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Viewpoint

The car and fuel of the future

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Abstract

This paper is based on a review of the technical literature on alternative fuel vehicles (AFVs) and discussions with experts in vehicle technology and energy analysis. It is derived from analysis provided to the bipartisan National Commission on Energy Policy.

The urgent need to reverse the business-as-usual growth path in global warming pollution in the next two decades to avoid serious if not catastrophic climate change necessitates action to make our vehicles far less polluting.

In the near-term, by far the most cost-effective strategy for reducing emissions and fuel use is efficiency. The car of the near future is the hybrid gasoline–electric vehicle, because it can reduce gasoline consumption and greenhouse gas emissions 30 to 50% with no change in vehicle class and hence no loss of jobs or compromise on safety or performance. It will likely become the dominant vehicle platform by the year 2020.

Ultimately, we will need to replace gasoline with a zero-carbon fuel. All AFV pathways require technology advances and strong government action to succeed. Hydrogen is the most challenging of all alternative fuels, particularly because of the enormous effort needed to change our existing gasoline infrastructure.

The most promising AFV pathway is a hybrid that can be connected to the electric grid. These so-called plug-in hybrids or e-hybrids will likely travel three to four times as far on a kilowatt-hour of renewable electricity as fuel cell vehicles. Ideally these advanced hybrids would also be a flexible fuel vehicle capable of running on a blend of biofuels and gasoline. Such a car could travel 500 miles on 1 gal of gasoline (and 5 gal of cellulosic ethanol) and have under one-tenth the greenhouse gas emissions of current hybrids.

Keywords: Alternative fuels; Hydrogen; Hybrids

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1. Introduction

Any energy and environmental policy effort must come to grips with transportation. Roughly 97% of all energy consumed by our cars, sport utility vehicles, vans, trucks, and airplanes is still petroleum-based.

In the 1990s, the transportation sector saw the fastest growth in carbon dioxide emissions of any major sector of the US economy. And the transportation sector is projected to generate nearly half of the 40% rise in US carbon dioxide emissions forecast for 2025 (EIA, 2005).

Internationally, the situation is equally problematic. As Claude Mandil, Executive Director of the International Energy Agency (IEA), said in May 2004, "In the absence of strong government policies, we project that the worldwide use of oil in transport will nearly double between 2000 and 2030, leading to a similar increase in greenhouse gas emissions" (IEA, 2004)

Significantly, between 2003 and 2030, over 1400 GW of new coal capacity will be built. These plants would commit the planet to total carbon dioxide emissions of

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some 500 billion metric tons over their lifetime, unless "they are backfit with carbon capture equipment at some time during their life," as David Hawkins, Director of Natural Resources Defense Council's Climate Center told the US House Committee on Energy and Commerce in June 2003. Hawkins continued: "To put this number in context, it amounts to half the estimated total cumulative carbon emissions from all fossil fuel use globally over the past 250 years!" (Hawkins, 2003)

It is critical that whatever strategy the world adopts to reduce GHG emissions in the vehicle sector does not undermine our efforts to reduce GHG emissions in the electricity sector. With this caveat in mind, I explore some of the pathways most widely discussed for reducing or replacing oil while significantly reducing transportation greenhouse gas emissions: efficiency, electricity (particularly plug-in hybrid-gasoline vehicles); ethanol from cellulosic biomass; and hydrogen.

2. Alternative fuels and alternative fuel vehicles

Alternative fuel vehicles (AFVs) and their fuels face two central problems. First, they typically suffer from several marketplace disadvantages compared to conventional vehicles running on conventional fuels. Hence, they inevitably require government incentives or mandates to succeed. Second, they typically do not provide cost-effective solutions to major energy and environmental problems, which undermines the policy case for having the government intervene in the marketplace to support them.

On the second point, in September 2003, the US Department of Transportation Center for Climate Change and Environmental Forecasting released its analysis, Fuel Options for Reducing Greenhouse Gas Emissions from Motor Vehicles. The report assesses the potential for gasoline substitutes to reduce greenhouse gas emissions over the next 25 years. It concludes that "the reduction in GHG emissions from most gasoline substitutes would be modest" and that "promoting alternative fuels would be a costly strategy for reducing emissions" (DOT, 2003).

The US government and others (such as of California and Canada) have tried to promote AFVs for a long time. The 1992 Energy Policy Act established the goal of having alternative fuels replace at least 10% of petroleum fuels in 2000, and at least 30% in 2010. Currently, alternate fuels consumed in AFVs substitute for under 1% of total consumption of gasoline. A significant literature has emerged explaining this failure (GAO, 2000, Flynn, 2002). Besides the question of whether AFVs deliver cost-effective emissions reductions, there have historically been six major barriers to AFV success:

1. high first cost for vehicle
2. on-board fuel storage issues (i.e. limited range)
3. safety and liability concerns
4. high fueling cost (compared to gasoline)
5. limited fuel stations: chicken and egg problem
6. improvements in the competition (better, cleaner gasoline vehicles).

All AFVs that have so far been promoted with limited success—electric vehicles, natural gas vehicles, methanol vehicles, and ethanol vehicles—have each suffered from several of these barriers. Any one of these barriers can be a showstopper for an AFV or an alternative fuel, even where other clear benefits are delivered. MTBE, for instance, has had its biggest difficulty with the safety and liability issue, even though it has minimal problems in the other areas because it can be blended directly with gasoline. Electric vehicles deliver the clear benefit of zero tailpipe emissions, and can even have lower per mile costs than gasoline cars, but range, refueling, and first-cost issues have limited their success and caused most major auto companies to withdraw their electric vehicles from the marketplace.

The chicken and egg problem—who will build and buy the AFVs if a fueling infrastructure is not in place and who will build the fueling infrastructure before the AFVs are built—remains the most intractable barrier. Consider that there are millions of flexible fuel vehicles already on the road capable of running on E85 (85% ethanol, 15% gasoline), 100% gasoline, or just about any blend, for about the same price as gasoline-powered vehicles, and yet the vast majority of them run on gasoline and there are have been very few E85 stations built.

In the case of natural gas light-duty vehicles, the environmental benefits were oversold, as were the early cost estimates for both the vehicles and the refueling stations: "Early promoters often believe that 'prices just have to drop' and cited what turned out to be unachievable price levels." One study concluded, "Exaggerated claims have damaged the credibility of alternate transportation fuels, and have retarded acceptance, especially by large commercial purchasers" (Flynn, 2002).

All AFVs face the increasing "competition" from improved gasoline-power vehicles. Indeed, two decades ago when tailpipe emissions standards were being developed requiring 0.02 g/mile of NO_x, few suspected that this could be achieved by internal combustion engine vehicles running on reformulated gasoline.

The new generation of hybrid PZEVs such as the Toyota Prius and Ford Escape hybrid have substantially raised the bar for future AFVs. These vehicles have no chicken and egg problem (since they can be fueled everywhere), no different safety concerns than other gasoline cars, a substantially *lower* annual fuel bill, *greater* range, a 30% to 50% reduction in greenhouse gas emissions, and a 90% reduction in tailpipe emissions. The vehicles do cost a little more, but that is more than offset by the current government incentive and the large reduction in gasoline costs, even ignoring the performance benefits. Compare that to many AFVs, whose environmental benefits, if any, typically come at the expense not merely of a higher first cost for the vehicle, but a much higher annual fuel bill, a reduced range, and other undesirable attributes from the consumer's perspective.

2.1. Hydrogen

Widespread use of stationary fuel cells running on natural gas seems likely post-2010, particularly if high-temperature fuel cells achieve their cost and performance targets. The transition to a transportation system based on a hydrogen economy will, however, be much slower and more difficult than widely realized.

In particular, it is unlikely that hydrogen vehicles will achieve significant ($>5\%$) market penetration by 2030. A variety of major technology breakthroughs and government incentives will be required for them to achieve significant commercial success by the middle of this century. Continued R&D in hydrogen and transportation fuel cell technologies remains important because of their potential to provide a zero-carbon transportation fuel in the second half of the century. But neither government policy nor business investment should be based on the assumption that these technologies will have a significant impact in the near- or medium-term.

Bill Reinert, US manager of Toyota's advanced technologies group said in January 2005, absent multiple technology breakthroughs, we won't see high-volume sales of fuel cell vehicles until 2030 or later (Truett, 2005). When Reinert was asked when fuel cells cars would replace gasoline-powered cars, he replied "If I told you '*never*,' would you be upset?" (Butters et al., 2005).

Hydrogen cars face enormous challenges in overcoming each of the major historical barriers to AFV success.

The central challenge for any AFV seeking government support beyond R&D is that the deployment of the AFVs and the infrastructure to support them must cost effectively address some energy or environmental problems facing the nation. Yet in the spring issue of Issues and Science and Technology, two hydrogen experts, Dan Sperling and Joan Ogden of U.C. Davis, wrote, "Hydrogen is neither the easiest nor the cheapest way to gain large near- and medium-term air pollution, greenhouse gas, or oil reduction benefits"(Sperling and Ogden, 2004). A 2004 analysis by the Pacific Northwest National Laboratory and the University of Maryland concluded that even "in the advanced technology case with a carbon constraint … hydrogen doesn't penetrate the transportation sector in a major way until *after 2035*"(Geffen et al., 2004). A push to constrain carbon dioxide emissions actually delays the introduction of hydrogen cars because sources of zero-carbon hydrogen such as renewable power can achieve emissions reductions far more cost-effectively simply replacing planned or existing coal plants. As noted above, our efforts to reduce GHG emissions in the vehicle sector must not come at the expense of our efforts to reduce GHG emissions in the electric utility sector.

In fact, Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, a January 2004 study by the European Commission Center for Joint Research, the European Council for Automotive R&D, and an association of European oil companies, concluded that using hydrogen as a transport fuel might well *increase* Europe's greenhouse gas emissions rather than reduce them (JRC, 2004). That is because many pathways for making hydrogen, such as grid electrolysis, can be quite carbon-intensive and because hydrogen fuel cells are so expensive that hydrogen internal combustion engine vehicles may be deployed instead (which is already happening in California). Using fuel cell vehicles and hydrogen from zero-carbon sources such as renewable power or nuclear energy has a cost of avoided carbon dioxide of more than $600 a metric ton, which is more than a factor of ten higher than most other strategies being considered today.

A number of major studies and articles have recently come out on the technological challenges facing hydrogen. Transportation fuel cells currently cost about $4000/kW, some 100 times greater than the cost of internal combustion engines (Wald, 2004). A 2004 article for the Society of Automotive Engineers noted, "Even with the most optimistic assumptions, the fuel cell powered vehicle offers only a marginal efficiency improvement over the advanced [diesel]-hybrid and with no anticipation yet of future developments of IC engines. At $100/kW, the fuel cell does not offer a short-term advantage even in a European market" (Oppenheim and Schock, 2004).

A prestigious National Research Council panel concluded a major report in February 2004 with a variety of important technical conclusions (NRC, 2004). For instance, the panel said, "The DOE should halt efforts on high-pressure tanks and cryogenic liquid storage…. They have little promise of long-term practicality for light-duty vehicles." A March 2004 study by the American Physical Society concluded that "a new material must be discovered" to solve the storage problem (APS, 2004). An analysis in the May 2004 issue of Scientific American stated, "Fuel-cell cars, in contrast [to hybrids], are expected on about the same schedule as NASA's manned trip to Mars and have about the same level of likelihood" (Wald, 2004).

There is a tendency in analyses of a future hydrogen economy to assume the end state—mass production of low-cost fuel cells, pipeline delivery, and so on. Yet while transportation fuel cells would undoubtedly be far cheaper if they could be produced at quantities of one million units per year, the unanswered question is who will provide the billions of dollars in subsidies during the many years when vehicle sales would be far lower and vehicle costs far higher. And while pipelines are the desired end game, and "the costs of a mature hydrogen pipeline system would be spread over many years," as the National Research Counicl panel noted, "the transition is difficult to imagine in detail" (NRC, 2004). The AFV problem is very much a systems problem where the transition issues are as much of the crux as the technological ones. We believe all AFV analysis should be conservative in nature, stating clearly what is technologically and commercially possible today, and, when discussing the future, be equally clear that projections are speculative and will require both technology breakthroughs and major government intervention in the marketplace. Analysis should treat the likely competition fairly: If major advances in cost reduction and performance are projected for hydrogen technologies, similar advances should be projected for hybrids, batteries, biofuels, and the like.

Hydrogen fuel cell vehicles face major challenges to overcome each and every one of the barriers discussed earlier. It is possible we may never see a durable, affordable fuel cell vehicle with an efficiency, range, and annual fuel bill that matches even the best *current* hybrid vehicle. Of all AFVs and alternative fuels, fuel cell vehicles running on hydrogen are probably the least likely to be a cost-effective solution to global warming, which is why the other pathways deserve at least equal policy attention and funding.

2.2. *E-hybrids*

One AFV, however, has clear environmental benefits, including substantially lower greenhouse gas emissions, a much lower annual fuel bill, a much longer range than current cars (with the added ability to fuel at home), and far fewer infrastructure issues than traditional AFVs. This AFV is the plug-in hybrid, also called the e-hybrid.

A straightforward improvement to the current generation of hybrids can allow them to be plugged into the electric grid and run in an all-electric mode for a limited range between recharging. Since most vehicle use is for relatively short trips, such as commuting, followed by an extended period of time during which the vehicle is not being driven and could be charged, even a relatively modest all-electric range of 20 or 40 miles could allow these vehicles to replace a substantial portion of gasoline consumption and tailpipe emissions. If the electricity were from CO_2-free sources, then these vehicles would also have dramatically reduced net greenhouse gas emissions.

Because they have a gasoline engine, and are thus a duel-fuel vehicle, e-hybrids avoid two of the biggest problems of pure electric vehicles. First they are not limited in range by the total amount of battery charge. If the initial battery charge runs low, the car can run purely on gasoline and on whatever charging is possible from the regenerative braking. Second, electric vehicles take many hours to charge, so that if for some reason owners were unable to allow the car to charge—either because they lacked the time between trips to charge or there was no local charging capability—then the pure-electric car could not be driven. Thus, e-hybrids combine the best of both hybrids and pure electric vehicles.

Battery improvement will lead to increased functionality for e-hybrids. Improvements in specific energy (Wh/kg) and specific power (W/kg) will reduce weight. Reductions in cost and increases in cycle life (durability) will make PHEVs more affordable. Adequate safety is a requirement. Operating temperature is important, but batteries with unusual operating temperatures may be considered if other benefits are demonstrated. Convenience of recharging is crucial, but the definition of "convenience" varies by users. A full recharge overnight from an ordinary home outlet is generally considered to be sufficient for a personal e-hybrid.

2.3. *Barriers*

E-hybrids avoid many of the barriers to AFVs discussed earlier. They do not have a limited range. They do not have major safety and liability issues—although great care would have to be taken in the design of any home-based system that charged e-hybrids or allowed them to feed back into the grid. They do not have a high fueling cost compared to gasoline. In fact, the per-mile fueling cost of running on electricity is about one-third the per-mile cost of running on gasoline. The chicken and egg problem is minimized because electricity is widely available and charging is relatively straightforward.

The vehicle will almost certainly have a higher first cost, but this is likely to be more than compensated by the economic benefit of a lower fuel bill, as a 2003 study by the California Energy Commission and California Air Resources Board concluded (CEC and CARB, 2003). Also, that study did not consider a large potential revenue stream the vehicle owner may be able to extract from the utility by having what is essentially a portable electric generator.

An e-hybrid owner may be able to extract revenue for grid regulation services—generators that can provide fast response when grid voltage needs to be increased or decreased. Utilities would pay for this service if there was a guarantee that the car could deliver juice when needed, which suggests that this is more practical for vehicle fleets or for a corporate sponsor. The potential value of such services is significant: $700 to $3000 per year (Letendre and Kempton, 2002). This value is so large that it might allow the monthly cost of purchasing or leasing an e-hybrid to be *lower* than a conventional car, and perhaps even cover the replacement cost for batteries if they prove not to have a 100,000+mile lifetime typically expected of modern cars. It is critical that we fund some real-world demonstrations of e-hybrids providing these services, to see if this value can be extracted. If it can, we might see major utilities helping to subsidize the cost and/or financing of e-hybrids.

Environmentally, e-hybrids offer two potentially significant benefits. First, since they are designed to run all-electric for short trips such as commuting, they offer the possibility of being zero-emission vehicles (ZEVs) in cities. The best early uses of e-hybrids may well be to replace dirty diesel engine vehicles used regularly in cities, such as buses, maintenance vehicles, and delivery trucks. If we are unable to overcome the multiple technical and practical hurdles to hydrogen fuel cell cars, then e-hybrids may be the only viable option for urban zero emission vehicles.

The potential greenhouse gas benefits of e-hybrids are even more significant, if a source of zero-carbon electricity can be utilized for recharging. E-hybrids have an enormous advantage over hydrogen fuel cell vehicles in utilizing zero-carbon electricity. That is because of the inherent inefficiency of generating hydrogen from electricity, transporting hydrogen, storing it onboard the vehicle, and then running it through the fuel cell. The total well-to-wheels efficiency with which a hydrogen fuel cell vehicle might utilize renewable electricity is roughly 20% (although that number could rise to 25% or a little higher with the kind of multiple technology breakthroughs required to enable a hydrogen economy). The well-to-wheels efficiency of charging an onboard battery and then discharging it to run an electric motor in an e-hybrid, however, is 80% (and could be higher in the future)—four times more efficient than current hydrogen fuel cell vehicle pathways.

As Dr. Alec Brooks, who led the development of the Impact electric vehicle has shown, “Fuel cell vehicles that operate on hydrogen made with electrolysis consume *four times as much* electricity per mile as similarly sized battery electric vehicles” (Brooks, 2004).

Ulf Bossel, founder of the European Fuel Cell Forum, comes to a similar conclusion in a recent article, “The daily drive to work in a hydrogen fuel cell car will cost four times more than in an electric or hybrid vehicle” (Bossel, 2004).

This relative inefficiency has enormous implications for achieving a sustainable energy future. To replace half of US ground transport fuels (gasoline and diesel) in the year 2050 with hydrogen from wind power, for example, might require 1400 GW of advanced wind turbines or more. To replace those fuels with electricity in e-hybrids might require under 400 GW of wind. That 1000 GW difference may represent an insurmountable obstacle for hydrogen as a GHG mitigation strategy—especially since the US will need several hundreds of gigawatts of wind and other zero-carbon power sources in 2050 just to sharply reduce GHG emissions in the electricity sector.

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