20 percent more than the baseline transit bus. This results in a cost per mile increase of $0.0175 to $0.07. We have assumed an average increase of $0.04 per mile.

The demonstration fleets have not accumulated sufficient miles in order to assess the long term effects on engine durability. However, it is reasonable to assume there will be some improvement in engine life because of the reduced particulate emissions. We have assumed a 10 percent increase in engine life and vehicle life.

Cost analysis of a CNG lean burn spark ignition bus is shown in Table 8-22.

Liquified Petroleum Gas Lean Burn Spark-Ignition

While there is no currently available production LPG bus, estimates were developed based on OCTA's experience with the Cummins L-10. OCTA staff estimated that an LPG bus would cost about $30,000 more than a standard diesel (Reference 68).

Cost analysis for the LPG bus is shown in Table 8-23.

LNG Lean Burn Spark-Ignition

LNG buses will include increased costs for the engine, on-board fuel delivery system, fire protection system, and structural modifications. We have assumed a 10 percent increase in engine life and vehicle life. Cost analysis is shown in Table 8-24.

Urban Bus Cost Summary

A summary of the urban transit bus life cycle costs for all technologies costed above is shown in Table 8-25. Life cycle costs vary from $1.36 per mile for the low baseline LPG lean burn spark-ignited urban transit bus to $1.74 per mile for the high LNG lean-burn spark-ignited urban transit bus estimates.

Table 8-22. CNG lean burn spark-ignition bus costs (1992 Dollars)

COST ITEM	LOW		HIGH	
.....ONE TIME.....				
PURCHASE PRICE- BASE PRICE (1)	$200,000		$210,000	
DIFFERENTIAL COST				
ENGINE	$10,000		$14,000	
FUEL SYSTEM	$32,000		$32,000	
EXHAUST SYSTEM	$500		$1,000	
FIRE SUPPRESSION SYSTEM	$3,000		$7,000	
OTHER	$5,000	(2)	$5,000	(2)
SUB-TOTAL	$250,500		$269,000	
SALES TAX AT 6.5%	$16,408		$17,620	
SALVAGE AT 5% OF PRICE (3)	$12,525		$13,450	
LIFETIME IN YEARS	12		12	
GROSS VEHICLE WEIGHT (IN LBS)	30,000		30,000	
NPV VEHICLE CAPITAL COST	$254,383		$273,170	
.......ANNUAL........				
MILES PER YEAR	40,000		40,000	
LIFETIME FUEL ECONOMY (MILES/100 SCF) (4)	2.3		2.1	
FUEL COST PER 100 SCF (5)	$0.41		$0.54	
ANNUAL FUEL COST	$7,130		$10,286	
APRX ANNUAL LICENSE (6)	$0		$0	
REGISTRATION FEES PER YEAR (6)	$0		$0	
CLAIMS COSTS (10% LESS THAN INSURANCE)	$13,280		$13,280	
MAINTENANCE COST/MILE	$0.95		$1.07	
TOTAL ANNUAL COSTS/YEAR	$58,410		$66,366	
NPV ANNUAL COSTS (7)	$463,936		$527,122	
TOTAL VEHICLE NPV	$718,319		$800,292	
TOTAL COSTS PER MILE	$1.50		$1.67	

(1) FROM "PUBLIC TRANSPORTATION ALTERNATIVE FUELS" 1992 DATA
(2) STRUCTURAL MODIFICATIONS
(3) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(4) ASSUMES EQUIVALENT EFFICIENCY TO DIESEL
(5) ACUREX ESTIMATES
(6) PUBLIC AGENCIES EXEMPT FROM LICENSE & REGISTRATION FEES
(7) ASSUMES A DISCOUNT RATE OF 7%

Table 8-23. LPG lean burn spark-ignition bus costs (1992 Dollars)

COST ITEM	LOW	HIGH
.....ONE TIME.....		
PURCHASE PRICE- BASE PRICE (1)	$200,000	$210,000
DIFFERENTIAL COST		
ENGINE	$12,000	$14,000
FUEL SYSTEM	$8,000	$13,000
EXHAUST SYSTEM	$500	$1,000
FIRE SUPPRESSION SYSTEM	$0	$3,000
OTHER	$0	$0
SUB-TOTAL	$220,500	$241,000
SALES TAX AT 6.5%	$14,443	$15,786
SALVAGE AT 5% OF PRICE (2)	$11,025	$12,050
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	27,000	27,000
NPV VEHICLE CAPITAL COST	$223,918	$244,736
.......ANNUAL........		
MILES PER YEAR	40,000	40,000
LIFETIME FUEL ECONOMY (MILES/GAL)	5.5	5.5
FUEL COST PER GALLON	$0.60	$0.60
ANNUAL FUEL COST	$4,364	$4,364
APRX ANNUAL LICENSE (3)	$0	$0
REGISTRATION FEES PER YEAR (3)	$0	$0
CLAIMS COSTS (10% LESS THAN INSURANCE)	$11,457	$12,499
MAINTENANCE COST/MILE	$0.95	$1.07
TOTAL ANNUAL COSTS/YEAR	$53,821	$59,663
NPV ANNUAL COSTS (4)	$427,480	$473,882
TOTAL VEHICLE NPV	$651,398	$718,617
TOTAL COSTS PER MILE	$1.36	$1.50

(1) FROM "PUBLIC TRANSPORTATION ALTERNATIVE FUELS" 1992 DATA
(2) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(3) PUBLIC AGENCIES EXEMPT FROM LICENSE & REGISTRATION FEES
(4) ASSUMES A DISCOUNT RATE OF 7%

Table 8-24. LNG lean burn spark-ignition bus costs (1992 Dollars)

COST ITEM	LOW		HIGH	
.....ONE TIME.....				
PURCHASE PRICE- BASE PRICE (1)	$200,000		$210,000	
DIFFERENTIAL COST				
ENGINE	$14,000		$14,000	
FUEL SYSTEM	$15,000		$22,000	
EXHAUST SYSTEM	$500		$1,000	
FIRE SUPPRESSION SYSTEM	$0		$7,000	
OTHER	$4,000	(2)	$7,000	(2)
SUB-TOTAL	$233,500		$261,000	
SALES TAX AT 6.5%	$15,294		$17,096	
SALVAGE AT 5% OF PRICE (3)	$11,675		$13,050	
LIFETIME IN YEARS	12		12	
GROSS VEHICLE WEIGHT (IN LBS)	27,000		27,000	
NPV VEHICLE CAPITAL COST	$237,119		$265,046	
.......ANNUAL........				
MILES PER YEAR	40,000		40,000	
LIFETIME FUEL ECONOMY (MILES/GAL)	1.8		1.6	
FUEL COST PER GALLON (4)	$0.52		$0.62	
ANNUAL FUEL COST	$11,886		$15,500	
APRX ANNUAL LICENSE (5)	$0		$0	
REGISTRATION FEES PER YEAR (5)	$0		$0	
CLAIMS COSTS (10% LESS THAN INSURANCE)	$13,020		$13,541	
MAINTENANCE COST/MILE	$1.00		$1.07	
TOTAL ANNUAL COSTS/YEAR	$64,906		$71,841	
NPV ANNUAL COSTS (6)	$515,526		$570,611	
TOTAL VEHICLE NPV	$752,645		$835,656	
TOTAL COSTS PER MILE	$1.57		$1.74	

(1) FROM "PUBLIC TRANSPORTATION ALTERNATIVE FUELS" 1992 DATA
(2) STRUCTURAL MODIFICATIONS
(3) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(4) ACUREX ESTIMATES
(5) PUBLIC AGENCIES EXEMPT FROM LICENSE & REGISTRATION FEES
(6) ASSUMES A DISCOUNT RATE OF 7%

Table 8-25. Urban transit bus life cycle cost summary (1992 Dollars)

CONFIGURATION	COST RANGE	PURCHASE PRICE	LIFETIME (YEARS)	GVW (LBS)	REG WGT (LBS)	LENGTH (FT)	NO OF AXLES	NO OF TIRES	MILES PER YEAR	COST PER MILE
BASELINE	LOW	$200,000	12	30,000	22,000	40	2	6	40,000	$1.42
	HIGH	$210,000	12	30,000	23,500	40	2	6	40,000	$1.47
DI DIESEL WITH TRAP	LOW	$215,000	12	30,000	22,000	40	2	6	40,000	$1.48
	HIGH	$240,000	12	30,000	23,500	40	2	6	40,000	$1.58
DI DIESEL WITH DE-NOx	LOW	$206,000	12	30,000	22,000	40	2	6	40,000	$1.46
	HIGH	$221,500	12	30,000	23,500	40	2	6	40,000	$1.52
M100 2 STROKE	LOW	$220,500	12	30,000	23,000	40	2	6	40,000	$1.55
	HIGH	$231,000	12	30,000	24,500	40	2	6	40,000	$1.64
M100 GLOW PLUG 4 STROKE	LOW	$220,500	12	30,000	23,000	40	2	6	40,000	$1.54
	HIGH	$231,000	12	30,000	24,500	40	2	6	40,000	$1.62
CNG LEAN BURN SPARK	LOW	$250,500	12	30,000	24,000	40	2	6	40,000	$1.50
	HIGH	$269,000	12	30,000	25,500	40	2	6	40,000	$1.67
LPG LEAN BURN SPARK	LOW	$220,500	12	30,000	23,500	40	2	6	40,000	$1.36
	HIGH	$241,000	12	30,000	25,000	40	2	6	40,000	$1.50
LNG LEAN BURN SPARK	LOW	$233,500	12	30,000	23,500	40	2	6	40,000	$1.57
	HIGH	$261,000	12	30,000	25,000	40	2	6	40,000	$1.74

8.3.4 Medium Heavy-Duty Delivery Truck

Baseline Vehicle

The baseline vehicle is a delivery truck using diesel fuel. This model has two axles with double tires in the rear. The gross vehicle weight is calculated at 30,000 lb. Table 8-26 presents projected costs. Annual costs assume a fuel consumption rate of 12 mpg.

Alternative Technologies

Direct Injection Diesel With EGR and Catalytic Trap

Table 8-27 presents projected costs for a medium heavy-duty vehicle with this technology. Differential costs for this technology include $2,000 to $3,000 for the engine, and $4,500 to $5,700 for the catalytic trap system.

The annual costs assume a fuel consumption rate of 11.6 mpg.

M100 Direct Injection Compression Ignition Four Stroke

Table 8-28 presents projected costs for a medium heavy-duty vehicle with this technology. Differential costs for this technology include $1,000 to $2,000 for the engine, $1,000 to $2000 for the fuel system, and $500 to $1,000 for improvements in the exhaust system.

The annual costs assume a fuel consumption rate of 5 mpg.

CNG Lean Burn Spark-Ignition

Table 8-29 presents projected costs for a medium heavy-duty vehicle with this technology. Differential costs for this technology include $1,000 to $2,000 for the engine, $2,000 to $3,000 for the fuel system, and $500 to $1,000 for an oxidation catalyst.

The annual costs assume a fuel consumption rate of 7.5 miles per 100 scf.

LNG Lean Burn Spark-Ignition

Table 8-30 presents projected costs for a medium heavy-duty vehicle with this technology. Differential costs for this technology include $1,000 to $2,000 for the engine, $2,000 to $4,000 for the fuel system, and $500 to $1,000 for an oxidation catalyst.

The annual costs assume a fuel consumption rate of 5.7 mpg.

Table 8-26. Baseline MHD vehicle costs (1992 Dollars)

COST ITEM	LOW	HIGH
......ONE TIME......		
PURCHASE PRICE- BASE PRICE	$70,000	$70,000
DIFFERENTIAL COST		
ENGINE	$0	$0
FUEL SYSTEM	$0	$0
EXHAUST SYSTEM	$0	$0
FIRE SUPPRESSION SYSTEM		
SUB-TOTAL	$70,000	$70,000
SALES TAX AT 6.5%	$4,585	$4,585
SALVAGE AT 5% OF PRICE (1)	$3,500	$3,500
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	30,000	30,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	0 (2)	0 (2)
NPV VEHICLE CAPITAL COST	$71,085	$71,085
.......ANNUAL........		
MILES PER YEAR	25,000	25,000
LIFETIME FUEL ECONOMY (MILES/GAL)	12	12
FUEL COST PER GALLON	$1.32	$1.42
ANNUAL FUEL COST	$2,750	$2,958
APPRX. ANNUAL LICENSE (3)	$512	$512
REGISTRATION FEES PER YEAR (3)	$501	$501
INSURANCE/YR (4)		
INCL COLLISION	$4,051	$4,051
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$2,678	$2,678
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$3,250	$3,250
ROUTINE MAINTENANCE COST/YEAR (5)	$1,242	$1,242
TOTAL ANNUAL COSTS/YEAR	$7,743	$7,951
NPV ANNUAL COSTS (6)	$52,759	$79,514
.......PERIODIC.......		
TIRE REPLACEMENT MILES	100,000	100,000
TIRE REPLACEMENT COST EA SET	$2,350	$2,350
LIFETIME TIRE REPLACMENTS	3	3
ENGINE REBUILD MILES	250,000	250,000
ENGINE REBUILD COST EA	$9,250	$10,175
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (6)	$7,016	$7,373
TOTAL VEHICLE NPV	$130,860	$157,972
TOTAL COSTS PER MILE	$0.44	$0.53

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) BASED ON CA DMV 1992
(4) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(5) FROM RYDER TRUCK LEASE COST AND MAINTENANCE SCHEDULE
(6) ASSUMES A DISCOUNT RATE OF 10%

Table 8-27. DI diesel with EGR and catalytic trap MHD vehicle costs (1992 Dollars)

COST ITEM	LOW	HIGH
......ONE TIME......		
PURCHASE PRICE- BASE PRICE	$70,000	$70,000
DIFFERENTIAL COST		
ENGINE	$2,000	$3,000
FUEL SYSTEM	$0	$0
EXHAUST SYSTEM	$4,500	$5,700
FIRE SUPPRESSION SYSTEM		
SUB-TOTAL	$76,500	$78,700
SALES TAX AT 6.5%	$5,011	$5,155
SALVAGE AT 5% OF PRICE (1)	$3,825	$3,935
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	30,000	30,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	0 (2)	0 (2)
NPV VEHICLE CAPITAL COST	$77,686	$79,920
.......ANNUAL........		
MILES PER YEAR	25,000	25,000
LIFETIME FUEL ECONOMY (MILES/GAL)	11.6	11.6
FUEL COST PER GALLON	$1.34	$1.42
ANNUAL FUEL COST	$2,888	$3,060
APPRX. ANNUAL LICENSE (3)	$533	$533
REGISTRATION FEES PER YEAR (3)	$501	$501
INSURANCE/YR (4)		
INCL COLLISION	$4,224	$4,340
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$2,793	$2,869
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$3,389	$3,482
ROUTINE MAINTENANCE COST/YEAR (5)	$1,329	$1,416
TOTAL ANNUAL COSTS/YEAR	$8,107	$8,459
NPV ANNUAL COSTS (6)	$55,240	$84,593
.......PERIODIC.......		
TIRE REPLACEMENT MILES	100,000	100,000
TIRE REPLACEMENT COST EA SET	$2,350	$2,350
LIFETIME TIRE REPLACMENTS	3	3
ENGINE REBUILD MILES	250,000	250,000
ENGINE REBUILD COST EA	$9,250	$10,175
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (6)	$7,016	$7,373
TOTAL VEHICLE NPV	$139,942	$171,886
TOTAL COSTS PER MILE	$0.47	$0.57

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) BASED ON CA DMV 1992
(4) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(5) ASSUMES 20-40% INCREASE IN ENGINE/FUEL SYSTEM COSTS
(6) ASSUMES A DISCOUNT RATE OF 10%

Table 8-28. M100 DI compression ignition 4-stroke MHD vehicle costs (1992 Dollars)

COST ITEM	LOW	HIGH
......ONE TIME......		
PURCHASE PRICE- BASE PRICE	$70,000	$70,000
DIFFERENTIAL COST		
ENGINE	$3,000	$4,000
FUEL SYSTEM	$2,000	$3,000
EXHAUST SYSTEM	$500	$1,000
FIRE SUPPRESSION SYSTEM		
SUB-TOTAL	$75,500	$78,000
SALES TAX AT 6.5%	$4,945	$5,109
SALVAGE AT 5% OF PRICE (1)	$3,775	$3,900
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	30,000	30,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	0 (2)	0 (2)
NPV VEHICLE CAPITAL COST	$76,670	$79,209
.......ANNUAL........		
MILES PER YEAR	25,000	25,000
LIFETIME FUEL ECONOMY (MILES/GAL)	5	5
FUEL COST PER GALLON (3)	$0.62	$0.69
ANNUAL FUEL COST	$3,100	$3,450
ANNUAL LICENSE (4)	$552	$566
REGISTRATION FEES PER YEAR (4)	$501	$501
INSURANCE/YR (5)		
INCL COLLISION	$4,369	$4,485
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$2,888	$2,965
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$3,505	$3,598
ROUTINE MAINTENANCE COST/YEAR (6)	$1,329	$1,416
TOTAL ANNUAL COSTS/YEAR	$8,435	$8,965
NPV ANNUAL COSTS (7)	$57,474	$89,653
.......PERIODIC.......		
TIRE REPLACEMENT MILES	100,000	100,000
TIRE REPLACEMENT COST EA SET	$2,350	$2,350
LIFETIME TIRE REPLACMENTS	3	3
ENGINE REBUILD MILES	250,000	250,000
ENGINE REBUILD COST EA	$9,250	$10,175
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (7)	$7,016	$7,373
TOTAL VEHICLE NPV	$141,161	$176,235
TOTAL COSTS PER MILE	$0.47	$0.59

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) ACUREX ESTIMATES
(4) BASED ON CA DMV 1992
(5) ASSUMES 20-40% INCREASE IN ENGINE/FUEL SYSTEM COSTS
(6) FROM RYDER TRUCK LEASE COST AND MAINTENANCE SCHEDULE
(7) ASSUMES A DISCOUNT RATE OF 10%

Table 8-29. CNG lean burn spark-ignition MHD vehicle costs (1992 Dollars)

COST ITEM	LOW	HIGH
......ONE TIME......		
PURCHASE PRICE- BASE PRICE	$70,000	$70,000
DIFFERENTIAL COST		
ENGINE	$2,000	$3,000
FUEL SYSTEM	$4,000	$6,000
EXHAUST SYSTEM	$500	$1,000
FIRE SUPPRESSION SYSTEM		
SUB-TOTAL	$76,500	$80,000
SALES TAX AT 6.5%	$5,011	$5,240
SALVAGE AT 5% OF PRICE (1)	$3,825	$4,000
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	30,000	30,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	0 (2)	0 (2)
NPV VEHICLE CAPITAL COST	$77,686	$81,240
.......ANNUAL........		
MILES PER YEAR	25,000	25,000
LIFETIME FUEL ECONOMY (MILES/100 SCF)	10.1	10.1
FUEL COST PER 100 SCF (3)	$0.51	$0.73
ANNUAL FUEL COST	$1,262	$1,807
ANNUAL LICENSE (4)	$559	$581
REGISTRATION FEES PER YEAR (4)	$594	$594
INSURANCE/YR (5)		
INCL COLLISION	$4,427	$4,600
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$2,927	$3,041
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$3,552	$3,691
ROUTINE MAINTENANCE COST/YEAR (6)	$1,217	$1,304
TOTAL ANNUAL COSTS/YEAR	$6,625	$7,396
NPV ANNUAL COSTS (7)	$45,143	$73,955
.......PERIODIC.......		
TIRE REPLACEMENT MILES	80,000	80,000
TIRE REPLACEMENT COST EA SET	$2,350	$2,350
LIFETIME TIRE REPLACMENTS	3	3
ENGINE REBUILD MILES	250,000	250,000
ENGINE REBUILD COST EA	$9,250	$10,175
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (7)	$7,517	$7,873
TOTAL VEHICLE NPV	$130,346	$163,068
TOTAL COSTS PER MILE	$0.43	$0.54

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) ACUREX ESTIMATES
(4) BASED ON CA DMV 1992
(5) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(6) ASSUMES 5% SAVINGS TO 15% INCREASE IN ENGINE/FUEL SYSTEM
(7) ASSUMES A DISCOUNT RATE OF 10%

Table 8-30. LNG lean burn spark-ignition MHD vehicle costs (1992 Dollars)

COST ITEM	LOW	HIGH
......ONE TIME......		
PURCHASE PRICE- BASE PRICE	$70,000	$70,000
DIFFERENTIAL COST		
ENGINE	$2,000	$3,000
FUEL SYSTEM	$4,000	$6,000
EXHAUST SYSTEM	$500	$1,000
FIRE SUPPRESSION SYSTEM		
SUB-TOTAL	$76,500	$80,000
SALES TAX AT 6.5%	$5,011	$5,240
SALVAGE AT 5% OF PRICE (1)	$3,825	$4,000
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	30,000	30,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$77,686	$81,240
.......ANNUAL........		
MILES PER YEAR	25,000	25,000
LIFETIME FUEL ECONOMY (MILES/GAL)	5.7	5.7
FUEL COST PER GALLON (3)	$0.61	$0.81
ANNUAL FUEL COST	$2,675	$3,553
ANNUAL LICENSE (4)	$559	$581
REGISTRATION FEES PER YEAR (4)	$594	$594
INSURANCE/YR (5)		
INCL COLLISION	$4,427	$4,600
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$2,927	$3,041
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$3,552	$3,691
ROUTINE MAINTENANCE COST/YEAR (6)	$1,217	$1,304
TOTAL ANNUAL COSTS/YEAR	$8,038	$9,141
NPV ANNUAL COSTS (7)	$54,771	$91,412
.......PERIODIC.......		
TIRE REPLACEMENT MILES	90,000	90,000
TIRE REPLACEMENT COST EA SET	$2,350	$2,350
LIFETIME TIRE REPLACMENTS	3	3
ENGINE REBUILD MILES	250,000	250,000
ENGINE REBUILD COST EA	$9,250	$10,175
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (7)	$7,256	$7,613
TOTAL VEHICLE NPV	$139,714	$180,265
TOTAL COSTS PER MILE	$0.47	$0.60

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) ACUREX ESTIMATES
(4) BASED ON CA DMV 1992
(5) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(6) ASSUMES 5% SAVINGS TO 15% INCREASE IN ENGINE/FUEL SYSTEM
(7) ASSUMES A DISCOUNT RATE OF 10%

Table 8-31 projects costs for a medium heavy-duty LPG vehicle.

Medium Heavy-Duty Vehicle Cost Summary

A summary of the heavy heavy-duty transfer truck life cycle costs for all technologies costed above is shown in Table 8-32. Life cycle costs vary from $0.43 per mile for the low CNG lean-burn spark-ignited vehicle to $0.60 per mile for the high LNG lean-burn spark-ignited vehicle estimates.

8.3.5 Light Heavy-Duty Delivery Truck

Baseline Vehicle

The baseline vehicle is a delivery truck using California phase 2 reformulated gasoline. The engine technology for the baseline vehicle and for each of the alternative fuels is stoichiometric spark-ignition with a three-way catalyst (TWC). The vehicle has two axles, with double tires on the rear axle. Gross vehicle weight is calculated at 10,500 lb. Table 8-33 gives projected costs for this vehicle.

Alternative Technologies

M85 Stoichiometric Spark-Ignition with TWC

Table 8-34 presents projected costs for a light heavy-duty vehicle with this technology. Differential costs for this technology include $3,000 to $4,000 for the engine, $2,000 to $3,000 for the fuel system, and $500 to $750 for an oxidation catalyst.

The annual costs assume a fuel consumption rate of 7 miles per gallon.

CNG Stoichiometric Spark-Ignition with TWC

Slightly lower maintenance costs are expected for spark ignited CNG vehicles over gasoline powered ones because of increased engine life and less engine deposits. Reduced preventive maintenance costs are also possible through increasing the intervals between oil changes, however since this is often tied to warranties these are usually not extended. The Colorado Governor's Task Force study predicted that maintenance costs for heavy duty diesel vehicles would vary from slightly higher to slightly lower because of the more complex technology. They predicted that

Table 8-31. LPG lean burn spark-ignition MHD vehicle costs (1992 Dollars)

COST ITEM	LOW	HIGH
......ONE TIME......		
PURCHASE PRICE- BASE PRICE	$70,000	$70,000
DIFFERENTIAL COST		
ENGINE	$2,000	$3,000
FUEL SYSTEM	$3,000	$4,000
EXHAUST SYSTEM	$500	$1,000
FIRE SUPPRESSION SYSTEM		
SUB-TOTAL	$75,500	$78,000
SALES TAX AT 6.5%	$4,945	$5,109
SALVAGE AT 5% OF PRICE (1)	$3,775	$3,900
LIFETIME IN YEARS	12	12
GROSS VEHICLE WEIGHT (IN LBS)	30,000	30,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$76,670	$79,209
.......ANNUAL........		
MILES PER YEAR	25,000	25,000
LIFETIME FUEL ECONOMY (MILES/GAL)	6.6	6.6
FUEL COST PER GALLON (3)	$0.79	$0.79
ANNUAL FUEL COST	$2,992	$2,992
ANNUAL LICENSE (4)	$552	$566
REGISTRATION FEES PER YEAR (4)	$594	$594
INSURANCE/YR (5)		
INCL COLLISION	$4,369	$4,485
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$2,888	$2,965
NO OF YEARS	7	7
SUB-TOTAL AVG ANNUAL INSURANCE	$3,505	$3,598
ROUTINE MAINTENANCE COST/YEAR (6)	$1,217	$1,242
TOTAL ANNUAL COSTS/YEAR	$8,309	$8,427
NPV ANNUAL COSTS (7)	$56,612	$84,268
.......PERIODIC.......		
TIRE REPLACEMENT MILES	90,000	90,000
TIRE REPLACEMENT COST EA SET	$2,350	$2,350
LIFETIME TIRE REPLACMENTS	3	3
ENGINE REBUILD MILES	250,000	250,000
ENGINE REBUILD COST EA	$9,250	$10,175
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (7)	$7,256	$7,613
TOTAL VEHICLE NPV	$140,538	$171,090
TOTAL COSTS PER MILE	$0.47	$0.57

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(4) ACUREX ESTIMATES
(5) BASED ON CA DMV 1992
(6) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(7) ASSUMES 5% SAVINGS TO NO CHANGE IN ENGINE/FUEL SYSTEM COSTS
(7) ASSUMES A DISCOUNT RATE OF 10%

Table 8-32. Medium heavy-duty vehicle life cycle cost summary (1992 Dollars)

CONFIGURATION	COST RANGE	PURCHASE PRICE	LIFETIME (YEARS)	GVW (LBS)	REG WGT (LBS)	NO OF AXLES	NO OF TIRES	MILES PER YEAR	COST PER MILE
BASELINE	LOW	$70,000	12	30,000	12,000	2	6	25,000	$0.44
	HIGH	$70,000	12	30,000	13,000	2	6	25,000	$0.53
DI DIESEL WITH TRAP	LOW	$76,500	12	30,000	12,000	2	6	25,000	$0.47
	HIGH	$78,700	12	30,000	13,000	2	6	25,000	$0.57
M100 GLOW PLUG 4 STROKE	LOW	$75,500	12	30,000	13,000	2	6	25,000	$0.47
	HIGH	$78,000	12	30,000	14,000	2	6	25,000	$0.59
CNG LEAN BURN SPARK	LOW	$76,500	12	30,000	14,000	2	6	25,000	$0.43
	HIGH	$80,000	12	30,000	15,000	2	6	25,000	$0.54
LNG LEAN BURN SPARK	LOW	$76,500	12	30,000	13,500	2	6	25,000	$0.47
	HIGH	$80,000	12	30,000	14,500	2	6	25,000	$0.60
LPG LEAN BURN SPARK	LOW	$75,500	12	30,000	13,500	2	6	25,000	$0.47
	HIGH	$78,000	12	30,000	14,500	2	6	25,000	$0.57

Table 8-33. Baseline LHD vehicle costs (1992 Dollars)

COST ITEM	LOW	HIGH
....ONE TIME....		
PURCHASE PRICE- BASE PRICE	$35,000	$35,000
DIFFERENTIAL COST		
ENGINE	$0	$0
FUEL SYSTEM	$0	$0
EXHAUST SYSTEM	$0	$0
FIRE SUPPRESSION SYSTEM		
SUB-TOTAL	$35,000	$35,000
SALES TAX AT 6.5%	$2,293	$2,293
SALVAGE AT 5% OF PRICE (1)	$1,750	$1,750
LIFETIME IN YEARS	20	20
GROSS VEHICLE WEIGHT (IN LBS)	10,500	10,500
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$35,543	$35,543
......ANNUAL......		
MILES PER YEAR	15,000	15,000
LIFETIME FUEL ECONOMY (MILES/GAL)	12	12
FUEL COST PER GALLON	$1.36	$1.36
ANNUAL FUEL COST	$1,700	$1,700
APPRX. ANNUAL LICENSE FEES (3)	$512	$512
REGISTRATION FEES PER YEAR (3)	$406	$406
INSURANCE/YR (4)		
INCL COLLISION	$2,025	$2,025
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$1,339	$1,339
NO OF YEARS	15	15
SUB-TOTAL AVG ANNUAL INSURANCE	$2,518	$2,518
ROUTINE MAINTENANCE COST/YEAR (5)	$525	$525
TOTAL ANNUAL COSTS/YEAR	$5,661	$5,661
NPV ANNUAL COSTS (6)	$48,191	$56,605
......PERIODIC.......		
TIRE REPLACEMENT MILES	40,000	40,000
TIRE REPLACEMENT COST EA	$540	$540
LIFETIME TIRE REPLACMENTS	7	7
ENGINE REBUILD MILES	175,000	175,000
ENGINE REBUILD COST EA	$1,075	$1,185
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (6)	$1,905	$1,941
TOTAL VEHICLE NPV	$85,638	$94,088
TOTAL COSTS PER MILE	$0.29	$0.31

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) BASED ON CA DMV 1992
(4) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(5) FROM RYDER TRUCK LEASE COST AND MAINTENANCE SCHEDULE
(6) ASSUMES A DISCOUNT RATE OF 10%

Table 8-34. M85 stoichiometric/TWC LHD vehicle costs (1992 Dollars)

COST ITEM	LOW	HIGH
....ONE TIME....		
PURCHASE PRICE- BASE PRICE	$35,000	$35,000
DIFFERENTIAL COST		
ENGINE	$1,000	$2,000
FUEL SYSTEM	$1,000	$2,000
EXHAUST SYSTEM	$500	$750
FIRE SUPPRESSION SYSTEM		
SUB-TOTAL	$37,500	$39,750
SALES TAX AT 6.5%	$2,456	$2,604
SALVAGE AT 5% OF PRICE (1)	$1,875	$1,988
LIFETIME IN YEARS	20	20
GROSS VEHICLE WEIGHT (IN LBS)	10,500	10,500
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$38,081	$40,366
......ANNUAL......		
MILES PER YEAR	15,000	15,000
LIFETIME FUEL ECONOMY (MILES/GAL)	7	7
FUEL COST PER GALLON	$0.73	$0.73
ANNUAL FUEL COST	$1,564	$1,564
APPRX. ANNUAL LICENSE FEES (3)	$380	$400
REGISTRATION FEES PER YEAR (3)	$220	$220
INSURANCE/YR (4)		
INCL COLLISION	$2,170	$2,286
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$1,435	$1,511
NO OF YEARS	15	15
SUB-TOTAL AVG ANNUAL INSURANCE	$2,698	$2,841
ROUTINE MAINTENANCE COST/YEAR (5)	$562	$599
TOTAL ANNUAL COSTS/YEAR	$5,424	$5,625
NPV ANNUAL COSTS (6)	$46,179	$56,245
......PERIODIC.......		
TIRE REPLACEMENT MILES	30,000	30,000
TIRE REPLACEMENT COST EA	$540	$540
LIFETIME TIRE REPLACMENTS	10	10
ENGINE REBUILD MILES	175,000	175,000
ENGINE REBUILD COST EA	$1,075	$1,185
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (6)	$2,543	$2,579
TOTAL VEHICLE NPV	$86,803	$99,190
TOTAL COSTS PER MILE	$0.29	$0.33

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) BASED ON CA DMV 1992
(4) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(5) ASSUMES 20-40% INCREASE IN ENGINE/FUEL SYSTEM MAINTENANCE COSTS
(6) ASSUMES A DISCOUNT RATE OF 10%

direct-injection engines would have costs similar to diesel, but that multi-fueled, fumigated engines were likely to be slightly higher (Reference 69).

Fleet operators have reported increased costs associated with tire and brake systems attributed to the increased vehicle weight from the CNG tanks.

Table 8-35 presents projected costs for a light heavy-duty vehicle with this technology. Differential costs for this technology include $2,000 to $3,000 for the engine, $4,000 to $6,000 for the fuel system, and $500 to $750 for an oxidation catalyst.

The annual costs assume a fuel consumption rate of 10.1 miles per 100 scf.

LPG Stoichiometric Spark-Ignition with TWC

Table 8-36 presents projected costs for a light heavy-duty vehicle with this technology. Differential costs for this technology include $2,000 to $3,000 for the engine, $3,000 to $4,000 for the fuel system, and $500 to $750 for an oxidation catalyst.

The annual costs assume a fuel consumption rate of 8.8 miles per gallon.

LNG Stoichiometric Spark-Ignition with TWC

Table 8-37 presents projected costs for a light heavy-duty vehicle with this technology. Differential costs for this technology include $2,000 to $3,000 for the engine, $4,000 to $6,000 for the fuel system, and $500 to $750 for an oxidation catalyst.

The annual costs assume a fuel consumption rate of 7.6 miles per gallon.

Electric

It is assumed that the basic vehicle purchase price is essentially the same as for the baseline light heavy-duty vehicle. Costs have declined in recent years because of AC powertrains, low cost inverters, and on-board chargers. The increased costs are estimated as $8,000 for the batteries and $500 for structural changes to support the additional battery weight.

Projections for increased vehicle life range from 25 to 100 percent. We have used the more conservative 25 percent increase from 20 years to 24 years. However, because of constraints on

Table 8-35. CNG stoichiometric spark-ignition LHD vehicle costs (1992 Dollars)

COST ITEM	LOW	HIGH
....ONE TIME....		
PURCHASE PRICE- BASE PRICE	$35,000	$35,000
DIFFERENTIAL COST		
ENGINE	$1,000	$2,000
FUEL SYSTEM	$2,000	$3,000
EXHAUST SYSTEM	$500	$750
FIRE SUPPRESSION SYSTEM		
SUB-TOTAL	$38,500	$40,750
SALES TAX AT 6.5%	$2,522	$2,669
SALVAGE AT 5% OF PRICE (1)	$1,925	$2,038
LIFETIME IN YEARS	20	20
GROSS VEHICLE WEIGHT (IN LBS)	10,500	10,500
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$39,097	$41,382
......ANNUAL......		
MILES PER YEAR	15,000	15,000
LIFETIME FUEL ECONOMY (MILES/100 SCF)	10.1	9.8
FUEL COST PER 100 SCF	$0.51	$0.73
ANNUAL FUEL COST	$757	$1,117
APPRX. ANNUAL LICENSE FEES (3)	$390	$410
REGISTRATION FEES PER YEAR (3)	$268	$268
INSURANCE/YR (4)		
INCL COLLISION	$2,228	$2,344
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$1,473	$1,549
NO OF YEARS	15	15
SUB-TOTAL AVG ANNUAL INSURANCE	$2,770	$2,913
ROUTINE MAINTENANCE COST/YEAR (5)	$515	$551
TOTAL ANNUAL COSTS/YEAR	$4,700	$5,259
NPV ANNUAL COSTS (6)	$40,014	$52,593
......PERIODIC.......		
TIRE REPLACEMENT MILES	28,000	28,000
TIRE REPLACEMENT COST EA	$540	$540
LIFETIME TIRE REPLACMENTS	10	10
ENGINE REBUILD MILES	175,000	175,000
ENGINE REBUILD COST EA	$1,075	$1,185
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (6)	$2,659	$2,695
TOTAL VEHICLE NPV	$81,769	$96,669
TOTAL COSTS PER MILE	$0.27	$0.32

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) BASED ON CA DMV 1992
(4) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(5) ASSUMES 5-15% INCREASE IN ENGINE/FUEL SYSTEM MAINTENANCE COSTS
(6) ASSUMES A DISCOUNT RATE OF 10%

Table 8-36. LPG stoichiometric spark-ignition LHD vehicle costs (1992 Dollars)

COST ITEM	LOW	HIGH
....ONE TIME....		
PURCHASE PRICE- BASE PRICE	$35,000	$35,000
DIFFERENTIAL COST		
ENGINE	$1,000	$2,000
FUEL SYSTEM	$1,000	$2,000
EXHAUST SYSTEM	$500	$750
FIRE SUPPRESSION SYSTEM		
SUB-TOTAL	$37,500	$39,750
SALES TAX AT 6.5%	$2,456	$2,604
SALVAGE AT 5% OF PRICE (1)	$1,875	$1,988
LIFETIME IN YEARS	20	20
GROSS VEHICLE WEIGHT (IN LBS)	10,500	10,500
REDUCTION IN VEHICLE	7% (2)	7% (2)
EFFICIENCY/10% INC WT		
NPV VEHICLE CAPITAL COST	$38,081	$40,366
......ANNUAL.....		
MILES PER YEAR	15,000	15,000
LIFETIME FUEL ECONOMY (MILES/GAL)	8.8	8.8
FUEL COST PER GALLON	$0.79	$0.79
ANNUAL FUEL COST	$1,347	$1,347
APPRX. ANNUAL LICENSE FEES (3)	$380	$400
REGISTRATION FEES PER YEAR (3)	$268	$268
INSURANCE/YR (4)		
INCL COLLISION	$2,170	$2,286
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$1,435	$1,511
NO OF YEARS	15	15
SUB-TOTAL AVG ANNUAL INSURANCE	$2,698	$2,841
ROUTINE MAINTENANCE COST/YEAR (5)	$515	$525
TOTAL ANNUAL COSTS/YEAR	$5,208	$5,381
NPV ANNUAL COSTS (6)	$44,334	$53,808
......PERIODIC.......		
TIRE REPLACEMENT MILES	36,000	36,000
TIRE REPLACEMENT COST EA	$540	$540
LIFETIME TIRE REPLACMENTS	8	8
ENGINE REBUILD MILES	175,000	175,000
ENGINE REBUILD COST EA	$1,075	$1,185
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (6)	$2,118	$2,154
TOTAL VEHICLE NPV	$84,533	$96,328
TOTAL COSTS PER MILE	$0.28	$0.32

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) BASED ON CA DMV 1992
(4) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(5) ASSUMES 5% SAVINGS TO NO CHANGE IN ENGINE/FUEL SYSTEM MAINTENANCE COSTS
(6) ASSUMES A DISCOUNT RATE OF 10%

Table 8-37. LNG stoichiometric spark-ignition LHD vehicle costs (1992 Dollars)

COST ITEM	LOW	HIGH
....ONE TIME....		
PURCHASE PRICE- BASE PRICE	$35,000	$35,000
DIFFERENTIAL COST		
ENGINE	$1,000	$2,000
FUEL SYSTEM	$2,000	$4,000
EXHAUST SYSTEM	$500	$750
FIRE SUPPRESSION SYSTEM		
SUB-TOTAL	$38,500	$41,750
SALES TAX AT 6.5%	$2,522	$2,735
SALVAGE AT 5% OF PRICE (1)	$1,925	$2,088
LIFETIME IN YEARS	20	20
GROSS VEHICLE WEIGHT (IN LBS)	10,500	10,500
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	0 (2)	0 (2)
NPV VEHICLE CAPITAL COST	$39,097	$42,397
......ANNUAL......		
MILES PER YEAR	15,000	15,000
LIFETIME FUEL ECONOMY (MILES/GAL)	7.6	7.6
FUEL COST PER GALLON	$0.61	$0.81
ANNUAL FUEL COST	$1,204	$1,599
APPRX. ANNUAL LICENSE FEES (3)	$390	$421
REGISTRATION FEES PER YEAR (3)	$268	$268
INSURANCE/YR (4)		
INCL COLLISION	$2,228	$2,401
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$1,473	$1,588
NO OF YEARS	15	15
SUB-TOTAL AVG ANNUAL INSURANCE	$2,770	$2,985
ROUTINE MAINTENANCE COST/YEAR (5)	$263	$394
TOTAL ANNUAL COSTS/YEAR	$4,895	$5,667
NPV ANNUAL COSTS (6)	$41,670	$56,671
......PERIODIC.......		
TIRE REPLACEMENT MILES	31,500	31,500
TIRE REPLACEMENT COST EA	$540	$540
LIFETIME TIRE REPLACMENTS	9	9
ENGINE REBUILD MILES	175,000	175,000
ENGINE REBUILD COST EA	$1,075	$1,185
LIFETIME REBUILDS	1	1
NPV PERIODIC LIFETIME COSTS (6)	$2,388	$2,424
TOTAL VEHICLE NPV	$83,155	$101,493
TOTAL COSTS PER MILE	$0.28	$0.34

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) BASED ON CA DMV 1992
(4) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(5) ASSUMES 5% SAVINGS TO 15% INCREASE IN ENGINE/FUEL SYSTEM
(6) ASSUMES A DISCOUNT RATE OF 10%

recharging and vehicle range, we have limited the annual vehicle mileage to 12,000 miles rather than 15,000 miles.

Maintenance costs assume a reduction to 75 percent of the gasoline vehicle. Periodic costs will rise. Tire mileage will be reduced because of the increased vehicle weight. The increased rate of changes plus the increased vehicle life result in an increase of lifetime tire changes from 7 to 12. No engine rebuild is anticipated during the vehicle user lifetime. Cost analysis is shown in Table 8-38.

Light Heavy-Duty Vehicle Cost Summary

A summary of the light heavy-duty transfer truck life cycle costs for all technologies costed above is shown in Table 8-39. Life cycle costs vary from $0.27 per mile for the low electric and CNG light heavy-duty vehicles to $0.34 per mile for the high LNG stoichiometric spark-ignited vehicle estimate.

Small Transit Bus

Baseline

The baseline small transit vehicle is a 22 ft gasoline-powered vehicle that seats 22 seated passengers. It is used as an urban area shuttle with slow speeds, frequent stops, and a maximum daily range of 75 miles. These vehicles are typically a body-on-chassis. An example of this kind of operation is the shuttle service operated by Santa Barbara Transit between downtown and the beach.

The basic vehicle purchase cost assumes a minimally equipped vehicle without a wheelchair lift. These vehicles have a short life of only four years as compared to 12 years for the standard 40 ft transit bus. The lifetime fuel economy is similar to that for the light heavy-duty baseline vehicle, but is slightly worse because of the frequent stop conditions. Maintenance costs for small buses average about $0.80 per mile for this type of operation. Cost analysis is shown in Table 8-40.

Table 8-38. LHD electric delivery truck costs (1992 Dollars)

COST ITEM	LOW	HIGH
....ONE TIME....		
PURCHASE PRICE- BASE PRICE	$35,000	$35,000
DIFFERENTIAL COST		
ENGINE	$0	$0
FUEL SYSTEM (BATTERIES)	$8,000	$8,000
EXHAUST SYSTEM	$0	$0
STRUCTURAL	$500	$500
SUB-TOTAL	$43,000	$43,000
SALES TAX AT 6.5%	$2,817	$2,817
SALVAGE AT 5% OF PRICE (1)	$2,150	$2,150
LIFETIME IN YEARS	24	24
GROSS VEHICLE WEIGHT (IN LBS)	11,500	15,000
REDUCTION IN VEHICLE EFFICIENCY/10% INC WT	7% (2)	7% (2)
NPV VEHICLE CAPITAL COST	$43,667	$43,667
......ANNUAL......		
MILES PER YEAR	15,000	15,000
LIFETIME FUEL ECONOMY (MILES/KWH)	2	1
FUEL COST PER KWH	$0.08	$0.08
ANNUAL FUEL COST	$600	$1,200
APPRX. ANNUAL LICENSE FEES (3)	$272	$272
REGISTRATION FEES PER YEAR (3)	$268	$268
INSURANCE/YR (4)		
INCL COLLISION	$2,499	$2,654
NO OF YEARS	5	5
INSURANCE/YR		
NO COLLISION	$1,652	$1,652
NO OF YEARS	15	15
SUB-TOTAL AVG ANNUAL INSURANCE	$3,106	$3,171
ROUTINE MAINTENANCE COST/YEAR (5)	$525	$525
TOTAL ANNUAL COSTS/YEAR	$4,771	$5,436
NPV ANNUAL COSTS (6)	$42,868	$54,358
......PERIODIC.......		
TIRE REPLACEMENT MILES	30,000	30,000
TIRE REPLACEMENT COST EA	$540	$540
LIFETIME TIRE REPLACMENTS	12	12
ENGINE REBUILD MILES	500,000	500,000
ENGINE REBUILD COST EA	$1,075	$1,075
LIFETIME REBUILDS	0	0
BATTERY COST/MILE (7)	$0.05	$0.05
NPV PERIODIC LIFETIME COSTS (6)	$9,049	$9,049
TOTAL VEHICLE NPV	$95,584	$107,073
TOTAL COSTS PER MILE	$0.27	$0.30

(1) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(2) EPA TEST DATA,HEAVENRICH ET AL
(3) BASED ON CA DMV 1992
(4) FROM FHWA 1984 ADJUSTED FOR VEHICLE PRICE DIFFERENCE AND CA INFLATION
(5) ASSUMES 25-50% SAVINGS OF MAINTENANCE OVER BASELINE VEHICLE
(6) ASSUMES A DISCOUNT RATE OF 10%
(7) INCLUDES BATTERY REPLACEMENT

Table 8-39. Light heavy-duty vehicle life cycle cost summary (1992 Dollars)

CONFIGURATION	COST RANGE	PURCHASE PRICE	LIFETIME (YEARS)	GVW (LBS)	REG WGT (LBS)	NO OF AXLES	NO OF TIRES	MILES PER YEAR	COST PER MILE
BASELINE	LOW	$35,000	20	10,500	6,000	2	6	15,000	$0.29
	HIGH	$35,000	20	10,500	6,000	2	6	15,000	$0.31
M85 STOICHIOMETRIC/TWC	LOW	$37,500	20	10,500	6,000	2	6	15,000	$0.29
	HIGH	$39,750	20	10,500	6,000	2	6	15,000	$0.33
CNG STOICHIOMETRIC/TWC	LOW	$38,500	20	10,500	7,500	2	6	15,000	$0.27
	HIGH	$40,750	20	10,500	7,500	2	6	15,000	$0.32
LPG STOICHIOMETRIC/TWC	LOW	$37,500	20	10,500	7,000	2	6	15,000	$0.28
	HIGH	$39,750	20	10,500	7,000	2	6	15,000	$0.32
LNG STOICHIOMETRIC/TWC	LOW	$38,500	20	10,500	7,000	2	6	15,000	$0.28
	HIGH	$41,750	20	10,500	7,000	2	6	15,000	$0.34
ELECTRIC	LOW	$43,000	24	11,500	6,000	2	6	15,000	$0.27
	HIGH	$43,000	24	15,000	6,000	2	6	15,000	$0.30

Table 8-40. Baseline small transit bus costs (1992 Dollars)

COST ITEM	LOW	HIGH
....ONE TIME....		
PURCHASE PRICE- BASE PRICE (1)	$55,000	$55,000
DIFFERENTIAL COST		
ENGINE	$0	$0
FUEL SYSTEM	$0	$0
EXHAUST SYSTEM	$0	$0
FIRE SUPPRESSION SYSTEM	$0	$0
OTHER	0	0
SUB-TOTAL	$55,000	$55,000
SALES TAX AT 6.5%	$3,603	$3,603
SALVAGE AT 5% OF PRICE (2)	$2,750	$2,750
LIFETIME IN YEARS	4	4
GROSS VEHICLE WEIGHT (IN LBS)	11,000	11,000
NPV VEHICLE CAPITAL COST	$55,853	$55,853
......ANNUAL......		
MILES PER YEAR	12,000	12,000
LIFETIME FUEL ECONOMY (MILES/GAL)	10	10
FUEL COST PER GALLON	$1.36	$1.36
ANNUAL FUEL COST	$1,632	$1,632
APRX ANNUAL LICENSE (3)	0	0
REGISTRATION FEES PER YEAR (3)	0	0
CLAIMS COSTS (10% LESS THAN INSURANCE)	$2,864	$2,864
MAINTENANCE COST/MILE	$0.80	$0.80
TOTAL ANNUAL COSTS/YEAR	$14,096	$14,096
NPV ANNUAL COSTS (4)	$47,746	$47,746
TOTAL VEHICLE NPV	$103,599	$103,599
TOTAL COSTS PER MILE	$2.16	$2.16

(1) FROM "PUBLIC TRANSPORTATION ALTERNATIVE FUELS" 1992 DATA
(2) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(3) PUBLIC AGENCIES EXEMPT FROM LICENSE & REGISTRATION FEES
(4) ASSUMES A DISCOUNT RATE OF 7%

Electric

The purchase price for a similar electric vehicle is currently about $140,000. This is not a body-on-chassis vehicle, so is not as closely comparable as the other technology alternatives are to the representative vehicle type. However, there are no current production electric transit vehicles that are a direct match.

For this vehicle it is assumed that the more optimistic lifetime increase of 100 percent over the gasoline vehicle can be achieved. This still results in a projected vehicle life of only 10 years—a time period during which the other vehicle systems can still be expected to provide continued operation.

Maintenance costs are assumed to be 75 percent of those of the baseline bus—a reduction of $0.20 per mile.

Recent studies of electric vehicle purchase prices project an initial price (excluding battery) of about the same and perhaps lower than a comparable internal combustion engine. These projections assume a "reasonable" production volume which may be as little as 10,000 units per year. Progress in powertrain development, and the elimination of the need for pollution control equipment are contributing to these recent improvements in electric vehicle cost projections.

Battery cost will add significantly to the total vehicle costs. The battery cost for the vehicle can vary greatly depending upon cycle life, efficiency, energy density, total energy capacity, and salvage value. Cost projections for an Na/S technology battery vary from a low of $80 per kilowatt hour of rated capacity to a high of $110. This results in an initial cost of batteries for a passenger car of $4,000 to $7,200, and for a van of $3,900 to $7,000 (Reference 73).

Electric vehicles are expected to have significantly longer lives. However, how much of the potential savings can be realized is yet to be seen. Electric milk vans in Britain are reported to last three times as long as their comparable gasoline vans. Electric trolley coaches at the San Francisco Municipal railway have a life cycle of 20 years as compared to 12 for a standard diesel coach. Vehicle components not associated with the engine are likely to deteriorate before the engine and result in increasing maintenance costs that will lead to vehicle replacement before the engine has reached the end of its useful life.

We have assumed that electric vehicles will last from 25 to 100 percent longer than a standard vehicle. Cost analysis is shown in Table 8-41.

Small Transit Bus Cost Summary

A summary of the small transit bus life cycle costs for both technologies costed above is shown in Table 8-42. Life cycle costs vary from $2.16 per mile for the baseline gasoline small transit bus to $2.56 per mile for the high electric small transit bus estimates.

Table 8-41. Electric small transit bus costs (1992 Dollars)

COST ITEM	LOW	HIGH
....ONE TIME....		
PURCHASE PRICE- BASE PRICE (1)	$140,000	$140,000
DIFFERENTIAL COST		
ENGINE	$0	$0
FUEL SYSTEM	$0	$0
EXHAUST SYSTEM	$0	$0
FIRE SUPPRESSION SYSTEM	$0	$0
OTHER	0	0
SUB-TOTAL	$140,000	$140,000
SALES TAX AT 6.5%	$9,170	$9,170
SALVAGE AT 5% OF PRICE (2)	$7,000	$7,000
LIFETIME IN YEARS	8	8
GROSS VEHICLE WEIGHT (IN LBS)	15,000	15,000
NPV VEHICLE CAPITAL COST	$142,170	$142,170
......ANNUAL......		
MILES PER YEAR	12,000	12,000
LIFETIME FUEL ECONOMY (MILES/KWH)	1.5	1
FUEL COST PER KWH	$0.08	$0.08
ANNUAL FUEL COST	$640	$960
APRX ANNUAL LICENSE (3)	0	0
REGISTRATION FEES PER YEAR (3)	0	0
CLAIMS COSTS (10% LESS THAN INSURANCE)	$7,291	$7,291
MAINTENANCE COST/MILE (4)	$0.45	$0.71
BATTERY COST/MILE (5)	$0.05	$0.05
TOTAL ANNUAL COSTS/YEAR	$13,931	$17,371
NPV ANNUAL COSTS (6)	$83,186	$103,727
TOTAL VEHICLE NPV	$225,356	$245,897
TOTAL COSTS PER MILE	$2.35	$2.56

(1) FROM "PUBLIC TRANSPORTATION ALTERNATIVE FUELS" 1992 DATA
(2) % OF BASE PRICE EXCLUDING TAX AND REGISTRATION
(3) PUBLIC AGENCIES EXEMPT FROM LICENSE & REGISTRATION FEES
(4) INCLUDES BATTERY REPLACEMENT
(5) ASSUMES A DISCOUNT RATE OF 7%

Table 8-42. Small transit bus life cycle cost summary (1992 Dollars)

CONFIGURATION	COST RANGE	PURCHASE PRICE	LIFETIME (YEARS)	GVW (LBS)	REG WGT (LBS)	NO OF AXLES	NO OF TIRES	MILES PER YEAR	COST PER MILE
BASELINE	LOW	$55,000	4	11,000	6,500	2	6	12,000	$2.16
	HIGH	$55,000	4	11,000	6,500	2	6	12,000	$2.16
ELECTRIC	LOW	$140,000	8	15,000	10.500	2	6	12,000	$2.35
	HIGH	$140,000	8	15,000	10,500	2	6	12,000	$2.56

SECTION 9

RESEARCH NEEDS AND RECOMMENDATIONS FOR DEMONSTRATIONS

Through continued research and development efforts, diesel engine manufacturers have met increasingly more stringent emission standards. However, rapid and continued research and development will be needed in the next 5 to 10 years for manufacturers to produce low and ultra low emission engines.

Several areas of research are currently underway by research organizations coupled with engine manufacturers. Many areas are producing promising results, while others show great potential. These areas are listed in Table 9-1.

One of the largest areas of research activity centers on producing a low emission engine through the use of exhaust gas recirculation (EGR). Several development areas are still pending and need further work. To produce an advanced production diesel engine with EGR capable of 2 g/bhp-hr NO_x, extensive development needs to be performed in the following areas:

- The combustion system must be made tolerant to EGR to accomplish low carbon emissions at part load and full load
- Recirculation and admission systems must avoid unfavorable pressure gradients and give adequate flow
- EGR cooling should be used for high load operation. At part load, hot EGR will be needed. Control and cooler sizing/cost will be key issues
- Turbomachinery and manifolding/EGR admission systems will need to be rematched for increased boost at full load. A variable geometry turbocharger can give acceptable EGR flow and increased boost.

Table 9-1. Research areas of various low-emission engine technologies

Technology	Research Areas	Technology Available
Advanced DI Engine Design	Variable Geometry Turbochargers Advanced Electronic Control Matched Fuel Injection System/Swirl Advanced Combustion Chamber Design	1998
Exhaust Gas Recirculation	EGR Admission Systems Engine Optimization with EGR EGR Control Strategies Engine Durability	1998+
Selective Catalytic Reduction	Amount of Reductant Needed Control Strategies Miniaturization of equipment	2000+
DE-NO_x Catalysts	Catalyst Materials and Washcoats Molecular Sieve Sizing Temperature Sensitivity Hydrocarbon Input requirements	2000+
Catalytic Traps	Regeneration Methods Cost Reduction Regeneration Triggering Durability	1994
Advanced Methanol Engines	Optimization of Engine Design for Methanol Formaldehyde Emission Control Durability	1992
Advanced Lean Burn Gas Engines	Optimization of Engine Design for Gaseous Fuels Methane Emission Control Closed Loop Feedback Control Systems	1992
All Advanced Engine Technologies	Understand Engine to Engine variability Understand In-service DFs Improve Engine Reliability/Durability Improve Engine Fuel Economy	Varied

- Wear, fouling and durability issues will involve development of lubricating oil specification and conditioning systems, and the mechanical design of the engine
- Combustion, fuel and air systems optimization to enable NO_x goals to be achieved with minimum EGR rate.
- Transient control strategy will need to be developed

Additional research and development efforts are focusing on lean NO_x catalysts, both selective catalytic reduction (SCR) catalysts and DE-NO_x catalysts (Diesel Engine NO_x catalysts designed to reduced NO_x emissions in fuel lean environments). Both show much promise of reducing NO_x emissions to low levels without increasing PM emissions. SCR catalyst research revolves around reducing the amount of reductant needed to reduce NO_x emissions, while DE-NO_x catalyst research is attempting to reduce the sensitivity of these catalysts to HC concentration, exhaust temperature, space velocity and other variables. Currently, DE-NO_x catalysts must be individually designed for each engine and are only 10 to 20 percent effective in reducing NO_x. Current research efforts are attempting to raise NO_x efficiencies to 50 to 70 percent. SwRI believes they will have a research solution within the next 3 to 6 years.

Alternative-fueled engines show excellent promise of becoming ultra low emission engines. With only minor development, diesel and gasoline engines have been converted to use methanol, natural gas and LPG and are currently achieving low emission levels. Further research and development efforts are needed to optimize these engines for the given fuel. In methanol engines, formaldehyde is an issue of concern and needs to be further addressed. In natural gas engines, methane catalysts need to be developed to reduce methane emissions. In addition, the fuel supply issue of alternative fuels also needs to be addressed.

Engine and vehicle demonstrations of low NO_x technology can provide significant support to the commercialization of low NO_x engines. Information from ARB sponsored demonstrations could provide technical advancements in emission control systems that engine manufacturers might incorporate in their engines. More importantly, a demonstration program would prove the feasibility of achieving low NO_x levels and provide support for ARB's emission standards.

Development of new engine technologies follow four basic steps. The first step is the research stage in which a concept is demonstrated by a research organization on one engine. This can take between three and six years. The next step in the development process is for the engine manufacturers to take the "recipe" developed during the research stage and apply it to their engine lines. This usually takes two to three years. The third step is the pre-production field test of the new engines. During this stage, manufacturers perfect their designs and correct any problems. The field tests usually run one to two years. Finally, the engines go through a certification process taking approximately six to twelve months. Thus the time between concept and certification can run between six and twelve years.

Figure 9-1 shows the path towards commercialization with four low-emission technologies. The time from initial engine research to certification and commercial sale are shown on a time line. The DDC methanol technology required nine years from initial engine research to the first certified engine. This engine was initially developed for a demonstration project and probably would not be commercially available today if it were not for these initial demonstration efforts. Particulate traps have also required about the same amount of time from initial engine research to commercialization. The initial demonstration efforts with methanol and traps provided support for the 1991 ARB emission standards. Interestingly, the development time for the Cummins and Tecogen natural gas engines was about five years. These natural gas engines could benefit from additional development with electronic closed-loop controls; however, they have been able to meet emission standards without these systems.

Additional demonstrations should be aimed at supporting the feasibility of Scenario 1 and Scenario 2 emission levels. This is particularly important with diesel engines since these will continue to play the leading role in the truck market. Acurex Environmental recommends that the demonstration projects in Tables 9-2 and 9-3 be supported by the ARB. Since EGR has the

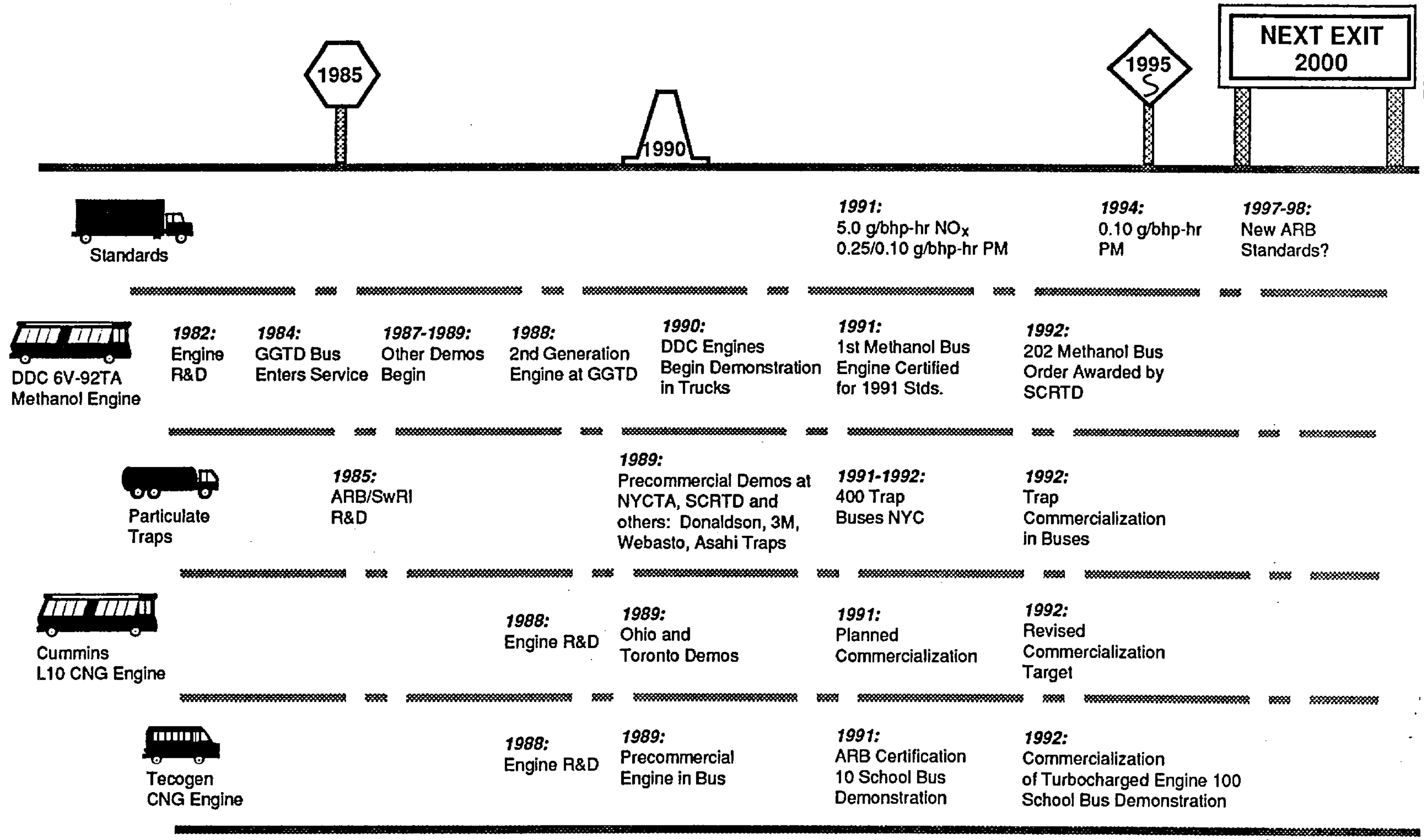

Figure 9-1. Demonstration programs of low-emission heavy-duty engine technologies

Table 9-2. Diesel low emission heavy-duty engine demonstrations

Demonstration	Emission goals (g/bhp-hr)		Description
	NO_x	PM	
Advanced DI diesel with EGR	2	0.05	Develop combustion, fuel and air systems optimized with EGR and aftertreatment to achieve goals and establish trade-offs. Demonstrate engine durability and reliability of diesel engines with advanced engine design, EGR and necessary particulate control. Examine in-use fuel economy and emissions. Determine in-use deterioration factors, engine life and reliability.
Advanced DI diesel with DE-NO_x control	2	0.05	Develop combustion, fuel and air systems optimized to work with DE-NO_x catalyst to achieve goals and establish trade-offs. Demonstrate durability and reliability of DE-NO_x catalyst. Determine need for further particulate control. Examine in-use fuel economy and emissions. Determine in-use deterioration factors, engine life and reliability.
Advanced DI Diesel with EGR and DE-NO_x	2	0.05	Develop combustion, fuel and air systems optimized to work with EGR and DE-NO_x catalyst to achieve goals and establish trade-offs. Demonstrate compatibility of EGR with DE-NO_x. Look at in-use fuel economy and emissions. Determine durability and reliability of system. Determine in-use deterioration factors, engine life and reliability.
Advanced DI Diesel with Oxidation Catalyst	2	0.05	Demonstrate reliability and durability of oxidation catalyst with advanced diesel concept. Document fuel economy and in-use emissions.

Table 9-3. Alternative fuel low emission heavy-duty engine demonstrations

Demonstration	Emission goals (g/bhp-hr) NO$_x$	Emission goals (g/bhp-hr) PM	Description
Advanced Methanol Engines	1	0.05	Demonstrate reliability and durability of advanced methanol engines. Examine in-use fuel economy and emissions. Determine in-use deterioration factors and engine life.
Advanced CNG/LNG Engines	1	0.05	Demonstrate reliability and durability of advanced gaseous engine technology. Document in-use fuel economy and emissions. Determine in-use deterioration factors and engine life.
Hybrid/Electric Vehicles	0.5	0.01	Demonstrate hybrid/electric concepts for heavy-duty applications. Determine in-use emissions and reliability/durability of vehicle.
Electric Vehicles	0	0	Demonstrate battery technologies. Determine range and charging requirements. Determine costs of operation.

potential for meeting 2 g/bhp-hr NO$_x$ levels, this technology should be a prime candidate. Other technologies or combinations of technologies can also meet the 2 g/bhp-hr NO$_x$ level and should also be demonstrated. At this point, demonstrating low emissions on an engine dynamometer over the FTP should be the first step in a demonstration. This accomplishment alone would go a long way towards supporting a 2 g/bhp-hr NO$_x$ standard. Information on engine-to-engine variability, reliability, durability, cold operability and in-service deterioration must be ascertained before final emissions standards and implementation schedule can be proposed. Additional on-road demonstrations of low NO$_x$ technologies should also be performed. Further efforts should also be taken to push the lower NO$_x$ technologies. Some data in the previous sections show NO$_x$ levels close to 1 g/bhp-hr. A demonstration of an alternative fuel or other technology meeting a 1 g/bhp-hr standard should also be a priority.

SECTION 10

CONCLUSIONS

Based on the technical feasibility assessment described in Sections 3 through 7 of this report, low emissions can be obtained from heavy-duty engines. The Scenario 1 goals of 2 g/bhp-hr NO_x and 0.05 g/bhp-hr PM are achievable now by using methanol or natural gas. For diesel engines to meet those goals, however, new or radically redesigned versions of current engines and a significant advancement in aftertreatment technology will be required. Heavy-duty gasoline engines are presently closer to the Scenario 1 goals than heavy-duty diesel engines, but again a breakthrough in a high temperature three-way catalyst is needed.

There are several interesting research efforts that could thrust diesel engines below the 4 g/bhp-hr NO_x set by the EPA for 1998. By using a combination of very high pressure fuel injection, variable geometry turbocharger, air-to-air aftercooler, optimized combustion chamber, electronic unit injectors with minimized sac volume, optimized fuel injection nozzles, fuel injection rate shaping, exhaust gas recirculation and sophisticated electronic control of all engine systems, diesel engines may meet a 2.5 g/bhp-hr NO_x standard at 0.15 g/bhp-hr PM with a 5 percent penalty in fuel economy. Advanced oxidation catalysts might reduce PM emissions to less than 0.1 g/bhp-hr while particulate traps could be used to reduce the particulate emissions to 0.05 g/bhp-hr. Durability of the engine may be reduced to 80 percent of the 1994 counterpart. Several manufacturers and research organizations are studying these refinements in diesel technology and predict such engines may be available as early as 2000. Concentrated research and development, tied with demonstration programs, will be needed to bring these engines into reality.

Another interesting effort for reducing diesel NO_x emissions is in the area of catalytic aftertreatment. Two types of catalysts show promise for reducing diesel exhaust emissions. The first is an advanced oxidation catalyst that will reduce PM emissions 20 to 40 percent and gaseous HC emission 50 to 60 percent. These will require additional breakthroughs in noble metals and catalyst washcoating. However, advanced oxidation catalysts can complement new engine technology by allowing manufacturers to concern themselves with NO_x control and use advanced exhaust aftertreatment to reduce excess particulates. Engine manufacturers can reduce development costs by this method in light and medium heavy-duty engines. Heavy heavy-duty engines will require further refinements.

The second type of catalytic aftertreatment is the DE-NO_x catalyst (Diesel Engine NO_x catalyst designed to reduce NO_x in fuel lean environments), which uses copper zeolite sieves to capture exhaust hydrocarbons during idle and low load operation. These trapped hydrocarbons are then used to reduce NO_x emissions during high load operation. Presently DE-NO_x catalysts are only 10 to 20 percent effective, yet by decreasing the air/fuel ratio from over 22 to 16 or 18, exhaust temperatures and hydrocarbon concentrations will be enough to increase catalyst NO_x reduction efficiencies to 50 to 70 percent. Research must find a way for DE-NO_x catalysts to work over the range of temperatures found in diesel engines, the variety of hydrocarbons present and the air/fuel ratios at which diesel engines operate. Navistar claims that their hydraulically-actuated electronic unit injector (HEUI) system is capable of operating at air/fuel ratios of 16 or 18 without significant increases in smoke emissions. Fuel consumption is estimated to increase 10 to 20 percent at those lower air/fuel ratios, but further development in fuel injection system and catalyst design can limit the fuel economy degradation. Research in Japan shows that 50 to 70 percent efficiencies are possible with only a 5 percent fuel penalty at steady-state conditions.

Clean diesel fuel also will play an important role in future diesel engines. Oxygenates and cetane improvers can substantially reduce CO, HC, and PM emissions. Further research needs to be done to determine the best combination of diesel fuel constituents to significantly reduce PM emissions. A research effort similar to gasoline's Auto/Oil program is needed for diesel fuel.

Gasoline heavy-duty engines currently are producing 3 to 3.5 g/bhp-hr NO_x. With cleaner gasoline, additional EGR, and significant breakthroughs in high temperature three-way catalyst materials, gasoline engines could meet 2 g/bhp-hr NO_x. Higher temperature three-way catalysts are needed to handle the range of exhaust temperatures typical in heavy-duty gasoline engines.

Alcohol fuels already produce low emissions in diesel engines. Detroit Diesel Corporation has certified their 6V-92TA engine on methanol at 1.7 g/bhp-hr NO_x and 0.03 g/bhp-hr PM. DDC has been the only manufacturer who has continued to develop a methanol engine past the demonstration stage. With better air management, an improved fuel injection system, better oil control and further optimization for methanol use, this engine could reach 1 g/bhp-hr NO_x and still keep particulates low. Additional efforts by other manufacturers to develop four-stroke methanol engines with lean-burn or stoichiometric technology also could show very low emission results.

Natural gas shows considerable promise as a heavy-duty engine fuel. Lean-burn homogeneous charge engines currently are attaining 2 to 2.5 g/bhp-hr NO_x and 0.05 g/bhp-hr PM. Homogeneous stoichiometric engines with three-way catalysts are being demonstrated at 1 to 1.5 g/bhp-hr NO_x and less than 0.05 g/bhp-hr PM. In addition, DDC has shattered the myth that natural gas will not autoignite. With their 6V-92TA "DING" engine, DDC directly injects natural gas into the engine cylinder at high pressure and autoignites the mixture without the use of spark plugs or diesel pilot injection. DDC estimates emissions from this engine to be 2 g/bhp-hr NO_x and 0.05 g/bhp-hr PM. As with alcohols, engine development for dedicated natural gas engines is lacking. Further research and development efforts will optimize these engines and determine the future for lower emission standards.

Finally, electric and hybrid electric technology is just beginning to bloom. With breakthroughs in battery technology, electric buses and pick-up and delivery trucks could become zero emission vehicles. This will be of utmost importance in urban areas where pollution levels are already exceeded.

Thus, as stated above and in Sections 3 through 7, several low emission technologies exist or will exist in the future to justify setting lower emission standards. Life-cycle costing for these technologies can be found in Section 8. Further research areas and demonstration recommendations can be found in Section 9.

As the heavy-duty engine market is dominated by diesel engines, future emission standards must be based on low emission diesel engine availability. This is particularly true for long-haul trucks which do not fuel at a central location. Until a wide alternative fuel infrastructure exists, heavy-duty emissions standards must be based on diesel fuel technology.

Taking this into account, we believe diesel engines capable of achieving 2 g/bhp-hr NO_x and 0.05 g/bhp-hr PM on an engine test stand will be available for pre-production field testing in California by 2002. The timelines for this stage of technology for diesel and alternative fuel technologies are shown in Table 10-1 for heavy-duty diesel trucks, Table 10-2 for heavy-duty diesel urban buses, Table 10-3 for heavy-duty alternative fuel trucks and Table 10-4 for heavy-duty alternative fuel urban buses. These tables do not take into account the reliability and durability of engine/emission control systems over the emission life of the engine (290,000 miles for heavy heavy-duty engines, 185,000 miles for medium heavy-duty engines and 110,000 for light heavy-duty engines), nor do they consider certification deterioration factors, in-use emission levels or engine-to-engine variability. These issues will need to be resolved in demonstration fleets and engine laboratories before future emission standards can be met.

In order to meet low emission levels, advanced technology engines will need to be available in all heavy-duty classes. Tables 10-5 through 10-8 show low emission engine technology availability for the four heavy-duty classes.

With the pervasive ozone problem in California and the fact that heavy-duty engines contribute a significant portion of NO_x emissions in California, we believe NO_x emissions from

Table 10-1. Heavy-duty diesel truck availability

	NO_x (g/bhp-hr)	PM (g/bhp-hr)
1994	5.0	0.10
1998	4.0	0.10
2002[a]	2.0	0.05

[a] Pre-production field test vehicles available

Table 10-2. Heavy-duty diesel urban bus availability

	NO_x (g/bhp-hr)	PM (g/bhp-hr)
1994	5.0	0.07
1996	4.0	0.05
2002[a]	2.0	0.05

[a] Pre-production field test vehicles available

Table 10-3. Alternative fuel heavy-duty truck availability

	NO_x (g/bhp-hr)	PM (g/bhp-hr)
1997	2.0	0.05
2001	1.0	0.05
2002[a]	0	0

[a] Fuel cell trucks

Table 10-4. Alternative fuel heavy-duty transit bus availability

	NO_x (g/bhp-hr)	PM (g/bhp-hr)
1992	2.0	0.05
1998	1.0	0.05
1996[a]	0	0

[a] Battery powered or fuel cell 40-ft buses

Table 10-5. Projected light heavy-duty technologies

Projected Fuel/Vehicle Systems	NO_x (g/bhp-hr)	PM (g/bhp-hr)	Year[a] Available
Gasoline Engine with Advanced TWC	3	0.10	1999
Gasoline Engine with Electrically Heated TWC Stoichiometric Methanol Engine with TWC Stoichiometric CNG/LNG Engine with TWC Stoichiometric LPG Engine with TWC	2	0.05	2002 1996 1996 1996
Stoichiometric Methanol Engine with TWC Stoichiometric CNG/LNG Engine with TWC Stoichiometric LPG Engine with TWC	1	0.05	1998 1998 1998
Battery Powered vehicle	0	0	1998

[a] Pre-production field test units

Table 10-6. Projected medium heavy-duty technologies

Projected Fuel/Vehicle Systems	NO_x (g/bhp-hr)	PM (g/bhp-hr)	Year[a] Available
DI diesel with DE-NO_x and oxidation catalyst DI diesel with EGR and oxidation catalyst	3	0.10	2000 1999
DI diesel with DE-NO_x and oxidation catalyst DI diesel with EGR and DE-NO_x & oxidation cat. DI diesel with EGR and catalytic trap 2-Stroke DI methanol engine with oxidation catalyst 4-Stroke DI methanol engine with oxidation catalyst Stoichiometric methanol engine with TWC Lean burn CNG/LNG engine with oxidation catalyst Stoichiometric CNG/LNG engine with TWC Stoichiometric LPG engine with TWC	2	0.05	2002 2002 2002 1994 1997 1997 1994 1994 1994
2-Stroke DI methanol engine with oxidation catalyst Stoichiometric methanol engine with TWC Lean burn CNG/LNG engine with oxidation catalyst Lean burn LPG engine with oxidation catalyst Stoichiometric CNG/LNG engine with TWC Stoichiometric LPG engine with TWC Hybrid/Electric truck	1	0.05	1998 2001 2001 2001 1998 1998 2002
Battery Powered vehicle Fuel Cell vehicle	0	0	1998 2000

[a] Pre-production field test units

Table 10-7. Projected heavy heavy-duty technologies

Projected Fuel/Vehicle Systems	NO_x (g/bhp-hr)	PM (g/bhp-hr)	Year[a] Available
DI diesel with DE-NO_x and oxidation catalyst DI diesel with EGR and oxidation catalyst	3	0.10	2000 1999
DI diesel with DE-NO_x and oxidation catalyst DI diesel with EGR and catalytic trap DI diesel with EGR and DE-NO_x & oxidation cat. 2-Stroke DI methanol engine with oxidation catalyst 4-Stroke DI methanol engine with oxidation catalyst Lean burn CNG/LNG engine with oxidation catalyst Lean burn LPG engine with oxidation catalyst	2	0.05	2002 2002 2002 1996 1997 1997 1997
2-Stroke DI methanol engine with oxidation catalyst Lean burn CNG/LNG engine with oxidation catalyst Lean burn LPG engine with oxidation catalyst Hybrid/Electric truck	1	0.05	2001 2001 2001 2002

[a] Pre-production field test units available

Table 10-8. Projected urban transit bus technologies

Projected Fuel/Vehicle Systems	NO_x (g/bhp-hr)	PM (g/bhp-hr)	Year[a] Available
DI diesel with DE-NO_x and oxidation catalyst DI diesel with EGR and oxidation catalyst DI diesel with EGR and catalytic trap	3	0.10	2000 1999 1999
DI diesel with DE-NO_x and oxidation catalyst DI diesel with EGR and DE-NO_x & oxidation cat. 2-Stroke DI methanol engine with oxidation catalyst Stoichiometric methanol engine with TWC Lean burn CNG/LNG engine with oxidation catalyst Lean burn LPG engine with oxidation catalyst Stoichiometric CNG/LNG engine with TWC Stoichiometric LPG engine with TWC	2	0.05	2002 2002 1992 1994 1992 1994 1992 1994
2-Stroke DI methanol engine with oxidation catalyst Stoichiometric methanol engine with TWC Lean burn CNG/LNG engine with oxidation catalyst Lean burn LPG engine with oxidation catalyst Stoichiometric CNG/LNG engine with TWC Stoichiometric LPG engine with TWC Hybrid/Electric bus	1	0.05	1998 1998 1998 1998 1998 1998 1998
Battery Powered bus Fuel Cell bus	0	0	1996 1996

[a] Pre-production field test units available

heavy-duty engines need to be reduced dramatically. Furthermore, we suggest hydrocarbon emission standards be set on a reactivity adjusted non-methane organic gas basis with a maximum total hydrocarbon "cap" set to limit greenhouse methane emissions. We also feel that it is important to monitor toxic emissions from all heavy-duty engines and insure that toxic emissions not increase with new technologies over present levels. In addition, PM emissions are important to regulate to at least the "smokeless" level. Reduction of PM emissions below this level should be carefully considered to determine the cost-effectiveness in relation to control of other sources of PM emissions.

Based on the finding outlined in this report, low emission technologies can be available to make a significant impact in California's air quality. Technology forcing regulations and incentive programs for alternative fuels will bring these technologies into reality.

REFERENCES

1. 1990 ARB official emissions inventory projections.

2. Khair, M. K., "Progress in Diesel Engine Emission Control," presented at the ASME Energy Sources Technology Conference and Exposition, Houston, Texas, January 1992.

3. Bykowski, B. B., "Aftertreatment Control Technology for Heavy-Duty Diesels," presented at the ARB Technical Seminar on Low Emission Technology for Heavy Duty Engines, Diamond Bar, California, February 1992.

4. Doyle, D. M., "Direct Injection Combustion Principles and Practice for Low Emissions," CIMAC, 1991.

5. Essigm G., H. Kamp and E. Wacker, "Diesel Engine Emissions Reduction—The Benefits of Low Oil Consumption Design," SAE paper 900591, presented at the International Congress and Exposition, Detroit, Michigan, February-March 1990.

6. Stumpp, G., W. Polach, N. Muller and J. Warga, "Fuel Injection Equipment for Heavy-Duty Diesel Engines for U.S. 1991/1994 Emission Limits," SAE paper 890851, presented at the International Congress and Exposition, Detroit, Michigan, February-March 1989.

7. Knuth, H. W. and H. Garthe, "Future Diesel Fuel Compositions—Their Influence on Particulates," SAE paper 881173, presented at the Future Transportation Technology Conference and Exposition, San Francisco, California, August 1988.

8. Ullman, T. L., R. L. Mason and D. A. Montalvo, "Effects of Fuel Aromatics, Cetane Number and Cetane Improver on Emissions from a 1991 Prototype Heavy-Duty Diesel Engine," SAE paper 902171, presented at the International Fuels and Lubricants Meeting, Tulsa, Oklahoma, October 1990.

9. Baranescu, R. A., "Influence of Fuel Sulfur on Diesel Particulate Emissions," SAE paper 881174, presented at the Future Transportation Technology Conference and Exposition, August 1988.

10. Barclay, H., "New Yorkers Introduced to Clean Diesel Buses," Clean Air Technology News, Winter 1992.

11. Ha, K., M. Sumar, H. Houben and J. Sauerteig, "Performance Testing and Field Evaluation of an In-Line Particulate Trap System for the DDC 6V-92TA Two Stroke Engine," SAE paper 920366, presented at the International Congress and Exposition, Detroit, Michigan, February 1992.

12. Personal communication with Julian Imes and Doug Hagen of Donaldson Company Inc., February 24, 1993.

13. Porter, B. C., et al., "Engine and Catalyst Strategies for 1994," SAE paper 910604, presented at the International Congress and Exposition, Detroit, Michigan, February-March 1991.

14. Farrauto, B., J. Adomaitis, J. Tiethof and J. Mooney, "Reducing Truck Diesel Emissions: A Status Report," Automotive Engineering, pp 19-23, February 1992.

15. Mele, J., "The '94 Engines, Finally—Good News," Fleet Owner, pp. 40-45, November 1991.

16. McCandless, J., "Heavy Duty Diesel Exhaust Emissions—State of Technology Report," presented at the ARB Technical Seminar on Low-Emission Control Developments for Heavy-Duty Vehicles, Diamond Bar, California, February 1992.

17. Minami, T., I. Yamaguich, M. Shintani, K. Tsujimura and T. Suzuki, "Analysis of Fuel Spray Characteristics and Combustion Phenomena under High Pressure Fuel Injection," SAE Paper 900438, presented at the International Congress and Exposition, Detroit, Michigan, February-March 1990.

18. Pilley, A. D., A. D. Noble, A. J. Beaumont, J. R. Needham and B. C. Porter, "Optimization of Heavy Duty Diesel Engine Transient Emissions by Advanced Control of a Variable Geometry Turbocharger," SAE paper 890395, presented at the International Congress and Exposition, Detroit, Michigan, February-March 1989.

19. Bennethum, J. E. and R. E. Winsor, "Toward Improved Diesel Fuel," SAE paper 912325, presented at the International Fuels and Lubricants Meeting and Exposition, Toronto, Canada, October 1991.

20. Imes, J., "Donaldson Diesel Exhaust Aftertreatment Systems," presented at the ARB Technical Seminar on Low-Emission Control Developments for Heavy-Duty Vehicles, Diamond Bar, California, February 1992.

21. Held, W., A. Konig, T. Richtar and L. Puppe, "Catalytic NO_x Reduction in Net Oxidizing Exhaust Gas," SAE paper 900496, presented at the International Congress and Exposition, Detroit, Michigan, February-March 1990.

22. Personal communication with Bruce Bykowski, May 1, 1992.

23. Konno, M., T. Chikahisa, T. Murayama and M. Iwamoto, "Catalytic Reduction of NO_x in Actual Diesel Engine Exhaust," SAE paper 920091, presented at the International Congress and Exposition, Detroit, Michigan, February 1992.

24. Akiyama, K., K. Masunaga, K. Kado, T. Yoshioka, "Cylinder Wear Mechanism in an EGR Equipped Engine and Wear Protection by the Engine Oil," SAE paper 872158, presented at the International Fuels and Lubricants Meeting and Exposition, Toronto, Canada, November 1987.

25. Needham, J., "A Green Future for the Heavy Duty Diesel?," presented at the ARB Technical Seminar on Low-Emission Control Developments for Heavy-Duty Vehicles, Diamond Bar, California, February 1992.

26. Personal communication with Dave Millerick, Ford Motor Company, May 1992.

27. Personal communication with Jim Feiten, General Motors Corporation, May 1992.

28. Dettling, J.C. and Y. Lui, "A Non-Rhodium Three-Way Catalyst for Automotive Applications," SAE paper 920094, presented at the International Congress and Exposition, Detroit, Michigan, February 1992.

29. Obert, E., Internal Combustion Engines and Air Pollution, Harper and Row, 1973.

30. Personal communication with Mr. John Polasek, DDC.

31. Miller, S. and C. Savonen, "Development Status of the Detroit Diesel Corporation Methanol Engine," SAE paper 901564, presented at the International Off-Highway and Powerplant Congress and Exposition, Milwaukee, Wisconsin, September 1990.

32. Miller, S., "DDC's Production 6V-92TA Methanol Bus Engine," SAE paper 911631, presented at the Future Transportation Technology Conference and Exposition, Portland, Oregon, August 1991.

33. Savonen, C., "California Energy Commission Heavy-Duty Methanol Truck Engine Emission Testing," for Acurex Environmental Corporation, June 1991.

34. Miller, S., "DDC Alcohol Engine Development and Field Experience," presented at the IX International Symposium on Alcohol Fuels, Florence, Italy, November 1991.

35. SCRTD, "Alternate Fuel Section Quarterly Status Report," October-December 1991.

36. Weinberg, L., City of New York Department of Transportation and Department of Environmental Protection, "City of New York Methanol Bus Program Monthly Report #15," July 1991.

37. Riverside Transit Agency, "Methanol Project Data Report," December 1991.

38. Miller, S. and C. Savonen, "Development Status of the Detroit Diesel Corporation Methanol Engine," SAE 901564, presented at the International Off-Highway and Powerplant Congress and Exposition, Milwaukee, Wisconsin, September 1990.

39. Unnasch, S. and M. Jackson, "Methanol-Fueled Transit Bus Demonstration: Phase I Technical Analyses," for the California Energy Commission, October 1986.

40. Sypher:Mueller International, Inc., "Project Mile Report, A Report on the Use of Methanol in Large Engines in Canada," prepared for Energy, Mines and Resources Canada, May 1990.

41. Baranescu, R., U. Hilger, B. Bartunek, E. Scheid, F. Pischinger, G. Rogers and R. Last, "Prototype Development of a Methanol Engine for Heavy-Duty Application-

Performance and Emissions," SAE paper 891653, presented at the Future Transportation Technology Conference, Vancouver, Canada, August 1989.

42. Bartunek, B., V. Scholz, E. Scheid, R.A. Baranescu and G.W. Rogers, "Prototype Development of a Methanol Engine for Heavy-Duty Application: System Design Options," SAE paper 901519, presented at the Future Transportation Technology Conference and Exposition, San Diego, California, August 1990.

43. Cipolat, D., H. Jawured, C. Rallis, "Methanol/Dimethyl-Ether Fueling of a Compression Ignition Engine," presented at the IX International Symposium on Alcohol Fuels, Florence, Italy, November 1991.

44. Carroll, J., T. Ullman, R. Winsor, "Emission Comparison of DDC 6V-92TA on Alcohol Fuels, SAE Paper 902234," presented at the International Congress and Exposition, Detroit Michigan, February-March 1990.

45. Unnasch, S., G. Short, V. Pelegrin and J. Leonard, "Emissions Reductions from a DDC 6V-92TAC Engine Operating on Ignition-Improved Methanol," presented at the IX International Symposium on Alcohol Fuels, Florence, Italy, November 1991.

46. Southern California Rapid Transit District, "Alternate Fuels Section Quarterly Status Report," July-September, 1991.

47. Personal communication with Stan Miller of Detroit Diesel Corporation, May 1992.

48. Martin, S., "Transient Cycle Emissions Confirmation Test of Alternative Fuel Engine," for Ford-New Holland, September 1990.

49. Personal communication with Vinod Duggal, Cummins Engine Company Inc., April 1992.

50. Personal communication with Kevin Bruck of Caterpillar Inc., May 1992.

51. Presented by Hercules Engine Inc. at the NYSEG NGV Conference in August 1992.

52. Personal communication with Paul Cassidy of Hercules Engines Inc., May 1992.

53. Beaty, K.D., R. Egnell and M. Ekelund, "Development of a Low Emission Volvo 9.6 Liter Natural Gas Fueled Bus Engine," SAE Paper 921554, presented at the Future Transportation Technology Conference & Exposition, Costa Mesa, California, August 1992.

54. Personal communication with Kevin Beaty of Southwest Research Institute, May 1992.

55. Koplow, M.D., "Natural Gas Engine Development Activities," presented at the ARB Technical Seminar on Low-Emission Control Developments for Heavy-Duty Vehicles, Diamond Bar, California, February 1992.

56. Cullen, D., "Considering the Alternatives," <u>Fleet Owner</u>, November 1991.

57. Hundleby, G.E. and J.R. Thomas, "Low Emission Engines for Heavy-Duty Natural Gas-Powered Urban Vehicles--Development Experience," SAE paper 902068, presented at the International Fuels and Lubricants Meeting and Exposition, Tulsa, Oklahoma, October 1990.

58. Fischer, J., Detroit Diesel Corporation presentation at the ARB Urban Bus Regulation Workshop, April 1992.

59. Personal communication with Stan Miller of Detroit Diesel Corporation, May 1992.

60. Kingston Jones, M.G. and D.M. Heaton, "Nebula Combustion System for Lean Burn Spark Ignited Engines," SAE Paper 890211, presented at the International Congress & Exposition, Detroit, Michigan, February-March 1989.

61. Ha, K., "Development and Evaluation of an NH_3 + SCR System for a Heavy Duty Natural Gas Engine," presented at the ARB Technical Seminar on Low-Emission Control Developments for Heavy-Duty Vehicles, Diamond Bar, California, February 1992.

62. DeLuchi et al., "Electric Vehicles—Performance Life Cycle Costs, Emissions and Recharging Requirements,: 1989.

63. U.S. Department of Energy, "Electric and Hybrid Electric Vehicle Program," May 1992.

64. Romano and Price, "Installing a Fuel Cell in a Transit Bus," 1990.

65. Personal communication with James McDowell of TMC, February 17, 1993.

66. California Energy Commission, "Fuels report, Appendix E, December 1987.

67. California Air Resources Board, testimony to the AB 234 Advisory Board on Air Quality and Fuels Economics Workshop, February 2, 1989.

68. Interviews conducted with transit operators, February 1992, including Bill Norwich NYCTA, Bruce Vermeychuk S.E. Pennsylvania Transit Authority, Efren Medellin Orange County Transit District, Cleet Page L.A. Times.

69. "Final Report of the Governor's Alternative Fuel Task Force," State of Colorado, December 19, 1991.

70. "Public Transportation Alternative Fuels. A Perspective for Small Transit Operations," Booz Allen & Hamilton, Inc. in association with Acurex Corporation and Nelson\Nygaard, Final Report, June 1992.

71. "Alternative Fuels Section Quarterly Status report," October—December 1991, Southern California Rapid Transit district, Volume 2 Number 3.

72. "Clean Air Program, Status of Particulate Trap Developments Related to the Transit Industry," UMTA-OH-06-0056-91-6, Battelle, May 1991.

73. "Electric Vehicles: Performance, Life-cycle Costs, Emissions, and Recharging Requirements," Mark DeLuchi, Quanlu Wang, and Daniel Sperling, Transportation Research Group, University of California, Davis, Davis, California 95616.

74. Light Duty Automotive Fuel Economy and Technology Trends Through 1987," R.M. Heavenrich, J.D. Murrill, and J.P. Cheng, 1987, Society of Automotive Engineers, Warrendale, Pennsylvania.

75. Federal Highway Administration, "Cost of Owning and Operating Automobiles and Vans, 1984, U.S. Department of Transportation, Washington, DC.

APPENDIX A

EMISSIONS CONVERSION FACTORS

Since truck and bus engine certifications are based upon engine dynamometer testing, as opposed to chassis dynamometer testing, it would be useful to define conversion factors (CF) to convert from engine dynamometer values of grams per brake horsepower-hour (g/bhp-hr) to grams per mile (g/mi). This conversion factor can be calculated from engine brake specific fuel consumption, fuel density and vehicle fuel economy. While they will vary depending on duty cycle, average factors used by ARB for buses are shown in Table A-1.

The conversion factor for diesel in the below table was calculated based on non-trap-equipped engine and vehicle data. However, this value should provide sufficient accuracy for trap-equipped and catalyst-equipped vehicle calculations.

These conversion factors will be updated by the Air Resources Board in the future as more data for alternative-fueled vehicles becomes available. As other types of alternative-fueled engines and other types of vehicles (e.g., electric, fuel cell) reach production status, appropriate conversion factors will also be calculated.

Table A-1. Emission conversion factors

Fuel	CF (bhp-hr/mi)
Diesel	4.3
Methanol	4.3
Natural gas	4.1