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# Transportation fuels of the future?

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## Abstract

Society is putting more emphasis on the mobile transportation sector to achieve future goals of sustainability and a cleaner environment. To achieve these goals, does society need to jump to a new combination of fuel and vehicle technology or can we just continue to improve on the current fuels and drive train technology that has powered us the past 70 or more years? Do we need to move to more exotic energy conversion technology (fuel cell vehicles?), or can improving fuel properties further allow us to continue using combustion engines to power our vehicles? What fuel properties can still be improved in gasoline and diesel? Besides removing sulfur, should there be less aromatics in fuels? Should aromatics be eliminated? Is there a role for oxygenates in gasoline and diesel? Do blending oxygenates in fuels help or hinder in achieving the environmental goals? Can we and should we reduce our dependency on crude oil for transportation energy? Why have not the previous government-sponsored Alternative Fuel programs displaced crude oil?

The marketplace will determine which fuel and vehicle technology combination will eventually be used in the future. Does the information we know today give us insight to this future? This paper will attempt to address some of the key issues and questions on the role fuels may play in that marketplace decision. © 2001 Published by Elsevier Science B.V.

*Keywords:* Transportation; Fuel; Crude oil

## 1. Introduction

Since the first oil embargo, many people in government, industry and academia have been operating on the belief that alternative transportation fuels (and vehicles) need to be developed to meet society's mobile transportation requirements in the relatively near future. The reasons for their beliefs varied over time from projected future high crude oil prices (economics), energy security, reducing mobile source pollutants and more recently, reducing green house gases. As energy prices stabilized or declined, the eco-

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nomic and security arguments generally diminished. An example of using alternative fuel vehicles (AFVs) for reducing mobile source pollutants was the US Administration's original proposal for the 1990 Clean Air Act Amendments that would have required the use of methanol fueled vehicles in the 10 most polluted cities. The reformulated gasoline (RFG) program eventually replaced that policy proposal. California made a similar attempt with their M85 (methanol) fuel program, which also seems to have stagnated.

In more recent years, California has ratcheted down the tailpipe emission standards to pressure automakers to market AFVs. However, the automakers discovered that the cleaner burning gasoline allowed them to develop gasoline vehicles that meet the tighter standards without making large investments in an expensive AFV program. The most recent argument for AFVs has been to reduce green house gases. In response, the auto industry appears to be developing combustion engine technologies that achieve the high-energy efficiency goals without switching to AFV technology. Instead of converting vehicles to run on alternative fuels in the future, the marketplace will more likely convert the alternative energy sources into synthetic liquid fuels that look like gasoline or diesel. Pursuing this pathway avoids many of the economic hurdles and pitfalls that has burdened the development of an AFV market such as limited fuel infrastructure and poor economies of scale during the introductory market phases.

Therefore, does a social or market "need" exist for transitioning to alternative fuels for future mobile transportation? Past and recent experiences suggest that as gasoline and diesel quality becomes cleaner, the automakers are finding that they can burn it in vehicles more efficiently and cleanly by improving both the combustion engines and exhaust after-treatment technologies. This dampens, if not eliminates, the incentive for society to transition to an entirely new power train technology such as fuel cells. Therefore, it is very likely that the fuel of the future will be a very clean gasoline or diesel. A more appropriate question is probably what will be the hydrocarbon or energy source in the future for making gasoline and diesel in the future (natural gas or biomass?) as crude oil resources eventually begin to be depleted. The following discussion reviews some of the issues that has driven the need (or belief) to switch to alternative fuel vehicles (AFV).

## 2. Discussion

The oil embargoes of the 1970s created a fear that oil supplies were declining and prices would continue to climb. This belief helped spur the creation of the US Department of Energy and the original push to develop fuel alternatives for gasoline derived from crude oil. Even though crude oil and energy is a commodity product, energy forecasters in the 1980s projected that crude supply alternatives to OPEC controlled crude supplies would not develop (Fig. 1) [1]. As a result, they underestimated the ability and the incentive of the marketplace to advance the technology to develop alternative crude supplies, and therefore projected that crude oil prices would climb much higher than US$20/barrel (Fig. 2) [1].

A common flaw in projecting a tightening crude supply market is to compare future oil consumption to the present conventional crude oil reserves and thereby ignore the

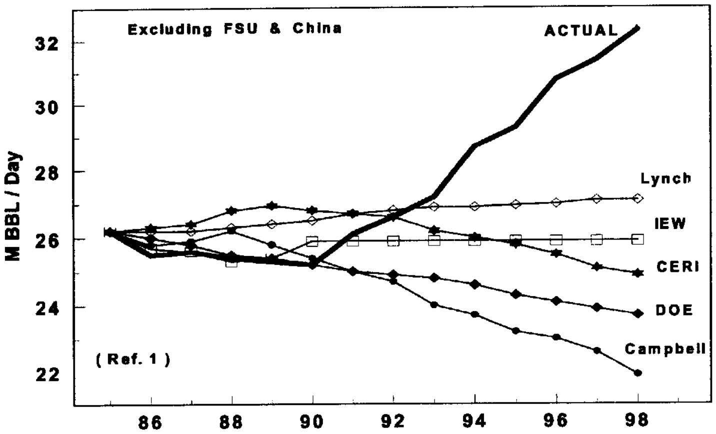


Fig. 1. Non-OPEC oil production forecasts for 1987–1998.

much larger supply of other oil resources and additional occurrences. The major fallacy in this simple economic supply/demand analysis is the implicit assumption that oil recovery technology will not substantially improve to economically tap into the large source of other potential oil supplies [25]. When projected consumption is actually stacked against all oil sources, Fig. 3 suggests that there may be a century worth or more of oil supply available for future oil markets [2] if recovery technology continues to improve. Fig. 4 shows that historical crude prices corrected to a 1996 dollar basis lies mostly between US$10 and US$20 per barrel [3]. Assuming oil recovery technology

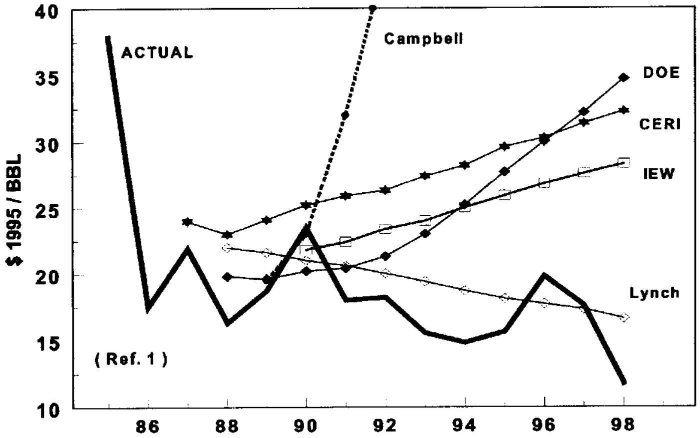


Fig. 2. 1987–1998 crude oil price forecast.

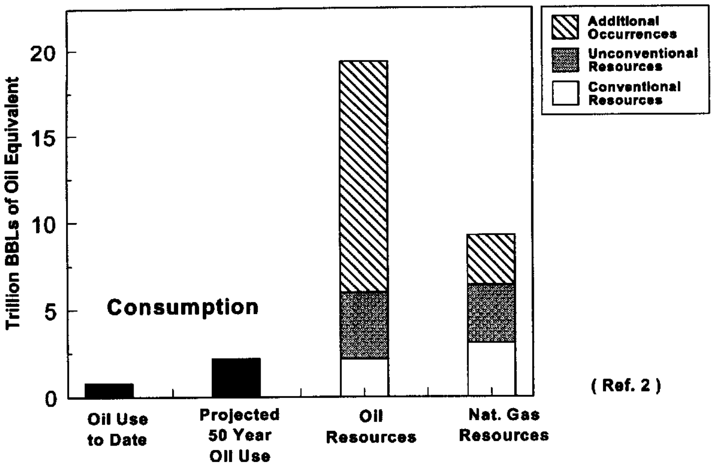


Fig. 3. World oil consumption vs. oil and gas resources.

continues to improve, one should expect that this price range might continue into the foreseeable future. However, this same history shows that the margin spread (crack) between retail gasoline prices and crude oil costs had been shrinking as the oil refining industry becomes more efficient. Therefore, if crude oil prices continue to stay near US$20/barrel and refining margins and gasoline prices continue to decline through refinery efficiency improvements, it will be even more difficult to economically develop alternative fuel substitutes for gasoline and diesel in the future.

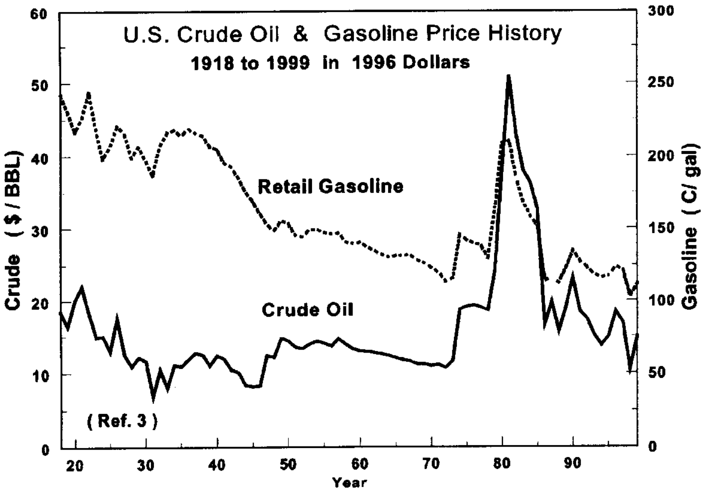


Fig. 4.

Fig. 5 shows the whole sale prices of a number of possible alternative fuels on an energy equivalent basis compared to conventional gasoline [4]. Only compressed natural gas (CNG) and liquid petroleum gas (LPG) appear to have some economic advantage relative to gasoline while ethanol, methanol and electricity are at a severe economic disadvantage. However, even these simple economics do not capture the added cost necessary to build the supporting fuel distribution infrastructure as well as the increased cost of the vehicle to use that alternative fuel. These added costs would usually eliminate most, if not all of CNGs and LPGs economic advantage over gasoline and further disadvantage the other alternative fuels. These unfavorable economics help explain the small market share of AFVs that has developed since the crude oil price spike of the early 1980s. As shown in Fig. 6, all the AFV fleets combined represent less than a quarter percent of the total US vehicle fleet, and even these AFVs are usually found in niche markets that are artificially supported by central fueling locations and favorable tax supports [5]. As a result, the combined alternative fuels market supplies less than a minute quarter percent of the US transportation fuel market requirements.

The economics do not appear to support a transition to alternative fuels and may not in the foreseeable future if crude prices stay near US$20 a barrel. Therefore, AFV supporters have been using non-economic arguments such as using AFVs to reduce mobile source emissions from the vehicle fleet. Air quality agencies have been reducing tailpipe emission standards to create an incentive to switch to AFVs. In response, efforts by the oil and auto industries have determined ways to further clean up gasoline, which not only reduce the emissions from the current vehicle fleet, but also allow the automakers to develop even lower emission vehicles that generally approach the low emissions of the AFVs. Fig. 7 shows the estimated emission reductions using the typical California reformulated gasoline in the current vehicle fleet relative to the 1990 industry average gasoline. As a result of the cleaner burning gasoline, the auto industry is now

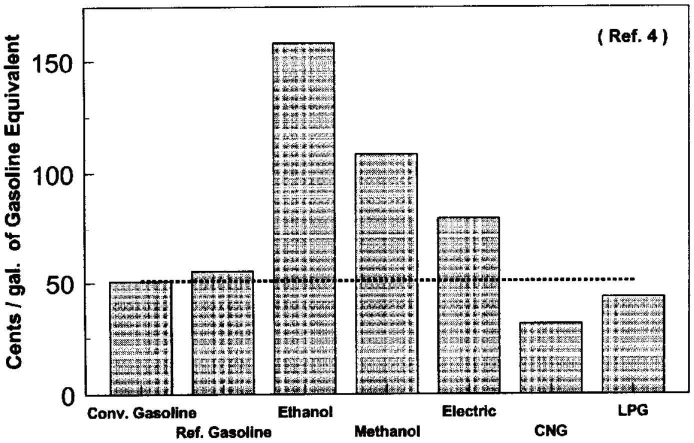


Fig. 5. Economics of gasoline alternative fuels. 1995 wholesale cost before adding market infrastructure and vehicle costs.

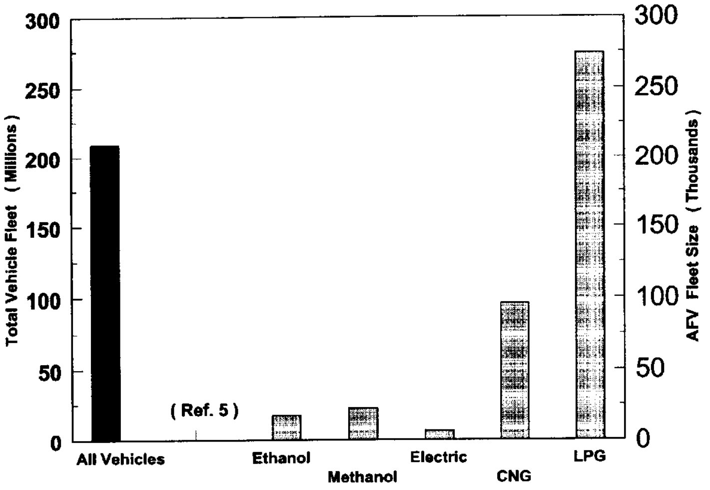


Fig. 6. 1999 US vehicle fleet: alternative fuel vs. total fleet.

introducing vehicles that not only meet California's ultra low emission vehicle (ULEV) standard but also the super ultra low emission vehicle (SULEV) standard without using AFVs [7–11]. As new model gasoline vehicles becomes cleaner, the shrinking emission advantage of the AFVs diminishes to a point where the cost of reducing this small remaining emission becomes very expensive compared to other options for reducing emissions elsewhere.

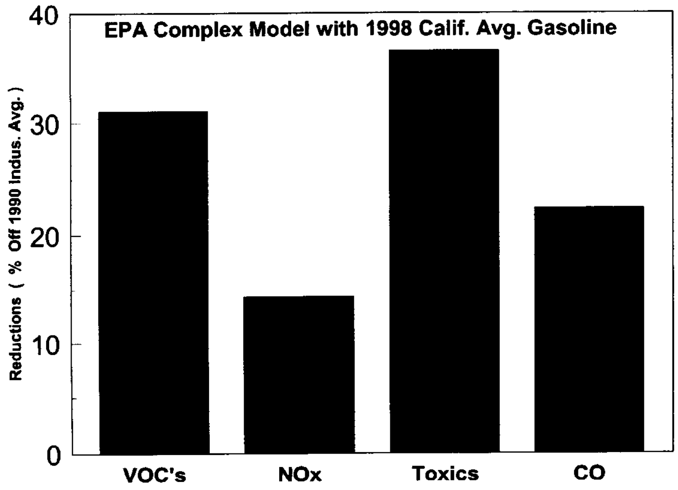
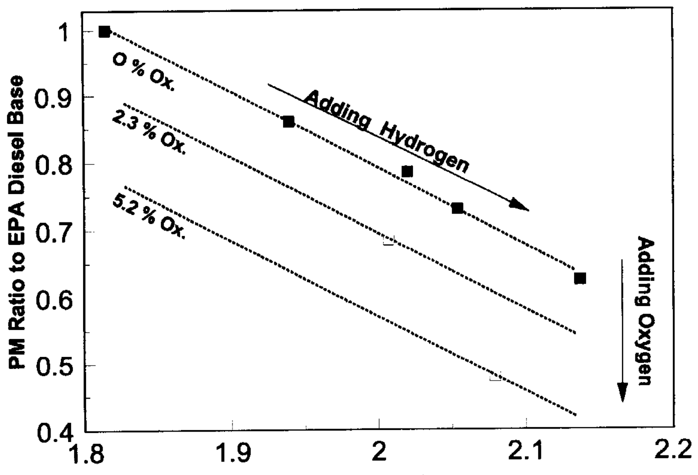


Fig. 7. Emission reductions with California reformulated gasoline.

The most recent social quest has been to reduce the production of greenhouse emissions (mainly $CO_2$). To decrease mobile sources of these gases, the drive has been to reduce vehicle fuel consumption by developing a more efficient vehicle with a fuel economy of 80 miles/gal or 3 1/100 km. To achieve this goal, many thought it would require a higher efficiency power train such as a fuel cell using an alternative fuel such as hydrogen or methanol. However, the old workhorse internal combustion engine again appears to be rising to the challenge with the development of the high efficiency diesel engines coupled with hybrid electric drive trains [8,9,12–21]. Although the responsiveness and performance of the diesel engine has been improved to be comparable to that of the gasoline engine, a major hurdle still exists for reducing the diesel's $NO_x$ (nitrogen oxides) and PM (particulate matter) emissions to be comparable to gasoline engines. To help reduce these emissions, the reformulation of diesel continues to be studied. An example of recent work is shown in Fig. 8, which shows that increasing the hydrogen content of the fuel will help reduce PM emissions by as much as 30%. In addition, adding as much as 5% oxygen in fuel can reduce emissions by another 25% [6]. Therefore, it now appears that improvements in exhaust after-treatment technology coupled with diesel fuel improvements such as sulfur reduction will enable the diesel engine emissions to be comparable to that of gasoline [9,12–14,16,20,22–24].

If social economics determine that it is necessary to move to a high-energy efficiency vehicle, it will likely have an electric drive to take advantage of regenerative braking and other energy efficiencies. However, the energy source of the electric power for the vehicle is still being studied and debated. Initially, the push was for an electric battery-only vehicle where the electricity is generated off-board from fuel at stationary electric power plants. However, after many years of trying, the cost of a battery-only vehicle is still too cost prohibitive [26,27]. Therefore, the debate seems to be now



( Ref. 6 )

Fig. 8. Adding hydrogen and oxygen reduces diesel PM.

centered between a combination fuel cell/battery vehicle (FCV) and a hybrid (internal combustion/generator/battery) vehicle (HEV). In the case of the fuel cell vehicle, which must use hydrogen, should the source of the hydrogen be generated on-board the vehicle from liquid fuels or should it be generated off-board and transferred to the vehicle? Numerous studies are trying to sort out the economics of these various options of which a few are sited here [28–30]. The following discussion will provide insight by making an overall economic comparison of some of the more competitive options observed in this literature.

Before comparing the vehicle technology options, it is useful to examine the cost of various potential transportation fuels being delivered in the US marketplace. The most convenient method is to compare their cost on a basis of US dollar per million BTU of lower heating value (LHV). The reason for using LHV vs. HHV is to remove the heat that is lost as water vapor in the engine exhaust that no power train is capable of recovering economically. Fig. 9 shows a historical comparison of potential transportation fuels available in the existing US infrastructure and is developed by converting volume prices from EIA sources [31]. These costs represent the average delivered cost of fuel to the marketplace before fuel taxes are added. The industry cost for natural gas and electricity currently do not reflect any added costs required for supplying the fuel to the vehicle. For reference, the wellhead cost of natural gas and average acquisition cost of crude oil is also included to the chart. A number of observations can be made from this data. Electricity is still relatively expensive but appears to be decreasing with time. The cost of diesel is about US$1/MM BTU above crude cost but about US$2.5 MM BTU lower than gasoline cost that is due to both its lower cost per volume and higher energy density. This suggests that it might be more cost-effective for the refining industry to convert crude oil to diesel on an energy efficiency basis. The cost of diesel is approaching industry natural gas cost as crude oil and wellhead natural gas appears to

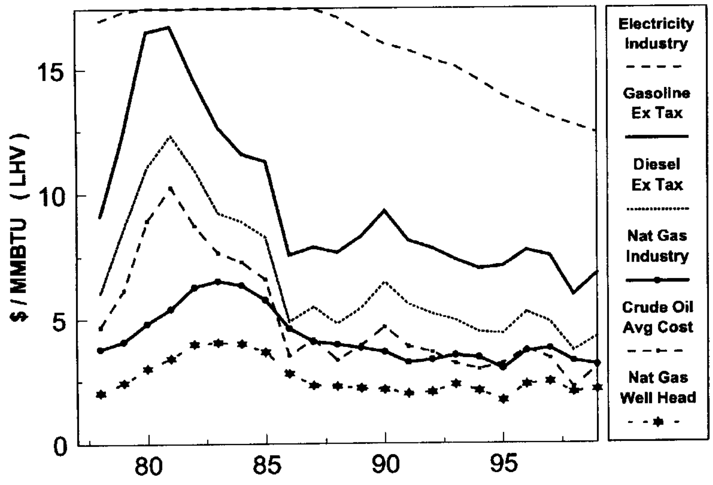


Fig. 9. Historical energy cost of transportation fuels and sources.

converge with time. This simple comparison suggests that diesel might be the economically preferred liquid fuel in future vehicle power trains. This is also consistent with the use of diesel in the PNGV concept vehicles developed by GM, Ford and Daimler Chrysler [18,19,21]. Therefore, for this economic comparison, diesel will be assumed to be the preferred liquid fuel.

This economic analysis will attempt to compare a diesel HEV, diesel FCV and hydrogen FCV with a current gasoline ICE vehicle. To reflect total social cost, it will be helpful to add some air pollution cost to capture some of the low emission benefits of these new technology vehicles. The current gasoline production vehicles meet the transition low emission vehicle standards (TLEV) for 100,000 miles. It will be assumed that both diesel vehicles will meet TLEV standards while the hydrogen vehicle will have zero emission even though there are probably off-board emissions associated with making the hydrogen. The vehicle emission comparison is shown in Fig. 10, where the costs of alternatives for reducing emissions are from Ref. [28]. The cost of the emissions associated with the current TLEV gasoline vehicle is about US$100/year. Due to diesel's very low vapor pressure, an advantage of the diesel vehicle is that it generates negligible evaporative VOCs that gives it an emission advantage of about US$25/year over gasoline vehicles.

The table in Fig. 11 summarizes the economic comparison for the four vehicle systems. The diesel HEV and hydrogen FCV are assumed to meet the 80-mpg (mile per gallon) target of the US PNGV program. Given that some commercial gasoline HEVs are reaching 60–70 mpg and the automaker concept vehicles are about 80 mpg with diesel, the added efficiency of using a diesel engine will surely allow the 80 mpg to be reached. The cost for the ICEV power train is from Ref. [28], while the costs of the FCVs power train are from Ref. [30] using the upper bound range of US$/kW estimates. Even this may be too low since Arthur D. Little has estimated the cost of a multi-fuel HEV power train at US$14,000 using the best known technology today [32]. Similar to the PNGV targets, the FCVs are assumed to need 50 kW fuel cells to meet the driving requirements of a mid-size sedan. The fuel consumption of the diesel FCV is increased to reflect an 84% efficiency of the fuel processor [32]. Though Ref. [28]

| | **TLEV Standards** | **Gasoline ICEV** | **Diesel HEV** | **Diesel FCV** | **Hydrogen FCV** | **Alternative Emission Cost** |
|---|---|---|---|---|---|---|
| **Vehicle Emission Standard** | | TLEV | TLEV | TLEV | ZEV | |
| **Evaportive HC** | 2.5 Gm/test | 38.3 Kg | 0 Kg | 0 Kg | 0 Kg | $ 5.8 /Kg |
| **Exhaust NMHC** | 0.125 gm/mi | 12.5 Kg | 12.5 Kg | 12.5 Kg | 0 Kg | $ 5.8 /Kg |
| **NOx** | 0.4 gm/mi | 40 Kg | 40 Kg | 40 Kg | 0 Kg | $ 7.2 /Kg |
| **PM** | 0.08 gm/mi | 8 Kg | 8 Kg | 8 Kg | 0 Kg | $ 4.4 /Kg |
| **Emission Cost $ / Year** | | $ 99.4 | $ 74.2 | $ 74.2 | $ 0 | |

Fig. 10. Vehicle lifetime emissions (100 M miles) and annual cost.

| Investment Cost $ / Vehicle | | Gasoline ICEV 27 MPG | Diesel HEV 80 MPG | Diesel FCV 67 MPG | Hydrogen FCV 80 MPG |
|---|---|---|---|---|---|
| Fuel Infrastructure - | Nat. Gas. P/L | 0 | 0 | 0 | 50 |
| | Hydrogen P&D | 0 | 0 | 0 | 380 |
| | Total | 0 | 0 | 0 | 430 |
| Vehicle Powertrain - | Engine/Drivetrain | 2300 | | | |
| | HEV System | | 5300 | | |
| | FC,MC & Battery | | | 7300 | 7300 |
| | Fuel Processor | | | 1250 | |
| | Fuel Storage | 150 | 100 | 100 | 1000 |
| | Total | 2450 | 5400 | 8650 | 8300 |
| | Higher Vehicle Cost | | + 2950 | + 6200 | + 5850 |
| Annual Cost $ / Year | Fuel MMBTU/Yr | 47.9 | 16.1 | 19.3 | 16.1 |
| | Fuel Price $/MMBTU | 7.0 | 4.6 | 4.6 | 13.9 |
| | Fuel Cost $/Year | 335 | 74 | 89 | 224 |
| | Emission Cost $/Yr | 100 | 74 | 74 | 0 |
| | Total Cost $/Year | 435 | 148 | 163 | 224 |
| | Savings vs Gasoline | | ( 287 ) | ( 272 ) | ( 211 ) |
| Simple Investment | Payback ( Years ) | | 10 | 23 | 28 |

Fig. 11. Increased vehicle costs vs. annual cost savings.

estimates the cost of a diesel HEV at less than US$2000 over an ICE, this analysis uses a US$3000 increase mentioned by Ford Motors [18].

For reference, the added infrastructure on a per vehicle basis is also shown in the table. No infrastructure cost is assumed for the diesel cases since it should be relatively easy for the gasoline marketing system to switch over to diesel in the current fuel distribution system. The lowest cost option for supplying hydrogen from Ref. [30] is assumed for this analysis, which is producing hydrogen on-site (service station) from natural gas. Though not included in Ref. [30], the cost for expanding the natural gas pipeline infrastructure is also included here since the natural gas supply is about equal in size to the liquid fuel transportation system on a BTU basis. Even though the infrastructure investment cost is shown as dollars per vehicle, it is only captured in the price of the fuel and not the car investment.

The delivered fuel costs for 1997 are used in this analysis since it is a year when the market price of WTI crude oil was approximately US$20/barrel. This is about equal to the current projection in the Crude Futures Market as well as being consistent with the historical cost of crude oil as discussed earlier. Under this assumption, the annual combined fuel and emission costs of the conventional gasoline ICE vehicle is about US$435/year. Due to the lower cost of diesel fuel, the diesel vehicles provide the lowest fuel cost to the consumer. The hydrogen cost is taken from Ref. [30] and is based on servicing 240 cars/day at the filling station.

Using the annual cost savings over the gasoline ICE case, the simple investment payback in years is also shown in Fig. 11. Of the three new power train technologies considered in this analysis, the hydrogen FCV has the least favorable economics due to a combination of high fuel cost and high vehicle investment. For the hydrogen vehicle to be competitive with the diesel HEV, the investment cost of the FCV would have to be less than the HEV. Since this is not likely to happen, the delivered cost of the hydrogen will also have to decrease. However, this analysis already uses the lowest cost distribution option developed in Ref. [30]. Of the two FCVs, it would appear that the diesel FCV would be more economical than the hydrogen FCV. This cost gap will not likely close even if a technology breakthrough occurs for fuel cells since it will likely benefit the diesel FCV as well. Under the assumptions used in this analysis, it seems unlikely that the hydrogen FCV will be the economically preferred vehicle unless the price gap between crude oil and natural gas widens by at least US$4/MM BTU (HHV), which is equivalent to a US$23/barrel increase (or about US$43/barrel). The conclusion that the diesel HEV is more environmentally cost-effective than the FCV also seems to be consistent with the analysis from the German environmental protection agency (UBA) [20]. In addition, it may not be necessary to use HEV technology to achieve PNGV goals since it appears that the target is being achieved with conventional ICE technology [33] using diesel fuel.

## 3. Conclusions

When one looks at the recent history and current events, it still suggests that the fuels of the foreseeable future will still be gasoline and diesel, but improved, cleaner burning versions. These cleaner fuels will allow automakers to further develop even cleaner vehicles that will produce minimal emissions and consume much less fuel. Major improvements in the diesel engine performance and cleanliness with improved after-treatment technology will likely allow a shift in the light duty vehicle market toward the higher efficiency and more economical diesel engine vehicle. That transition already seems to be occurring in Europe. Crude oil supplies tend to be more plentiful than estimated due to technology improvements. In addition, the technology and economic hurdles to convert other alternative energy sources into diesel and gasoline-like fuels continues to improve. As a result of all these improvements, the economic incentives to switch to AFVs will not likely exist for the foreseeable future except for small niche markets.

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## Glossary

*AFV:* Alternative fuel vehicle
*BTU:* British thermal unit
*FCV:* Fuel cell vehicle
*HEV:* Hybrid electric vehicle
*HHV:* Higher heating value
*ICEV:* Internal combustion engine vehicle
*LHV:* Lower heating value
*MM:* Million
*PNGV:* Partnership for new generation of vehicles
*BBL:* Barrel (42 US gallons)
*FC:* Fuel cell
*HC:* Hydrocarbon

*MC:* Motor and controller
*PM:* Particulate matter
*TLEV:* Transition low emission vehicle
*VOC:* Volatile organic compound
*SAE:* Society of automotive engineers

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