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HYDROGEN AS A NEAR-TERM TRANSPORTATION FUEL

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ABSTRACT

The health costs associated with urban air pollution are a growing problem faced by all societies. Automobiles burning gasoline and diesel contribute a great deal to this problem. The cost to the United States of imported oil is more than US$50 billion annually. Economic alternatives are being actively sought.

Hydrogen fuel, used in an internal combustion engine optimized for maximum efficiency and as part of a hybrid-electric vehicle, will give excellent performance and range (>480 km) with emissions well below the ultra-low emission vehicle standards being required in California. These vehicles can also be manufactured without excessive cost. Hydrogen-fueled engines have demonstrated indicated efficiencies of more than 50% under lean operation. Combining engine and other component efficiencies, the overall vehicle efficiency should be about 40%, compared with 13% for a conventional vehicle in the urban driving cycle. The optimized engine-generator unit is the mechanical equivalent of the fuel cell but at a cost competitive with today's engines. The increased efficiency of hybrid-electric vehicles now makes hydrogen fuel competitive with today's conventional vehicles.

Conservative analysis of the infrastructure options to support a transition to a hydrogen-fueled light-duty fleet indicates that hydrogen may be utilized at a total cost comparable to what U.S. vehicle operators pay today. Both on-site production by electrolysis or reforming of natural gas and liquid hydrogen distribution offer the possibility of a smooth transition by taking advantage of existing low-cost, large-scale energy infrastructures. Eventually, renewable sources of electricity and scalable methods of making hydrogen will have lower costs than today. With a hybrid-electric propulsion system, the infrastructure to supply hydrogen and the vehicles to use it can be developed today and thus can be in place when fuel cells become economical for vehicle use.

Key Words: Hydrogen, hybrid-electric vehicles, transportation

BACKGROUND

In the United States, 188 million gasoline- and diesel-powered cars and trucks were responsible for 29% of NO_x, 22% of hydrocarbons, and 58% of CO emissions in 1991 (AAMA, 1993). The health costs of urban air pollution are significant: an estimated $9 billion/yr in the Los Angeles air basin alone (Hall et al., 1992). To address this threat the California Air Resources Board (CARB) has mandated lower emission standards on new vehicles sold in California beginning in 1998, and the standards will become increasingly stringent into the next century. A number of other states are considering adopting California's standards. By 2005 millions of ultra-low and zero emission vehicles will be required to meet these goals.

High-efficiency, hydrogen-powered hybrid-electric vehicles would virtually eliminate tailpipe emissions (with emis-sions less than one-tenth the ultra-low-emissions requirements), *without* the complex and costly emission control technology of hybrid-electric vehicles fueled by carbon-based fuels. Such vehicles would also have greater range, lower cost, and better performance than pure battery-powered electric vehicles. Based on detailed vehicle simulations of the conceptual hydrogen-fueled hybrid-electric vehicle discussed below and our analysis of the options for a hydrogen refueling infrastructure, hydrogen is a realistic near-term transportation fuel.

Hydrogen has been investigated for more than 50 years as an alternative fuel, but the low energy density and high cost of hydrogen production and storage have been obstacles. Today, advances in electric vehicle technology make hybrid-electric vehicles fueled by hydrogen feasible through a 250–300% increase in fuel economy over today's vehicles.

A HYDROGEN HYBRID-ELECTRIC VEHICLE

A concept is evolving at LLNL for a highly efficient hybrid-electric vehicle that produces significantly less pollution than a gasoline-powered vehicle (Smith and Aceves, 1995). The engine for the vehicle operates at a constant speed and power at its maximum efficient point, without ever idling. The engine is started when it is necessary to charge the power storage system, and it is turned off when the charging process is complete. The engine takes advantage of hydrogen's special properties to operate very lean at a very high compression ratio. Even without a catalyst, the engine produces less NO_x, hydrocarbons, and CO than would be

produced by a gas-fired power plant generating the amount of electricity needed to charge a battery car.

A 34 km/liter (gasoline-equivalent energy) hydrogen-fueled vehicle would require only 3.75 kg of hydrogen for a 480-km range, sufficient to compete with today's gasoline vehicles. The crucial element of the design is a small (30–40 kW) internal combustion engine that runs at its maximum efficiency point (45% brake thermal), generating electricity for onboard peak power storage (1–2 kWh of flywheels, ultracapacitors, or batteries). The hydrogen engine is sized to climb 6% grades at 96 km/h. Peak power (100 kW) is sufficient to accelerate the vehicle from 0–96 km/h in less than 10 seconds.

Combining this high-efficiency power-train with the weight, drag, and regenerative braking already demonstrated by the GM Impact III, and accounting for the reduced aerodynamics and added mass of a five-passenger version, would create a 1140-kg hydrogen-powered vehicle with a gasoline energy-equivalent mileage of 34 km/l. Such a vehicle is shown in Fig. 1. The greatest challenge facing the vehicle is onboard hydrogen storage. Hybrid-electric vehicle prototypes have already been built, but none run on hydrogen.

HYDROGEN FUEL STORAGE

Hydrogen has a greater variety of storage options than other fuels. It can be stored as a gas (at room temperatures or cryogenic temperatures) or as a cryogenic liquid. Hydrogen can also be stored in room-temperature liquid "hydrogen carriers," such as methanol and ammonia, or adsorbed in metal powders, which release hydrogen when heated. Each approach has quite different characteristics. Figure 2 presents the weight and volume requirements for various hydrogen fuel storage systems. No storage technology is clearly preferred at present. At room temperature, a hydrogen gas pressure vessel is very bulky. Hydrogen becomes significantly denser at liquid nitrogen temperatures (approxi-mately 80 K), but this increases the fuel system complexity and energy requirements. Liquid hydrogen tanks are even lighter and more compact but have even greater energy requirements and complexity. However, the technology to refuel the vehicle with liquid hydrogen exists today in BMW prototypes. The problems of cryogenic and high-pressure hydrogen storage can be avoided by using metal hydrides, but these tend to use valuable and heavy materials (titanium, manganese, lanthanum, nickel, etc.) Lighter, cheaper hydrides based on magnesium have great potential but require relatively high temperatures (200–300°C) to operate.

Fig. 1. Conceptual hydrogen-powered vehicle with an electric drivetrain. High powertrain efficiency, low drag, and low weight combine so that only 3.75 kg of hydrogen must be stored on board for 480-km range. Electricity is stored for peak accelerations in high-power, high-efficiency batteries, ultracapacitors, or an advanced flywheel.

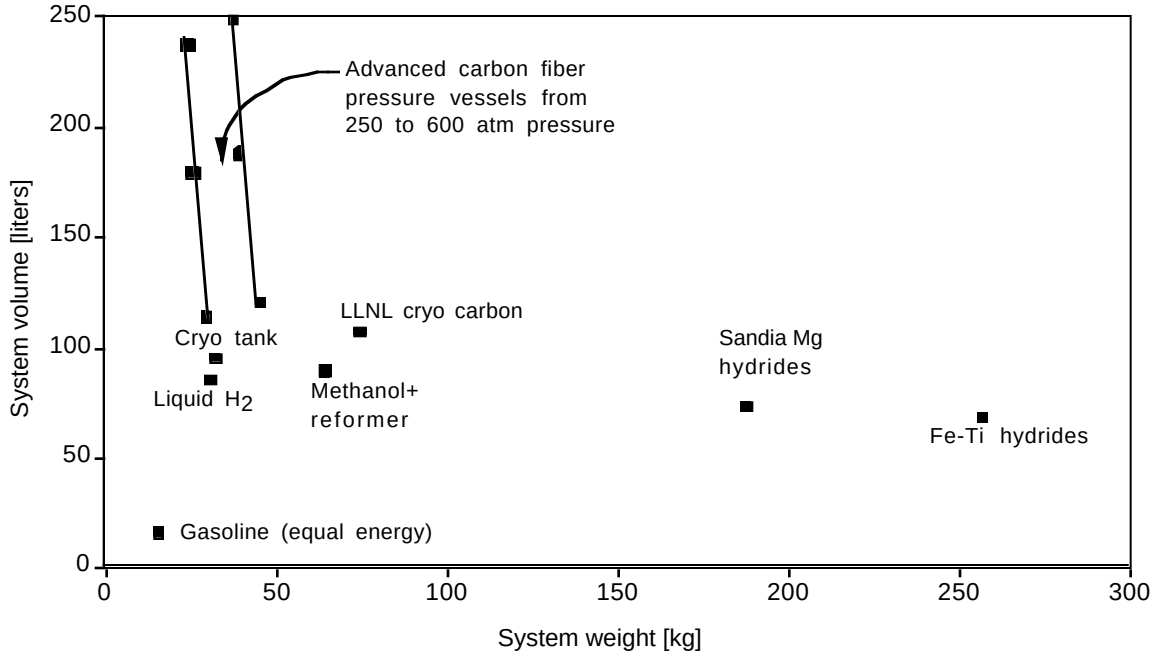

Fig. 2. Storage systems for 3.75 kg hydrogen (480-km range at 34 km/l). Energy penalties are as follows: 612-atm tank, 10%; Mg hydride, 25%; liquid hydrogen, 32%; cryotank, 25%; cryogenic carbon aerogel, 25%; and methanol reformer, 10%.

Table 1. Hydrogen distribution infrastructure options compared in terms of scale, economic flexibility, relative safety, and construction lead times. Hydrogen distributed by pipeline or rail would require mass-produced hydrogen vehicles. Liquid-hydrogen tanker trucks could serve fleets. Local production of hydrogen by off-peak electrolysis could smoothly support up to 40 million vehicles, with a minimum in new infrastructure requirements.

Infrastructure technology	**Vehicles supported**[a]	**Economic flexibility**	**Relative safety**	**Lead times**
Large pipeline (1.7 m, with 24 GW throughput, or 17 million kilograms of hydrogen per day)	45 million	poor	medium	long
Rail (60-car train)	1.2 million	medium	medium	medium
Small pipeline (100,000 kg/day)	275,000	poor	medium	medium
Tanker truck (1 truck)	9600	good	low	short
From high-voltage electricity (with on-site electrolysis)	1 vehicle to 40 million[b]	good	high	short

Sources: Data for the large pipeline are quoted from Ogden and Nitsch, 1992. Other hydrogen transport technologies are from Daniel Morgan, "Hydrogen as Fuel," a Congressional Research Service report to the U.S. Congress, March 22, 1993. Railcars are assumed to carry 101,292 liters (23,000 gallons) of liquid hydrogen. Tanker trucks are assumed to carry 57,252 liters (13,000 gallons) of liquid hydrogen.

[a]Vehicles travel an average of 19,308 km (12,000 miles) per year, using 3.75 kg H_2 in a 40% efficient hydrogen-powered electric drivetrain to travel 480 km. Hydrogen transport methods are fully dedicated in determining the number of hydrogen vehicles served.

[b]Using up to 15% of total U.S. 1992 electricity consumption (2.76 trillion kWh) at 68% electrolysis efficiency and 65% distribution efficiency.

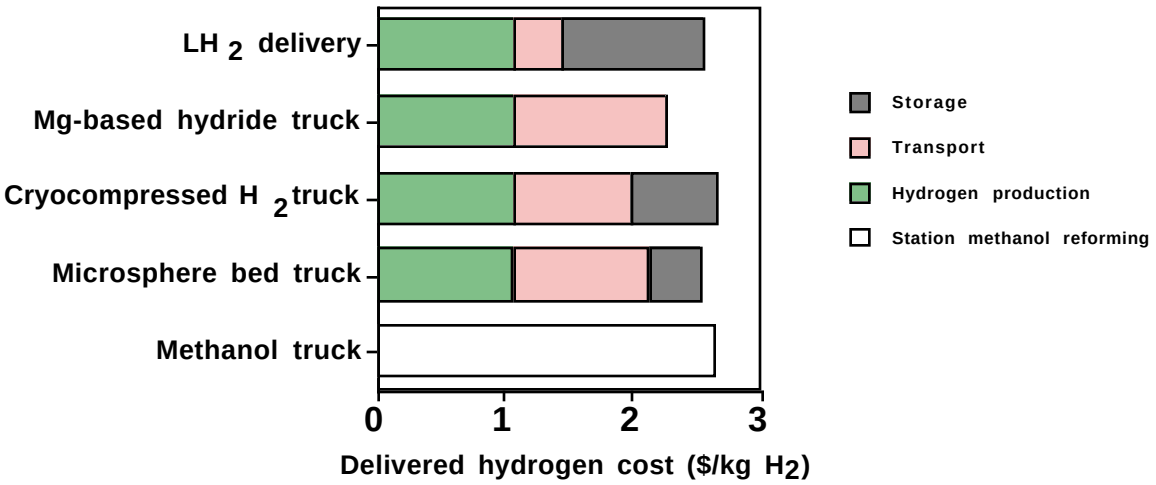

Fig. 3. Estimated costs of hydrogen transport by truck for liquid hydrogen delivery and projections for lightweight hydrides, cryogenic compressed gas (612 atm, 80 K), and high-pressure (612-atm) glass microsphere storage. Methanol delivery and on-site decomposition costs are from Korenz (1992).

Another alternative is to store methanol or ammonia onboard the vehicle, to be reformed to generate hydrogen as needed. Hydrogen carriers have the advantage of being lightweight, high-density, and low-cost storage systems, but they also have the potential for low energy efficiency (ammonia) and increased emissions. In summary, the hydrogen storage debate has not yet been resolved, but the improved energy efficiency of hybrid-electric vehicles has enhanced the flexibility and potential of onboard storage options and should drive technological advancements.

HYDROGEN PRODUCTION AND DISTRIBUTION

A chicken-and-egg dilemma faces any fuel alternative to gasoline. Large numbers of vehicles are required to support a fuel production and delivery infrastructure, and in turn a fuel production and delivery infrastructure must be in place before vehicles will be mass-produced. Large-scale production of vehicles and infrastructure components is crucial to making an alternative fuel cost-competitive. Hydrogen is especially suited to overcome these difficulties because of its flexibility in production, distribution, and storage methods. Hydrogen can be produced at much smaller scales than other alternative fuels. It can also be produced at or near the point of use, avoiding the start-up problems of fuel distribution for a small number of vehicles. As the number of hydrogen vehicles grows, hydrogen can also be produced at large plants and delivered by truck or possibly by pipeline.

Table 1 compares the basic options for hydrogen distribution. The major difference between distribution options is scale. On-site electrolysis can serve any number of vehicles, from an individual car up to 40 million vehicles, using 15% of 1992 U.S. electricity consumption. Producing hydrogen at central plants and distributing it by truck, train, or pipeline is most appropriate once significant numbers of hydrogen vehicles are in use.

Figure 3 presents estimated production and distribution costs for hydrogen delivered by truck using different storage technologies. Costs are broken down into production, storage, and transport costs. Methanol delivery by truck with onsite reforming is also shown for comparison. The first point to note is that hydrogen delivery costs are roughly equal to production costs. Second, although total delivery costs are roughly equal between methods, the composition of these costs varies widely between methods. Whichever method is preferred, the truck-delivered hydrogen costs are approximately $2.40/kg ($20/GJ).

HYDROGEN STATIONS

Even after hydrogen vehicles are in an area supported by hydrogen filling stations, on-site production of hydrogen from electrolysis or reforming is an alternative to truck distribution. Figure 4 shows the estimated cost breakdowns of on-site production of hydrogen, with liquid

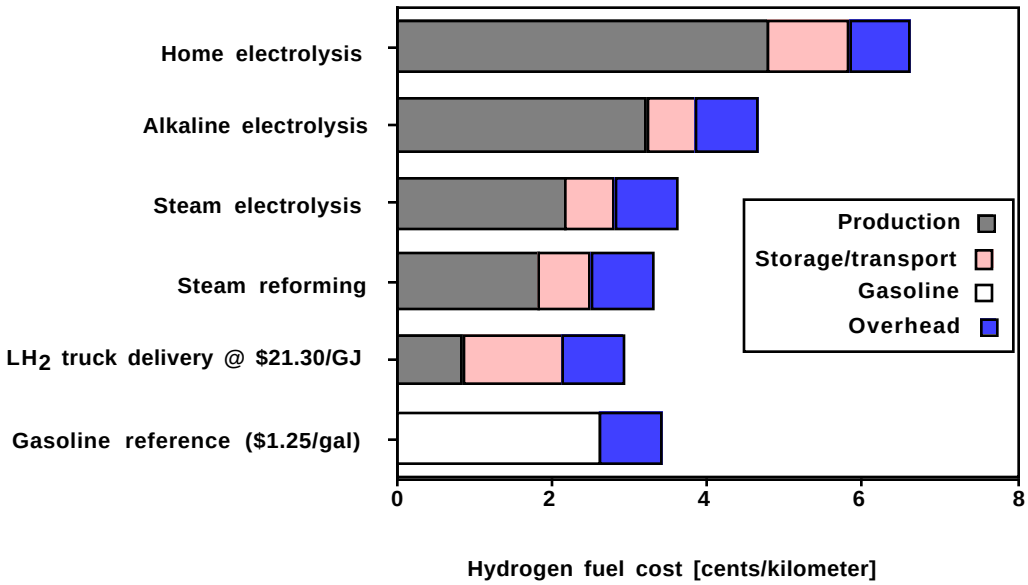

Fig. 4. Hydrogen fueling costs at a filling station or home for refueling a 3.75-kg/480-km hydrogen-powered vehicle. Capital, energy, and overhead costs are shown. The first hydrogen hybrid-electric vehicles introduced with home electrolysis will have fuel costs competitive with battery-powered vehicles, in large part because of the capital investment for electrolyzers. Hydrogen fueling costs will approach levels comparable to today's gasoline vehicles.

hydrogen truck distribution hown for comparison. Production, delivery, and storage costs of five scenarios are presented:

(1) Home electrolysis for an individual vehicle (sized for 480 km of driving per week).

(2) Alkaline electrolysis at a filling station serving 300 cars per day.

(3) Steam electrolysis at a filling station serving 300 cars per day.

(4) Steam reforming at a filling station serving 300 cars per day.

(5) Liquid hydrogen produced at a central plant and delivered 250 miles by truck.

Conservative cost estimates were used in all scenarios. Capital was discounted commercially at 20% and 10% for consumers. High energy prices were used in the cost estimates. Electricity was assumed to cost $0.05/kWh. Natural gas was assumed to be $4.00/GJ. Steam-reformed hydrogen from central plants was assumed to cost $9/GJ. Using these conservative assumptions, hydrogen fueling costs range from $30–70/GJ or 2.5–6 cents per kilometer (4–10 cents per mile) in a 34-km/l equivalent hydrogen vehicle. The broad conclusion represented in Fig. 4 is that hydrogen hybrid-electric vehicles can be refueled economically, initially at a cost competitive with battery-powered electric vehicles, and then with costs declining to become competitive with today's gasoline-powered vehicles, once several hundred hydrogen-fueled cars are available and hydrogen filling stations are built.

A SMOOTH TRANSITION FROM GASOLINE

The preceding conceptual vehicle design and hydrogen refueling cost estimates point the way toward a smooth transition from gasoline-powered vehicles to hydrogen-fueled vehicles. Hydrogen hybrid-electric vehicles can develop the hydrogen infrastructure early, paving the way for fuel cell vehicles when they become economically feasible. Fuel costs will be initially comparable to battery-powered electric vehicles but will compete with gasoline as the number of vehicles grows. Hydrogen's flexibility in production method, scale, and location—coupled with a spectrum of storage options—allows smooth cost versus-benefit tradeoffs. Hydrogen can take advantage of renewable energy sources wherever and whenever the benefits become worth the costs. Hydrogen's unsurpassed versatility, sustainability, and cleanliness support a single, smooth, flexible, and ultimate fuel transition from today's gasoline-powered vehicles, avoiding the financial risks and duplication of multiple fuel transitions.

ACKNOWLEDGMENTS

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REFERENCES

American Automobile Manufacturers Association (1993). *AAMA Motor Vehicle Facts & Figures '93.* AAMA, Detroit, MI.

Hall, J.V., et al. (1992). Valuing the health benefits of clean air. *Science* **255,** 812–17.

Korenz, Nick (1992). Economics of Hydrogen Manufacture. Report by SFA Pacific Inc. for Texaco and others.

Ogden, Joan, and Joachim Nitsch (1992). Solar Hydrogen. In: *Renewable Energy: Sources for Fuels and Electricity.* Island Press, Washington, DC.

Smith, J. Ray, and Salvador Aceves (1995). *Hybrid Vehicle System Studies and Optimized Hydrogen Engine Design.* Lawrence Livermore National Laboratory report UCRL-JC-120151.

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