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A Strategic Pathway to Hydrogen Fueled Powertrains for Light, Medium, and Heavy-Duty Vehicles



December 2006

Final Draft

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This paper addresses an evolutionary approach to reach the Hydrogen Economy that will presumably include hydrogen fuel cells as one of the sources of primary motive power for heavy-duty as well as light and medium-duty vehicles. This evolutionary approach for vehicles and powertrains consists of moving from existing internal combustion engines (ICE) operating on conventional fuels; to engines operating on hydrogen (HICE) and hydrogen blends (HBICE); to hybrid electric vehicles using hydrogen-fueled internal combustion engines (HHICE); and, ultimately, to a portfolio of fuels and advanced powertrains that include hydrogen fuel cells (HFC).14. SUBJECT TERMS **Hydrogen ICE, Hydrogen Blend ICE, Hybrid Hydrogen ICE, Hydrogen Fuel Initiative**

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A Strategic Pathway to Hydrogen Fueled Powertrains for Light, Medium, and Heavy-Duty Vehicles

Objective

This paper addresses an evolutionary approach to reach the Hydrogen Economy that will presumably include hydrogen fuel cells as one of the sources of primary motive power for heavy-duty as well as light and medium-duty vehicles. This evolutionary approach for vehicles and powertrains consists of moving from existing internal combustion engines (ICE) operating on conventional fuels; to engines operating on hydrogen (HICE) and hydrogen blends (HBICE); to hybrid electric vehicles using hydrogen-fueled internal combustion engines (HHICE); and, ultimately, to a portfolio of fuels and advanced powertrains that include hydrogen fuel cells (HFC).

Although this concept can be accepted as a plausible approach, little credibility has been given to the evolutionary approach due to the questionable efficiency of hydrogen-fueled ICEs and the doubt of the long-term applicability of ICEs with fuel cell technology looming large. We will attempt to address these concerns while identifying the ability of HICE technology to fill a gap between existing propulsion technology and fuel cells, as well as providing the possibility of being an on-going complement to vehicular fuel cell power systems.

A few assumptions are necessary to provide a structure on which to build this approach. These assumptions are:

- The Hydrogen Economy will happen, although the timeframe isn't critical to this thesis
- Economical production of hydrogen will occur
- Hydrogen infrastructure (fueling station) build-out is occurring and will continue, requiring a need for vehicles to use the fuel
- Development of on-board storage of hydrogen will eventually enable a vehicle range commensurate with conventional fuels

Background

In his 2003 State of the Union Address, President Bush announced a Hydrogen Fuel Initiative intended to reduce America's growing dependence upon foreign oil. The initiative is focused on the development of technology for hydrogen-powered fuel cells for both stationary and vehicle use. It also addresses the necessary technologies and infrastructure to produce, store, and distribute hydrogen on an economical basis, so that it becomes an affective alternative to conventional fuels.

In August 2005, the U.S. Department of Transportation/Federal Transit Administration (DOT/FTA) was given authority in Section 3045 of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: a Legacy for Users (SAFETEA-LU) to undertake a

National Fuel Cell Bus Technology Development Program (NFCBP). The FTA has traditionally been a leader in motivating the implementation of alternate fuels, particularly natural gas, and hybrid electric technologies in the nation's transit fleets and will continue to pursue more efficient and cleaner alternatives by aligning with the Hydrogen Fuel Initiative (HFI) through the activities of the NFCBP. The NFCBP will facilitate the development of commercially viable fuel cell bus technologies and related infrastructure for application in transit revenue service operations. The primary focus of the NFCBP is on advancing the commercialization of 40-foot, heavy-duty, fuel cell transit buses.

The U.S. Department of Energy (DOE) is also focused on implementing the HFI under projects within their Office of Energy Efficiency and Renewable Energy (EERE)/Hydrogen, Fuel Cells, and Infrastructure Technologies (HFCIT) Program. These projects address the production, delivery, storage, and utilization of hydrogen in the transportation arena. Specifically, the HFCIT program is focused on: (a) lowering the cost of hydrogen to make it competitive with gasoline by 2010; (b) creating effective on-board-vehicle storage of hydrogen to equate the driving range of a conventional vehicle (approximately 300 miles); and (c) creating affordable fuel cells.¹

The DOE Office of Fossil Energy (FE) is also accomplishing research in the utilization of hydrogen in stationary and transportation vehicle internal combustion engines, investigating durability issues that may arise in combusting hydrogen or hydrogen-methane mixtures in advanced engines.²

The FreedomCAR (Cooperative Automotive Research) and Fuel Partnership, which began in September 2003, is an expansion of the FreedomCAR Partnership that was originally established in January 2002 by the Secretary of Energy and senior executives of DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation. New partners to the organization include: BP America, Chevron Corporation, ConocoPhillips, Exxon Mobil Corporation, and Shell Hydrogen LLC. A "major thrust" of this organization, as stated in their Partnership Plan, is "to examine and advance precompetitive research and development of technologies to enable high volume production of affordable hydrogen fuel cell vehicles, and the national hydrogen infrastructure necessary to support them. The Partnership also examines and advances precompetitive R&D for other advanced automotive technologies through the continuation of key enabling research on advanced internal combustion engines and emission control systems, lightweight materials, power electronics and motor development, high-power/energy battery development, and alternative fuels."³

Significant activities are in place to research and develop the necessary technologies to enable the implementation of the HFI. However, the objective of the push towards the "Hydrogen Economy" is not only reduced dependence on foreign oil. Emissions reduction from fuel cells and engines using hydrogen as a fuel are also a primary driver in the move towards hydrogen as an automotive fuel. Fuel cells operate at a higher thermal efficiency than conventional internal combustion engines, providing better utilization of the energy content of a relatively sparse, non-dense fuel.

Alternative Fuel Issues and Lessons Learned

The implementation of alternative fuels into the U.S. transportation industry has been an initiative of varying importance since the Arab oil embargo that occurred in the early 1970s. As the U.S. becomes more dependent upon imported foreign oil, and as the price of that oil continues to increase, the push towards domestically produced alternatives is becoming more intense.

However, the road from the embargo to the present-day situation has not been smooth nor without considerable detours and pot-holes. Without going into detail on the rise and fall of different alternative fuels, we can identify significant issues that determine the success or failure of alternative fuels and vehicles.

1. Performance (acceleration, driving range, handling, etc.) of alternative fuel vehicles should be as good as or better than conventional vehicles.
2. The availability of fueling stations must match the needs of the customers and the number and location of vehicles.
3. The fuel and fueling station costs should be comparable to or less expensive than conventional fuels,
4. The fuel must be environmentally safe and relatively easy to handle, transport, and store.
5. The fuel and vehicles must have durability and longevity. That is, the vehicles must be as durable as conventional vehicles and must also have an acceptable resale value in the market. Vehicle resale value is not as critical with transit vehicles, but the longevity of the fuel in the marketplace is critical to meet life-cycle cost effectiveness in order to justify the initial equipment investment.
6. Persistent and active leadership is required on the part of the Federal and state governments (both Executive and Legislative branches) through national/state initiatives, tax incentives, discounts, etc. for alternative fuels and vehicles in order to maintain incremental costs to a minimum (or net benefit) when compared to conventional fuels and vehicles.

The most common metaphor describing the fundamental problem of implementing alternative fuels and vehicles has been, “which comes first, the chicken (vehicles) or the egg (fueling stations)?” Early attempts by natural gas utilities to “build it and they will come” placed fueling stations at convenient locations in anticipation that people would purchase their natural gas alternative fuel vehicles and flock to the station. However, people apparently expect an extensive network of stations before they’re comfortable with purchasing an alternative fuel vehicle. This approach of building stations with the expectation of vehicle purchases by fleets and, subsequently, private individuals has not been demonstrated to be successful in previous attempts.

Alternately, U.S. automakers have built millions of vehicles that are capable of operating on E85 (85% ethanol; 15% gasoline) with few stations being in existence. These vehicles were built to take advantage of beneficial provisions in federal regulations concerning corporate average fuel economy (CAFE) requirements. However, the vast majority have

not operated on the alternative fuel due to the lack of fueling stations, except in Minnesota, which has a statewide initiative to implement E85 fueling stations. After a number of years of producing these vehicles without public advertisement by the automobile companies, automakers are now beginning to publicize their flex-fuel capability. E85 fueling stations are becoming more numerous. The motivation for the increase in the vehicle visibility and number of ethanol stations appears to be the rising cost of gasoline as well as a national patriotic movement towards more domestically produced fuels.

Biodiesel is beginning to make significant inroads into the U.S. fuel portfolio, primarily due to the same reasons that ethanol is; i.e., increasing cost of diesel fuel and domestic production, as well as some improvement in exhaust emissions over conventional diesel. Engine manufacturers are replying to this interest by specifying that their diesel engines are compatible with various blends (from 5% to 20%) of biodiesel.

Natural gas as a vehicle fuel has surged and fallen several times without making significant headway as a transportation fuel. It has, however, been integrated in a moderately successful manner within the transit industry. Several key points have been learned from the natural gas experience.

1. “Anchor” fleets, such as taxis or service trucks, are necessary to ensure the minimum required fuel throughput for economic viability of a public fueling station.
2. Niche markets, such as transit/shuttle buses and refuse vehicles, that use centralized fueling where the fleet vehicles return to a central location on a daily basis, can be very good, cost-effective applications. In fact, transit bus applications are where natural gas has found the most success.
3. The technology must be as robust and durable as the technology it is intended to replace; i.e., heavy-duty natural gas, spark-ignited engines must be comparable to the diesel engines they replace.

The DOE Energy Information Administration (EIA) estimated that for 2004, alternative fuel use in the U.S. represented approximately 0.25% of the total fuel use.⁴ This amount jumps up to only 1.4% when the use of alternatives for oxygenates are considered. So, the dilemma of the “chicken and the egg” has obviously been difficult to overcome to this point in time. E85 appears to be making some progress in moving forward, biodiesel is gaining market share, and natural gas is finding its niche, but can hydrogen, the fuel of newest interest, become a viable alternative in the fuel portfolio?

Hydrogen Fueling Infrastructure

Hydrogen fueling stations are currently being built. The California Hydrogen Highway is developing a network of fueling stations throughout California in preparation for these new vehicles. The first phase of this activity will focus on “clusters” of vehicles in major metropolitan areas, expanding into regions, and, ultimately, into a statewide network. Phase 1, expected to be completed by 2010, plans to implement 50 to 100 stations serving

roughly 2,000 vehicles. Phase 2, the timeframe of which has yet to be determined, consists of 250 stations serving 10,000 vehicles. And finally, Phase 3, will utilize those 250 stations more heavily serving 20,000 vehicles. The first 39 stations are already being funded through existing public-private partnerships with the U.S. DOE, South Coast Air Quality Management District (SCAQMD), and California Fuel Cell Partnership (CaFCP). There is also a movement to begin a similar hydrogen corridor along Interstate 95 between Boston and Washington, DC on the east coast. Likewise, Canada is considering hydrogen corridor efforts including one in British Columbia linking Vancouver, Whistler, and Surrey and eventually linking to hydrogen corridors in California and Alberta. Another Canadian hydrogen corridor is planned between the heavily traveled route between Windsor, Ontario and Montreal, Quebec.

The Upper Midwest Hydrogen Initiative (UMHI), which is an industry-led, U.S.-Canadian, public-private venture of the non-profit Great Plains Institute, is developing a multi-fuel Clean Fuels Network to support the development of a renewable hydrogen infrastructure across the Northern Plains of the U.S. and Canada. The Northern H fuels network will offer biofuels and hydrogen at Energy Stations that link urban centers along key trade corridors in the Northern Plains. The intent is to demonstrate renewable hydrogen production options at each station that is appropriate to each area's strengths and economic goals. Among the technologies to be demonstrated are ethanol-to-hydrogen, wind-to-hydrogen, methane-to-hydrogen, and coal-to-hydrogen using carbon sequestration.

Europe is also developing a string of hydrogen corridors that are destined to be linked at some point in the future. The Scandinavian Hydrogen Highway Partnership including HyNor (Norway), Hydrogen Link (Denmark) and HyFuture (Sweden) has been formed to enable the Scandinavian region to be one of the first regions in Europe to make hydrogen commercially available in a network of fueling stations.

However, these approaches seem vaguely similar to the “build it and they will come” approach that was led by the natural gas utility companies in the U.S. in the 1980s. It is critical that as the hydrogen fueling stations are built, they become more fully utilized to create revenue for their further operation. Otherwise, they will “die on the vine,” as have many public CNG fueling stations in the U.S.

Given the growing hydrogen fueling infrastructure, increased near-term hydrogen utilization can be motivated by the introduction of HICE or HBICE vehicles as we work towards fuel cell maturity. This would enable growing familiarity and experience with hydrogen as a fuel, leading to earlier optimization of production, storage, and handling; significantly reducing VOC, NOx, CO, and air toxic emissions as well as greenhouse gas emissions from vehicles; and taking advantage of the remaining CNG infrastructure in the U.S.

Hydrogen ICE Projects

Fuel cell vehicles may take another 5 to 10 years to attain adequate technical maturity to bring to market. The earliest estimates for market entry of fuel cell vehicles appear to be around 2010. Cost and durability issues may prevent them from being a significant share of the automotive market early in their implementation, so other means of utilizing the hydrogen at the fueling stations need to be developed in order to adequately support the existence of those stations.

The development and implementation of hydrogen and hydrogen-blend ICEs could increase the use of hydrogen in the transportation industry, providing the needed support for hydrogen fueling stations and playing a significant role in the Hydrogen Fuel Initiative. However, there are few well-funded development activities focused on this relatively near-term technology. Hydrogen ICEs have been “sidelined” from the federal perspective, presumably due to the lower thermal efficiency expected from ICEs and the intense focus necessary to bring fuel cells to technical maturity. Although HICEs are mentioned in program plans as a transition technology, little federal funding is provided to support their development.

Projects that have occurred with ICEs using hydrogen or hydrogen blends as a fuel have varied from simple fuel substitution, to minor engine modifications specific to the fuel being used, to dedicated engine development. We’ll investigate what has been learned from these activities and how that information can be used to establish that HICEs are a realistic stepping stone to fuel cells and are a viable candidate for additional support and development.

HICE Symposium

On February 22, 2006, WestStart-CALSTART and the FTA sponsored a symposium on HICE in conjunction with the Clean Heavy Duty Vehicle conference. The purpose of the symposium was to bring together organizations who had been accomplishing work in the HICE, HBICE, and HHICE areas and to compare notes on the results of those studies. A collection of the presentations is available on CD from WestStart-CALSTART.⁵

Three questions were proposed to be answered by the presentations during the course of the symposium:

1. Can HICE systems achieve efficiencies that exceed the best of those obtained with diesel and gasoline?
2. Can HICE systems support advanced technology, partial-zero emission vehicles or near-zero emission buses?
3. Can HICE provide the same or an increase in power density as their conventional counterparts?

The bottom-line objective was to determine whether HICE and its variants have a role during the transition to hydrogen as a transportation fuel.

Fuel Substitution and Blends

Several projects have focused on using hydrogen or hydrogen/methane (HCNG) blends as a substitute fuel for gasoline or CNG. Results of these experiments have been variable,

but generally positive, depending upon the care that was taken in modifying the engine for the hydrogen or blended fuel.

- Idaho National Laboratory (INL), under funding from DOE, has been investigating the use of hydrogen and HCNG blends as a substitute fuel in several different vehicles. Their activities have demonstrated that simple fuel substitution, with no special engine tuning, can result in an improvement in most criteria emissions, except for NO_x, which can increase substantially. An increase in NO_x emissions in hydrogen fueled ICEs can be attributed to the higher flame temperature and flame speed, so appropriate engine tuning and timing is required to reduce this effect. Other fuel substitution projects at INL have utilized third-party aftermarket engine modifications on GM and Ford pickups to assess performance using various blends of HCNG and also 100% hydrogen fuel. These experiments provide interesting benchmarks of what is possible using a retrofit approach; however, they also demonstrate that original equipment manufacturer (OEM) involvement will be necessary to develop credible hydrogen ICE solutions. This is consistent with retrofit attempts that have occurred in the past with other alternative fuels.
- SunLine Transit Agency, under sponsorship of FTA, DOE, SCAQMD, and others, has evaluated a variety of alternative fuels for transit vehicles over a number of years. One project involved the operation of 40-foot transit buses on 20% HCNG. SunLine worked with Westport Innovations to modify and test a Cummins Westport (CWI) B Gas Plus, 5.9L, spark-ignited, natural gas engine to operate on HCNG.⁶ A variety of HCNG blend levels were assessed during engine testing to determine the optimal mix for this application. After the engine testing and re-calibration for hydrogen's more rapid combustion rate, it was determined that the optimal blend was 20% HCNG with the only modification necessary to the engine being a higher volume mass fuel flow sensor due to the heat transfer characteristics of the added hydrogen. Results of vehicle chassis testing at SunLine indicated a 55% reduction in NO_x for HCNG compared to the natural gas engine. Other criteria emissions remained low due to the oxidation catalysts on both HCNG and CNG engines. Fuel consumption did increase by 12%, but it is projected that additional transient calibration of the engine could improve upon that – probably by avoiding unintended errors in air/fuel ratio or spark timing. This project demonstrated that conventional, heavy-duty, CNG engines could be modified to operate on HCNG with relatively few hardware changes. This success provides a stepping-stone for a transition to greater use of hydrogen by incorporating it into the CNG fuel that many transit or refuse fleets are already using.
- In a similar project funded by the Canadian government, Westport Innovations will be modifying a CWI 8.3L, C Gas Plus engine to utilize waste hydrogen from a sodium chlorate plant in four HCNG transit buses that will operate in the Vancouver area. Lessons learned from the SunLine project will be incorporated into this more recent project.
- Another project based at SunLine that provides a stepping-stone in the transition is the test and evaluation of a HHICE drive system in a 40-foot New Flyer bus. The bus

uses an ISE ThunderVolt® hybrid-electric drive system that generates power with a Ford hydrogen-burning, V-10, turbocharged, intercooled internal combustion engine.⁷ Testing at SunLine, in Palm Springs, CA and in Winnipeg, Manitoba, Canada has demonstrated the ability of the system to operate in environmental extremes while providing 2 – 6 miles/kg of fuel economy, which is comparable to conventional natural gas buses being operated at SunLine. No significant problems, other than some fueling issues in extremely cold weather, have been identified.

- SCAQMD is sponsoring a project with Quantum Technologies to deliver 36 HHICE Prius vehicles into the South Coast Air Basin for test and evaluation. The vehicles are expected to have equivalent fuel efficiency of their fuel cell counterparts at a fraction of the system cost. The Prius is modified to include multi-port hydrogen fuel injection, turbocharging with an intercooler, and compressed hydrogen storage. Test results have indicated almost total elimination of CO and CO₂ emissions compared to a conventional gasoline Prius. Range has been demonstrated to be approximately 90 miles, limited by the capacity (1.6 to 2.4 kg of compressed hydrogen) of the 5,000 psi on-board storage tanks. Performance is reported to be comparable to the gasoline Prius with a small increase in fuel economy.

Engine Development

While the previous projects focus on retrofitting existing engines to operate on hydrogen or hydrogen blends, usually under a third-party (not original equipment supplier) subcontracted effort, the following projects are representative of activities that focus on specific engine design changes by engine manufacturers to enable the most efficient use of hydrogen as a fuel.

- Ford announced in June 2006 that it plans to place eight E-450 shuttle vehicles into service at tourist destinations in Florida. The vehicle uses Ford's 6.8L Triton™ V-10 gasoline engine that has been modified by Ford to operate on 100% hydrogen. The engine uses port injection of hydrogen. Hardening of the valve heads and seats is typically accomplished with gaseous fuel engines due to the lack of liquid fuel lubrication or damping. This is also an issue with the fuel injectors. Dr. Gerhard Schmidt, Ford Motor Company Vice President of Research and Advanced Engineering, has stated that "we (Ford) believe that HICE vehicles will play a key role in justifying infrastructure development and accelerating a transition to a hydrogen economy."
- BMW is scheduled to introduce a hydrogen powered 7-series luxury sedan in the 2010 timeframe. The engine will be bi-fuel, able to operate on hydrogen or gasoline. BMW's Group spokesperson, Bill Scully, has been quoted stating, "BMW has been developing hydrogen-fueled internal combustion engine vehicles for nearly 25 years. We have researched other hydrogen technologies extensively and have a commitment to the hydrogen combustion engine."

- Westport Innovations is working with both Ford and BMW to develop direct injection hydrogen injectors for their engines. As mentioned previously, injectors for gaseous fuels suffer from a lack of damping or lubrication that is present with liquid fuels and are, therefore, more subject to wear. Hydrogen embrittlement of the injector material is another characteristic that is being addressed to enhance the durability of this component. Direct injection of hydrogen into the combustion cylinder, rather than port injection, is now being investigated in more detail and promises to significantly increase the performance of the HICE.
- In Europe, MAN Nutzfahrzeuge AG and NEOMAN Bus GmbH are participating in the EU HyFLEET:CUTE project and will be delivering 14 HICE buses to the Berlin transport authority. The engines are based on the MAN natural gas engine and will include naturally aspirated as well as supercharged turbo-engines in the fleet. MAN is also proposing to provide 20 HICE buses to Rotterdam, Holland to become part of a project with Shell Hydrogen BV that is being advertised as the world's largest hydrogen fueled public transport system. In a move to improve fuel efficiency over retro-fit engines, MAN is developing a new six-cylinder engine to operate specifically on hydrogen.
- Volvo announced the development of a multi-fuel vehicle at the 2006 Michelin Challenge Bibendum. This prototype vehicle had been developed to operate on five different fuels: gasoline; E85; natural gas; bio-methane; or a 10% HCNG blend. Volvo developed a unique catalyst system to achieve a PZEV/SULEV emission rating for the U.S. market. High temperature materials in the exhaust manifold and turbo allow extremely high exhaust gas temperatures enabling the vehicle to run cleaner, accelerate quicker and operate more smoothly at higher speed.
- Pivotal Engineering is developing a unique engine that is capable of operating on a variety of fuels.⁸ The engine is a redesign of the conventional two-stroke engine and proposes to significantly reduce emissions usually associated with this engine type, while maintaining a high power density. Using direct injection of the fuel and no poppet valves enables the engine to operate on hydrogen at a combustion condition closer to stoichiometric than conventional 4-stroke engines, thereby increasing power and efficiency. This approach represents new thinking that may be appropriate in order to take full advantage of the characteristics of hydrogen as a fuel.

Next Steps in HICE Technology Development

Research at Ford has demonstrated that naturally aspirated, port-injected, hydrogen-fueled engines are limited to approximately 65% of the gasoline engine output at peak torque; otherwise pre-ignition and damage to internal components can occur.⁹ This lower torque and power is the reason engine manufacturers have typically incorporated intercooled turbochargers onto their HICE, to bring performance back to the level of a comparably sized naturally-aspirated gasoline engine. However, Ford has been able to demonstrate a peak thermal efficiency of 38% for its port-injected, lean-burn, high compression ratio HICE, which approaches that of a diesel in the same engine size class.

Direct injection (DI) of hydrogen into the combustion chamber appears to have significant benefits for HICE operation. Theoretically, a naturally aspirated HICE with direct injection can have a power output that is 17% greater than a port-injected gasoline engine. This can be enhanced further by turbocharging, allowing the use of a smaller, more economical engine for a specific platform size. However, injector wear issues become more dramatic with DI of a dry, gaseous fuel, severely constraining the durability of this component.

Westport Innovations has identified these key benefits of hydrogen DI technology:

- High power density at low speeds with high load; competitive with diesel
- High efficiency exceeding 40% peak for medium sized engines.
- Extremely low emissions with hydrocarbons, CO, and CO₂ being virtually zero. NO_x is controllable with air/fuel ratio management and advanced injection strategies without aftertreatment being required.
- Potential for very high power density engines (BMEP >> 15 bar) if NO_x control strategies using advanced fuel injection technologies (homogeneous & stratified) and emerging NO_x control hardware (lean NO_x adsorbers, Urea –SCR) are utilized.
- Engine reliability and durability that is well understood and already in mass production. Components such as the intake and exhaust valves benefit greatly from previous efforts with CNG engines.

Westport and Ford have believe that a robust DI fueling system is a critical enabler of the HICE technology that requires:

- component redesign
- review of material selection
- accelerated component methods,
- control strategy development to realize the full potential of hardware.

Injection of hydrogen into conventional fuels during combustion also appears to have other benefits. The higher flame speed and hotter flame of hydrogen results in more thorough combustion of the fuel and reduces engine-out emissions by reducing wall-wetting and reducing catalyst heat-up time upon starting. Delphi is developing an on-board reformer that can supply the necessary hydrogen from gasoline. Presumably, the system would be less expensive than the two or three catalysts that are currently required attain SULEV emission levels.

Based on what was learned in the HICE Symposium and in subsequent document research concerning further HICE development, it appears that the answers to three questions posed at the Symposium are:

1. Given adequate development of DI, HICE systems should be able to achieve efficiencies that meet or exceed those obtained with diesel and gasoline.
2. HICE systems, particularly with hybridization, can achieve emission levels that approach partial-zero emission and near-zero emission classifications.

3. HICE can provide the same or an increase in power density as their conventional counterparts.

A Proposed Timeline for HICE

Given the objective of the Hydrogen Fuel Initiative to incorporate hydrogen as a major component in the fuel portfolio of the U.S., it stands to reason that we need to develop a multitude of technologies that can efficiently use this clean, domestically produced energy source. Planning on the success of a single technology, fuel cells, to justify the use of hydrogen constrains the timeline of fuel implementation and restricts the breadth of impact the fuel could have in the near-term and in the future. Therefore, the timeline illustrated in Figure 1 (with the dates being highly approximate, especially with the duration of the technologies), begins with natural gas and hybrid electric vehicles, quickly progresses to the use of hydrogen as a fuel almost immediately and evolves towards a future that includes a variety of hydrogen-using power sources.

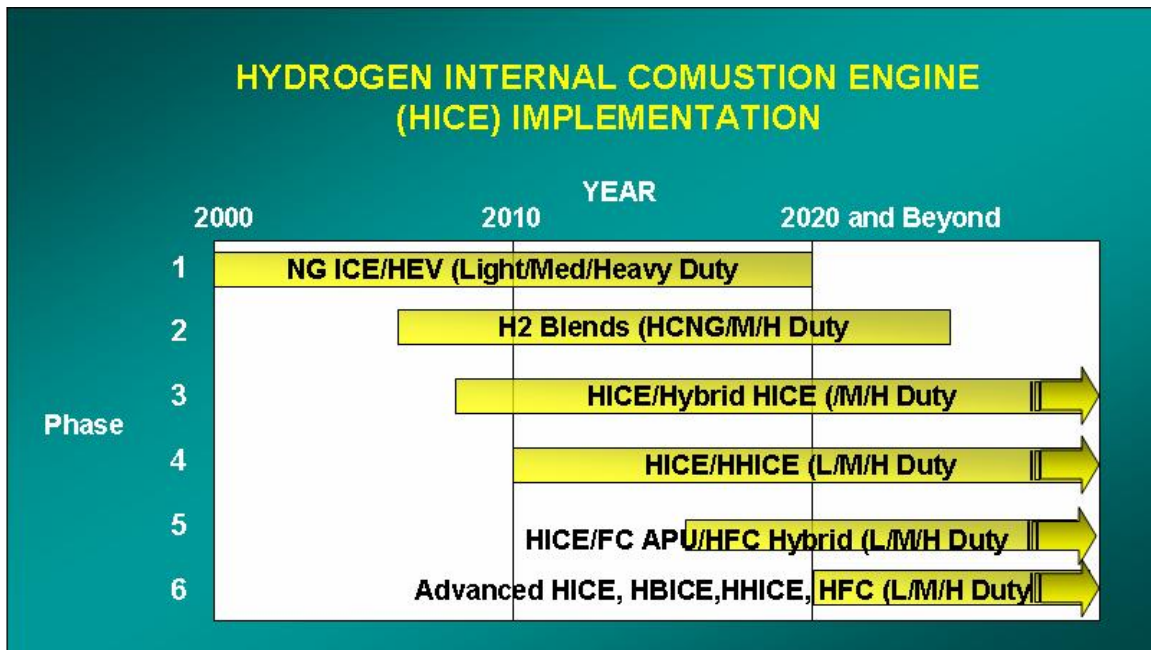


Figure 1

Phase 1: Current vehicles using natural gas ICEs (NG ICE) and hybrid electric drivetrains (i.e., hybrid electric vehicles - HEV) provide the technology base for moving technology forward towards hydrogen.

Phase 2: Hydrogen mixed with methane at a volume fraction of approximately 20% will provide significant emission reduction benefits for already relatively clean natural gas engines. Minimal modification is necessary to the natural gas engine to operate on HCNG, although additional fuel storage may be needed to maintain range. This blended fuel application is most easily adapted to vehicles and fleets that are already using natural gas as one of their prime fuels, i.e., transit bus, shuttle, and refuse fleets, with the addition

of the appropriate hydrogen supply and fueling infrastructure. Placement of the hydrogen fueling infrastructure at sites with centralized fueling, where maintenance is a priority, will help to identify early problems and assist in optimizing system design and evolution.

Phase 3: In conjunction with HCNG use or as a push into new technology, transit agencies and fleets can begin to incorporate new vehicles using HICE integrated into hybrid electric drivetrains to extend the fuel economy of the HICE and, therefore, the vehicle's range. The fleet would then gain experience with 100% hydrogen, possible hydrogen blends, and hybrid electric components that are destined to be used in fuel cell vehicles.

Phase 4: With further development of HICE and HBICE technologies and through the use of DI, fuel efficiency and power can be improved. Concurrently, the viability of injecting hydrogen in conjunction with conventional fuels to enhance the combustion process will be better developed, proven, and established. At this point, HICE and HBICE will have been demonstrated in fleet vehicles and should gain wider acceptance by the public. This, of course, assumes that the cost of hydrogen as a transportation fuel becomes competitive with conventional fuels.

Phase 5: Ultimately, fuel cells may prove themselves to be viable power sources for transportation vehicles. However, their expense and unknown durability may necessitate the use of fuel cell and HICE (or battery) hybridization. A smaller fuel cell could carry a base (or auxiliary) load while the HICE would handle transient loads. Fuel cells may also be used as an auxiliary power unit (APU) aboard Class 8 truck tractors to carry "housekeeping" loads.

Phase 6: A portfolio of advanced fuel and powertrain choices will be needed within the next 20 to 30-years to offset the use of imported petroleum. This portfolio may extend into the future until a clear winner is identified by technology advancement, economics, politics, and/or consumer preference.

Conclusions

The current and near-term availability of internal combustion engine technology and expertise, along with the tremendous amount of funding that has been invested in its development, suggests that the ICE not be cast-off as obsolete just yet. The flexibility of ICEs enable them to burn a variety of fuels, given appropriate tuning and combustion optimization. Their inherent inefficiency is gradually being improved and refined. Fuel cells have not yet demonstrated a similar capability to survive in the relatively harsh automotive and truck environment, nor be economically competitive with the ICE. Further HICE development promises to provide excellent performance, efficiency, and power density at a fraction of the cost of HFCs. Several engine manufacturers, suppliers, and vehicle manufacturers are committing significant, though substantially limited, resources to the development and testing of these engines.

With the objective of the Hydrogen Fuel Initiative being to reduce the use of imported petroleum, the increased use of hydrogen fuel in automobiles and trucks is imperative to building and maintaining a market for this new fuel. Adequate numbers of fuel cell vehicles will not be produced prior to 2010 to justify the expense of placing new hydrogen fueling stations, except in very limited locations. But an adequate number of stations must be in place for fuel cell vehicles to be successful with consumers. A variety of hydrogen fueling corridors are being placed in the U.S., Canada, and Europe. In the interim before HFCs are widely available, HICE vehicles can begin using the fuel to support the stations and provide an adequate flow-through of product to help bring the cost of hydrogen down at the pump. In the longer term, HICE can become an important component of the hydrogen portfolio, acting as a well-proven and relatively inexpensive workhorse or as a complement to a fuel cell power supply.

The application of HICE, HBICE, and HHICE to transit, paratransit, shuttle, delivery, and refuse fleets that are already using natural gas as a fuel is a natural evolution of gaseous fuel technology. This step could be taken in the near term and would serve to provide valuable operational experience with hydrogen as a transportation sector fuel.

The transition to hydrogen cannot happen overnight and will require a market pull as well as a government and supplier push. The market pull will not occur until the benefits to the user are well established and identified. The proliferation of hybrid automobiles has demonstrated that people may be willing to pay more for a cleaner, more fuel efficient vehicle. But it's doubtful the reception would have been quite as warm if the purchaser had to pay more for their fuel as well. The correct value proposition needs to be in place for hydrogen to succeed. Based on lessons learned, the cost of the fuel should be similar to or, preferably, less than conventional fuel and the incremental cost for the vehicle should be minimal. HICE can provide a means to attaining these objectives by providing early experience to fill the gap between conventional fuels and the hydrogen future.

Recommendations

The following suggested actions should be implemented to identify and enhance the development of HICE concepts:

1. Complete a survey of U.S. transit/shuttle and other fleets, hydrogen corridor groups, industry suppliers, and funding organizations to establish alignment of HICE perceptions and expectations.
2. Conduct a technical scanning tour in Berlin, Frankfurt, and Rotterdam to meet with BMW, MAN, and the HyFleet Transit properties and fueling station partners to gain a better understanding of their commitment and plans for HICE.
3. Organize a series of dialogs to be held in conjunction with hydrogen-related conferences to focus on applications, development needs, barriers, and next steps.
4. Facilitate development of an action plan for funding appropriate research, development, demonstration, and deployment of HICE, HBICE, and HHICE technologies.

5. Engage appropriate Federal, State, and local agencies for input to the Action Plan and follow-up action.

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