Driving to New Sources of

Gaining Flexibility, Ensuring Supply, and Reducing Emissions

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In July 2002, three TRB Committees—on Energy, on Transportation and Air Quality, and on Alternative Fuels—convened representatives of the automobile and fuels industries, U.S. and Canadian regulatory agencies, academia, national laboratories, and research organizations to discuss air quality, global warming, future fuels and vehicles, and transportation energy policy.[1] The conference presented an overview of energy and technology options and possible solutions to some vexing transportation challenges.

Harnessing Hydrogen

Promising Fuel Cells

Major automobile makers have announced the impending rollout of fuel-cell vehicles. The FreedomCAR Partnership between the U.S. Department of Energy and the U.S. Council for Automotive Research—representing DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation—is a prominent proponent of fuel-cell vehicles. But major challenges include customer acceptance, cost, hydrogen storage, infrastructure development, and technological progress.

More surprising than the positive outlook on fuel cells was the widely held view that the need for a widescale switch to hydrogen-based fuel cells within 20 to 30 years has not been established conclusively. Viable competitors include advanced conventional vehicles with gasoline and diesel options, as well as hybrid and compressed natural gas (CNG) vehicles. Hydrogen-powered internal combustion engines (ICE) also appear attractive, and fuel-cell fuels besides hydrogen also may prove successful.

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[1] For presentation materials and additional information, see the TRB Energy Committee website, gulliver.trb.org/wb/wbpx.dll/~A1F01.

Transportation Energy

General Motors Hy-wire fuel-cell car runs on hydrogen and electricity.

Testing the Limits

Dedicated hydrogen ICEs have nearly the same tailpipe emission benefits as fuel cells and use the same fuel feedstocks (*1*). Because they are similar to conventional gasoline engines, ICEs can capitalize on investments in engine transmission and component plants. In addition, unlike fuel cells, hydrogen ICEs are not constrained by fuel quality—for example, ICEs can burn carbon monoxide, which would contaminate fuel cells.

Hydrogen ICEs, however, have several limitations. Hydrogen is the smallest molecule but has the highest diffusivity, requiring the development of hydrogen sensors. In addition, gaseous hydrogen is severe on fuel injection equipment. Hydrogen engines also have lower specific output—that is, power and torque—than gasoline engines. Overcoming these limitations must be a core technological objective.

Weighing Investments

Many of the benefits of fuel cells and hydrogen ICEs accrue to society—such as zero tailpipe emissions, improved energy efficiency, and energy security. Many conference participants therefore believe that a transition to fuel-cell vehicles within the next 20 years would not be consumer-driven but would be undertaken for societal reasons. Consequently, only an active public sector can accelerate adoption of the technology. Many participants maintain that catastrophic climate change also may force near-term change in vehicle technologies and expedite the introduction of fuel-cell vehicles.

A minority viewpoint holds that the transition to fuel-cell vehicles will not require a high level of public investment, because fuel-cell vehicles have desirable characteristics—such as smooth electric drive and remote power generation—and will be perceived as superior. In addition, other technological breakthroughs may create a market-driven transition.

Researchers and policy makers must decide on the baseline vehicle for measuring the incremental energy and environmental benefits of fuel-cell vehicles. Should the baseline be the performance of a conventional vehicle, an advanced conventional vehicle, or a hybrid vehicle? The answer will affect desirability and cost.

Transitioning to Hydrogen

Large-scale renewable hydrogen fuel, produced from biomass or from nuclear, solar, or wind power, could be the solution to many transportation energy problems, including greenhouse gas (GHG) emissions,[2] criteria pollutants,[3] and energy security. Solutions at a reasonable economic cost, however, remain out of reach. If a transition to a hydrogen fuel occurs in the near term, several different feedstocks and pathways for hydrogen are technically viable, many from traditional nuclear and fossil fuels.

Marianne Mintz of Argonne National Laboratory presented results from a recent study by the U.S.

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[2] Any gas that absorbs and traps heat in the atmosphere. GHGs include water vapor, carbon dioxide, methane, nitrous oxide, hydrochlorofluorocarbons, ozone, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride.

[3] Criteria air contaminants include particulate matter (liquid or solid aerosols), carbon monoxide, nitrogen oxide, sulfur dioxide, and volatile organic compounds.

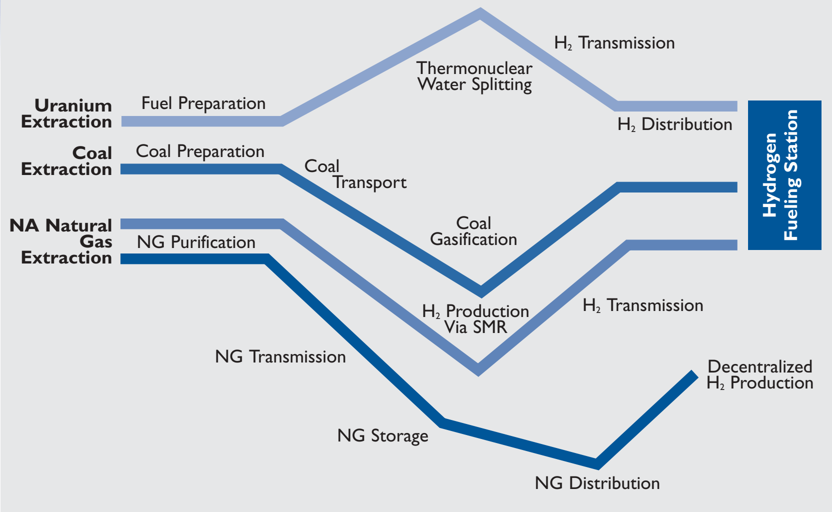


FIGURE 1 Four hydrogen pathways.

Source: M. Mintz, Argonne National Laboratory, used with permission.

Department of Energy and Natural Resources Canada (*2*), examining four pathways to large-scale hydrogen production and use: nuclear, coal, natural gas, and a mix of centralized and decentralized transmission options (Figure 1). The study did not consider biomass or other renewable fuel pathways.

The transport and production of hydrogen were the largest cost components for each path. According to the study, the unit cost of hydrogen was likely to be two to three times that of gasoline, on a well-to-pump basis using current technologies: $20–$23 per million BTU for hydrogen vs. $7 per million BTU for gasoline, excluding taxes and markups. The pathway that is most cost-effective and provides the greatest environmental and energy security benefits remains an important question.

GM diesel hybrid can switch to auxiliary power from hydrogen fuel cell.

Considering Alternatives

Policy makers and niche markets can assist in the adoption of hydrogen and other alternative fuels. Some participants were optimistic about the increased use of alternative fuels, particularly CNG, biodiesel (mono alkyl esters), and ethanol.

Finding Niches

Military installations are a niche for alternative fuels and hybrid vehicles. Jim Muldoon of the U.S. Air Force noted that a Department of Defense goal for 2020 is to reduce "sustainment requirements"—the logistical demands of getting water and fuel to a battlefield—which will require greater fuel efficiency (*3*).

Hybrids and fuel cells may be the enabling technologies—hybrids can reduce fuel consumption on the battlefield and provide onboard electric power in remote locations, and fuel cells can offer modular, standardized, "plug and play" compatibility across vehicles. Moreover, fuel cells can maintain performance if one unit in a multiple-cell system fails, which could reduce maintenance and increase resilience during a military engagement.

Going Natural

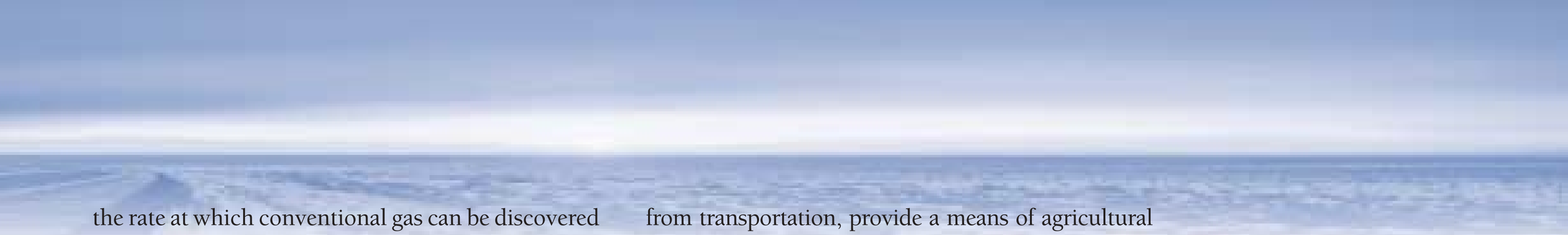
According to Rich Kolodziej of the Natural Gas Vehicle Coalition, natural gas vehicles (NGVs) are the alternative-fuel vehicle leader, with 110,000 on America's roads (*4*). Natural gas offers the most engine and vehicle choices of any alternative fuel.

DaimlerChrysler, Ford, General Motors, and Honda offer dedicated or bifuel natural gas vehicles as original equipment. For medium- or heavy-duty applications, Caterpillar, Cummins, Deere Power Systems, Detroit Diesel, Mack, AFT, and Crusader/IMPCO produce natural gas engines. Many transit bus and truck manufacturers provide a natural gas option.

The NGV market will continue to grow. Primarily a domestic product, natural gas is an attractive alternative to foreign oil—85 percent of current consumption comes from U.S. sources, and most of the rest is produced in Canada. Moreover, new technologies can enhance low-grade natural gas with hydrogen for power generation and for use in vehicles (*5*).

Although only 1,600 fueling sites serve NGVs, compared with 95,000 for gasoline-fueled vehicles, natural gas is available throughout the country. In addition, natural gas is clean-burning with relatively low GHG emissions. Stricter National Ambient Air Quality Standards for ozone and particulates and stricter heavy-duty vehicle emission standards will give NGVs an advantage over diesel vehicles.

The long-term cost and availability of natural gas, however, remain questions. Long-term supply is uncertain, depending on the worldwide demand and



the rate at which conventional gas can be discovered and produced, according to Steve Plotkin of Argonne National Laboratory (*6*). Accurate, long-term U.S. natural gas prices are impossible to predict, with such unknowns as the size of the world gas resource base; world economic growth rates; changes in energy intensity; the development of a worldwide gas trading system; improvements in technology for gas discovery, production, and transport; the development of methods to exploit gas hydrates; and cost reductions in gas backstops, such as coal gasification with carbon sequestration.

Riding on Alcohol

The U.S. Environmental Protection Agency (EPA) initiated research and engine test programs on alcohol fuels in the late 1970s and early 1980s. EPA had focused on methanol but recently has transitioned to ethanol research, responding to shifts in market and legislative interests.

According to Matt Brusstar of EPA, alcohol fuels have several advantages over gasoline: alcohol has a higher octane content, greater vaporization heat, more flame speed, and cooler combustion. These features promise to lower emissions of oxides of nitrogen (NOx) and produce higher thermal efficiency. The manufacturing costs of engines optimized for alcohols are similar to those of gasoline engines.

There are now 2.3 million ethanol flexible-fuel vehicles on the road in the United States. These vehicles could use E85 (ethanol for light-duty vehicles) if it were more widely distributed. If ethanol, which is made primarily from corn, can be produced more cheaply, a renewable, domestically produced fuel could power dedicated or flexible alcohol engines, providing an economic alternative to conventional gasoline engines.

The current demand for fuel ethanol is in low-volume blends with gasoline; these blends comprise 15 percent of all U.S. gasoline (*7*). Under a renewable fuel standard proposed in the Energy Policy Act of 2002 (H.R.4), fuel ethanol demand would grow from 2.1 billion gallons in 2002 to 5.1 billion gallons by 2012.

But greater use of ethanol also raises the question of supply. Cellulosic ethanol, from feedstocks such as agricultural residues, softwoods, hardwoods, and municipal solid waste (MSW), may play a significant role in ethanol supply. All of the feedstocks, however, present problems in harvesting, collection, transportation and storage, lack of bulk density, supply (for example, weather variations can have an effect), and moisture content; moreover, MSW presents the additional problem of variable composition (*8*). Nonetheless, cellulosic ethanol can reduce GHG emissions from transportation, provide a means of agricultural diversification, and help manage biomass residue.

Some conversion processes for cellulosic ethanol are commercially available; others are in demonstration or are experimental. The conventional method is the simple and inexpensive dilute acid process. The concentrated acid process is also simple and inexpensive and has improved sugar recovery, but with losses in materials compatibility and acid recovery. Experimental processes in development include enzymatic, organosolv, and thermochemical gasification.

The commercial viability of cellulosic ethanol depends on low-cost feedstocks and low-cost processes to produce ethanol and valuable coproducts. A dozen companies are either seeking financing for chemical plants to manufacture commercial dilute and concentrated acid or are operating small pilot plants for the enzymatic, organosolv, and thermochemical processes. The first commercial plant employing any of these technologies will not be in operation before 2006 (*8*).

Natural Resources Canada and the U.S. Department of Energy have examined a range of energy scenarios, from environment-friendly to business-as-usual. The preliminary conclusion is that ethanol is a potentially significant alternative fuel. By 2050, biofuels could account for 11 percent of transportation energy in Canada, and petroleum-based fuels would decline from a 99 percent to an 84 percent market share (*9*).

Blending Diesels

E-diesel and biodiesel could increase the use of renewable fuels with little or no infrastructure or engine changes for heavy-duty, on- and off-road compression-ignition engines. E-diesel contains conventional diesel blendstock with up to 15 percent (by volume) of anhydrous ethanol stabilized with 1.0 percent to 5.0 percent additives, as well as cetane enhancement, if required.

Diesel systems generally include a substantial amount of water, posing the risk of phase separation, the formation of solid crystals or a separate liquid layer on the bulk diesel fuel; but new technologies can maintain stability in the presence of water (*7*). Adding ethanol, however, lowers the flashpoint of diesel, normally 132°F, to about 75°F degrees—so that e-diesel must be handled like gasoline.

Biodiesel is produced by combining triglycerides (oils or fats) with alcohol (ethanol or methanol) in the presence of a catalyst to produce mono alkyl esters and glycerine. The source of oil or fats could be soybeans, corn, canola, cottonseeds, sunflowers, beef tallow, pork lard, or used cooking oils. Biodiesel has a 7 percent to 9 percent lower heating value and freezes at a higher temperature than Number 2 diesel. Biodiesel

Diesel hybrid military pickup truck equipped with a fuel-cell auxiliary power unit, introduced in January 2003, by General Motors and the U.S. Army. Built on a Chevrolet Silverado crew cab frame, the diesel hybrid improves fuel consumption by 20 percent, reduces emissions, and provides troops with a source of electrical power.

can be used as a pure fuel or blended with petrodiesel (petroleum diesel).

Soy-based biodiesel costs $2 per gallon. The EPA low-sulfur rule for diesel fuel has led to an increase in the use of biodiesel—adding 2 percent biodiesel, as in B2 diesel, can restore the lubricity lost in reducing sulfur.

In addition, biodiesel offers environmental advantages. Compared with petrodiesel, B20 diesel (20 percent biodiesel and 80 percent petrodiesel) has lower emissions of carbon monoxide (10 percent to 20 percent), hydrocarbons (20 percent to 30 percent), particulate matter (5 percent to 15 percent), and GHG emissions. Emissions of NOx, however, are higher than from petrodiesel (4 percent) but should be controllable with improved vehicle systems (*10*).

Resort shuttle bus and other municipal vehicles in Breckenridge, Colorado, run on B20 fuel—20 percent biodiesel and 80 percent petroleum diesel.

PHOTO: UNITED SOYBEAN BOARD

Keeping Conventional

Relying on Oil

Other participants endorsed the continuing importance of oil. John Johnston reported ExxonMobil's long-term energy outlook:

- World energy use will grow by 1.9 percent annually;
- Oil will remain the dominant source of fuel and maintain market share, growing by 1.8 percent per year;
- Natural gas will grow by about 3 percent per year, picking up market share for power generation;
- Other fuels including hydro, nuclear, solar, wind, and biomass will grow moderately, with no near-term breakthrough in liquid biofuels; and
- Fossil fuels, therefore, will remain critical to energy needs for the next 20 years.

In ExxonMobil's view, vehicle and fuel systems will change, with many high-potential options now in development, such as advanced gasoline, advanced diesel, gasoline hybrid electric vehicles (HEV), diesel HEV, and fuel-cell vehicles. Many additional options also would improve conventional internal combustion engines, but adoption of new technologies will depend on marketplace acceptance.

Refining Sands

Kevin Cliffe of Natural Resources Canada described Canada's 141,000 square kilometers (55,000 square

PHOTO: SYNCRUDE CANADA, LTD

Trucks haul Canadian oil sands from the Athabasca Oil Sands Deposit, Alberta.

miles) of oil sands deposits. Oil sands are composed of 80 percent to 85 percent mineral materials (sands and clays), 4 percent to 6 percent water, and 10 percent to 12 percent bitumen, a tar-like mixture of petroleum hydrocarbons with a density 20 percent greater than that of light crude oil. The bitumen is upgraded into a light, high-grade synthetic crude oil with a low sulfur and nitrogen content.

Since 1996, investments in completed oil sands projects have totaled $17 billion (Canadian), and $86 billion is invested in additional projects. Canadian oil sands could produce 5 million barrels of synthetic crude oil per day, which would satisfy 200 percent of Canadian, 16 percent of U.S., and 4 percent of world petroleum demand in 2025.

Key issues include refinery compatibility and capacity, pipelines, market segments, cost reductions, and dilutent alternatives. Additional research is needed to reduce the substantial impacts on water and the high levels of carbon dioxide (CO_2) emissions, as well as to guide land use in oil sands development.

Steering the Transitions

Recognizing Barriers

Participants observed that significant barriers to alternative fuels and alternative-fuel vehicles remain:

- The technological successes in reducing the emissions and increasing the efficiency and performance of gasoline and diesel vehicles;
- The low cost of petroleum; and
- The lack of a retailing infrastructure for alternative fuels, especially for hydrogen.

Paul Leiby and Jonathan Rubin presented results from the Transitional Alternative Fuels and Vehicles Model, which simulates market outcomes for alternative-fuel and hybrid vehicles. The model considers possible transitional barriers related to infrastructure needs, production scale, and investments in vehicle and fuel production capacity. These transitional barriers accounted for approximately $1 per gallon of alternative fuel in 2000 but will account for $0.50 per gallon by 2010 (*11*).

Electric cable shovel loads Canadian oil sands into hauling truck.

Meeting the Standards

Motor vehicles emit criteria pollutants, contributing to unhealthy air for millions in urban areas. Conference participants disagreed over what to do about the problem. An EPA representative expressed belief that the next generation of standards must anticipate growth in vehicle miles traveled. The new standards may require a long-term move to cleaner technologies in some metropolitan areas.

Others, including John German of Honda Motor Company, advanced the view that vehicle criteria emissions can be reduced through advanced conventional gasoline or CNG vehicles. For example, all 2003 Honda Accord four-cylinder automatic transmission vehicles sold in California will meet California's super-ultra-low-emission vehicle standards.

Evaluating the Alternatives

Two directions emerged in discussions about the potential for alternative fuels and alternative-fuel vehicles to reduce criteria and GHG emissions. One direction depends on individual fuel analyses that compare the emissions of a particular alternative fuel with a gasoline or diesel baseline. The other direction depends on studies that predict emissions as alternative fuels and alternative-fuel vehicles are integrated into the transportation system, taking into account rates of adoption, costs, and driving behavior.

Participants agreed that evaluations of individual technologies should use a well-to-wheels (WTW) approach to compare the combined production and combustion processes of fuels and vehicles. Some, however, questioned the ability of WTW studies to assess robustly competing technologies, because the results can reflect the input assumptions. One participant noted that WTW estimates for CO_2 emissions from gasoline hybrid, diesel hybrid, gasoline fuel-cell, hydrogen fuel-cell-from-gas, E85, and ethanol fuel-cell engines show little difference and concluded that policy makers should not be picking winners yet.

A WTW assessment of the carbon impacts of biofuel must include the entire cycle of feedstock production, distribution, and conversion (Figure 2). According to Michael Wang of Argonne National Laboratory, an assessment of ethanol must consider agrochemical production and transport, farming energy, crop or feedstock transport, ethanol production efficiency, and coproduct energy allocation (*12*). An assessment of biodiesel would involve consideration of soybean farming, crop transport, soy oil extraction, and coproducts. An important issue for ethanol is the use of nitrogen-based fertilizers and the mobilization of resulting nitrogen oxides into the atmosphere.

Another key issue is the allocation of energy use and GHG emissions to coproducts such as animal feed and electricity. Corn-based ethanol and biodiesel have different coproduct allocations: depending on the method, the allocation for corn ethanol coproducts could be 16 percent or 52 percent, and for soybean diesel, 38 percent or 82 percent—or somewhere in between.

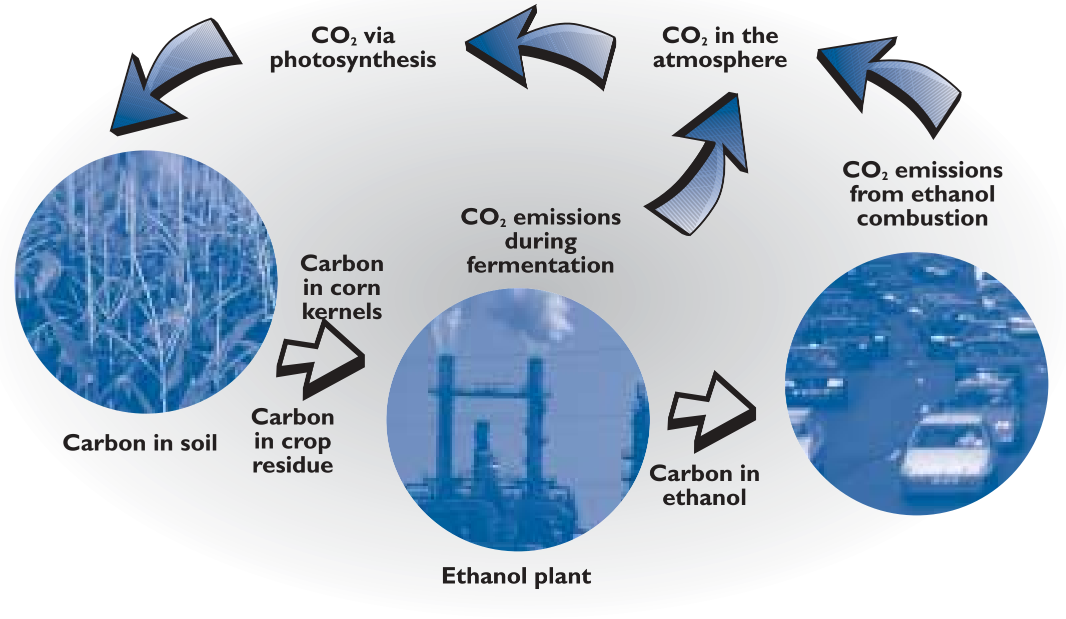


FIGURE 2 Recycling of carbon by biofuels results in net CO_2 benefits.

Source: M. Wang, Argonne National Laboratory, used with permission.

The displacement method, which yields the 16 percent coproduct allocation for ethanol, assigns a 25 percent reduction in GHG to corn-based E85 on an energy-equivalent comparison with gasoline. Cellulosic ethanol fares better, with an estimated reduction of 65 percent to 120 percent in GHGs for E85, compared with gasoline. The GHG reductions for biodiesel range from 10 percent to 15 percent for B20, and proportionally higher for B100 (100 percent biodiesel), compared with petrodiesel.

A systemwide study by Don Pickrell of the Volpe National Transportation Systems Center compared future GHG emissions from light-duty vehicle travel with results from an all-gasoline baseline (*13*). Pickrell's study focused uniquely on total GHG emissions, instead of on per-vehicle or per-mile emissions.

By 2010, assuming that alternative fuels will have replaced 10 percent of gasoline, Pickrell estimates only a slight reduction in GHG emissions, because of increases in emissions from fuel production and in vehicle miles traveled. In the longer term, however, according to the study, commercial development of technology to produce ethanol from cellulosic biomass could reduce GHG emissions significantly, assuming a 25 percent displacement of gasoline by alternative fuels by 2025.

Developing Public Policy

The public sector has a vital role in any major transition in the fuel-vehicle transportation system to address GHG, criteria emissions, and energy security. As Barry McNutt of the U.S. Department of Energy pointed out, environmental or clean air concerns historically have driven the development of many energy policies, but energy policy for energy policy's sake—that is, without the supporting public concern—has been less successful (*14*). Fuel flexibility and diversity that only serve to achieve energy security may not be worth the cost—the social costs of oil price swings may not be high enough to justify the cost of flexibility and diversity in infrastructure, vehicle investments, and operating costs.

For many participants, global warming and criteria emissions are important social problems that require action. Other important goals include homeland security, economic security, and energy security.

To some participants, transportation's environmental trends are mostly negative: the rise in vehicle miles traveled, the decline in fuel economy, and the minimal use of alternative fuels. Several participants suggested that the public sector ought to promote research, assist with infrastructure development, facilitate demonstrations and pilot programs, and provide incentives to accelerate early market acceptance of new technologies, especially of hydrogen fuels.

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