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Vehicles and Fuels for 2020: Assessing the Hydrogen Fuel-Cell Vehicle

Even with aggressive research, the hydrogen fuel-cell vehicle will not be significantly better than diesel and gasoline hybrids in terms of total energy use and greenhouse gas (GHG) emissions by 2020, says a study released by the MIT Laboratory for Energy and the Environment. And while hybrids—vehicles powered by conventional engines supplemented by electric motors—are already appearing on the roads, adoption of the hydrogen-based vehicle will require major infrastructure changes to make fuel-cell cars and hydrogen fuel available. The MIT study involved a systematic and comprehensive assessment of a variety of engine and fuel technologies as they could develop by 2020 with intense research but no real "breakthroughs." An extension of an assessment completed in 2000, this study used far more optimistic assumptions about fuel-cell performance, but key conclusions remained unchanged. If we need to curb GHGs within the next 20 years, improving mainstream gasoline and diesel engines and transmissions and vehicle design and expanding the use of hybrids is the way to go. Singling out hydrogen fuel-cell vehicles for research—the Bush administration's current strategy—has long-term promise but will have little effect by 2020. Such vehicles are efficient and low-emitters on the road, but making the necessary hydrogen fuel from natural gas or gasoline uses substantial energy and emits GHGs that have to be added to road behavior for a "life-cycle" assessment. If dramatically lower GHG emissions are required 30 to 50 years in the future, hydrogen now appears to be the only major fuel option. But the hydrogen must be made from non-carbon sources such as solar energy or from fossil fuels while capturing and sequestering carbon dioxide emissions.

During the past year, the Bush administration has undertaken programs that may devote billions of dollars to developing a passenger vehicle powered by a hydrogen-based fuel cell (FC). Government announcements have deemed that technology to be the best means of reducing energy use and cutting harmful emissions from the transportation sector, which is now responsible for about a third of the nation's GHG emissions. However, some people are concerned that hydrogen FC cars will not enter the fleet in large numbers for decades and that the federal programs are not encouraging work to develop nearer-term fuel-efficient technology options that warrant support.

Researchers in the Laboratory for Energy and the Environment (LFEE) have now released a study that supports that concern. The new study is an extension of *On the Road in 2020*, an assessment released in 2000 in which a team led by Dr. Malcolm A. Weiss and Professor John B. Heywood evaluated new automobile technologies with the potential for lower emissions of GHGs, which are generally believed to contribute to climate change. Using data from a wide variety of sources, they systematically

Onboard and Life-Cycle Energy Consumption Can Be Very Different for New Technologies

Technology	Onboard Consumption	Life-Cycle Consumption
2020 Baseline (see text)	100	100
Hydrogen FC hybrid	31	52
Diesel ICE hybrid	52	56

This figure demonstrates the importance of considering not only the energy used to operate the vehicle on the road ("onboard consumption") but also the energy used in making both the vehicle and the fuel it consumes ("life-cycle consumption"). In terms of onboard energy consumption, the hydrogen fuel cell (FC) hybrid significantly outperforms the diesel internal combustion engine (ICE) hybrid. But that advantage almost disappears in a comparison of life-cycle energy consumption, largely because so much energy is required to make hydrogen fuel from natural gas, the approach assumed in this study.

compared various combinations of fuel and vehicle technologies, assuming the likely state of each technology in 2020 as a result of "diligent" research but without counting on technical breakthroughs.

For each fuel-vehicle combination they calculated energy use and emissions, not just in operating and maintaining the vehicle but also in manufacturing the vehicle, making and delivering the fuel, and ultimately scrapping and recycling the vehicle. Their life-cycle assessment produced no unequivocal winners. The much-touted hydrogen FC hybrid did no better than the diesel internal combustion engine (ICE) hybrid did in terms of energy efficiency and GHG emissions, and the equivalent gasoline engine hybrid was not far behind. Moreover, the hydrogen FC technology would cost more, and its adoption would require major infrastructure changes to make FC vehicles and compressed hydrogen widely available.

On the Road in 2020 received substantial attention from government and industrial groups as well as the press. But some observers—including the researchers themselves—were surprised that the hydrogen FC did not fare better. Could their assumptions about future FC performance have been too conservative?

To find out, Dr. Weiss, Professor Heywood, Dr. Andreas Schafer, and Vinod K. Natarajan repeated the assessment using more optimistic assumptions about certain characteristics of the technology—assumptions closer to what FC advocates cite. The changes focused on sources of "energy losses," which reduce the fraction of the fuel's energy that ends up as electrical energy available for powering the vehicle. The assessment considered two designs incorporating FCs. One is fueled with pure compressed hydrogen gas, which is stored onboard the vehicle; the other is fueled by gasoline, which is converted into hydrogen gas by a "fuel processor" onboard the vehicle. In both designs, energy losses occur within the FC system itself. As the hydrogen is being electrochemically converted into electric power, some of the fuel energy is lost as heat. And some of the generated electricity is diverted from powering the vehicle to running pumps, blowers, and a compressor. In the gasoline-based design, additional significant energy losses occur inside the fuel processor as the gasoline is converted to hydrogen.

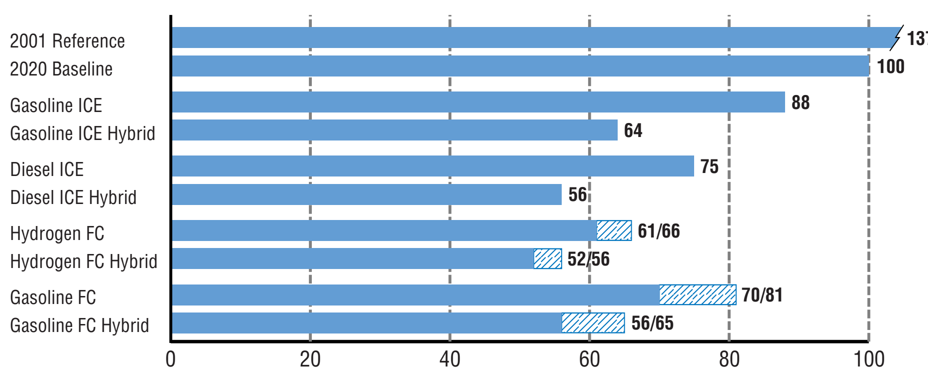
Based on reviews of recent literature and discussions with FC analysts and commercial component and vehicle developers, the researchers identified several advances that were feasible with aggressive development. Accordingly, in the new study they assumed better materials, improved designs, and more efficient operation to reduce the energy losses described above. They did, however, limit the changes to those whose cost looked at least plausible commercially. For example, further increasing the size of the FC or the concentration of platinum catalysts inside it would further increase its efficiency but would result in unrealistically high costs. Analysis showed that the new, more optimistic assumptions about FC performance reduced the previous estimates of fuel consumption onboard the vehicle by a quarter to a third.

The charts below show estimates of life-cycle energy use and GHG emissions for a variety of technologies. All outcomes are compared on a relative scale where 100 is defined as characteristic of a midsize car comparable

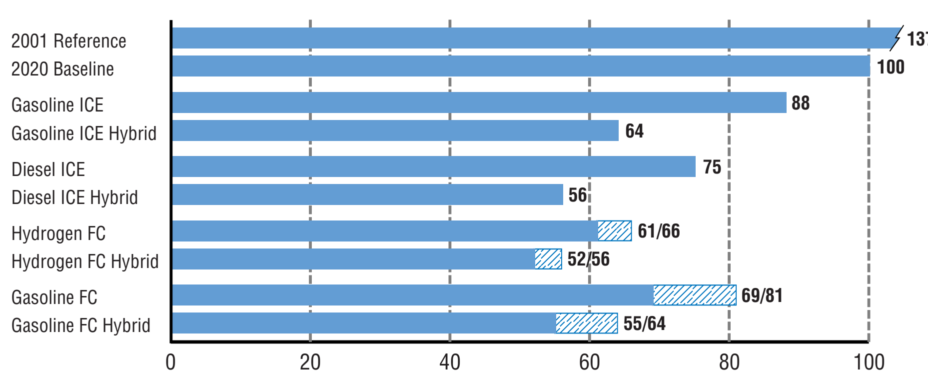
Comparative Assessment of Vehicle Technologies for 2020

- Total energy and greenhouse gas (GHG) emissions from all sources consumed during vehicle lifetime
- GHGs include only CO_2 and CH_4
- Shown as percentage of baseline vehicle energy consumption and GHG emissions
- Total energy and GHG emissions include vehicle operation and production of both vehicle and fuel

Relative Life-Cycle Consumption of Energy



Relative Life-Cycle Emissions of Greenhouse Gases



in capacity and performance to a Toyota Camry in 2020, assuming “evolutionary” changes in the engine, vehicle body, and fuel. All the other vehicles assume more aggressive advances. The hydrogen FC technologies assume that hydrogen is produced by reforming natural gas at local filling stations; it is then compressed for charging vehicle tanks. The gasoline FC technologies assume that gasoline is fed onto the vehicle and converted to hydrogen inside an onboard fuel processor.

The striped extensions on the bars for the four FC technologies require explanation. In each case, the more optimistic outcome—the solid bar—results from assuming that each component of the FC system is separately optimized for maximum performance. However, when engine developers integrate all the components to make a commercial car, they must compromise the performance of some of those components to keep the overall system from being too expensive, heavy, bulky, and so on. The striped extensions represent the outcomes under those less optimistic—but the researchers think more realistic—conditions. In several cases, the loss in performance is considerable.

The charts for both energy consumption and GHG emissions confirm that the 2020 baseline is dramatically better than the 2001 reference and that all the other technologies do even better, some of them significantly. Nevertheless, the hydrogen FC—even with the most optimistic assumptions—still does not beat the diesel ICE hybrid. Incorporating the hydrogen FC into a hybrid system helps, but its performance is still similar to that of the diesel ICE hybrid. (Modest differences are not meaningful because of uncertainties in the results.) The gasoline ICE and gasoline FC hybrids do almost as well. The hydrogen FC is thus not a big winner in terms of either energy use or GHG emissions. The results consistently point to the advantages of both improving ICE technology and using the hybrid approach. Regardless of the propulsion system choice, the hybrid version significantly reduces both energy consumption and GHG emissions, with the gains greater for ICE than for FC designs.

These results raise some obvious questions. First, why did the hydrogen FC technologies not do as well as some expected? A major part of the problem is that people often consider only onboard energy consumption and emissions (during operation of the vehicle on the road). But also taking into account the energy consumption and emissions associated with making and delivering the fuel and making, operating, and disposing of the vehicle dramatically changes the picture.

The table on page 1 demonstrates this effect. The first column shows onboard energy consumption for the hydrogen FC hybrid and the diesel ICE hybrid (both relative to the baseline 2020 vehicle). The former significantly outperforms the latter. The second column shows energy consumption considering the entire life cycle. The diesel ICE does a bit worse than before; but the hydrogen FC does significantly worse, largely because converting the hydrocarbon fuel to hydrogen both consumes energy and generates GHG emissions. (Hydrogen is also much more costly to manufacture and distribute than gasoline or diesel is.) Thus, studies that consider only onboard data give a misleading impression.

Another frequently cited advantage of the hydrogen FC vehicle is that it has no tailpipe emissions of air pollutants. The researchers agree with that claim, but they believe it will be only a small advantage by the year 2020. Current US Environmental Protection Agency mandates on fuels and emissions ensure that by 2010 tailpipe emissions from all new vehicle technologies will be so low that the remaining emissions will not be a significant share of all emissions from all sources. Reducing emissions from other sources is likely to be a more cost-effective way to clean up the atmosphere. The only uncertainty is whether engine designers can develop and introduce diesel technology that cuts emissions of particulates and of nitrogen oxides without incurring large efficiency penalties. However, history suggests that auto manufacturers have usually found a way to meet new regulations that originally seemed too difficult or costly to meet.

Another question is why ICE hybrids did better than some people have predicted. Were the assumptions in the study unrealistically optimistic? According to the researchers, studies with less-positive outcomes tend to focus only on the propulsion system—the engine, transmission, and drive train. In contrast, the MIT assessment also assumed reductions in the weight of the vehicle and in driving resistances—aerodynamic drag and tire rolling friction. Such changes are achievable by 2020 and are significant contributors to improving mileage.

Why does the hybrid approach do so well, regardless of the technology involved? Hybrid designs use both an engine (an ICE or FC) and an electric motor and battery. The electric motor runs the car at low loads such as slow, stop-and-start city driving—conditions under which an ICE is least energy efficient, so the fuel-economy gain is greatest. The electric motor also provides extra power for acceleration and hill climbing, which means the engine can be smaller than otherwise needed to satisfy momentary passing requirements. Also, most hybrid concepts allow the recovery of energy dissipated in braking. Thus, in each case the hybrid vehicle is more efficient than its non-hybrid counterpart.

The researchers caution that they are not discouraging work on developing the hydrogen FC. If auto systems with GHG emissions much lower than the lowest predicted here are required in the long-run future (perhaps in 30 to 50 years or more), hydrogen is the only major fuel option identified to date—but only if the hydrogen is produced without making GHG emissions. Hydrogen has been manufactured on a commercial scale for almost 100 years, mostly from natural gas. Trying to fine-tune existing methods for slightly better efficiency is not the best investment of research time and money. The focus should be on developing the technology and infrastructure for the large-scale production of hydrogen from non-fossil sources of primary energy (nuclear, solar, biomass) or from fossil primary energy with carbon capture and sequestration (see *e-lab*, July–September 2002 and April–September 2001).

While the hydrogen FC does not look promising for the near term, the good news is that several types of technologies have the potential to dramatically reduce energy use and GHG emissions from passenger cars in the next few decades. Already, fuel-efficient ICE hybrids are appearing on the roads, major auto companies are announcing more models to come, and public response is positive.

Malcolm A. Weiss is a senior research staff member in the LFEE. John B. Heywood is the Sun Jae Professor of Mechanical Engineering and director of MIT's Laboratory for 21st Century Energy. Andreas Schafer is a principal research engineer in the Center for Technology, Policy, and Industrial Development. Vinod K. Natarajan received his Master's Degree from the Department of Mechanical Engineering in 2002. Further information can be found in the references.

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