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A strategy for introducing hydrogen into transportation[☆]

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Abstract

Considerable effort is being expended on research and demonstration projects aimed at introducing hydrogen into the transportation sector as a fuel, generally motivated by concerns about carbon dioxide emissions and petroleum imports (or scarcity). In this paper we focus on one aspect of strategy for introducing hydrogen—the choice of transportation mode. Our analysis suggests that cost of introducing hydrogen can be reduced by selecting a mode that uses a small number of relatively large vehicles that are operated by professional crews along a limited number of point-to-point routes or within a small geographic area. In addition, technological innovation in vehicle design will take place most quickly in modes where individual vehicles are produced to order and each receives significant engineering attention (not those manufactured in vast quantities on assembly lines). The immediate environmental benefits of introducing hydrogen fuel will occur in modes that have relatively less stringent pollution regulations applied to them. These insights, suggest that heavy-duty freight modes would be a less costly way to introduce hydrogen as a transportation fuel and a more effective way to advance hydrogen-related technologies so that they could subsequently be used more widely in light-duty vehicles.

Keywords: Hydrogen; Transportation; Technological change; Alternative fuels

1. Introduction

Hydrogen has long been advocated as a transportation fuel for a variety of reasons: as a means of responding to resource (e.g. petroleum) scarcity and growing US dependence upon petroleum imports (Hoffman, 2001; Mathis, 1976), as a means of improving environmental quality (Berry et al., 1996; DeLucchi and Ogden, 1993), as a high-performance aircraft and rocket fuel (Sloop, 1978), as a means of expanding the use of nuclear energy (Marchetti, 1976), and as a means of responding to climate change (Lenssen and Flavin, 1996; Ogden, 1999). Interest in hydrogen has recently been renewed, as evidenced by Iceland's plans to develop a "hydrogen economy" (Arnason and Sigfusson, 2000; Jones, 2002), the passage of the US Hydrogen Future Act of 1996, and the development of numerous hydrogen research activities around the world (Barbier, 2001). These activities include the recent "FreedomCAR" proposal from the Bush Administration (Abraham, 2002), and, most notably, investments by major automobile manufacturers in fuel cell vehicles for possible production in just a few years (Hanisch, 2000; Pearce, 2000). Recent advances in fuel cell technologies have also played a role. Finally, there is enormous power in the (exaggerated) popular view that fuel cells offer the potential for affordable, compact, silent, efficient, emission-free energy from 'unlimited' resources.

Most of the recent interest in hydrogen is due to concerns about carbon dioxide (CO_2, the principal greenhouse gas) and petroleum imports (or scarcity). Since light duty vehicles (LDVs) dominate fuel consumption and CO_2 emissions in the transportation sector, effectively dealing with these problems will likely require changes in LDV design and use. The best strategy for attaining these long-term goals may not, however, involve the early introduction of hydrogen-powered LDVs. Focusing on the ultimate goal—low CO_2 emissions and/or petroleum independent

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transportation—without paying sufficient attention to the role of near-term decisions in shaping long-term technological innovation and change is a serious gap since these processes are central to the ultimate costs of meeting policy goals (Grübler et al., 1999; Peters et al., 1999). The strategy outlined here will not achieve immediate deep reductions in CO_2 emissions or petroleum use, but should subsequently allow an efficient introduction of hydrogen as transportation fuel on a widespread basis to help achieve those long-term goals.

Introducing new transportation fuels is a rare, difficult and uncertain venture, so paying attention to how to maximize the likelihood of success while minimizing the costs and risks is likely to be worthwhile. In this paper we focus on one aspect of strategy for introducing hydrogen—the choice of transportation mode. We ask: Into which modes should hydrogen first be introduced? The strategy outlined here might be only a first step to a hydrogen economy in which hydrogen LDVs *eventually* become widely used, but a preferable step to the current default of considering LDVs as the *first* mode into which to introduce hydrogen.

2. Hydrogen as a transportation fuel

2.1. Current research

Most research on hydrogen as a transportation fuel (or, simply, hydrogen fuel) has focused on LDVs (Jensen and Ross, 2000; Linden, 1999; Lovins and Williams, 2001; McNicol et al., 2001; Mintz, 2002; Ogden, 1999; Thomas et al., 2000). For example, the recent *Clean Energy Futures* study included over a dozen alternative fuel configurations for LDVs, but none whatsoever for freight vehicles (Greene and Plotkin, 2001; Interlaboratory Working Group on Energy—Efficient and Clean Energy Technologies, 2000). The emphasis on LDVs is perhaps understandable in studies of transportation policy since LDVs dominate transportation fuel use; yet hydrogen-focused research uncritically adopts this emphasis as well. A few exceptions exist, such as various analyses of aircraft applications (Armstrong et al., 1997; Contreras et al., 1997; Jones, 1971; Victor, 1990), brief mentions of heavy vehicles here and there (for example, see Berry and Lamont, 2002, p. 17), and, interestingly, the earliest detailed study now forgotten, of a 'hydrogen economy' (Dickson et al., 1976).

The emphasis on LDVs is evident in US Department of Energy (DOE) funding for hydrogen. For instance, the 2003 DOE budget request contained approximately \$150 million for the FreedomCAR program, plus another \$125 million for hydrogen and fuel cell related research. Of this total, only \$11.5 million (4%) is devoted to heavy-duty vehicles (HDVs), although heavy freight modes (trucks, trains, and vessels) consume over 20% of all transportation energy (Davis, 2001, Table 2.5). The National Renewable Energy Laboratory's *Blueprint for Hydrogen Infrastructure Development* assumes that hydrogen-powered vehicle production in the future will be dominated by LDVs, with perhaps a few percent being transit buses (Ohi, 2000, p. 3). On the other hand, DOE programs that focus on HDVs essentially ignore hydrogen. For instance, the Office of Heavy Vehicle Technologies' *Technology Roadmap for the 21st Century Truck Program* focuses on improvements in safety, efficiency and emissions from diesel-powered trucks, laying out detailed research plans for each (US Department of Energy, 2000). It also includes a brief mention of demonstration projects for hydrogen to be used in hybrid electric or fuel-cell transit buses. However, the *Roadmap* also suggests that demonstration projects may be of limited use: "Because of their additional cost and complexity, alternative gaseous-fueled vehicles may be limited to vocational use [e.g. natural gas vehicles used by gas companies] and niche applications unless further incentives or legislative mandates are established" (pp. 4–48).

2.2. Fuel transitions

The introduction of new transportation fuels is an infrequent, uncertain, and slow (decadal) process, largely due to the difficulties associated with major changes in the social and economic systems in which new technologies are always embedded (Kemp, 1994). Throughout history, transportation fuels have included a succession of human and animal muscle, wind, wood, coal, petroleum, and electricity (Smil, 1991, pp. 128–136, 168–175). These changes have been driven by the fact that they provided private benefits—new fuels have historically provided greater mobility, so that investment in them proved worthwhile to private firms and individuals. Today, non-petroleum-derived energy accounts for less than 0.4% of all transportation energy in the US (ignoring pipelines), almost all of which is accounted for by electrified rail (Davis, 2001, Table 2.5). Although natural gas now powers over 6% of all transit buses and some municipal and state vehicles, this has come at a cost of over \$2 billion and has failed to lead to the widespread development of natural gas refueling infrastructure (Kreith et al., 2002).

Petroleum-based fuels dominate the transportation sector, largely because some of their basic physical characteristics make them relatively easy (and therefore inexpensive) to use onboard vehicles. Key characteristics include compatibility with internal combustion engines and turbines (which have high power to weight ratios and simple operating characteristics suitable for vehicle use), easy handling and storage, and very high-energy densities.

In addition to these purely physical factors, there is a significant problem associated with the introduction of a new fuel (sometimes called the "chicken and egg" problem) of coordinating between investments in hydrogen vehicles and refueling infrastructure (Jensen and Ross, 2000; Winebrake and Farrell, 1997). Simply put, consumers and businesses are reluctant to buy vehicles for which no refueling infrastructure exists while investors are reluctant to build refueling infrastructure for which there is no demand. These difficulties have plagued efforts to introduce alternative fuels less exotic than hydrogen, such as natural gas, because both refueling infrastructure and vehicle conversion remained unprofitable (Flynn, 2002). "The primary barriers for alternative-fuel vehicles are cost, market acceptance, and deployment because a variety of proven technologies are already commercially available" (US Department of Energy, 2000, pp. 4–48).

2.3. *Characteristics of hydrogen*

Hydrogen is a not a resource (like petroleum), it is an energy carrier that must be manufactured (or derived) from a primary energy resource. Hydrogen is relatively inexpensive to manufacture at large scales; it can be produced from natural gas or coal at a cost on par with the price of petroleum. Steam reforming of methane is currently the cheapest and (therefore) most common way to manufacture hydrogen. Electricity can be used to create hydrogen via electrolysis. Emissions from steam methane reforming are essentially limited to carbon dioxide, but even these could be mitigated by sequestering the carbon dioxide underground in geological formations (Herzog et al., 2000; Parson and Keith, 1998).

Onboard energy conversion of hydrogen can be accomplished several ways. Hydrogen-powered gas turbines have been investigated since the mid-1950s and commercial versions are now available. Internal combustion engines that use hydrogen have been tested. These technologies vary only slightly from commercial natural gas engines and present no significant technological challenges (Das, 2002; Van Blarigan, 1998). An interesting feature of these two technologies is that each can operate on a mixture of hydrogen and natural gas (sometimes called hythane), which is another method for introducing hydrogen as a transportation fuel, assuming natural gas vehicles (Norbeck et al., 1999; Sierens and Rosseel, 2000). Lastly, of course, fuel cells can create usable energy from hydrogen fuel at great efficiencies, although their costs are very high (Hanisch, 2000; Lave et al., 2000). Direct-hydrogen fuel cells have essentially no emissions other than water, while hydrogen-powered turbines and engines have extremely low emissions.

It is in storage and delivery that hydrogen suffers. Hydrogen has low volumetric energy density, is difficult to compress, and requires extremely low temperatures for liquefaction. Hydrogen storage systems are typically larger but lighter than equivalent systems for petroleum-derived fuels, and more expensive. Liquefied hydrogen has higher energy densities than does compressed gas storage, but the energy required to liquefy hydrogen is equal to approximately one-third its energy content, while compression (to 5000 psi, or about 350 bar) takes only one-tenth. New, non-cryogenic storage technologies (e.g., carbon nanotubes) may dramatically improve the performance of storage systems, but progress has been slow despite decades of research (Dillon and Heben, 2001). Bulk shipment of hydrogen and local delivery will thus be more expensive and more complex than for liquid hydrocarbon fuels (Compressed Gas Association, 1990; Federal Transit Administration, 1998; Linden, 1999). And although hydrogen itself has very high energy per unit mass—perhaps its only private benefit in transportation applications—the extra weight of storage (relative to the simple steel or plastic tanks used for petroleum-based fuels) may largely negate this advantage.

2.4. *Policy considerations*

Because hydrogen has few (if any) private benefits compared to petroleum-based fuels, widespread use will require either radically different market conditions or new policies. The combination of physical challenges to using hydrogen onboard vehicles, the widespread availability of less problematic substitutes for petroleum (e.g. efficiency improvements or bio-ethanol) suggests that market forces are unlikely to induce a switch to hydrogen for the next several decades (Lave et al., 2001; Weiss et al., 2000). Therefore, the introduction of hydrogen is likely to require forceful government action, such as mandates or substantial economic incentives. Unfortunately, this amounts to 'picking a technological winner' (hydrogen, in this case), which government often does quite poorly.

For instance, owners of vehicle fleets might be required to buy 'hydrogen fueling' credits based on their fleet size. These credits would be created by the sale of hydrogen as a transportation fuel, not dissimilar to how a renewable portfolio standard might be implemented (Berry and Jaccard, 2001; Jensen and Skytte, 2002) Note, however, that DOE was given authority to implement a similar approach under the 1992 Energy Policy Act, but chose not to do so, suggesting significant changes in political conditions might be required before any forceful hydrogen fuel policy might be feasible (Kreith et al., 2002; Winebrake and Farrell, 1997) Further, because the benefits of switching to hydrogen fuel are largely public and not private, it is not clear that the costs of such a policy should be borne by a single mode (or industry). It is even less clear that forcing one mode to bear such disproportionate costs would be politically feasible.

Several important issues cannot be addressed here due to space constraints. First, the issue of end-use technology (i.e., the onboard energy conversion device) will not be analyzed. This omission is a significant limitation because the efficiency improvement of fuel cells over automotive internal combustion engines may be large, and may affect the relative attractiveness of different transportation modes (Berry, 1996). However, there is good reason to think that over a decade stands between now and the availability of commercial fuel cell vehicles (McNicol et al., 2001; Weiss et al., 2000). Second, we set aside comparisons of hydrogen to other alternative fuels, and assume for the purpose of analysis the desirability of introducing hydrogen in transportation.[1]

3. Technological change

3.1. Basic principles

Current research and demonstration efforts generally acknowledge that the introduction of hydrogen fuel would be an enormous, expensive change, but they do not attempt to evaluate the relative merits of modes other than LDVs. Because of this, they fail to properly consider the dynamics of a transition to a 'hydrogen economy'.[2] Yet, understanding such a transition is crucial to formulating coherent public policy, and that understanding must build on our growing knowledge of the dynamics of technological change. Using insights from engineering principles and the economics of technological change, we develop the logic needed to identify a lowest-cost, low-risk approach to the introduction of hydrogen fuel into the transportation sector. Current research and demonstration efforts also fail to consider even the possibility of something like 'strategic niche management' in which new technologies are introduced (by government action) into a small set of applications where they can be better tested and improved before used in larger applications (Kemp et al., 1998).

The basics of technological change are simple; new technologies typically enter tiny niche markets before diffusing into widespread use. Identifying the "lead adopters" who have a high willingness to pay for the new technology and make up those niche markets is the key to successfully introducing new technologies (Griliches, 1956). A related effect is "technological learning" or learning-by-doing, which reduces the cost of producing goods, especially in the early years (Argote, 2000; Epple et al., 1996). Learning-by-doing promotes the diffusion of new technologies through a virtuous circle in which experience drives down the cost of the new technology, opening up larger markets, which in turn encourages further investment in the new technology and yields greater experience, and so forth.

The key insight into this process is that the best way to think about technological innovation is to consider a technological system, or a "cluster" of closely related technologies, not just one. To be successful, a new technological cluster must receive continued R&D investments in order to improve performance and remain competitive. As suggested above, delivery and storage technologies might be the most important area for innovation in the hydrogen cluster.

3.2. Dilemmas for environmental technologies

Research into technological change has also uncovered several dilemmas that stem from using the technological change model to think about energy efficiency, pollution control and other environmental technologies. These dilemmas arise because environmental protection is a public good, as is knowledge, and public goods are underprovided by markets (Arrow, 1994; Tietenberg, 1996, pp. 56–59).

The first dilemma concerns the difficulty in establishing niche markets (Norberg-Bohm and Rossi, 1998). In the commercialization of private goods, firms are able to charge more to "lead adopters," consumers willing to pay a premium for the qualities that a new product possesses. Over time, the cost of successful products comes down, due to learning and economies of scale, allowing the market for the new product (i.e. the new technology) to expand. However, new technologies that are designed to provide public goods are unable to command a premium (by definition), and thus the development of niche markets is hindered.

This suggests a role for government. If there were sufficient lead adopters, there would be no need for government to identify strategic niches (Kemp et al., 1998). Indeed, environmental regulation often causes technological change: firms frequently must develop processes and products to meet the new requirements while still meeting consumer demand (Faucheux et al., 1998; Skea, 1996). However, the need for government action sets up the second dilemma.

The second dilemma is that private industry generally possesses the capability to develop new technologies and will have to use them, not the government. Thus, it is very difficult for government to appropriately direct technological development, or even to predict what technological innovation is possible within desired

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[1] The authors are not committed to this assumption, but observe that it is currently driving considerable R&D investment. Thus, this paper is motivated by a desire for more rigorous and insightful thinking about hydrogen so that cost-effective public policy on the topic can be made.

[2] Victor (1990) is a notable exception.

timelines. This creates fundamental problems, such as determining what goals should be incorporated in environmental legislation, especially if costs and benefits are to be balanced. Several policy choices can deal with this problem. One alternative, "technology forcing" regulation can be used, but this is difficult politically and can also be quite inefficient (Jaffe and Stavins, 1995). Another option is to introduce strong economic incentives aimed at achieving very significant emissions reductions in the long run (Norberg-Bohm, 1999).

The third dilemma is that significant mismatch exists between the processes of policy development and technological change. The latter can take considerably longer than the former, which tend to be driven by the daily news cycle and 2–4 year election cycles. Further, when legislators or regulators set standards they can only select from available technological solutions, which are much more limited than those that will be developed subsequently. This is particularly problematic if they attempt to balance costs and benefits, since prospective cost estimates will be highly uncertain and systematically biased upwards. Lengthy litigation and implementation processes tend to follow this rule making process, which extends the time before diffusion begins and serves as another economic barrier to technological change.

3.3. *Issues for new transportation fuels*

Energy technologies (or, more properly, energy technology systems) are very long-lived, capital intensive, and have enormous economies of scale, all of which intensify the importance of early choices in research, development, and deployment (Antonelli, 1997; Gritsevskyi and Nakicenovic, 2000). This effect, called path dependence, is particularly true on the supply side, where fuel production technologies (mines, wells, refineries, railroad lines, pipelines, and delivery outlets) are necessary before even the first retail sale can be made. In order to pay off these investments, they must have long service lives, and as scale increases costs must decline, making it more and more difficult for new technologies to enter the market.[3]

Network effects arise in markets for composite goods or services that can be obtained from alternative combinations of basic products, such as fuel/vehicle combinations (Roson and van den Bergh, 2000; Unruh, 2000). The extreme case is personal vehicles due to the reliance of consumers on a ubiquitous refueling infrastructure that allows them to travel and refuel at will. One of the main problems of such markets is that two different industries (fuel and vehicle) must coordinate on technologies and investment patterns in the face of different incentives (Winebrake and Farrell, 1997). Unfortunately, US research efforts do not address this problem, including the new FreedomCAR initiative (Sperling, 2002). In addition, network effects can hamper technological innovation, a condition called "excessive inertia" (DeBijl and Goyal, 1995). The presence of network effects implies that even if they were superior in cost and performance, new fuels would find it hard to compete against existing fuels. The timescales for the diffusion of new energy technologies is typically long due to this need for a coordinated evolution of infrastructure and end-use equipment (Grübler et al., 1999).

4. Guidelines for introducing hydrogen fuel

4.1. *A single mode as a protected niche*

One way to reduce the cost of the introduction of hydrogen fuel is to limit it to a single mode, in line with the notion of strategic niche management discussed above. If an entire mode shifts to hydrogen, competitive pressures will act to reduce costs and improve performance. Before commitments in vehicles and infrastructure are made for a wide range of transportation modes, it would be better to start small, to let innovation and competition weed out lower-performance technologies before risking broader disruptions of the transportation system.

In order to achieve real learning by doing and advance the hydrogen technology cluster effectively, however, one cannot start out too small. Isolated demonstration projects often accomplish little in the way of innovation because market forces, among the most powerful influences on technological innovation, are not at work. Instead of focusing on reducing costs and meeting customer needs, government-funded demonstration projects often focus on public relations and overtly political objectives. In addition, demonstration projects tend to be one-off efforts that offer little opportunity to realize the benefits of learning-by-doing. These benefits can be brought about only by a significant level of adoption, which will create competition between different providers and create demand for the associated products and services in the technology cluster. By introducing hydrogen so that it achieves significant market penetration into a single transportation mode, or perhaps in a geographically restricted area, the benefits of learning-by-doing will be maximized while society incurs the minimal overall costs and risks.[4]

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[3] This phenomena is sometimes called "technological lock-in".

[4] Suggestions to convert Iceland's entire transportation sector to hydrogen have been made, and as a small, isolated island with unique conditions these plans deserve some consideration (Arnason and Sigfusson, 2000; Arnason et al., 1993; Jones, 2002).

Technologies associated with hydrogen can be usefully divided into three groups: production, distribution and storage, and end-use conversion (e.g. propulsion). Of these three, distribution and storage seem to be the most limiting today and in the near future, although there are important tradeoffs between different groups (particularly if currently expensive, high-efficiency fuel cells can reduce the need for on-board storage at lower prices). This has two implications: cost-minimizing mode selection will likely be particularly sensitive to these factors, and market forces are likely to focus most research and development efforts to solving these problems.

Below, we identify five factors that help identify the cost-minimizing transportation mode into which hydrogen can be introduced.

4.2. Vehicle design and performance

The challenges of hydrogen storage dictate that hydrogen powered vehicles will generally perform more poorly than their petroleum-powered counterparts. For example, the low volumetric density of hydrogen storage may reduce payload volume or decrease range. The importance of these decreases in performance varies strongly across modes. The cost of using hydrogen as a transportation fuel would be less for larger than smaller vehicles, since larger vehicles (such as trucks) tend to have less tightly constrained volumetric limitations. Similarly, in most freight modes, the payload weight greatly exceeds the weight of the vehicle and its fuel, whereas in passenger modes the opposite is typically true. Thus, changes in volume or mass for the vehicle and fuel will have less impact on freight modes than on passenger modes. This cuts both ways—it will tend to reduce the cost of introducing hydrogen into freight modes, but will also reduce the incentive for the development of better storage technologies. Further, potential hydrogen-caused degradations in some performance aspects, such as reduced acceleration, may be less important for freight modes than for passenger modes.

4.3. Infrastructure

One of the largest and most obvious issues for hydrogen fuel is to minimize the costs of the delivery system. In general, larger refueling sites would be preferable, especially those close to the point of hydrogen production, which today are refineries. The more intensively these sites are used, the greater their cost is spread over different users and the lower the marginal cost for any individual user. In addition, the fewer the number of refueling sites that an application needs the better. Vehicles that operate either within a very small geographic area or only along well-defined point-to-point routes tend to need smaller refueling infrastructures. Commercial vehicles (e.g. a local courier-delivery fleet) sometimes use a single, centralized fueling facility (although this is becoming less common, see Nesbitt and Sperling, 1998) or utilize a small number of automated, “key-lock” stations designed for large vehicles and operated under contract.

4.4. Operation and management

Vehicles that use hydrogen fuel are likely to cost more than current vehicles, due to the more complex fuel storage requirements and possibly due to more expensive prime movers (e.g. fuel cells). Vehicles that are operated more intensely will tend to depreciate capital costs quicker and thus minimize this problem. In addition, for modes in which fuel costs tend to be important (e.g. freight), additional capital spending to reduce fuel consumption (and thus operating costs) may reduce overall costs. If liquid hydrogen is used as the fuel, another issue becomes important; cryogenic fluids will begin to boil off and need to be vented to the atmosphere if left unused too long. This problem is a function of tank insulation and time between use, and can be minimized if the vehicle is used daily and around the clock. Another approach would be to use storage tanks that can hold both liquefied and compressed hydrogen (Aceves et al., 2000).

Any transportation mode into which hydrogen fuel is introduced will have higher costs, at least in the short run. This causes two problems. First, it will reduce the quantity of transportation services demanded by the market. This could reduce profits and possibly raise prices to the public, who consume transportation services directly or indirectly through freight delivery. Second, increased costs might cause consumers to substitute away from the mode using hydrogen, further reducing the quantity of transportation service demanded from that mode (a form of the “leakage” problem). For example, if hydrogen was introduced into passenger cars, making them less desirable to consumers, more people might buy light trucks. Since the introduction of hydrogen fuel would be done to achieve a public good, there is no reason that one sector should have to bear this burden. Therefore, government will likely need to compensate with subsidies or other policies. Preferred modes will have smaller cost increases associated with the use of hydrogen and present less opportunity for mode substitution.

It is easier to introduce new technologies where user characteristics are most favorable to managing technological change. These include ensuring proper safety precautions, adequate maintenance, and user training, which will be easier in commercial vehicles with professional crews than in private automobiles “with the wide spectrum of technical sophistication of the operators” (Jones, 1971). Other important user characteristics include the technological sophistication of the relevant institutions and ability to manage change, including both the firms that will use hydrogen fuel vehicles and their regulators (if any).

Hydrogen fuel is different from other transportation fuels, with some parameters that would tend to make accidents more severe and other parameters that would make accidents less severe. Therefore, it is not clear if it would present more or less risk *in toto* (Morgan and Sissine, 1995). The good safety records of trucks carrying compressed and liquefied hydrogen over the road, and of liquefied natural gas (LNG) tankers adds confidence that there are not large, unknown risks associated with hydrogen fuel use. With experience, however, any problems with hydrogen should eventually make themselves known, and methods to remedy them will be found. Thus, the way to limit risk during the introduction of hydrogen as a transportation fuel would be to reduce the exposure routes by which people and property might be affected by accidents. Modes with trained, professional operators and routes that are relatively distant from people and property will tend to expose the public to fewer risks, other things being equal.

4.5. Pollutants

Vehicles operating on hydrogen will have extremely low emissions, approaching zero for fuel cell-powered vehicles. Maximizing the benefit of this emission reduction will help to minimize the cost of introducing hydrogen as a transportation fuel. One approach to maximizing the benefit would be to introduce hydrogen into a relatively dirty mode. Since emissions rates are essentially a function of regulation, the largest of these collateral benefits will be gained by introducing hydrogen fuel into modes with little or no pre-existing emissions regulation.

4.6. Vehicle production

The engineering and production of the first widely used hydrogen-fueled vehicles will be a major undertaking, but the level of effort will vary substantially across modes. Further, it is critical that the opportunities for minor, continuous improvements can be integrated into subsequent vehicle designs relatively quickly, since this will allow for more rapid technological change. The more quickly and easily vehicle designs are modified the better. Mass-produced vehicles present special challenges, since they typically involve enormous engineering investments before the first vehicle rolls off the assembly line (so much so that firms are sometimes described as having to "bet the company" on new designs). In addition, it is very costly to alter the designs once production has begun, so the fundamental engineering of a specific model can remain static for many years. A final factor is capital turnover, preferred modes will be ones in which the stock of vehicles changes relatively quickly, allowing for increased learning-by-doing.

5. A strategy for introducing hydrogen as a transportation fuel

A brief comparison across several modes is presented in Table 1. This data suggest that the cost of introducing hydrogen as a fuel for HDVs may be lower than for LDVs. Choosing among different HDVs and the transportation modes to identify possible strategic niches will require further research. However, as an example, marine freight will be briefly examined as a potentially interesting mode for the introduction of hydrogen as a transportation fuel. Several of the factors identified above act most strongly on this mode, including vehicle performance, infrastructure size, and traditional pollutants.

Vehicle production varies significantly among HDV modes. Costs for engineering, regulatory approval, and tooling up the assembly line are highest in aircraft production. At the other end of the spectrum are LDVs, for which the immense development costs are spread out over years of mass production. Somewhat in the middle are cargo ships, customers place orders from more or less standard designs. By law,[5] freight vessels that sail from point to point within the US must be domestically built, but all others, including ocean-going vessels, are built elsewhere, typically in Asia, at lower cost (about 20–30% of the US-build cost). Marine engines are produced by about two dozen firms worldwide, but sales are almost exclusively by European and Japanese firms. Large (up to 60 MW) diesel engines propel almost all oceangoing cargo vessels, but dual-fuel (diesel-natural gas) engines are now being sold commercially for use in freighters (to meet environmental regulations in some ports). These large, compression-ignition engines have energy efficiencies about equal to those of fuel cells (55% or more, with bottoming cycles), but cost about one-tenth as much. The use of cryogenic marine fuels in reciprocating engines is also well established, over 100 are LNG tankers are now in service and they have sailed without incident for over 20 years. These vessels consume the boil-off of their cargoes as fuel. Research on liquid hydrogen tankers shows that only slight modifications to existing LNG tanker technologies would be needed for satisfactory liquid hydrogen storage onboard ships (Abe et al., 1998; Sandman, 1998).

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[5] Section 27 of the Merchant Marine Act of 1920, commonly referred to as the Jones Act.

Table 1
Simple cross-modal comparison (Pollution data from Davis, 2001, Chapter 4)

Feature/Mode	Passenger automobiles	Commercial aircraft	Long-haul freight trucks	6.1.1.1 Marine freight
Vehicle design and performance	Very small, tight design. Consumers are very sensitive to performance.	Large, very weight-sensitive vehicles require extensive testing and certification.	Relatively large vehicles. Payload greatly exceeds tare weight.	Extremely large vehicles that carry very heavy cargoes.
Users	Highly variable technical competence and physical capabilities. Training is often minimal.	Highly trained crews and maintenance personnel subject to rigorous regulation.	Trained and licensed drivers, some certified to deliver compressed and liquefied hydrogen.	Well trained crews and varying (but increasing) levels of government regulation.
Operations	Operated on public roadways, stored and sometimes maintained at home. Refueled at public facilities. Can be used up to 2–3 h/day, may sit for weeks without attention.	Refueled in close proximity to passengers and operated over many areas, including all major population centers. Often in use 12–18 h/day, less on weekends.	Operated on public roadways, stored at rest stops, roadsides, and private lots. Maintained and refueled at special facilities. Often used 12–16 h/day over 250 days/year.	Refueled at commercial docks, most operations in harbors with tugs or at sea. Virtually 24-h operation either loading/unloading (up to 20%) or in transit (80% or more).
Infrastructure	Approximately 135,000 gasoline retail outlets in the U.S., with an average size of ~10 GJ/mo. (80,000 US gal./mo.)	40 large commercial airports in the U.S., with an average size of ~5200 GJ/mo. (38,000,000 US gal./mo.)	Approximately 1500 truckstops and fuel centers in the US, with an average size of ~85 GJ/mo. (600,000 US gal./mo.)	About 30 bunker fuel providers (refiners) in the US, with an average size of ~3,000 GJ/mo. (21,000,000 US gal./mo.)
Pollution (kg/GJ)	NO_x:270 VOC: 268 PM-2.5: 3.1	NO_x: 7.4 VOC: 8.3 PM-2.5: 1.4	NO_x: 536 VOC: 42 PM-10: 35	NO_x: 869 VOC: 35 PM-10: 35
Vehicle production	Mass production. New designs are large and risky undertakings that may require 5+ years. Natural gas vehicles available.	Large-scale production over decades with major incremental improvements. New designs extremely expensive and risky	Large-scale production of standard units. Trucks to carry compressed or liquefied hydrogen are standard.	Custom production based on standardized design. LNG tankers well established, but few (<10) are built annually.

Large differences exist in the elasticities of demand and substitution among different freight modes. In the US, for instance, rail and truck freight modes have competed fiercely for over 50 years. Imposing the costs of hydrogen fuel on one of them might, therefore, significantly disadvantage that sector. Mode substitution is less problematic for domestic marine freight, which consists largely of bulk shipments (coal, grain, petrochemicals, and so forth) between already-established port facilities (such as power plants on the Ohio River, which use the water for both cooling and fuel supply). River shipment of bulk commodities is so much cheaper than on road delivery that, even disregarding the impacts of adding huge numbers of trucks to the nation's highways, the elasticity of substitution between the two is likely to be low for most waterborne domestic cargoes. Rail transportation may have a greater ability to substitute for shipment by domestic waterways. Moreover, for intercontinental shipping substitutability is essentially zero, except for high-value freight that already travels by air. Finally, the cost of fuel is a small fraction of the price of internationally traded goods, so there is probably very low elasticity of demand.[6]

It is possible to sketch out various strategies to introduce hydrogen fuel that start with marine freight modes. One scenario is the case of two countries that have major international ports and are also interested in introducing hydrogen as a maritime fuel. (The Netherlands, Iceland, Japan, Germany, Korea, Norway, and Sweden may be good candidates.) An agreement might be struck between these two countries to design and operate hydrogen-fueled container ships between specific ports (such as Rotterdam and Tokyo). Ports might be particularly good places to start the development of a hydrogen supply infrastructure since many are close to refinery operations, where hydrogen is routinely produced for internal use. Further, cargo vessels today routinely refuel at or near refineries, often via barges. Thus, refueling infrastructure changes would be minimal

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[6] However, fuel costs are an important part of the cost of marine shipping (as opposed to the value of the shipped goods), so shippers have strong incentives to hold these costs down.

and could take advantage of the economies of scale of the existing hydrogen production capability. Subsequently, it would be relatively easy to scale hydrogen fuel use down within the same sector to harbor vessels (such as tugs and ferries), or possibly to begin a broader diffusion of hydrogen fuel technologies to landside port vehicles, or to the rail and heavy-duty trucking systems that move cargo into and out of ports. Beginning the development of a widely available hydrogen refueling infrastructure in refineries would also help enable the implementation of CO_2 capture and sequestration, which have large economies of scale. Each of these steps would raise the cost of the refueling infrastructure, but would do so incrementally. However, each would support the technology diffusion of the same transportation service—freight mobility—across different HDV modes, often used by the same cargo shippers.

However, there are some real barriers to introducing hydrogen fuels into international cargo shipping. The maritime industry employs long-lived capital (vessels last 20 years or more) and has traditionally been slow to adopt innovations not intrinsically maritime. Moreover, this is an industry that has emphasized low-cost propulsion and fuel systems, so lead adopters in maritime transportation may be less willing to pay a premium for hydrogen innovation than other modes, emphasizing the need for policy drivers.

In addition, policy drivers for the marine freight industry are complex. The multinational maritime sector is particularly difficult to regulate because of jurisdictional limitations (Corbett and Fishbeck, 1997). The biggest single exporter and the largest source for bunker fuels is the US (Corbett and Fishbeck, 1997), which could provide the US with unique leverage in this case. However, this is balanced by the fact more than 90% of the cargo ships calling on US ports are foreign-registered, often in developing countries. The net effect for environmental regulations is that the US government has long sought to “harmonize” national marine vessel regulations with international environmental standards, essentially deferring to relatively weak international standards.

International shipping also is wrapped up in general free-trade policy issues. A single global standard for vessel safety and environmental performance would facilitate the flow of global commerce, so that fleets can carry cargoes into all ports. The recent trends in maritime environmental policy have favored a “lowest common denominator” policy versus any more effective policy that may deter trade.

To overcome these policy barriers (especially the international treaty context), some combination of policy mandates and funded incentives may likely be needed. Use of direct mandates without public moneys to produce innovative behavior may work better for transportation modes that are “captured” by a single jurisdiction with the political will and authority to enact change across the fleet. However, subsidies, fee-bates, or other market-based approaches have shown potential to attract lead adopters, even in the maritime sector (Kageson, 1999). Incentive-based policies may be implemented more rapidly and may involve a greater fraction of the fleet as “lead adopters”. While maritime transportation may be an attractive mode for hydrogen introduction according to our lowest-cost strategy, a policy structure that is inconsistent with market conditions will likely fail here as in other modes. However, there is also some evidence that purely voluntary and only partly subsidized approaches may not be able to introduce a new transportation fuel on environmental grounds (Flynn, 2002; Kreith et al., 2002).

A key aspect of any strategy to introduce hydrogen as a transportation fuel first in HDV freight modes would be the potential spillovers of technological innovation into other modes while keeping costs low, mainly by limiting the size of the refueling infrastructure. While the marine freight mode appears to be a particularly good candidate for the reasons given in this analysis, a more general conclusion is that freight modes are uniformly more likely to be lower-cost avenues for hydrogen fuel introduction than LDVs. Technological solutions to the fuel handling and storage problems of hydrogen would be particularly valuable. This strategy would also address part of the “chicken and egg” issue—it would result in a sparse but nation-wide hydrogen fuel infrastructure at truckstops that automobile drivers could rely on for long-distance trips. Thus, the lowest-cost approach to hydrogen-powered automobiles may in fact start with the deployment of ships, trains, and trucks that use the fuel first.

6. Conclusions

Our review suggests that the overarching goal of introducing hydrogen as a transportation fuel should be to develop the cluster of technologies and practices associated with its use at least public cost and social disruption. This will reduce the cost and other social disruptions of wide-scale use, should that be the outcome of either market or policy choices. In committing public funds and political will to introducing hydrogen fuel vehicles and infrastructure for a wide range of transportation modes, the best strategy would be to start with protected niches, and to let innovation and competition weed out lower-performance technologies before risking broader disruptions of the transportation system. A protected niche would allow for companies to learn by doing in the design and operation of hydrogen-fueled vehicles. Relying on demonstration projects alone to spur the necessary technological innovation is inadequate because insufficient incentive or experience exists to achieve real learning by doing and advance the hydrogen technology cluster effectively.

The guidelines developed here suggest that the cost of introducing hydrogen fuel can be minimized by selecting a mode that uses a small number of relatively large vehicles, which are owned by a small number of technologically sophisticated firms and operated by professional crews, and which are used intensively along a limited number of point-to-point routes or operated within a small geographic area. In addition, technological innovation in vehicle design will take place most quickly in modes where individual vehicles are produced to order and each receives significant engineering attention (not those manufactured in vast quantities on assembly lines). The immediate environmental benefits of introducing hydrogen fuel will occur in modes that have little or no pollution regulations applied to them. These results suggest that heavy-duty modes would be a less costly way to introduce hydrogen as a transportation fuel and a more effective way to advance hydrogen-related technologies so that they could be used widely in light-duty vehicles. Using the example of international marine freight, we identify interesting opportunities as well as considerable barriers. Similar complex trade-offs are likely to appear for every mode, and these need to be more systematically evaluated. More generally, freight modes appear to be more consistent than LDV with a strategic approach for early public efforts to introduce hydrogen into transportation.

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