Transportation, Energy, and Environmental Policy

Managing Transitions

VIII Biennial Asilomar Conference

September 2001

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Transportation, Energy, and Environmental Policy

VIII Biennial Asilomar Conference

September 11–12, 2001

Editors
Dan Sperling and Ken Kurani
Institute of Transportation Studies
University of California, Davis

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Acknowledgments

Under the best of conditions, a publication such as this is the work of many people. This book draws on the efforts of many people, over many months. The VIII Biennial Asilomar Conference on Transportation, Energy, and Environmental Policy began on September 11, 2001. We will discuss the circumstances further in the Introduction. Here we simply observe that the conference could not be convened as planned. It required several months to complete in three steps: the first, an abbreviated meeting at Asilomar on September 11 and 12, 2001; then a session at the Annual Meeting of the Transportation Research Board in Washington, D.C. in January 2002 to present several papers originally scheduled for presentation at Asilomar; and, finally, several discussions to develop materials that would eventually be edited into the final chapter of these proceedings.

The first step was the conference, hosted and organized by the Institute of Transportation Studies, University of California, Davis (ITS-Davis). It was held at the Asilomar Conference Center in Monterey, California, under the auspices of the National Research Council's Transportation Research Board (TRB)—in particular, the Standing Committees on Energy and Alternative Transportation Fuels. Sponsors included the U.S. Department of Energy (USDOE), U.S. Environmental Protection Agency (USEPA), Ministry of Natural Resources Canada, ExxonMobil, Chevron, University of California Transportation Center, and Energy Foundation. The core members of the conference steering committee members were Debbie Adler (USEPA), Jack Johnston (ExxonMobil), Paul Leiby (Oak Ridge National Laboratory), Jason Mark (Union of Concerned Scientists), David Rodgers (USDOE), and Dan Sperling (UC Davis). ITS-Davis staff provided logistical and administrative support and services, under the direction of Shirley Long. The TRB session in Washington, D.C., was chaired by Danilo Santini (Argonne National Laboratory). The final chapter drew on the efforts of the Asilomar Conference attendees and presenters, as well as participants in other "agenda setting" discussions, including a chapter by Martin Lee-Gosselin (Université Laval) and Dan Sperling in TRB's *Special Report 268: Surface Transportation Environmental Research: A Long-Term Strategy*, as well as chapters by Kevin Heanue (U.S. Department of Transportation), Dan Sperling (*1*), David Greene (Oak Ridge National Laboratory), and David Rodgers (USDOE) in another TRB publication, *Conference Proceedings 28: Environmental Research Needs in Transportation* (*2*).

Each paper published in this volume was peer reviewed by at least two individuals. The peer review process was overseen by the editors and conducted with the cooperation of two TRB committees (the Standing Committee on Transportation Energy and the Standing Committee on Alternative Transportation Fuels). The two committee chairs—Marianne Mintz and Peter Reilly-Roe, respectively—offered invaluable assistance in the organization of the conference and the peer review process.

Many individuals participated in the three phases of the expanded "conference." Under trying circumstances, those at Asilomar on September 11, 2001, convened a day-and-a-half of thoughtful and insightful deliberation on the topic of transitions in transportation energy. Following Dan Sperling's opening remarks, Peter Brown and Lee Schipper presented papers under the theme of "Motivations and Forces for Change," both of which appear in this volume. Mike Walsh then chaired a session on "Vehicle Technology and Fuel Options During

Transition" that included presentations from Mark Delucchi, Robert Williams, David Greene, and Robert Moore. Chapters by Williams and Greene (see the chapter by Johnson, Greene, and Birky) are included here. The session titled "Lessons Learned, Transition Strategies and Policies" was chaired by Rob Chapman (Rand Corporation). It included presentations by Thomas White (USDOE) and C. J. Brodrick (UC Davis). Chapters based on both are included in this volume. It also included presentations by Robert Knight (Bevilaqua-Knight, Inc), Steve Plotkin (Argonne National Laboratory), David Greene, Tom Cackette (California Air Resources Board), and John DeCicco (Environmental Defense).

Other chapters in this book are based on papers presented at the TRB session in January 2002, or otherwise included because they had been solicited for the original conference plan. These include the chapters by Farrell (Carnegie Mellon) et al., Elzen (Twente University) et al., Kågeson (Nature Associates), and Hayashi (Nagoya University) et al.

While many people have contributed to this work, we the editors are solely responsible for any errors and omissions. The opinions expressed herein are not necessarily those of any sponsor or supporter of the conference or the production of these proceedings.

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1. *Special Report 268: Surface Transportation Environmental Research: A Long-Term Strategy*. TRB, National Research Council, Washington, D.C., 2002.
2. *Conference Proceedings 28: Environmental Research Needs in Transportation.* TRB, National Research Council, Washington, D.C., 2002.

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Introduction to the VIII Biennial Asilomar Conference on Transportation, Energy, and Environmental Policy: Managing Transitions

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Every two years since the late 1980s, a mix of experts and leaders has gathered to discuss critical and emerging issues in transportation, energy, and the environment. The group includes a cross-section from government, industry, academia, and advocacy groups. Most are from the U.S., but international participation has grown over time. While some people have attended most or all of the meetings, new faces and perspectives emerge at each meeting. These conferences also serve as the mid-year meeting of the Energy and Alternative Transportation Fuels Committees of the Transportation Research Board of the National Academies of Science. The gathering takes place in late summer at the Asilomar Conference Center in Pacific Grove on the central coast of California. The center is a quiet California State Park set in a pine forest bounded by quiet residential streets and the Pacific Ocean. The center provides neither televisions nor telephones in the guest rooms. A short boardwalk across the sand dunes leads to a small beach. In September, the area is typically cloaked in fog in the morning, the grey mist shrouding the conference grounds from the world outside.

The expected reverie of the most recent meeting was broken before it began, scheduled for the afternoon of September 11, 2001. Americans—and many others—have prospered from the growing interconnectedness of nations and economies made possible by global transportation and communication networks. On that day Americans—arguably more than others—were confronted with a horrifying perversion of that connectedness.[1]

Some conference attendees from across the country and around the world had already arrived at Asilomar when news broke of the terrorist attacks in New York City and Arlington, Virginia, as well as the crash of a fourth plane in rural Pennsylvania. Many attendees were en route to Asilomar at the time of the attacks. Many landed far short of their destination as the skies were cleared of air traffic. Over the course of that morning and afternoon, all scheduled conference attendees were accounted for, either stranded at home or at airports throughout the country. Fortunately, all were safe.

While their first thoughts were of family, friends, loved ones, and colleagues in or near the sites of the attacks, or en route, conference organizers were obliged to turn their attention to the community of people already gathered at Asilomar. Many were far from home, with no prospect of returning for days or longer. Was it appropriate to convene this meeting with such terrible events unfolding in the world?

The conference was missing speakers, session chairs, and much of its audience. But about one third of the expected attendees were on site. This group decided to proceed with the conference; not to meet would leave many as “stranded assets.” Attendees proceeded to meet, listen, and discuss as best as possible the topic of managing transitions in transportation, energy, and environmental policy. For many, events of the morning of September 11 simply underscored the importance of one such transition—away from transportation's dependence on petroleum. With the cooperation of everyone, and the dedicated staff of the Institute of Transportation Studies of the University of California, Davis, the original two-and-half-day agenda was condensed into one-and-a-half days. Ultimately, many of the presenters who could not make it to Asilomar were able to present their work at a session of the 81st Annual Meeting of the Transportation Research Board, in January 2002 in Washington, D.C.

MANAGING TRANSITIONS

The focus of the biennial Asilomar transportation and energy conferences alternates between technology and policy. In 2001, the focus was on policies to manage transitions. Technological discussions in previous years concluded that new and enhanced technologies show great promise, but that implementation was often problematic. Petroleum-fueled automobility is a web of entrenched, specialized, and linked networks. It constitutes a large part of our economy, and plays a central role in our lifestyles. Change is difficult.

That day, September 11, 2001, may prove pivotal. Many attendees arrived with firm views of desirable transitions and end states. Those views were tested by the events of that day. The question of transition paths and policies became more salient than any could have imagined. Faced with new (and old) imperatives, advancing technological possibilities, and established automobility patterns, many attendees began thinking of a transition to a "hydrogen economy"—a transition both facilitated by and facilitating a transition away from transportation systems dependent on petroleum.

As Dan Sperling noted in his introductory talk, transitions involve the interplay of *technology, markets,* and *policy*. While a previous Asilomar conference concluded, "Technology is enough," such a statement is qualified by behavioral responses to new technology, including those of manufacturers, marketers, and end-users. New technologies do not propagate themselves. They compete with other new technologies. More importantly, they compete within and against historical conditions defined by existing institutions, policies, modes of behavior, ways of living, and technologies. The choice of any new transportation energy system must answer the question of whether it is better to simply abandon existing technologies, policies, and ways of thinking and acting, or use them as springboards to launch the new.[2]

Similarly, understanding markets goes well beyond economics. Economic systems are shaped by historical conditions, policy, and politics—local and global. The processes of change are highly constrained. Government can only go as far as its citizens will go, and industry will only (willingly) provide products it believes consumers will buy. The conference and this book explore this interplay of economics, policy, and behavior. A central theme is the role of petroleum.

The age of petroleum continues to survive despite dire warnings of impending shortages, precarious dependencies, and high air pollution and carbon dioxide emissions. Most extraordinary has been the success in reducing air pollution. Just ten years ago, few people thought that gasoline powered, internal combustion engine (ICE) cars would be able to meet California's new super ultra-low emission vehicle standard. They now can. Similar progress is now following with diesel engines. The challenge with greenhouse gas emissions is greater, but progress is being made. Hybridizing those ultra-clean gasoline- or diesel-powered ICEs with electric drive technology offers the potential for large reductions in emissions of greenhouse gases (and criteria pollutants).

Petroleum-powered pathways continue to dominate. But for how much longer? What can and should be done now? What transitions and pathways are most promising and how might they be pursued? These transitions were the subject of much of the discussion during the VIII Biennial Asilomar Conference on Transportation, Energy, and Environmental Policy.

OUTLINE OF THIS VOLUME

The layout of this book follows the planned and realized agenda for the VIII Biennial Asilomar Conference on Transportation, Energy, and Environmental Policy: Managing Transitions. As such it contains some topics that were discussed at Asilomar, a few presented in Washington, D.C., four months later, and others prepared for the conference but never presented. The book also includes a concluding chapter in which the editors summarize and synthesize research recommendations that were generated by conference participants at the conference and in other forums. The remainder of this chapter highlights some important insights and findings of the chapters in this book.

Motivations and Forces for Change

Keeping in mind that the timeframe for planning this conference was prior to September 11, 2001, the first session addressed the question, What are the implications for change in the transportation sector? In particular, What emerging issues and trends are forcing change? What transportation energy issues are likely to be most pressing over the next few years because of public concern and approaching environmental and supply limitations?

The chapters by Peter Brown and Lee Schipper approach the issue of change very differently. Peter Brown identifies motivations and forces for change by subordinating the entire framework of mainstream economic thought into a more comprehensive *stewardship economics*. Lee Schipper, while giving attention to larger policy contexts, also plumbs the details of comparative analyses down to the level of what data are required to compare the causes and effects of individual transportation–land use projects.

Peter Brown does not simply apply economics to the problem of sustainability; he reshapes economics with the idea of sustainability. He discusses the application of stewardship economics to the case of greenhouse gas emissions and transportation. In his chapter, “Economics, Stewardship, and the Transportation Sector,” Brown asks, “…what transportation energy issues would likely be most pressing over the next several decades if we reformulate two of the dominant analytical paradigms, namely modern micro- and macro-economics?”

Brown argues that *stewardship economics* builds on the moral/conceptual framework offered by John Maynard Keynes that one goal of economics should be the prevention of war. Brown extends this goal to preserving the functioning of the natural world. The two starting points for his extension are 1) the recognition of the finite capability of natural systems to sustain and absorb flows of energy and materials, and 2) the expansion of the moral realm beyond people. Changes to economics would include a shift in the role of prices. While prices are used to maintain and protect what Brown calls the *commonwealth of life*, it is not done so simply with an eye to maximum efficiency as derived in modern economics. Rather, he develops the concept of *ultimate order efficiency*—essentially the value of a thing is measured by the amount of life that must be exchanged for it. This subordinates first order efficiency, which governs the pursuit of profit and welfare, to an "idea of efficiency *about* the economy."

While Brown motivates change in the economy and in transportation by placing their roles in a new analytical framework, Lee Schipper, in "Sustainable Urban Transport in the 21st Century: A New Agenda," grounds motivation for change in the ongoing and increasing problems faced by cities throughout the world. Schipper describes one of the fundamental contradictions of automobility—that the spatial reorganization and spreading that automobility facilitates leads to land-use patterns, transportation networks, and ways of living that ultimately threaten automobility itself. Deleterious effects on the local level include inequitable and differential access to housing and employment, traffic congestion, and poor air quality. The viability of many cities in the developing world is threatened by automobility.

His analytical framework for tracking and comparing transport options is summarized by the identity: $\mathbf{G} = \mathbf{A}\mathbf{S}_i\mathbf{I}_i\mathbf{F}_{ij}$, where $\mathbf{G}$ is emissions of any pollutant summed over modal sources; $\mathbf{A}$ is total travel (passenger-kilometers, ton-kilometers) across modes; $\mathbf{S}_i$ converts total travel to modal travel by mode i; $\mathbf{I}_i$ is modal energy intensity (fuel use per passenger- or ton-kilometer); and $\mathbf{F}_{ij}$ is fuel type j in mode i. This identity reminds policy makers, transport providers, and other decision makers how these "components of transport and emissions fit together, and make sure that the potential—and actual—impacts of their actions on each component are noted." He presents tabular summaries of which types of policies affect which components of travel-related emissions and which actors "care" about these policies. The actors he discusses include local and national governments, modal (primarily vehicle) manufacturers, end consumers (both households and commercial, e.g., taxi drivers), and other stakeholders. Application of the ASIF framework also highlights data needs, varying from data missing for local or individual projects and programs to the need for international data standards to insure comparable results.

The analysis of who cares about policy is only the first step in identifying and solving problems of implementing new policy. Schipper explores inadequacies in existing analytical and policy-making infrastructure, including data, models, communication between different decision-making actors, lack of advocacy for non-motorized transport, and the failure of international agencies to be sufficiently nuanced when dealing with myriad nations, cities, and localities.

Schipper provides examples of policy and technology initiatives from cities around the world to demonstrate the application of this framework. These include Mexico City's efforts to limit car travel; low sulfur diesel fuel in the U.S. and Europe; CNG buses in cities throughout the world; car-free days in Bogotá, Colombia; voluntary agreements between automobile manufacturers and the European Union to limit carbon dioxide emissions; and the pledge by Honda Motor Company to eliminate two stroke motors in small scooters and mopeds.

In the end, Brown and Schipper's contributions offer a similar lesson, despite radically different starting points. Each addresses the process of change in a broadened context. In the case of pricing, for instance, Brown discusses several additional measures of efficiency that flow from a stewardship economics, as well as types of decisions that perhaps should not be made on the basis of market prices at all. Schipper's concerns with pricing may be more pragmatic—can pricing schemes be implemented—but he recognizes that the question of pricing exists in a larger regulatory, technical, and political context (as argued by Sperling in his opening presentation).

Brown and Schipper both argue that long-term perspectives should prevail. Many of the problems with transportation will take a long time to solve; quick fixes cannot succeed. In recounting examples of policy and technology initiatives, Schipper acknowledges that not all of them succeeded. A willingness to try, and possibly to fail, foreshadows the later discussion of market niches.

Vehicle Technology and Fuel Options During Transition

In studying innovations that have large implications, such as CO_2 sequestration, conversion of hydrocarbons to hydrogen (and carbon dioxide by-product), world petroleum supply and demand, fuel cells, and alternative fuels, the second session considered which technologies could offer smooth transition paths, and which would require abrupt changes or significant investments. These questions are discussed in terms of 1) technology and fuels options, and 2) pathways and scenarios. The first approach characterizes Robert Williams' chapter, "Toward Zero Emissions for Transportation Using Fossil Fuels." The second describes Larry Johnson, David Greene, and Alicia Birky's "Is the Barrel Half Full or Half Empty? Implications of Transitioning to a New Transportation Energy Future." Currently, the most controversial technology is diesel engines. The session did not debate diesel's merits and problems, but instead addressed strategies and processes of change. More generally, the session addressed the following:

- The most significant issues regarding transitions for each of these options;
- Similarities and differences in issues that might be important, in terms of needed technology, policy, or economics;
- General strategies for stakeholders (regulators, industry) that would increase the probability that the transitions would provide benefits in some form for all stakeholders; and
- Barriers that would block these strategies.

As the editors discussed in the opening paragraphs of this introduction, many people—such as, but not limited to, the attendees at Asilomar—are contemplating a transition to a hydrogen economy. Robert Williams provides some motivation for why this is so. Acknowledging that a transition from the entrenched petroleum/ICE transportation system to a hydrogen fuel cell/electric motor system will be tremendously expensive, Williams sets out to establish which of fourteen combinations of vehicle and fuel technologies would be cost effective under what conditions. He summarizes his results by noting that if we believe median estimates of health damages and oil supply insecurity best represent the future, then none of the fourteen options is a clear winner. However, if one's strategy is to prevent the worst cases, then hydrogen-powered fuel cell automobiles are the least costly option.

With this motivation, Williams tackles the question of whether a transportation system with near-zero emissions of carbon dioxide can be achieved utilizing coal as the feedstock for hydrogen production. He discusses two technologically complex problems: the sequestration of carbon dioxide and the large-scale production of hydrogen from coal. He is generally positive about the prospects for the long-term success of such a system, while acknowledging significant technological and resource questions remain to be answered. His optimism regarding the use of coal in a near-zero carbon dioxide emission system is based on three considerations. First, he states the processes for extracting hydrogen from hydrocarbons tend to be fairly efficient and can be accomplished with low carbon dioxide emissions if those emissions are sequestered in locations such as deep saline aquifers or oil and natural gas fields, from which he posits they are unlikely to escape. Second, he argues the additional cost penalty for sequestration may be fairly modest. Third, he estimates the global capacity for sequestration may be vast compared to estimates of long-term energy use by human societies.

If these considerations prove to be accurate, Williams concludes that most of the required hydrogen for fuel cell vehicles could be provided by fossil fuels—and coal in particular. He proposes several long-term research experiments to test these considerations. For example, carbon dioxide can be injected into working oil fields (as part of enhanced oil recovery projects), deep saline aquifers, and coal beds (that cannot be mined). The ability of these media to effectively trap carbon dioxide can be monitored for decades.

Williams concludes with a discussion of policy instruments that might promote the specific coal-to-hydrogen-fuel pathway. These include the relative size of a carbon tax required to incite manufacturers in various hydrocarbon-to-hydrogen systems to sequester carbon dioxide rather than simply venting it to the atmosphere. He argues that the tax level required in the coal pathway is lower than in the natural gas-to-hydrogen pathway. Further, he explores the possible role of electric utilities that operate coal-fired power plants to "repower" those plants as "coal to electricity and hydrogen" plants, particularly as those plants approach their nominal retirement age (at which time, several types of investments in extending their lives might be made).

Larry Johnson, David Greene, and Alicia Birky, in "Is the Barrel Half Full or Half Empty?," characterize several possible scenarios for what they call an "inevitable transition" away from petroleum fuels for transportation. Their work describes the first phase of an effort by the U.S. Department of Energy's Office of Transportation Technology to assess long-term world petroleum supply and demand. The title of their paper plays on geologists' historical observation that when half the known reserves of a resource have been exploited, production levels begin to decline. They place the halfway point of the exploitation of known conventional and unconventional crude oil reserves at some point in the next few decades. They argue that a more precise estimate of when it will occur depends largely on how fast world petroleum demand will continue to grow, which in turn depends primarily on transportation.

As this "tipping point" nears, Johnson, Greene, and Birky argue all nations face an inevitable transition to something other than petroleum. They state in their chapter the transition "will have great significance for the global economy and will be a pivotal event for the world's transportation systems . . . It could lock the world into a high greenhouse gas future or break the link between climate change and energy use, depending on choices we make in the very near future." They demonstrate that while the world does indeed have a large amount of oil left, the world also uses a large and increasing amount of oil.

Recognizing the enormity of the choice of transition pathway, Johnson, Greene, and Birky's more modest goal is to describe a variety of policy/technology approaches to a transition away from petroleum. Some of these scenarios explicitly include non-petroleum energy sources; others describe more adaptive rather than transitional strategies—for example, how to use petroleum more efficiently, and one includes significant reductions in motor vehicle travel. In these adaptive scenarios, their work may be described as an effort to ease a transition. Using petroleum more efficiently can both reduce fuel costs as a proportion of total cost and extend the time to effect a transition. The scenarios are built on different combinations of alternative fuels and improvements in efficiency. The base case reflects continued growth in population and the economy, modest steady increases in fuel prices, and continued growth in vehicle miles traveled (though at a declining rate of growth). They characterize the base scenario "as one in which vehicle fuel economy remains stagnant; new technology provides performance, not efficiency, improvements." The six other scenarios assess energy and carbon dioxide emissions under the assumption that the fuels and vehicle technologies in each scenario achieve widespread market penetration by the year 2050.

Johnson, Greene, and Birky conclude that improved fuel economy pays long-term dividends under a wide variety of assumptions about the future. Improved fuel economy of the light duty vehicle (LDV) fleet reduces the importance of the uncertainty about possible future discoveries of significant new petroleum reserves. Aggressive fuel-economy improvements (such that by the year 2050 the on-road fleet of light duty vehicles is 2.5 to three times more efficient than today's fleet) coupled with various alternative fuels could reduce oil use in the U.S. transportation sector to below current levels. Whether that reduced petroleum consumption pays off in reduced greenhouse gas emissions may depend on the mix of alternative fuels and the viability of carbon sequestration.

Lessons Learned and Transition Strategies

Broad changes in the transportation sector imply major market shifts, as much as technology and policy shifts. Presentations in this session addressed the following: how consumer demand might be learned and shaped; the role for education and training; the role of technical innovation, engineering lead-times, and infrastructure development; the need for capital; and lessons learned from other transitions. Lessons learned relate to the speed of transition, depth of public involvement, role for public policies, and impact of external factors. In summary, this session addresses market transitions—how they have occurred (or not) and how they might occur.

Tom White and Barry McNutt excerpt lessons from ongoing transitions in their contribution, "Transportation Transitions: What Can We Learn From the Ongoing Fuels Transition?" The questions they address include the role of ongoing transitions in shaping the context for any other possible transitions, the potential for niche markets to effectively begin transitions, and what policies can effectively shape transitions.

This session included papers on two possible transportation market niches for hydrogen and fuel cells. Alex Farrell, David Keith, and James Corbett discuss the possible use of hydrogen in maritime shipping in their chapter, "A Strategy for Introducing Hydrogen into Transportation." Once freight arrives in ports around the world, much of it is moved to its ultimate marketing destination by heavy-duty trucks. Christie-Joy Brodrick, Nicholas Lutsey, Daniel Sperling, Harry Dwyer, and S. William Gouse, III, examine the case of introducing fuel cells into the trucking industry in "The Market for Fuel Cell Auxiliary Power Units for Heavy-Duty Diesel Vehicles: First Widespread Application of Fuel Cells in Transportation?" Taken together, these two chapters make an interesting case for factory-to-retail delivery of goods by heavy-duty vehicles employing hydrogen and fuel cells. The final paper included here was presented at a session of the 81st Annual Transportation Research Board meeting in January 2002 in Washington, D.C. Boelie Elzen, Remco Hoogma, and René Kem provide a framework for **"**Managing the Transition to Sustainable Transport through Strategic Niche Management."

In their chapter, White and McNutt argue that based on its sheer size and importance, the ongoing trends in the conventional vehicle-fuels system will shape the possible transitions away from it. They point out that elements of the existing transportation energy system are, and have been for many years, in transition. Many of the elements of this transition have been in vehicles, for example, engines and exhaust after-treatment; some have been in fuels, for example, reformulation of gasoline. White and McNutt summarize the history of regulatory actions driving this transition, starting with minimal vehicle emission controls in California in 1966 and extending to possible off-road emission standards for criteria pollutants in the year 2010. Over the same time period, gasoline has been reformulated many times—first to eliminate lead and later to limit specific criteria pollutants, often on a location-by-location and season-by-season basis.

The ongoing transitions have not been limited to vehicles and fuels—the business of producing and marketing them has changed too. Refining is accomplished in fewer, larger refineries. White and McNutt state this is driven by economies of scale in refining capital investment. Gasoline retailing changed from service stations, to convenience stores, to large, general product retailers such as Costco and Wal-Mart. The latter often offer gasoline, as well as many other products, at discounted prices. The businesses of petroleum mining and refining are being concentrated in the hands of fewer, larger corporations.

White and McNutt conclude these transitions are driven by four causes: environmental regulation, technology advances, competition and globalization, and energy-rich countries' exploitation of their energy resources. Equally instructive, they conclude that none of the oft-cited drivers of the next big transition in transportation are driving the on-going transition. Based on their analysis, they conclude that continued pressure on conventional vehicle-fuel systems will simply lead to their further entrenchment. Gasoline and diesel vehicles will continue to become cleaner and more efficient; and market power will be concentrated in fewer, larger actors. Because of these, White and McNutt are not sanguine about the prospects for niche markets to leverage changes in the homogeneous and integrated market for conventional vehicles and fuels. They note that of the four policy drivers that have affected the ongoing transition in transportation, environmental regulation is the only one directly influenced by domestic policy. The next three chapters are based on a different premise—that market niches will play a role in initiating a transition away from petroleum and internal combustion engines. The first two investigate niche markets for hydrogen and fuel cells, and the third presents a framework for pursuing and thinking about the development of niche markets.

In their contribution, "A Strategy for Introducing Hydrogen into Transportation," Farrell, Keith, and Corbett argue that the choice of a transportation mode in which to introduce a significant new energy system—hydrogen in their case—is key to determining ultimate success. They argue that the shipping industry may be a better choice for introducing hydrogen into large-scale use in transportation than the automotive market. They cite reduced costs, increased ease of technological innovation, and greater environmental benefits as favoring the introduction of hydrogen fuel in ships. They argue costs are reduced because shipping "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." Further, as ships tend to be built to order there is proportionally much greater expenditure on specialized engineering and construction in each vehicle. This contrasts with LDV manufacturing in which profitability depends on the production of large number of (nearly) identical units. Finally, as shipping is comparatively unregulated (as regards emissions of criteria pollutants and greenhouse gases), there would be immediate large environmental benefits from introducing hydrogen fuel.

Their proposed overall strategy is to provide a large market for hydrogen, but within a limited geographic area.[3] As such, demand for hydrogen in the shipping industry would provide an initial market for large-scale hydrogen production facilities. In effect, Farrell, Keith, and Corbett propose to overcome the chicken-and-egg problem that confronts the LDV sector, that is, which comes first, new vehicles or new fuels? In the LDV sector, it would take the summation of many individual vehicle purchase decisions to generate a sufficiently large number of vehicles to consume a large enough quantity of fuel to justify investments in large-scale hydrogen production facilities. In the shipping industry, a relatively small number of ships (and therefore a relatively small number of ship purchase decisions by ship owners) could generate sufficient demand for large-scale hydrogen production. Those facilities would also provide hydrogen for a local population of LDVs and provide experience in the construction and operation of hydrogen production plants (so that learning can occur to drive down costs of additional facilities located elsewhere).

Farrell, Keith, and Corbett go on to discuss three general dilemmas that often arise in the process of introducing new technologies. The first dilemma is establishing a niche market. The second is, that despite the fact government may play a role in helping to establish niche markets, private industry is generally called on to develop and deploy new technologies, not the government. The third dilemma is a potential for conflict between processes of policy development and technological change. They address the argument made by White and McNutt that the same pressures that may call forth a transition away from petroleum are also likely to promote further improvement (and thus entrenchment because of additional capital investment) in existing petroleum-based systems. Farrell, Keith, and Corbett frame this argument in terms of “path dependence” and “excessive inertia.”

With this background, they proceed to develop their case that the shipping industry provides a better opportunity to start the process of a shift to hydrogen in the transportation sector because it likely will be easier and less costly to overcome the dilemmas of technology development, path dependence, and excessive inertia. Agreements between a relatively small number of actors—governments and industries—could result in opportunities to develop complete “clusters” of hydrogen vehicle and fuel technologies. They also review a number of the difficulties such an application of hydrogen would face. Overall, though, they present compelling arguments to think outside the LDV box.

Brodrick, Lutsey, Sperling, Dwyer, and Gouse argue that a promising early market niche for fuel cells in transportation is as auxiliary power units (APUs) for heavy-duty trucks. For those readers unfamiliar with the trucking industry, they offer an eye-opening account of energy use in trucking. They cite evidence that in heavy-duty, long haul trucking as much as 40 percent of engine run time is spent idling to provide auxiliary (nonmotive) power. Many of these energy demands are “hotel” loads, for example, heating or cooling a sleeping/living compartment, refrigerators, stoves, entertainment systems, and so forth. Other large power demands include power take-off units and refrigeration units on trailers used to ship perishable goods. They note that extended engine idling has a number of deleterious impacts. Idling creates emissions of criteria pollutants and greenhouse gases. It consumes fuel. The latter is a matter of both global geopolitics of petroleum and private cost to the trucking company, including accelerated engine wear and reduced productivity.

Brodrick et al. review several options to meet these power needs, including fuel cell APUs. Further, they discuss the variety of state and local regulations that are increasingly being imposed to limit truck idling. These vary from outright bans on idling to incentives to buy APUs or establish other clean, quiet sources of energy to power auxiliary loads while trucks are parked.

Their examination concludes there is a sizable, but fragmented, market for APUs in the heavy-duty truck industry. The market is segmented by service type, for example, long haul or local, refrigerated or not, etc. It is segmented by the amount of power required; this is further complicated by differences between peak and sustained power needs. Finally, it is segmented by the organization of trucking companies themselves. Ultimately, Brodrick et al. conclude that large data gaps—notably for idle time, fuel consumption, infrastructure requirements, and APU costs—mean that it is currently not possible to conclude if the heavy-duty truck APU market is attractive to fuel cells. However, they make a clear case that alternatives to engine idling are actively being sought by the industry (satisfying at least in part White and McNutt's claim that transition options must be capable of being "mainstreamed" by existing entrenched systems) and that fuel cell APUs are worthy of further research and development.

The next chapter, "Managing the Transition to Sustainable Transport through Strategic Niche Management," offers a framework for conducting and synthesizing experiments in changing socio-technological systems. Elzen, Remco, Hoogman, and Kemp present "strategic niche management" (SNM) as an approach to experimentation aimed at testing both interrelated technological and behavioral change. They contend that the experimental approach allows for two important processes—learning and "institutional embedding." Their approach is based on two assumptions. First, technological change is a social process, and therefore is not solely determined by either narrow performance measures of the competing technologies or market forces. They characterize this as the "co-evolutionary" aspect of introducing new technology. Second, following from the idea of co-evolution, experiments are conducted in specified niches in which learning and embedding may occur. They discuss three case studies and evaluate them within the SNM framework: the electric vehicle (EV) program in La Rochelle (France); the Praxitéle station car program in Paris; and, a demand-responsive transit project in Camden (UK). These three cases studies in turn serve as a basis for evaluation of SNM.

Elzen et al. address whether or not new technologies are incremental improvements to existing socio-technological "regimes"—they refer to this as "regime optimization"—or whether the innovation requires or compels fundamental change to existing regimes—they refer to this as "regime renewal." They posit that more radical innovations are more likely to come from actors at the fringe of existing socio-technical regimes. The example they give is of PIVCO, a Norwegian firm that recently manufactured small, two-seat EVs. At first glance this seems a good example of a marginal actor attempting a radical innovation, and that innovation then being more closely integrated into the regime. Ford Motor Company purchased PIVCO, renaming it Th!nk Mobility. Ostensibly, Th!nk Mobility would build small battery EVs for the U.S. (or at least California and Arizona) market. That Ford later sold Th!nk Mobility, apparently abandoning small EVs, does not invalidate the choice of PIVCO as an example of an experiment in regime renewal. The apparent stalling of the innovation in the U.S., or more generally, the failure of any new technology to either improve or displace an existing socio-technical regime is not a failure in the SNM framework. The only failure would be the failure to learn from the experiment. SNM explicitly recognizes, as do other adaptive management frameworks, the value in trying and failing—though trying and succeeding is valued, too.

The definition of regime renewal depends on niches. Elzen et al. characterize niches as pathways to new regimes; the pathway may be built of a succession of niches. And as Farrell, Keith, and Corbett argued in the case of the potential use of hydrogen in shipping, scale matters. Niches and the experiments conducted within them must be of sufficient scale to permit real learning and to begin the process of embedding new ideas, new techniques, and new tools into the existing regime. The connection to regime renewal is made through this embedding process. However, Elzen et al. repeat, the failure of any given experiment does not invalidate the SNM approach. So while none of the case studies they cite resulted in a regime renewal in LDVs or transit, they are all part of an ongoing learning and embedding process.

These chapters on the nature of niches brings us back to the question posed in the introductory paragraphs—does the world face a transition in which it must abandon existing petroleum-based energy systems, or is it a case in which those systems could best serve as springboards to something new? White and McNutt make a case that path dependence—building on what we have now—will shape where we can go. In the language provided by Elzen et al., White and McNutt are arguing that any transition is likely to entail optimizing the current petroleum regime. Elzen et al. remind us though that technological transformation is a long-term process, and even slight deflection of the transition pathway early in the process can result in large differences, such as regime renewal, in the future. Farrell and his co-authors provide an example of an experiment that could result in regime renewal by considering hydrogen energy systems in a niche in the shipping industry. Their concept addresses scale, the clustering of several "co-evolutionary" technologies and practices. With only a small number of actors involved, it is sensitive to the social system in which the experiment would be embedded. It is also a niche that can serve as a stepping-stone back to LDVs through the establishment of hydrogen production facilities. Brodrick and her co-authors propose a niche in which actors—who are in the mainstream of the existing regime—already recognize a problem and are actively searching for a solution. Whether or not fuel cells are the solution to that problem is not the concern of an SNM approach; what matters is a willingness to experiment with a variety of possible solutions.

Public Policies and Other Cooperative Mechanisms

Past and present public policies in the U.S. and around the world shape transportation systems. Some are motivating the transition to a new transportation future and some are hindering it. Increasingly, these policies are expanding beyond direct government actions to embrace cooperative mechanisms between the public and private sectors. Some of these involve purely voluntary agreements. The two chapters in this section address the role of regulations and incentives, the potential for cooperative efforts, and the effectiveness of partnerships.

Per Kågeson provides a review of European polices and their likely effects in his chapter, "Assessment of European Initiatives to Reduce Fuel Consumption and CO_2." His review considers both national and European Union (EU) policy and policy statements. As such it provides a valuable reference to those less familiar with how the evolving and growing EU will affect energy consumption and greenhouse gas emissions.

The pattern of tax policies he reveals shows differential treatment between road and non-road modes. Most EU member states apply fuel taxes only to fuels used on-road while excluding rail, shipping, and air transport. Further, the UK is nearly alone in taxing on-road diesel fuel at a rate on par with on-road gasoline. Ten of the current 15 member states levy some sort of excise tax on car sales, though there is wide disparity in the specifics of each nation's system. Most of these taxes are based on some measure of fuel consumption. In addition, he provides the example in Germany where such taxes have been used to differentiate vehicles by exhaust emissions. All member nations levy taxes on vehicle use, though Kågeson contends that all these taxes are too low to have any significant impact on travel. With this, and additional background on current levels of fuel consumption and carbon dioxide emissions, he moves on to describe and assess the EU strategy toward climate change, primarily as it relates to transportation.

He characterizes the existing policy setting as "patchwork." Fuel excises (differentially applied by mode and fuel) and carbon taxes (varying in different member states from 0 to 330 euros per tonne of CO_2)[4] are in some cases supplemented by financial incentives for biofuels and by policies encouraging mode shift from roads to rails. Agreement by motor vehicle manufacturers to voluntary standards of specific fuel efficiency is part of the European Commission's strategy toward LDVs. Two other parts of this strategy are vehicle efficiency labeling, and increased use of financial instruments. The EU has currently negotiated agreements with European, Japanese, and Korean automobile manufacturer associations. In general, these agreements call for the associations to be selling vehicles in the EU with average CO_2 emission rates of 140 grams per kilometer by the year 2008 (European manufacturers) or 2009 (Japanese and Korean).

Kågeson explains that the automobile manufacturers are relying heavily on a shift to diesel fuels for LDVs (a trend uninhibited by the favorable tax treatment of diesel relative to gasoline) and to direct-injection gasoline engines. Notably, vehicle downsizing is not an obvious part of any manufacturer's strategy. (This in a market also showing upward trends in vehicle size and shifts toward minivans and SUVs.) Both these strategies bring CO_2 abatement policy into greater conflict with air quality policy through the increased emissions of NO_x and particulates from diesel engines, and particulates from direct injection gasoline engines. Further, he is not optimistic about the prospects for the Japanese and Korean manufacturers attaining their target. In general, he concludes that the shift toward diesel, direct injection gasoline, and low to zero carbon fuels, as well as the introduction of new drivetrain technologies such as hybrid electric and fuel cells, are likely to achieve only about half the necessary improvements within the specified time frame.

By his assessment the varied slate of European policies leaves a substantial shortfall between current and likely policy and CO_2 emission reduction targets. He is skeptical European politicians are likely to seriously attempt to reduce demand for transport given the limited options before them. He cites other evidence that over the long run increases in the unit cost of transport through taxation could be overcome by cost reductions brought about by efficiency improvements. He observes that systemic efficiencies in freight movements, taxi services, and other fleet applications might be brought about by improved logistics through the use of a Global Positioning System and other information systems.

Neither is he optimistic about modal split, improved efficiency, or a shift to renewable energy, arguing that operating costs compete with other goals, such as "time, quality, flexibility, and reliability." Further, though the EU has begun a process to internalize the social cost of transport, Kågeson argues that even if successfully implemented, such a program will do little to shift transport modes, as the existing tax structures are already more heavily weighted toward road transport. His discussion of motor vehicle efficiency was summarized above. His review of biofuels indicates that Europe's potential to produce such fuels in a cost effective manner is limited.

His recommendations go to the core of existing differences in how fuels and modes are treated. He argues for a system of tradable credits, stating that such "is the only policy instrument that can guarantee the achievement of a certain target as it is based on a cap." He insists such a system should be based on treating any unit of CO_2 emissions from any mode utilizing any fuel to the same marginal cost or incentive.

The next chapter addresses only LDVs and only fiscal policy instruments (taxes on automobile purchase, ownership, and use), yet develops an integrated modeling framework to simultaneously evaluate the various effects of each type of tax instrument. Yoshitsugu Hayashi, Hirokazu Kato, and Rene Val R. Teodoro present their model in the chapter, "An Analysis of the

Effects of Car and Fuel Taxes on CO_2 Emissions in Japan and Germany." Their case studies in Japan and Germany provide validation of the model system—addressing whether it is capable of reproducing historical data, and whether similar taxes have similar effects in different countries. The model evaluates the effects of alternative tax schemes on vehicle fleet composition, total CO_2 emissions, and tax revenues.

The model structure is made up of several different submodels. These submodels allow for the application of varying tax rates during different stages of vehicle purchase, ownership, and use; the tracking of the fleet composition by vehicle type and age; assessment of aggregate changes in driving behavior and vehicle disposal decisions. The model is capable of accounting for life-cycle CO_2 emissions since it tracks vehicle purchase, use, and disposal. The three main processes the model tracks are:

1. The effect of car purchase and ownership taxes on the sale and disposal of motor vehicles;
2. The effect of fuel taxes on vehicle use; and
3. The effect of these two on total CO_2 emissions.

The model estimated for Japan was used to evaluate the 1988 Tax Reform that nearly eliminated previous differences in the tax treatment of large and small vehicles. Previously, large vehicles had been taxed at rates nearly double those of small vehicles. Their results indicate that if the tax policy had not been changed, then (barring any other changes that might have caused a shift to larger vehicles), the ratio of large to small vehicles in the Japanese LDV fleet would not have increased. Further, by the year 2010 CO_2 emissions would be eight percent less than they are now modeled to be, and tax revenues would be 10 percent higher.

The German policy experience that Hayashi et al. analyze combined lower fuel prices and lower government taxes on vehicle ownership starting in the year 1985. The model estimates that by 1996 these changes had increased CO_2 emissions by four percent and cut tax revenues by nearly ten percent.

As a further step, the model is applied to the problem of searching for the most effective taxation policies to reduce CO_2 emissions. This analysis is limited to Japan. The same absolute increase in tax rates levied against purchase, ownership, or usage produced very different results. The authors conclude that the application of a usage tax was most influential in reducing CO_2 emissions, largely through changes in travel. The authors recognize the current model structure has several shortcomings. It is, however, an important step toward a tool for integrated analyses of tax policy, travel and vehicle purchase behavior, and environmental impacts.

An important, indeed surprising, finding is that a usage tax was most influential in reducing CO_2 emissions, given the very low fuel-price elasticities of travel demand estimated by many other studies. Further study on an expanded variety of tax instruments, including constant percentage increases in tax rates, will be useful, since it is widely believed that the base value affects people's perception of the increase, and therefore whether that increase is likely to affect changes in vehicle holdings and use.

Research Agendas

The concluding chapter presents a policy-relevant research agenda. It is a synthesis by the editors of many efforts by others in government, industry, academia, and nongovernmental organizations. In most cases these other efforts were led or written by individuals who also were attendees at Asilomar. Some of this effort was accomplished during the conference, and draws upon papers presented at Asilomar in September 2001 and Washington, D.C., in January 2002. More importantly, the research agenda draws from two major exercises overseen by the US Transportation Research Board: the Environmental Research Needs (ERN) Conference (TRB, 2002a) and Surface Transportation Environmental Research Program (STERP) (TRB, 2002b). Other source materials for the concluding chapter include the NAS review of the Corporate Average Fuel Economy standard (NAS, 2002), the report from a U.S. Department of Energy sponsored meeting on transitions to hydrogen (USDOE, 2002), and a meeting of the European Conference of Ministers of Transport (2002) on urban travel.

The research topics in the final chapter are organized into areas drawn from the ERN and STERP reports, though changes have been made to make the topical areas from the separate documents conform. Problem statements are also drawn from these two documents, but have been amended based on the papers presented in this volume and the other source documents. Similarly, research recommendations drawn from the ERN and STERP have been amended and, in places, reinterpreted by the editors based on the work presented in this volume.

NOTES

1. We are not saying the rest of the world does not appreciate this awful lesson, only that Americans are forced to contemplate it because of events of that particular day.
2. An important question in transportation energy transitions is how to either exploit the energy systems of other sectors of the economy or leverage change in transportation through concomitant change in other sectors.
3. Perhaps a better way to characterize the geographic distribution is “punctuated.” The scope of the hydrogen supply network for shipping could be international, but might consist of only a few locations.
4. The value of the euro is roughly comparable to the U.S. dollar.

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Economics, Stewardship, and the Transportation Sector

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> Global warming, if it is real and has the dire consequences predicted for it, will require a fundamental shift in driving behavior since it cannot be dealt with by marginal changes....Those who argue that we should be stewards of the earth, giving to our children a liveable world, are in effect arguing that the discount rate for future effects of current policies is too high.
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> —Kenneth D. Boyer, *Principles of Transportation Economics*

In this paper I argue for a fundamental reframing in how we think about the role of economic analysis in transportation planning. I use as a representative text Kenneth Boyer's *Principles of Transportation Economics.*[1] As this text shows, the economics of transportation is rooted, in large part, within the framework of neo-classical economics, and accepts the main tenet of macro-economics: the pursuit of economic growth. My comments will be directed in part to this text in two ways. First, it is an excellent example of the application of standard economics to the transportation sector, and I will make reference to some of the problematical dimensions of this framework. Second, the text represents a number of places where this framework is in the process of breakdown—though its author's final judgment seems to be to retain the framework. Both where it recognizes the shortcomings of the framework and where it does not, it points the way to the need for a regrounding and redirection of these efforts.

I will argue here for a reconceptualization of both micro- and macroeconomics within a framework I call *stewardship economics*. Many of the central concepts and policy tools of both branches of current economics remain but within a broader moral/conceptual framework. Many of my arguments are generic, applying to economics generally. But due to the scale of the social and ecological impacts of transportation, sketching a direction for the reform of one of its principal planning tools is imperative.

Stewardship economics builds on and extends the insight of John Maynard Keynes from the inter-war period that a major goal of economics should be the prevention of war. Keynes's insight has become enshrined in current economic policy, which seeks to preserve social stability through high levels of employment with stable prices. Stewardship economics carries this goal one step further—to the relative stability of the earth's life support systems. Currently, micro-economics is protestant in character: centering the world around the individual human self. Stewardship economics, as set out here starts from two different places: 1) its foundational premise is the finitude of the earth's life support systems; and 2) that there is no defensible grounds for limiting the moral realm to persons alone. I will call these respectively the scale premise and the moral premise of stewardship economics.

Take the issue of scale. The vast increase in the human population and the far greater surge in economic activity since World War II are increasingly overwhelming the biosphere. The individualistic starting point for conventional economics may have made sense when the world was relatively sparsely populated and economic activity much lower, but in the present circumstances this can no longer be accepted without question. Second, the moral premise of microeconomics also cries out for re-examination and reconstruction. As Darwin pointed out well over one hundred years ago there is no difference in kind between mankind and the rest of nature, only differences in degree. Without a difference in kind there is no way to bound the moral universe at persons. If we are to be concerned with the well being of persons then we must also be concerned with the well being of other species insofar as they are like persons. It is not that other species possess *human* qualities such as intelligence or the ability to run fast, but that these qualities are *shared* by many species. Yet, microeconomics carries over the Judeo-Christian premise of the uniqueness of humanity in its insistence that all other life forms are of instrumental value only. We need a new conception which recognizes moral duties to living things generally. Here I follow Albert Schweitzer that the common denominator of moral concern is the will to live.[2] I call this broader conception of the moral universe the commonwealth of life.[3] By the commonwealth of life I mean the interconnected ecosystems and the organisms within them that make up the biosphere. The "common" emphasizes the mutual dependence of organisms and systems, and the "wealth" the surplus generated by sunlight that they share. It includes but is not limited to three basic human rights: bodily integrity, moral, political and religious choice, and subsistence.

Constructing an economics of stewardship involves answering five questions.

1. What is the economy for?
2. Where does and how should the economy fit in the physical and biological world of which it is a part?
3. How much economic growth is enough?
4. How should we think about the byproducts of the processes of economic production?
5. How should we think about future?

The answers to these questions have specific implications for how we think about transportation. Here I show how key terms in current mainstream economics—efficiency, internalization, substitution, marginality, and cost—would be redefined within an economics of stewardship. We begin by looking at current economics and definitions of its key terms. I then set out five elements of stewardship economics, along with contrasts to the current regime. In conclusion objections to stewardship economics are considered, and an example of its implications for the transportation sector set forth.

I. CURRENT ECONOMICS

World economic integration has more and more gained center stage. It has become, and is becoming more so, the underlying theoretical perspective into which the rest of human endeavor must fit. This process is not "natural," rather it results from purposely established human institutions; for example, the World Trade Organization, the central banks, and so forth. The fundamental point of departure of this vision is the observation of the behavior of individuals who engage in exchange. This defines the domain of microeconomics. Each person who engages in a voluntary transaction with full information can reasonably be said to have benefited from the exchange simply because he or she did it. Or, in a slightly weaker version, he or she believed that the exchange would make himself or herself better off. The root idea is that of *consumer sovereignty:* the consumer knows his or her interests better than others and can act to advance them through exchange. Each consumer will pursue his or her opportunities until the *marginal* cost of a transaction exceeds the benefits of it. Thus each person maximizes his or her utility or happiness subject to the constraints of income by voluntary exchange.

This results in what is technically known as Pareto-superiority, after the Italian economist Vilfredo Pareto. In such a transaction some one has been made better off without someone else being made worse off. In a Pareto superior transaction there is, by definition, net social benefit. But we can go beyond making things better. We can make them best. This is the frontier where there is no more space for improvement, where further transactions will result in someone being worse off. For example, if there are a fixed number of some desired goods any transaction making one person better off will mean making someone else worse off. This condition where improvement in overall utility is impossible is called Pareto optimality. It defines an *efficient* allocation of goods. The goal of policy from the point of view of microeconomics is to reach Pareto optimality for then utility will be maximized for any given distribution of income and wealth.

There are complications, of course.[4] The three most important are externalities, public goods, and discounting. The first, conveniently named, are factors in production or exchange where the price of a good does not reflect its true costs. More tires may be produced than is desirable if their prices do not reflect the air pollution associated with their manufacture or the particulate matter that they leave on the road. A key role for the public sector is to correct these prices by adding a Pigovian tax (named after their proposer, Pigou). These taxes recover the lost social cost of the externality. This is known as cost internalization and is a central feature of micro-economic approaches to the environment.

Second, there are certain goods, what economists call “public goods,” that do not respond to market signals. These goods could be nonexcludable or nonrival. If we provide the good to someone we cannot avoid providing it to others, hence nonexcludability. For example, if the Air Force protects me from nuclear attack it cannot help protecting my neighbor, as well. Nonrival goods are those where exclusion may be technically possible, but where one person’s consumption of the good does not detract from another person enjoyment; for example, adding a few visitors to a large national park. If a highway is built with federal funds anyone may use it, though it is possible to restrict access to it in principle. In this way of looking at the world the task of the public sector is to remove, or at least to mitigate, the defects which are impediments on the road to maximum utility, such as externalities and public goods.

A third important issue concerns discounting. In this framework, the value of future events, the utility that we should attach to them, is assessed by calculating their value to us in the present. We need to have some way to compare an investment which will yield $1000 in ten years to another somewhat more risky one that could yield $1500 in twelve years. The way to make such a comparison is to calculate the *present value* of each. There are a number of reasons for discounting. The present value of future resources is less than that of present resources, because if we had the resources now we could use them–so there is an opportunity cost for not having it now. If one investment is more risky than another we will have to assign it a different discount rate. Or if we think future generations may be richer than we are, and hence have more utility, we may want to discount their well being so as to avoid the poorer present generation from subsidizing the richer people in the future.

Macroeconomics takes its point of departure not from the behavior of individuals, but from the study of the economy as a whole. Much of current macroeconomics has its origins in the work of the English economist John Maynard Keynes. As he worked on the *General Theory of Employment, Interest, and Money*[5] in the mid-1930s, Keynes was worried that large scale unemployment would lead to continued instability, especially on the European mainland, and to another world war. Furthermore, Keynes realized that the utilitarian project of Bentham, Mill, and Sedgwick had (for reasons we will discuss below) run its course.[6] The general theory is thus a theory of macroeconomics free of the utilitarian foundations of modern microeconomics. Keynes project for the thirties was a war prevention strategy, but it came too late to head off World War II. The objective of the management of the economy for Keynes was not the satisfaction of desire as it is in microeconomics, but social stability. One of Keynes' principle arguments was that thrift in times of economic downturn is undesirable because it shifts resources away from consumption and thus causes unemployment.

During the first world war Britain had come perilously close to having to seek an accommodation with Germany for economic reasons. And probably would have done so if it had not been for American entry into the war. Working in the British treasury at the time, Keynes believed that the British economy simply was not producing enough in goods and services to make it possible to finance the war effort. As World War II loomed, a measure was developed that would rectify this difficulty. This led to the development of a measure of total economic activity which was adopted by the United States early in the war. After the war it became a standard measure of economic performance. Hence the origin of the gross national product (GNP). This is a measure of all income received by residents of a nation for current services which are not transfers such as payments to the elderly, plus appreciation in the value of stocks including, but not limited to stocks in corporations, and then further adjusted for income received from abroad.[7] Gross domestic product (GDP) is the same as GNP except that the income from abroad is omitted.

The Great Depression was ended in Germany by Hitler's war-oriented stimulus package (it is possible that Keynes drew on observations of this process in Germany to derive his economic prescriptions), and by the debt financed responses to it by his military opponents in World War II. The surge in buying immediately following the end of the war was stimulated by savings accumulated during the war itself, and the downward edging of the U.S. economy during the 1950s was delayed by the expenditures required by the Korean War.

The revolutionary aspect of Keynes' approach was the intentional counter-cyclical stimulation of consumption to reduce unemployment. It provided the tools for the post war boom in Europe and the United States once its basic tenets were accepted around 1962.[8] This has lead us into the conundrum of having to stimulate consumption simply to keep the Keynesian squirrel cage from stalling, and the world from sliding toward instability and perhaps another catastrophic war. In the main Keynes' strategy has been successful. There has been no major conflict between the nations following his prescriptions.

As concern about large scale war has diminished, attention has turned more and more to the proper management of the overall economy, and the desirability of removing any factors that could reduce overall efficiency as defined by microeconomics. Many argue that macroeconomics has been reduced to microeconomics, and that it no longer exists as a separate body of thought. This is surely an overstatement. Though many economists have been critical of Keynes in a variety of ways, including the tools for how to achieve growth, Keynes remains a strong influence in the background. The success of his theory legitimated the view that a primary job of the government is to manage the economy to stimulate growth and to keep employment levels high.

Mainstream economics and stewardship economics may be seen as two edifices made of building stones.[9] In the next few pages I will show that current economics needs to be taken apart, but carefully. Many of the stones are essential elements in the needed reconstruction of economics within, not just atop, life's commonwealth. In stewardship economics many terms from the mainstream are repositioned and reshaped. These include: "objective function," "efficiency," "substitution," "marginality," "internalization," "protection," and the nature of "goods" themselves. I do not, therefore, reject the tools of economics, but only the current frameworks in which those tools are placed, and uses that are made of them in the current policy process. Indeed, many of my prescriptions for implementing a fiduciary agenda rely on reconceived and redirected macroeconomic institutions and microeconomic incentives. I wish to replace the growth interpretation of macroeconomics and the utility or welfarist interpretation of microeconomics.

II. STEWARDSHIP ECONOMICS

The elements of stewardship economics are set out in response to five questions:

1. What is an economy for?
2. Where does, and how should, an economy fit in the world's biophysical systems?
3. How much economic growth is enough?
4. How should we think about the byproducts of economic production? and
5. How should we think about time?

I conclude by considering objections to the fiduciary conception.

In *Principles of Transportation Economics*, Boyer accepts the standard view on the first, third, and fourth of these issues. He implicitly accepts the desirability of growth, but offers a few questions about the desirability of its composition concerning pollution and modes of travel. He does not seem to possess the tools for asking if there has been too much growth overall. His discussion of traffic congestion, for instance, does not question the desirability of more persons and more travel, but only the means by which it is accomplished.[10] His fundamental point of departure concerning the negative side effects of transportation rests on the theory of externalities.[11] He raises serious questions on the issue of the fit between the economy and the biosphere, and on the issue of discounting. (For example, the quotes at the beginning of this paper.) He does not draw out the full implications of these questions, but they are signs of an unease with the framework.

A. What Is an Economy For?

What is the goal of the economy; what would an economist would call its objective function? *The goal of stewardship economics is the restoration, protection, and enhancement of the* *commonwealth of life.* Mainstream economics has two goals that, at best, pull in opposite directions. Macroeconomics aims to bring about increases in economic activity as measured by GDP while maintaining high levels of employment with stable prices. Microeconomics aims at "efficiency," or to produce as much human well-being as possible through fair exchange.

1. The Purpose of Stewardship Economics

Stewardship economics respectfully alters Keynes' argument from the inter-war period that the purpose of economics, the *objective function* we have for the economic system itself, is the protection of human life and culture. As we have seen, Keynes prudently pointed out the disruptive effects of large scale unemployment in Europe and its tendency to spark warfare. Our aim should be similar, but broader, grounded in a concern for the commonwealth of life: the preservation and enhancement of the earth's life. Rather than construct a world view around the satisfaction of human desires we should begin with the whole system of which human life is a part, locate our species therein, and derive objectives from within the fiduciary conception. From this point of view the stimulation of overall demand—what Keynes called *aggregate demand*, the principle Keynesian tool for the creation of employment and hence social stability—must be evaluated from the perspective of its impact on life's commonwealth.

The implications of stewardship economics for the idea of efficiency are revolutionary. The overall standard of efficiency in stewardship economics, what I call "ultimate order efficiency," is derived from this idea: that we treat all life with respect, and justify differential treatment. *Ultimate order efficiency* is what the economy itself aims for. In this stewardship framework the ultimate cost of a thing is how much life had to be exchanged for it, including but not limited to human life. Ultimate order efficiency sets the framework in which first order efficiency occurs—individuals and firms pursuing their economic interests, and the satisfaction of their desires, values, and interests. We can have efficiency within the economy, and we can have an idea of efficiency *about* the economy.

There are other kinds of efficiency. Herman Daly distinguishes four in *Beyond Growth.*[12] *Service efficiency* concerns the technical design of a product and the uses to which it is put in satisfying our desires. Some vehicles are more efficient, using less fuel per mile traveled. *Maintenance efficiency* is a measure of durability. Some vehicles last longer than others. *Growth efficiency* is the ability of ecosystems to replenish themselves as we take things we want from them. Some biomass resources are more efficient for conversion to transportation fuel because they replenish themselves faster than others. *Ecosystem service efficiency* is the measure of how much we disrupt the functions of ecosystems when we take things from them or dispose of pollution in them. How much erosion control, or wildlife habitat, is lost when I harvest my biomass for fuel? How much air pollution can the Los Angeles basin absorb without impairing particular health functions of humans and other species. This efficiency is a measure of collateral damage. Each of these efficiencies define what we may call *stewardship policy space.* These are ways we can think about modifying and reducing our impact on life's commonwealth.

2. The Purposes of Stewardship Economics Contrasted with Those of Mainstream Macro- and Microeconomics

Mainstream economics in both its macro and micro forms offers an inadequate account of the objective of an economy.

a. Resisting the GNP/GDP Measures In mainstream economics the idea of progress has been compromised by being identified with economic growth as measured by the GDP or GNP. These measures are sometimes referred to as "the national accounts." From the point of view of the critiques offered here these measures are similarly troublesome. There are six reasons to abandon these measures:

- GDP growth is a measure of activity, *not a measure of wealth*. Since accounts are not adjusted for declines in natural resources such as topsoil, oil, or forests, it is possible for aggregate income to go up and total wealth to decline at the same time;
- GDP growth is *an undifferentiated measure of benefits AND costs*: the money spent on fighting disease and fighting hunger are both counted as benefits—but we want less disease and less hunger. There is no way to tell if we are better off or not simply because we have more of it;
- GDP growth does not measure its own costs—much of what we spend may be to *defend* ourselves against unwanted side effects of GDP growth. If I buy an air conditioner to cool my bedroom made hot by urbanization, GDP counts that as positive while it is really a cost;
- GDP growth is *indifferent to distribution* of income and other goods generated by the economy—GDP can rise while poverty increases;
- GDP growth is a *mismeasure of benefits* since it counts something that is bought and sold as a benefit while ignoring existing paid-for assets and things provided free such as house work, clean air, or the work of volunteers. Indeed, the conversion of things that were free and later must be paid for counts as an increase in GDP while obviously we are not better off as a result; and
- GDP growth takes no account of the *scale* of the economy relative to the biosphere on which it depends—how much of the biosphere is appropriated by the economy from other species, or how much it affects things like ecosystem and climate function.

Looking for alternatives to GDP growth is not a denial of what most of the people in the world want: food, clean water, shelter, leisure, healthy children, and the like. The point is that GDP is an unacceptably blunt instrument for figuring out whether these are being provided. It is ironic indeed that a measure adopted in the Second World War as a means to determine war-fighting capability should become the prime measure of peacetime economic success. Despite its numerous defects it continues to be the main measure of "progress" around the world.

Though GDP itself does not measure inequality, much of macroeconomics is concerned with distribution. This can be seen in the emphasis on the creation of employment in the indicators used to measure economic performance. Job creation is a major tool that we have to reduce poverty, ensure subsistence rights, and improve economic well-being more generally. We must go beyond these tools. The only way unemployment can be addressed in the Keynesian framework is by more and more aggregate growth. Obviously, this prescription is unworkable in a finite system unless we specify with considerable care—which the neo-classicists don't—what *kinds* of growth we are trying to promote. The destruction of ecosystems and the alteration of the world's climate itself are readily sacrificed on the twin altars of GDP and employment growth.

b. Restructuring Microeconomic Efficiency Let’s turn to an examination of the objective function of microeconomics: efficiency, or the idea that the goal of economics should be to produce as much happiness as possible. The following argument is not designed to prove that efficiency should never be a goal, but only that it should not be primary. From a stewardship perspective we begin with: 1) an account of the biophysical limits of the earth, *integrated with* 2) a moral structure of society—including an account of obligations to living things generally at what should be thought of as the constitutional level. This constitution, once in place, will set the context for and constrain the idea of economic efficiency, not eliminate it.

The moral foundation of microeconomics is utilitarianism. This doctrine, as formulated by John Stuart Mill in *Utilitarianism*, “holds that actions are right in proportion as they tend to promote happiness, wrong as they tend to produce the reverse of happiness.”[13] We should seek, according to utilitarians, the greatest happiness for the greatest number. In the philosophical literature written since the Second World War, there have been numerous serious criticisms of this doctrine. Microeconomics proceeds in the main as if this literature did not exist.

The utilitarian project has failed utterly to offer a satisfactory account of fundamental moral obligations for five reasons:

i) Me and You Utilitarians have been unable to show how to get from the (I believe false or untestable) proposition that everyone seeks to maximize his or her own utility, to the idea that we have a moral duty to maximize the utility of others, indeed everyone. As a moral system utilitarianism requires that we maximize the happiness of all affected persons. Yet it depends on the psychological premise that each person seeks to maximize his or her happiness. Absent heroic assumptions about interdependent utility functions (the degree to which one person’s happiness depends on that of another) the premise that each person seeks to maximize his or her utility does not support the conclusion that we should maximize the utility of all.

ii) Rights In offering no place for the language of rights (Bentham referred to rights as "nonsense, nonsense on stilts”[14]) classical utilitarianism authorizes the ruthless exploitation of a minority if a net gain in utility can be projected. Numerous attempts to rescue utilitarianism from this defect by arguing that we can reconstruct the language of rights out of summary rules are unsuccessful. This is because in each case we still have to decide whether *this* action that I am considering will lead to the maximization of utility even if it means overriding the rule.[15] Rule utilitarianism always collapses back into act utilitarianism.

iii) Altruism, Too Much or Too Little Utilitarianism is infeasible from a motivational point of view in the classical version (greatest happiness of the greatest number) because it requires more altruism than we can reasonably expect people to muster. In calculating what to do I must count my own happiness as only one in perhaps a very large group; say, given the world’s present population, one in six billion. Further, it is impossible to maximize two variables: Do we seek more happiness or to spread it over more people? The self-interested motivational assumption of the neoclassical school fails for the opposite reason in that it fails to offer any account whatsoever of what we owe one another.

iv) Happiness and Preference As an examination of its texts reveals, some of modern economics tries to distance itself from the failures of utilitarianism by dropping the language of utility in favor of that of preferences or tastes. It would appear that since they are not talking about utility then they can escape being entangled in the defect of utilitarianism. This strategy backfires. If preferences and tastes are not connected to utility then it is completely mysterious why one should care about them, as would be why one should care about the satisfaction of other people's preference.

v) Of Apes and Men A utilitarian should consider the preferences of at least some nonhuman animals since many of them can also experience pleasure and pain, and they surely also have preferences and tastes. Apes reveal their preferences for food by what they eat. Worms reveal their preferences for sidewalks as contrasted with lawns after rains by crawling on them. Since this is a preference why shouldn't we be concerned with satisfying it?

3. Macro and Micro

It is important to see that the objectives of efficiency and GDP maximization are unlikely to coincide. This is so for a number of reasons. The first has to do with the failure to distinguish between activity and wealth. For example, a practice of clear cutting forests on steep slopes may raise GDP in the present while depleting wealth, and also causing widespread, long-term, and uncompensated ecological and social havoc. Therefore utility is not maximized in the long run. Second, GDP growth can be uneconomic when seen from the perspective of efficiency. It can cost us more to defend ourselves against the side effects of economic growth than the benefits conferred by the growth itself. Rising GDP can *cause* declining utility. Third, we may often get more GDP growth by not internalizing costs, than by internalizing them. If we raise the costs of tires consumers will buy fewer of them. If we let tire producers dirty Mr. Jones' laundry we will get more tires consumed—expanding GDP, and Mr. Jones will have to do his wash more often—also expanding GDP. Thus the objective functions of current macro- and microeconomics taken singly, and taken together, fail.

There are several implications of this failure for the transportation sector. First, take macroeconomics. Growth in transportation activity should not, by itself, be taken to be a good thing. Rather we must ask, what are the implications of changes in that sector for the commonwealth of life? What are the implications of road construction for wetlands; for air pollution on birds and forests; of the reliance on fossil fuels for the stability and resilience of ecosystems? Second, from the perspective of microeconomics the well being of the individual consumer is no longer the deciding factor, but an element in a much broader framework. Consumer satisfaction with sport utility vehicles is not likely to prevail as a determinant of policy when the effects of fuel use on the biosphere are taken into account.

B. Where Does, and How Should, the Economy Fit in the World's Biophysical Systems?

In several places in Boyer's *Principles of Transportation Economics* he expresses concern about global warming, and the inadequacy of present policy tools and frameworks to respond to it successfully. One such passage is quoted at the beginning of this paper.

Stewardship economics explicitly sees the economy as imbedded in the earth's biophysical systems and framed by norms cognizant of the commonwealth of life. Mainstream economics offers no account of its location in the physical world, and offers no fundamental norms other than the expansion of GDP, the stimulation of employment and the control of inflation in the case of macroeconomics, and allocative efficiency, in the case of microeconomics.

1. Stewardship Economics and the Commonwealth of Life

Keynes entitled his work on the restructuring of economics *The GENERAL Theory of Employment, Interest, and Money*. I have emphasized the word "general" because Keynes is saying that the old economics, for example, that of Says—who held that supply creates its own demand—is not wrong, but it is a special case. Like Einstein's theory of special relativity which holds under limited circumstances, Keynes is saying the same thing about economics up to his day: it is a special case. Keynes saw his theory, not quite rightly, as *general.* It broadened the institutional context of the economy to include an active role for government in the stimulation of economic activity in times of recession and depression. But like the special theories it sought to supplant, Keynes theory still ignored the broader biophysical context of human economics. The GENERAL theory was in fact another special theory.

Stewardship economics extends, and may hope to complete, the quest for a general theory by explicitly locating the human economy in the earth's biophysical systems. It requires therefore both an accurate description of the economy in those systems and a normative structure that will allow us to say how these systems should function.

a. Descriptors Stewardship economics recognizes the finitude of the earth and its systems. We need to begin with descriptions of these systems. We begin with water, energy, and materials balances. Obviously, complete descriptions will be much more complex both in the number of factors and their descriptions.

i) Water There is only so much water on the earth. There is no way to change the total amount of water available to life, and the ratios between salt and fresh water cannot be altered to a significant degree given current technologies. Obviously, it is not the total amount of water that is mainly at issue; but where it is, its physical state (ice, liquid, or vapor), and its ability to support life directly as habitat and indirectly through commerce. Many of the issues central to life's commonwealth will have to be resolved on a watershed by watershed basis.

ii) Energy We also have to be concerned with the characteristics, amounts, and consequences of using, our energy supplies. The amount of energy reaching the earth during the life of the sun is fixed. Most of it is radiated back out into space; small amounts compared to the total flow have been stored in coal, oil, and natural gas, and in the biosphere. These represent the stock of resources available to us. How fast we draw down these stocks represents one element of the flow of energy, that is, of stored sunlight. The other element of the flow is how the sunlight reaching the earth each day is used. This is basically a question of the extent and characteristics of photosynthesis, technical means of capturing the energy of sunlight such as photovoltaic cells, and to a lesser degree the use of wind power. Other energy sources such as geothermal, tides, and nuclear are relatively minor in their ability to contribute to overall energy demands. Re-evaluation of expanded reliance on nuclear sources may be justified in conjunction with vigorous conservation efforts—currently not seriously undertaken at all in most of the richer countries.

Again, much of our attention will have to be paid to particulars. What is the impact of various energy strategies on the ability of human communities to protect basic rights and on the ability of other species to flourish? For example, the burning of biomass—such as residues from logging and farming—for the production of electricity may reduce soil fertility and species complexity. Heavy reliance on fossils fuels is substantially altering the earth's climate and imperiling the habitat and even the continued existence of many species through changing the zones in which plants and animals can live, altering water temperatures and depths, changing the patterns of monsoon rainfall, and eradicating coastal wetlands.

iii) Materials Balances I characterize the threat of global warming as a perturbation of a system for balancing carbon dioxide in the biosphere. The earth's temperature balance is determined by the interaction of the energy from the sun and the characteristics of the earth's surface and the gases that compose its atmosphere. At this time more carbon dioxide is introduced into the atmosphere than is taken out. It is widely agreed that this is causing a rise in the average temperature of the earth. There is a degree of human perturbations of other systems by a variety of elements including heavy metals and a variety of nutrients. The effects of these imbalances on life's commonwealth have to be estimated to allow an assessment of their impacts.

b. Norms The norms that should govern the relation of economics to the physical world are first the obligation to provide for the three basic rights, of bodily integrity; moral, political, and religious choice, and subsistence. The second obligation is to respect the flourishing of other species. The first obligation will tell us the amount of farmland we need relative to any given technology, climate, and consumption patterns. The second will constrain the use of some resources in ways already discussed under efficiency. The prolific use of water in the western United States for golf course and fountains in the desert, resulting in the extirpation of some species, is clearly a disallowed use within the framework of the commonwealth of life. Within the perspective of the commonwealth of life the mere survival of other species is insufficient protection; we look for a flourishing of other species, not the preservation of precarious remnant populations.

2. Mainstream Economics and the Biophysical World

Perhaps the most astonishing fact about current economics is that it provides no account of where the economy *is.* In standard economic textbooks the fact that the economy is in the world, in its physical and biological systems, is simply not recognized. There are a number of reasons to regret this. First, it legitimates an outmoded model of the way the world works. Second, it has tragic implications for the rest of nature, which is seen as made up of interchangeable parts. Third, it leads to a misunderstanding of resource abundance and scarcity.

a. Being Nowhere Perhaps the most pervasive scientific error made by mainstream economics is that it carries forward, as an unexamined background assumption, that humans are not significant actors in the earth's biophysical systems.

In most economic texts there is no description of any kind of nature; there are few, if any, entries under environment, natural resources, nature, or other cognate ideas. It is as if the rest of the physical world did not exist or that humans could not affect it. But, we know that this picture is completely misleading. Humans are instruments of change from microenvironment to global systems, from what goes on in our own blood streams to the shape of mountains and the course of rivers.

The world is made up of complex adaptive systems. It is not the Newtonian world where for every action there is an equal and opposite reaction, but a world in which complex adaptive systems respond in ways that are difficult to predict. Once an equilibrium is perturbed we cannot predict with assurance what the new equilibrium will be or whether it will be desirable. Even though economists have often described the complex, multi-faceted aspects of human behavior with great sophistication, these insights are not carried over into their views about nature.

b. Nature as Widget Mainstream economists typically assert that we need to have economic growth so that we can then be rich enough to afford the cost of cleaning up environmental problems. The argument is that as wealth rises people's preferences for environmental goods will rise as well.[16] There are at least two problems with this idea. First, it presupposes that economic growth is making us richer—thus begging the question at issue as to whether or not growth at the margin is *un*economic. Second, the notion that we can mess up nature and then clean it up, implies that nature is like an industrial process where we can make any artifact that we want. This in turn is not true for four reasons. First, natural processes are not reversible as this assertion implies: species loss and carbon dioxide loading of the atmosphere which leads to climate change cannot be repaired by any feasible amount of money within historic time periods. Second, natural processes are capable of non-linear—not just linear—change as the mainstream model supposes. Ecosystems sometimes respond gradually to change and then suddenly flip to a new level of organization.[17] Nor, third, does this view address what happens to the well-being of those injured—human and nonhuman alike—by polluted air and water while wealth is allegedly rising. Fourth, the rising incomes scenario implies that all environmental damage is local, so that people can clean up the mess that they made in their own backyard. But environmental problems like global warming are not confined to the countries that generate them. If one country blocks or pollutes a river that runs into another the problem is not just local, and if one country shifts its automobile production to another the associated pollution is distanced from those who are the primary beneficiaries.

There are *some* types of economic change that improve *some* environmental conditions, such as more efficient cars that pollute less and thus help reduce air pollution in metropolitan areas. But much economic growth contributes to environmental deterioration. Housing developments that are built in the countryside depend on septic systems that pollute the groundwater, require extensive road systems that alter runoff patterns, destroy habitat, are visually disruptive, and last indefinitely, at least in terms of historic time.

Moreover, the neo-classical view fails to take into account the great difficulty in knowing whether the environment is declining or not. Each person who is born sees the world anew and takes as the benchmark the world as he or she finds it. This point of departure serves as at least an intuitive guide as to whether things are improving or not. As a result, detecting long-term historical trends is difficult for the "man in the street." Here is how Farley Mowat in *Sea of Slaughter* contrasts the world of the western north Atlantic today to that found by early European explorers and exploiters:

> The living world is dying in our time.

> I look out over the unquiet waters of the bay, south to the convergence of sea and sky beyond which the North Atlantic heaves against the eastern seaboard of the Continent.
>
> And in my mind's eye, I see it as it was.
>
> Pod after spouting pod of whales, the great ones together with the lesser kinds, surge through the waters everywhere a-ripple with the living tides of fishes. Wheeling multitudes of gannets, kittiwakes, and other such becloud the sky. The stony finger marking the end of the long beach below me is clustered with resting seals. The beach itself flickers with a restless drift of shorebirds. In the bight of the bay, whose bottom is a metropolis of clams, mussels, and lobsters, a concourse of massive heads emerges amongst floating islands of eider ducks. Scimitar tusks gleam like a lambent flame...the vision ails.
>
> And I behold the world as it is now. In all that vast expanse of sky and sea and fringing land, one gull soars in lonely flight—one drifting mote of life upon an enormous, almost empty stage.[18]

Those of us who experience nature now are witnessing, in many cases, a mere remnant of the natural world as it once was. But only those who have taken the trouble to understand natural history know this. Most economics departments do not even teach the history of their own discipline. Even here, their focus on the margin, on the next change, keeps them from seeing, or even seeking, the whole picture. They are content with sub-optimization—making the best of an ever worsening situation.

c. Resources Abundance Some economists, typically the school of thought known as technological optimists, point to the fact that real prices (prices adjusted for inflation or deflation) are falling for most of the inputs to industrial society,[19] and if shortages should occur we will be able to substitute for them.[20] There are two arguments here: one about prices and the other about substitution, both problematic.

i) Prices and Costs The claim about real prices normally does not even pass the test set by neo-classical economics itself. To do this it would have to take into account all of the side effects of production, use, and disposal of goods. But this is not done. The fall in "real" prices of many natural resources is less real than it seems because extraction and processing of resources involves costs that are not reflected in the prices, these costs are what economists call "externalities." For example, much of the "industrial forest" of Northern New England and the Canadian Maritimes is sprayed with chemicals to inhibit the growth of hardwoods. These chemicals have ubiquitous and difficult-to-trace effects on wildlife, including commercial and sport fisheries, which are not reflected in the costs of pulp wood, and inhibiting hardwood growth changes the price of flooring and baseball bats. Similar points can be made for many other inputs of industrial society.

In addition, there are limits to the biosphere's ability to absorb waste, and these limits are already being exceeded, both locally and globally. In the United States, the Chesapeake Bay, once one of the world's most prolific fisheries, has undergone a substantial collapse, due in large part to polluted runoff from suburban development and agriculture, as well as overfishing and the introduction of exotic organisms. At the global level, the ability of the atmosphere to recycle carbon into the earth's crust is vastly exceeded, very likely resulting in accelerating climate change.

Nor do low prices by themselves necessarily signal resource abundance, even ignoring failure to achieve full cost pricing. Producers of natural and other resources can be trapped into price cutting actions simply because they have no other options but to sell at world prices. For example, it is likely that many of the world's tropical forests are being liquidated at foolishly low prices because the countries in question have no quicker way to earn the foreign exchange necessary to participate in a globalized trading regime. The low price of a good may not signal abundance, but production at prices set by desperation.

Both the technological optimist and the more sober neoclassical economist have failed to answer the question: costs to whom? From the fiduciary point of view the idea of costs needs to be expanded. The food we eat not only cost us money and the time, efforts, and sacrifice it took to earn it; it cost the world's ecosystems something to produce. It used part of the earth's finite energy supply, proximately in the form of fossil fuels and ultimately as part of the flow energy from the sun. If the good is meat, its production cost the animal its life, and probably some suffering. Those who sacrifice little for their money may tend to think that the world sacrificed little for what they buy with it. Even if price distortions are corrected according to neoclassical prescriptions, the moral problem of fulfilling our stewardship duties is not.

ii) Substitution Nor is the substitution argument as simple as it appears. These arguments work mainly by construing the use of resource in very narrow consumption terms. For example, from a *resource* point of view the collapse of the North Atlantic cod and other ground fisheries is not a matter for much alarm because soybeans or other proteins such as chicken can be substituted in human diets to replace that no longer available from the fish. Taken in these terms the argument carries the day in the main.

But there is no reason to take it on these terms alone. The amazingly complete commercial destruction of this resource does not simply give rise to a crisis of protein. It has deleterious effects on employment, the economic core of the region, and a way of life for humans stretching back to nearly the year 1500 for Europeans and even earlier for the traditional peoples whom the Europeans displaced. But seeing this, which the technologically optimistic neoclassicist does not, is to see only a portion of the ensuing disaster. The removal of several kinds of fish from a great fishery can be a catastrophe for the remnant bird, seal, and other species who must also make their livelihood from this source. A common result is the starvation of the young. Some species may decline in numbers, while others may grow substantially. What appears to be a factual claim on the part of the neoclassicist gains its plausibility from an account of the person-as-consumer, and of the responsibility of persons toward nature, that are both completely inadequate.

The stewardship framework gives us a different perspective on substitution. Gifford Pinchot argued nearly a century ago in *The Training of a Forester*[21] that forests serve a broad and irreplaceable cluster of functions in addition to their role as sources of raw material: erosion control that protects streams, bays, and lagoons; the cleansing of water for use by humans and wildlife; the mitigation of heavy runoff which would otherwise cause floods; a home for wildlife; a source of recreation; a source of aesthetic contemplation, and so on and so forth. Viewed with their broad functions in mind, forests are not technically or morally substitutable.

The very idea of substitutability is recast within an ethics of stewardship. A steward seeks the preservation and, where appropriate, the restoration of persons and the natural world.

This sets the standard by which we assess the desirability of substitution, following the structure of the fiduciary duties. Advances in agriculture which allow for the conservation of topsoil or the restoration of excess or abused farmland to woodland and wildlife habitat are desirable substitutions. Stewardship of climate would serve as a major catalyst for technological innovation since dramatic drops in greenhouse gases would be required. Tax increases to reduce emissions, and tax incentives for new technologies and other ways of spurring reductions in greenhouse gases will have to be centerpieces of the stewardship of climate. There would be robust substitution within stewardship economics, but its composition would be different, and it would be in service of different goals than in the current framework. We may state a principle that parallels Leopold's statement of the land ethic:[22] Substitution is good when it tends toward the conservation and restoration of persons and natural systems, bad when its tends otherwise.

The implications of trying to fit the economy into the biosphere are profound for the transportation sector. First, we do not start with the consumer, but with the concept of limits and then design our transportation systems to fit within them. The land use implications of the highway system (roads for autos) requires enormous amounts of land, and are perhaps the major infrastructure contributing to sprawl which in turn damages many ecosystems. A car based transport system also harms humans through air pollution generated, hours wasted in congestion, and so forth.

C. How Much Economic Growth Is Enough?

From the fiduciary perspective the economy should steer a course between being insufficient to supply the goods necessary to protect basic rights—most particularly subsistence rights—and not so large as to compromise the ability of other species to flourish. Mainstream economics has no answer to the question of whether the benefits of economic growth exceed its costs, and no way of calculating the appropriate size of economic activity relative to the biosphere on which it depends.

1. The Scale of Stewardship Economics

Though many people in the world do not have their subsistence rights guaranteed, the *aggregate* amount of food and other necessities for this purpose is more than adequate. Of course, tragic abuses of subsistence and other basic rights occur in many countries for a combination of institutional, economic, organizational, and environmental reasons. One of the elements of the fiduciary framework of which stewardship economics is a part is that national borders are not the ultimate determinants for deciding who has the obligation to secure these rights, and that these obligations default to the international community. We are over the necessary threshold on the low side, but need considerable institutional reform to meet our obligations to secure basic rights on a day-to-day basis. In a world arranged according to the principles of transparent sovereignty within the commonwealth of life, systematic starvation and malnutrition would be unknown. Of course, the best way to secure these rights is most likely to be local institutions accountable to the people whose rights are involved.

On the other side of the permissible range, chaos reigns. The current mix of population size, consumption patterns, technology, and an economics indifferent to the well being of nature are bringing havoc to many natural, not to mention many human, communities. According to stewardship economics, as we have seen, certain ecosystems could be set partly or largely off limits to human use; and others could be managed in manners that do reduce their ability to regenerate after use. *The space between the lower boundary of satisfying basic rights, and the upper boundary allowing other life forms to flourish, is the space for legitimate human wealth.*

2. The Scale of Mainstream Macroeconomics

The principle of marginality which is central to microeconomics says that we should stop any activity when its costs exceed its benefits. We continue an activity up to, but not beyond, the point when the benefits exceed the costs. We do what is most important to us first, then what is second, third, and so forth. We spend our last dollar on what we value least. This way we can satisfy our most central desires the most. While there are numerous reasons we will explore why this should not be a fundamental principle of choice, it does offer a means of deciding how much of something we want. Macroeconomics offers no comparable principle, no way to tell when growth has become uneconomic.

Even from a conventional anthropocentric view of the world we should use the resources that matter the least in terms of ecosystem function first, then the next valuable, and so on. But this is not what we do. Wetlands of enormous ecological importance are routinely destroyed. Prime farmland is carelessly committed to urban uses without significant, nay, in most cases *any* thought to other ways of accomplishing the objectives in question. Once we see an obligation to respect the commonwealth of life, the lack of a principle of ecosystem marginality, of what to use first, later, last, or never becomes even more evident, even more painful to witness.

The fiduciary perspective helps to redefine the idea of marginality. It reframes cost–benefit analysis by broadening the concept of both costs and benefits. The question of marginality from the point of view of stewardship economics is two-fold. On one side, will the change in question move us away from or toward the protection of the three basic rights? On the other, will it move us away from or toward respect for the commonwealth of life?

The transportation sector, particularly in the realm of automobiles and trucks, provide an outstanding example of economic growth that has become uneconomic. More car and trucks and more roads to move them do not seem to result in more satisfaction, but more lost time, uprooting of identity from place, and so on. Without an alternative infrastructure consumers are caught in a trap of more and more congestion. Stewardship economics also provides perspective on these major issues of infrastructure. From its point of view we should choose the type and location for infrastructure that does the least damage to ecosystem function and resilience while still supporting and facilitating the enhancement and preservation of life.

D. How Should We Think About the Byproducts of Economic Production?

By what standards should we judge the processes of production that serve the economy? From the point of view of stewardship economics, industrial processes have to be analyzed with a view to their effects on the whole commonwealth of life. From the mainstream perspective any industrial process is permitted so long as the costs as reflected in the market are fully internalized.

1. Production in the Stewardship Model

Stewardship economics requires the reconceptualization of industrial processes and waste.

a. Industrial Stewardship Once we see the nested limits of the world in which we live we can recognize that we are pushed in the direction of materials, not price, internalization. Karl Henrick Robert and his colleagues in the Natural Step Movement in Sweden have formulated the basic principles involved.[23]

i) Materials from the earth's crust, the lithosphere, should not be allowed to accumulate systematically in the ecosphere. Heavy metals like lead and cadmium are good examples of materials that we should keep out of the realm in which life exists. The goal is not that the person who wants to use lead in a battery should pay all the costs of that use, but that the lead should be managed with the goal of preventing its release into the biosphere. These substances have a life cycle from mining to disposal. Within the fiduciary system the goal is the control of that substance throughout that cycle to avoid dispersion during the period of use. There is no need to estimate a substance-by-substance damage function.

Some materials from the earth's crust have a natural cycle. It is not their release into the biosphere that is crucial, it is their balance. Carbon is a good example, though, of course, a certain amount of carbon is necessary for life at all. Carbon is removed from the atmosphere by being taken up in either terrestrial or aquatic plants. If these remain in the biosphere the storage is relatively temporary, lasting only until the organism decomposes. If the organism sinks to the ocean floor, particularly if it covered by other sediments and moved into the earth's crust by plate tectonics the removal is very long-term. From the point of view of materials internalization the goal is cycle balance: emissions into and extractions from the atmosphere should be in rough equilibrium. Of course, price changes may be a means to move us in this direction.

ii) Materials from society should not accumulate systematically in the biosphere. In addition to the issue of naturally occurring substances such as carbon that can get out of balance, there are tens of thousands of compounds that have been made by humans that are accumulating in the biosphere. This is in part attributable to current macroeconomics. Since markets for many existing products are satiated, stimulating further consumption requires novelty to inspire consumers to buy the new item. Product innovation depends, in many sectors, on chemical engineering that introduces novel and typically untested substances into the environment. For example, there is considerable evidence that a variety of substances that disrupt human (and other organisms') central nervous, immune, and reproductive systems are widespread, perhaps even ubiquitous in the biosphere. These effects are sometimes irreversible for the individuals affected, as in the case of persons who are rendered sterile due to the effects of chemicals during their embryonic development. In addition, as manmade compounds move up the food chain, they often become bioconcentrated as organisms consume one another. For example, high levels of industrial chemicals are precipitated in the arctic because of temperature and wind patterns. They are concentrating in the food chain of humans and other species. From the point of view of stewardship of the commonwealth of life these tendencies should be resisted. The burden of proof for the introduction of new substances should be on those who want to introduce them. They should have to show that their impact on life's commonwealth is benign.

b. Waste The idea of waste is re-conceptualized within the fiduciary framework. In the neoclassical view, waste causes unnecessarily unsatisfied human desires. The buck who dies of old age in the forest is a wasted deer, having frustrated the hunter's desire to bring him to ground with a bullet. In the fiduciary conception waste is life unnecessarily foregone. For this reason the resources of the biosphere should be retained within it. In the western industrialized countries sewage is regarded as something to be gotten rid of. Indeed, one of the most, perhaps *the* most, substantial advance in human health was brought about by keeping sewage segregated from water supplies. There can be no quarreling with this outcome. The fiduciary perspective sheds a different light on how we should think about sewage. It is not truly "waste," but an asset out of place. Sewage contains the results of photosynthesis. It represents an investment of the earth's limited capacity for the production and sustenance of life. Sequestering it from the biosphere by burying it in landfills or burning it, represents a waste of the earth's capacity to support life. Similar considerations apply to garbage generally.

2. Byproducts Within the Neoclassical Model

A central feature of the neoclassical model is the idea of correcting prices to reflect all costs associated with production, consumption, and disposal of goods. While stewardship economics will, as we will see, rely on prices as a means to preserve and protect the commonwealth of life, it does not seek an optimal efficiency as defined within the framework of consumer sovereignty. Seen from the fiduciary perspective there are a number of problems with the corrected prices mantra.

a. Harms and Wrongs The price internalization model fails to take into account the difference between a harm and a wrong. It is wrong to do some things even when we compensate for them. It is wrong to rape someone even if you pay her or him later. Yet the idea of corrected prices just says we should pay for the harm that we do. The cognate idea that the "polluter should pay" has the same defect when used without relation to principles designed to answer the question: pays for what?

What in fact happens in setting public policy is that a set of factors exogenous to the market determines which externalities we try to control. For example, many environmental laws having to do with clean air and clean water, as we have seen, draw their moral authority from concern for the vulnerable, not the idea of cost internalization. In some cases we can move toward protecting the vulnerable by internalizing costs, but in most cases the efficient level of pollution will leave those most susceptible to pollution inadequately protected. Suppose the number of people with impaired lung capacity is 10 per cent of the population. Damage to their lungs is unlikely to weigh heavily in arriving at an overall assessment of net costs and benefits. Hence they are likely to be placed at risk by this decision rule.

b. Damage Functions For the price internalization model to work we must be able to estimate the value of the damage in question to know how much to correct a price. Take the case of climate change. How much damage climate change will do in India a hundred years from now is a question to which it is not possible to develop a reliable answer. We do not know what the technology, agriculture, or settlement patterns will be at that time. Yet each of these will be a significant factor in projecting the impacts of climate change. Nor do we know how to calculate the costs of the damage even if we could know it. We have to know how those affected value the damage to be able to assign a price. Consequently, all interested parties must be allowed to bid if the market is to reflect true costs even in its own terms. But neither future generations nor nonhuman species can bid, and of course, poor humans effectively cannot bid.

c. Allocation and Scale The cost internalization model conflates allocation and scale. Getting a price “right” would help us reach allocative efficiency as understood within the neoclassical model. But it would not help at all in deciding whether an economy is of optimal size. Suppose that in 1950 the world had a population of about 2 billion persons and all its prices were right, and in 2000 a population of 6 billion persons and all its prices were right again. We still have no answer to the question of which state of affairs is preferable. From the perspective of the commonwealth of life the human economy is already much too large. The resource flows required to provide automobility to 6 billion people cannot be managed without violating the principles of stewardship economics. Carbon-based fuels are already a major factor in climate change, and transportation infrastructure continues to play a major role in the degradation of ecosystem function. Of course, these damages can be reduced by changes in technology, though these changes would have to be radical indeed to met the requirements of the stewardship perspective.

d. Privatizing Public Power This model moves the power of eminent domain—the power to take property with compensation in pursuit of the public good—from the public sector to the private sector. In the United States, for example, after public review and dialogue and under scrutiny of the court, private property may be taken assuming that just compensation is paid to the person whose property is taken. The right price model permits the taking of someone else’s lungs for private purposes of disposing of air pollution without the safeguards that attend the public exercise of eminent domain. Moreover, there is no assurance that the injured person will actually be paid. All the state would have to bring about allocative efficiency would be to collect the necessary taxes to get the price right—there would be no requirement in this model about where the money would be spent.

e. Fiduciary Goods Society has some goods that it does not wish to sell at any price. One reason is that in many cases these are fiduciary goods, goods that a society sets aside for the benefit of future generations. Examples of these are Gettysburg National Monument in the United States, the site in Newfoundland where the first transatlantic radio transmission occurred, Stonehenge in the United Kingdom, and the like. We also remove from the market places that are unusual, beautiful, or both, such as Victoria Falls or the game herds of the African Savannah.

E. How Should We Think About the Future?

In stewardship economics there is an explicit class of non-discountable (and nonsubstitutable) goods grounded in life’s commonwealth. In mainstream economics all goods are to be reduced to present discounted values.

1. Duties in Perpetuity

It is clear that in the case of fiduciary goods discounting is inappropriate. These goods I call the fiduciary structure. Elements of the fiduciary structure are those things necessary for the protection of human rights and the biosphere. These goods include: constitutions and wetlands; common law and common property; courts and water courses; fertilizers, and fields to put them on. They define the class of things that we hold in common trust.

2. The Voracious Present

Let's look at the defects of discounting in the context of climate change, a change altering the circumstances of all, or almost all, of life on earth. Here is the way William Nordhaus proposes that we think about the vast changes underway in the earth's energy balance.

> The fundamental assumption we adopt is that policies should be designed to maximize the generalized level of consumption now and in the future. This approach rests on the view that more consumption . . . is preferred over less, and in addition that increments of consumption become less valuable as consumption levels increase. In technical terms, these assumptions are embodied by maximizing a social welfare function that is *the discounted sum of the utility of per capita consumption.* [Emphasis added]

There are numerous problems with Nordhaus' decision to rely on discounting which are typical of mainstream economics.

a. Assuring Climate Change Any positive rate of discount assigns lower values to the future than the present. Ironically, if we assume a smooth warming path with slowly accumulating net damage (as these authors do for the most part) then the *adoption* of this framework alone constitutes the decision to do nothing. This is because the benefits of stabilization which occur in the perhaps distant future, say 100 years, are discounted; while the costs occur in the undiscounted present.[24] *This assures that the goal stated at the Earth Summit in Rio of "stabilization of greenhouse gas concentrations" will never be met.* The conclusion is such a short inference away from, and so completely determined by, the (unjustified) assumptions of the method that the "analysis" provided by these authors could be reduced from books to paragraphs.

b. Immortal Agents The authors of this literature ignore Thomas Schelling's criticism that long term discounting assumes an immortal agent.[25] Surely Schelling is right that there is a world of difference in thinking about my own future consumption and that of others. This difference causes the whole neoclassical framework to collapse for long term issues of any kind, by conflating issues of allocation (within a lifetime) with those of distribution (between generations). This is completely illegitimate within their own framework, which makes fundamental the difference between allocation—distributions of goods or services *through properly functioning market*—and distribution issues which *correct for markets* in the service of equity.

c. Time and Its Correlates Further still, the idea of discounting is far more problematical than normally assumed by neoclassical approaches to climate change. As Derek Parfit has argued,[26] discounting typically confuses things that are correlated with time with time itself. A variety of arguments are offered in support of discounting; risk, opportunity costs, the supposition that future generations will be better off than we are, and so on. But in none of these cases is time itself the key issue. We would think much more clearly about the future if we used a *disaggregated* vocabulary about risk and opportunity costs, and stated that poorer generations were not obligated to forego their well being to help those that could be better off, for example, rather than starting with the assumption there is a single social discount rate. Once we see this point, the word "discounting" could be dropped from our vocabulary as an unnecessary encumbrance for both long term and proximate issues.

d. Time Preference There are also reasons to doubt that individuals have a rate of time preference; or at least, that it functions in the broad way that economists assume. For example, why must present- and future-time value be related by an exponential function? Why not some other relationship? The assertion that there is time preference just doesn't accord with common sense. Most of the things I want I don't want right now—its the wrong time of day, week, or season of my life. I don't want to give my daughter her graduation present until she graduates.

What is referred to as time preference needs to be disaggregated in much the same way as "the" social discount rate; for instance, by the way individuals think about risk and opportunity cost. Once thinking is clarified in this way we are free to see that a person may value the third decade of life equally with the fifth, and drop the encumbering language of time preference as well.[27]

e. The Firm and the Earth The authors of this literature conflate decisions within a firm or public agency with a program of management for global systems. We need to distinguish between the means to achieve efficiency through markets or their surrogates, and the things that make markets possible—their preconditions. In "The Cultural Contradictions of Capitalism,"[28] Daniel Bell argues that capitalism depends on the very virtues (e.g. thrift, hard work etc.) that it tends to erode. Surely the earth's basic systems such as climate, and the ocean currents, ecosystems, rainfall patterns that depend on it, or are candidates for being among market preconditions, yet they are being destabilized by profligate markets, particularly in the energy sector. Of course, it is not just that preconditions of markets that must be constructed, protected, or secured on the fiduciary conception. It is all those things necessary for the protection and enhancement of the three basic rights and the commonwealth of life.

The arguments presented in this section require that we make certain decisions about what is to be subject to market and market-like decisions. Discounting the costs and benefits of different investment decisions within a firm makes sense. The same frame of reference is not appropriate to how we think about climate stability or the resilience of major ecosystems. For example, from the stewardship perspective, the massive highway systems in Florida that have restricted the flow of waters to the Everglades should never have been built.

IV. OBJECTIONS TO STEWARDSHIP ECONOMICS

There could be a number of objections to stewardship economics. First, it might appear to be infeasible. But it is no more an ethically unreachable objective than the present growth-oriented regime. As is the case now, the economy at the micro level, in the day-to-day transactions made by individuals, will necessarily be the result of individuals playing out their desires, interests, and convictions. As in the evolution of the institution of the central banks a set of institutions will need to be developed which direct these individual behaviors in the direction of conserving and restoring the biosphere.

Second, it might be claimed that it is not economics at all. Economics, in the eyes of many economists, is simply a description of behavior, how people make choices under conditions of scarcity. It has no normative structure. But both macro- and microeconomics do have normative structures; respectively, GDP growth and efficiency. Particularly in the case of macroeconomics there is a whole host of institutions which have been designed to facilitate achieving this goal. Stewardship economics simply proposes changing these institutions, in service to life's commonwealth.

Third, it could be objected that there is no consensus in favor of the ethical principles derived from the commonwealth of life. But, as argued in this paper, there is no consensus in favor of the current goals of micro- or macroeconomics either. The question is what set of goals is supported by the most convincing reasons, not which ones are the most popular.

Fourth, it could be argued that stewardship economics pays insufficient attention to employment and wealth creation, which are major public concerns. There is nothing in this framework that would prevent the use of various employment creating techniques such as monetary and fiscal policy that already exist. Indeed, many of the tools that would be needed to bring about the goals of the commonwealth of life would stimulate employment such as shifting the tax burden from employment to resource use. Indeed, the transportation sector is replete with examples (such as fuel and vehicle taxes) of how we can use economic incentives to change behavior at the corporate and individual level alike.

Nor is stewardship economics against the creation of wealth: indeed, it defines the range of legitimate wealth within a broad range. It does not begin with the undemonstrated assumption of the mainstream that resources are necessarily scarce, and desires infinite. Scarcity is not a fact about the world. Numerous societies have existed with a small fraction of our material wealth and perceived themselves to be affluent. There are two ways to be rich—to have a lot and not to need much.[29] Many in the mainstream believe that there is a positive correlation between money and happiness. But, as Aristotle noted, wealth has negative utility beyond a middle point. We should also be careful to calculate our true wealth, and not assume that economic growth is necessarily bringing more of it. At the very least wealth would have to be adjusted to net out the effects of expenditures that we make to defend ourselves against the untoward effects of economic growth.[30] In addition, it is almost surely one's relative position, once basic needs are met, that influences the level of happiness, not the absolute amount of money someone has. Since aggregate growth cannot increase people's relative position, it may not always increase their happiness.

V. TRANSPORTATION PLANNING FROM A STEWARDSHIP PERSPECTIVE

I will illustrate the implications of the stewardship perspective for transportation with reference to climate change. Before beginning this discussion I want recast the issue of climate change in terms of what I take to be the issue before us. We are accustomed to thinking of the issue in terms of marginal changes: somewhat dryer in many places, slightly elevated sea level, more intense storms, perhaps a few pockets of places that get colder, and so forth. Much of this description is the result of the hundred-year time frame used in the models to predict future climate and its geographical, economic, and social consequences. Public reactions to these predictions, insofar as there is any awareness at all, is to think that future citizens will play more golf and ski a little less. This grotesquely misdescribes choices before us. I think there are compelling reasons to act decisively and promptly even if we confine our predictions to the shorter time frame and consequently less dire predictions of the Intergovernmental Panel on Climate Change. But intermediate and long term issues are *much* more ominous.

On the present trajectory we are headed toward an ice-free world. If we reach an atmospheric concentration of somewhere around 750 ppm of CO_2 and its equivalents, and we stay at that level or surpass it for a century or two, all or at least much of the natural ice on the earth will melt. On the present path of steep increases in greenhouse gases we will reach this point within a few hundred years; on a temporal order of magnitude roughly the same as the amount of time that has passed since Luther posted his thesis on the church door, and Copernicus pointed out that the earth revolved around the sun, not vice-versa. In other words, seen from the stewardship perspective this will happen *very* soon. Nor should we think that we can simply wait until major change is upon us. For we may get into a situation where we can no longer turn back even if we choose to do so. For example, the arctic tundra could become a source of greenhouse gases instead of a sink—thus contributing to a self-reinforcing escalation in atmospheric concentrations.

The consequence of this will be the end of civilization as we know it. If we only take the issue of sea level rise as an example we can see why this is so; we will get increases in average sea level in excess of 250 *vertical* feet, if all the ice melts and proportionately less if some remains. All low lying coastal cities in the world will be flooded or surrounded by enormous dikes, vast amounts of farm, forest, and marshland will be lost. Several nations will be eliminated entirely and others such as Britain will be reduced dramatically in size. The attendant geo-political consequences will be staggering—as there is no reason to think that the citizens of those areas inundated will not try to migrate, and take resources from other areas. The stewardship perspective calls attention the problems that a no-ice or low-ice world creates for future generations and for plants and other animals. The present path is immoral because it is unnecessary.

This, of course, is only a small part of the case for stabilizing CO_2 concentrations at as low a level as feasible. Carbon emissions will have to be cut somewhere around 80 percent. There is a critical role for the transportation sector in achieving this result. It requires that we rethink the concept of efficiency. In the neoclassical model we think of efficiency as maximizing the satisfaction of desire. Within the stewardship perspective we begin in a different place: with what I called above *ultimate order efficiency.* The goal of the economy is to achieve social and ecological stability.

Looked at from this illustrative perspective alone, the Kyoto agreement is but the very first and very modest step on a long, but for reasons just given, urgent agenda. There will have to be some allocative mechanism for the right to emit greenhouse gases, perhaps initially to nations, and then by nations within themselves. For purposes of this argument, let us stipulate to some amount for the transportation sector. Efficiency within the transportation sector is then redefined as passenger- and ton-miles traveled such that the total emissions do not exceed those allotted to the sector. The other types of efficiency that we have considered define the policy space open to transportation planners. *Service efficiency* is the ability to deliver transportation at low emissions per unit of output. *Maintenance efficiency* is the design of the technology of transportation so that its creation and disposal produces as little in the way of greenhouse gases as feasible.

Of course, climate change issues are but one dimension of fitting the transportation sector into the biosphere. For example, the other two senses of efficiency are somewhat less directly relevant to climate issues, but remain important elements in specifying the implications of this framework. Gr*owth efficiency* calls attention to the necessity of saving the regrowth potential of perturbed ecosystems. For example, ground level ozone may impair the ability of plants to grow. *Ecosystem service efficiency* requires that we preserve and restore their resilience to produce the means to livelihood for humans and other species. For example, building highways that impair hydrologic flows through wetlands are likely to reduce this kind of capacity. Once these factors have been taken into account the traditional, consumer-oriented concept of efficiency reappears as a subordinate element. Microeconomic incentives such as prices and taxes become handmaidens of efficiency defined and defended on other grounds.

NOTES

1. Kenneth D. Boyer, *Principles of Transportation Economics* (Reading, Mass: Addison-Wesley, 1998).

2. Albert Schweitzer, *Out of My Life and Thought* (New York: Henry Holt and Company, 1933) pp. 184-190.

3. See my *The Commonwealth of Life: A Treatise on Stewardship Economics* (Montreal: Black Rose Books, 2001) for a more developed defense of this position.

4. In *A Primer for Policy Analysis*, pp. 297-308. Stokey and Zeckhauser list a total of six market failures: imperfect information; transaction costs; nonexistence of markets for some goods; monopolies or oligopolies; externalities; and public goods.

5. John Maynard Keynes, *The General Theory of Employment, Interest, and Money* (San Diego: Harcourt Brace & Company, 1964).

6. See Robert Skidelsky, *John Maynard Keynes: Hopes Betrayed*, op. cit., and *John Maynard Keynes: The Economist as Savior 1920-1937*, pp. 33-39.

7. This definition is taken from *The MIT Dictionary of Modern Economics* edited by David Pearce (Cambridge: MIT Press, 1997) pp. 297-8.

8. This analysis of the role of Keynesian economics depends on Robert Lekachman, *The Age of Keynes* (New York: Random House, 1966).

9. I am indebted to Neva Goodwin for suggesting a metaphor like this would be useful.

10. Boyer, op. cit., p. 8. Contrast this with the “new realism” discussed by Phil Goodwin in “Road traffic growth and the dynamics of sustainable transport policies” in *Transport and the Environment*, edited by Bryan Cartledge (Oxford: Oxford University Press, 1996) pp. 6-22. Cartlege argues that total demand must be limited.

11. Ibid., pp. 371-386.

12. Herman Daly, *Beyond Growth* (Boston: Beacon Press, 1996), pp. 84-6.

13. John Stuart Mill, Utilitarianism, in *The English Philosophers from Bacon to Mill* (New York: Modern Library, 1939) p. 900.

14. Jeremy Bentham, *Anarchial Fallacies: Being an Examination of the Declaration of Rights Issued during the French Revolution*, Vol. 2 of *Works of Jeremy Bentham*, ed. John Bowring (New York: Russell & Russell, 1962) art. II, p. 501.

15. See J. J. C. Smart and Bernard Williams, *Utilitarianism For and Against* (Cambridge: Cambridge University Press, 1973), especially pp. 100-107.

16. See The World Bank, *World Development Report 1992* (Oxford: Oxford University Press, 1992), pp. 10-11.

17. C. S. Hollings, A Cross-Scale Morphology, Geometry, and Dynamics of Ecosystems, *Ecological Monographs*, Vol. 62, No. 4, 1992, pp. 447-502.

18. Farley Mowat, *Sea of Slaughter*, p. 404.

19. Julian Simon, *Ultimate Resource*.

20. Bjorn Lomberg, *The Skeptical Environmentalist: Measuring the Real State of the World* (Cambridge: Cambridge University Press, 2001) is a recent example of this school of thought.

21. Gifford Pinchot, *The Training of a Forester* (Philadelphia: L.B. Lippincott, Co., 1914).

22. Aldo Leopold, *A Sand County Almanac*.

23. Karl-Henrik Robert, John Holmberg, and Karl-Erik Eriksson, Socio-ecological Principles for a Sustainable Society, a paper presented at the International Symposium “Down to Earth: Practical Applications of Ecological Economics,” October 24-28, 1994, in Heredia, Costa Rica.

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Sustainable Urban Transport in the 21st Century
A New Agenda

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This chapter reviews quantitative and qualitative trends in urban transportation and environment, focusing on developing countries. Reviewing recent efforts, the chapter adopts a definition of "sustainable transportation" that includes economic and environmental sustainability as well as equity as key criteria. It is further argued that governance sustainability is also important if policies and technologies are to reduce the main externalities from urban transport. An important identity is introduced to relate emissions to traffic, modal share, fuel use, and fuel characteristics, from which it is argued that transport policies must confront all of these components of the identity if emissions are to be reduced significantly. Focusing on why urban areas in developing countries have become the most polluted and congested cities in the world, the article notes addresses major barriers to serious transport sector reform that would address these ills. The pessimistic tone is lifted by citing recent examples of policies and technologies that have permitted some regions in Latin America and Asia to begin to turn the corner. It is concluded that strong actions by cities, backed by national government formulation of equipment and fuel standards and supported by private sector initiatives are all needed—together with political will—to reverse the unsustainable trends in urban transport in the largest urban areas today.

THE TRANSPORT CONUNDRUM

Transportation brings people and goods to people, returning enormous benefits to economies (Braudel).[1] But transportation also brings significant undesirable side effects or externalities, particularly in urban areas and on the global environment via CO_2 emissions. While its undesirable side effects have long been recognised, state efforts to tackle the transport problem have been limited because of its inherent complexity and the costs, disruptions, and long lead times involved—all of which have militated against politicians initiating substantive interventions.[2]

Nevertheless, society's benign neglect of the transport dilemma cannot be allowed to continue as transportation externalities—safety, air and other pollution, carbon emissions, congestion and noise, sprawl, and other side effects—are creeping pervasively into the daily lives of ever more millions of people each year. The situation is becoming problematic in developing countries, which are experiencing rapid growth in motorized transport. In China and India, growth rates in automobile and two-wheeler ownership often exceeded 10 percent per year in recent years. There is evidence everywhere one looks in Third World cities of transport's negative impact on local populations (particularly the poor), and the local environment, as well as of the way pollution and congestion act as a brake on local, national, and regional economic growth.[3] At the same time, experience shows that the longer the pervasive creep of transport externalities is left unaddressed, the harder it becomes to halt and then reverse this process through policy interventions.[4]

The size of these transportation externalities is surprising. The World Bank estimates that air pollution and traffic congestion lead to enormous losses in health, time, and ultimately economic growth.[3] These problems are visible today in virtually every sizeable city in the developing world. A rising number of program at local, national, and multinational (i.e. World Bank) levels have taken aim at these problems. There are some successes, such as the phase out of leaded gasoline in most developing countries. Yet smog and particulate fogs as well as grid-locked traffic remain the rule in most places, in part because the growth in vehicle use is often faster than the reduction in emissions per kilometer driven.

Perhaps the costliest externality of all in the very long term, however, is not visible locally but arises from the absolute size and relentless rise in the sector's share of total CO_2 emissions. These grew from 19.3 percent to 22.7 percent in the 1990s and are forecast to expand over the next two decades to 26 percent of total emissions (or 4.73 Gtonnes)—some 43 percent higher than the 1997 level. As a consequence of this, the need to take urgent, effective, and concerted action to tackle the energy-environment-transport conundrum is now shooting rapidly up the environmental agenda of the international community.[5] While few developing countries are expected to impose significant policy changes on transportation only for CO_2 emissions, many seek to exploit the hidden links between improvements in the transport system and local pollution and carbon emission restraint.[6] Further, few countries are keeping score on the changes within the transportation system that underlie growing emissions of all kinds.

The conundrum is this: transport, which makes cities viable, threatens their viability today. Transport, which allows cities to grow outward spatially, threatens to break down in the spatial dimension. But changes to the patterns of transport require cities to impose profound changes in the rules for location (i.e., land use planning), as well as the costs of moving around. These changes might be acceptable, but their results will not be seen for many years, which means those implementing the policies could see their work reversed if the population becomes impatient. Thus little political action is undertaken, and the cities' transportation systems get worse.

AWARENESS IS RISING OF THE NEED FOR ACTION

Rising volumes of air pollution and traffic congestion have gained the attention of authorities in virtually every major city of the world. Growing recognition that "something needs to be done" about transport is at last being translated into action of a sort. Notable, but least effective, are the rising tide of pronouncements by politicians, under pressure from their constituents to tackle the chaos on the roads and its side effects.[7] In some cases, words are being replaced by action, and recently, a small number of new policies and programs.

National and International Transport Policy Reform Positions

The European Union issued its green paper on transportation in 1995,[8] followed by a similar study of transport pricing by the European Council for Ministers of Transport in 1998.[9] The U.S. National Research Council's Transportation Research Board released its own assessment "Transport for a Sustainable Environment."[10] Each recognised that certain key externalities—safety, air pollution, congestion, noise, and so on.—represented enormous costs to society. These costs were borne not just by drivers but by non-drivers, particularly pedestrians and cyclists. The studies recognise that reducing the problems represents both challenges to technology and to behaviour, both that of individuals and governance, as in collective behaviour. What many see as "unsustainable" is the growth in transportation activity—vehicle acquisition and use—that proceeds much more rapidly without internalisation of costs or tough regulations to stem some of the worst problems.

The International Energy Agency (IEA) studied the way certain member countries have approached the CO_2 problem.[11] Four of the five European countries studied had begun to strengthen price signals, either through fuel taxes or other forms of taxation that favoured cleaner fuels and vehicles and in one way or another discouraged vehicle use. The initiatives in Europe echo the thoughts of the World Bank.

All of the aforementioned studies recognised the importance pricing and of regulations. While no one argues that pricing alone will achieve all of the goals of clean transport, most agree that few private actors (i.e., vehicle and fuel companies, private vehicle users) will change technologies or behaviour without both price signals *and* regulation. But it is widely recognised that charging for use of the transport infrastructure and for the externalities imposed on others is politically difficult.

The problems are now recognised in the developing world. Even before the World Bank's "Sustainable Transport" in 1996 broadened the topic to embrace most of the developing world, local and international studies of Mexico City, Santiago, Beijing, and other large metropolises recognised the real costs of both air pollution and congestion on health and human activity. These studies pointed to the rapidity with which the pollution from transportation often become dominant over that from stationary sources. The World Bank is now reviewing its entire urban transport strategy, with a great deal of attention paid to environment.[12] A forthcoming Pew Climate Centre review led by Professor Daniel Sperling of the University of California, Davis, organised thoughtful reviews by local experts from Delhi, Shanghai, Capetown, and Santiago.[13] The IEA is completing a study of advanced bus systems for more than a half-dozen of the world's largest cities.[14] These works point to solutions, but also show the challenges to technology, individual behaviour, and governance that any solution brings. Thus there is much happening on the urban transport front.

A Broader Perspective: "Sustainable Transportation"

This topic became popular after the Brundtland Commission report of 1987. Not surprisingly, it has been addressed in many of the aforementioned transport studies and dozens more, as can be seen by searching the web on "Sustainable Transport." I start with one early definition, "Sustainable transport means users and beneficiaries paying their full costs, including those imposed on the future" (Schipper, Sperling and Deakin 1996).[15] Yet making transport sustainable—however defined—is no simple matter.

The reasons for the difficulties can be seen in the World Bank's description of sustainablity with three characteristics:

- Economic and financial sustainability: "To be economically and financially sustainable, transport must be cost-effective and continuously responsive to changing demands;"
- Environmental sustainability: "Transport has significant effects on the environment that should be addressed explicitly in the design of programs [and systems in general, author's addition]. Making better use of readily available and cost-effective technology is necessary, but

not in itself sufficient. More strategic action is also required in the form of better-directed planning of land use and stricter management of demand, including the use of pollution and congestion charges to correct the relative prices of private and public transport;" and

- Social sustainability, i.e. equity: "Transport Strategies can be designed to provide the poor with better physical access to employment, education, and health services."

The problem with these otherwise lofty ideals is that they lead to conflicts in the sphere we would call "governance sustainability." Few local or national governments can impose the regulations, pricing, and land-use controls which, taken together, might provide a balanced and equitable set of underpinnings. Bus operators barely make money, often only by skirting safety rules, speeding, and ignoring environmental safeguards to cut costs further. Thus there are immediate apparent losers—private vehicle owners and transit riders who face higher costs or more inconvenience—and apparent losers in the longer term—transport operators, vehicle and fuel manufacturers, all of whom must adjust their business practices.

In IEA countries, unsustainable governance appears in many forms:

- Continual changes in the rules of the California Zero Emissions Vehicle rules (for better or worse), as the State of California was recently sued by General Motors Corporation;
- Challenges to European governments over fuel taxation in the fall of 2000 as a falling Euro and rising prices of crude oil stimulated truckers to demonstrate for lower road taxes, particularly environmental ones;
- Powerful resistance in the U.S. to proposed new rules for low-sulphur diesel fuel, even as political pressures are forcing many large bus authorities to switch to CNG-fuelled buses;
- Softening in many key areas of the original plans of European nations to deal with CO_2 in transportation, between the early conceptions of policies in the beginnings of the 1990s to what was on the books by 2000 (IEA 2000[11]); and
- The abrupt reversal by President George W. Bush of the United States' "commitment" to restraining carbon emissions.

The same problems plague the developing world in many more critical ways. If one works the first sustainability principal through economically healthy transport, one finds that transport operators, whether public or private, will fight higher costs imposed by the second principal, environmental sustainability. With fares for public transit barely covering costs, few operators want to improve their vehicles or fuels and risk not covering the incremental costs. And manufacturers of vehicles for individual personal or freight transport fight regulations on pollution or safety for the same reason: higher first costs threaten sales. In a few IEA countries, these problems are mitigated by differential taxation, such as lowering the acquisition or yearly fees on vehicles that are very low emission or low fuel users. But these countries already charge wealthy users high enough taxes to have room for such adjustments. By contrast, raising diesel taxes in India in 1998 and 1999 was met with wide-spread protest. Indeed, few developing countries even passed on the full force of crude oil price hikes in 2000. Some of the countries that are major oil producers sell road fuels at less than world market prices. Raising fuel prices to pay for cleaning up the fuel is difficult.

Transportation is complicated by the third principal, social equity. The new Metro in Calcutta, like many others, is too expensive to be used by the poor, and this despite being heavily subsidised (World Bank 1996; World Bank 2001). Studies of Delhi, India, point to the negative social impact of higher bus fares—the very poor are shut out of motorised transport, while middle class users often switch to polluting scooters, increasing pollution and congestion. The same concern is raised in Latin America when aim is taken at semi-legal paratransit (mini buses and vans): those riders would revert to cars or have no other way of getting around except with long walks to the trunk lines of "normal," or, poorly operated and inefficient public transit. Matching people to jobs and free time in an affordable way is what equity strives at, yet the spatial distribution of habitat, workplace, and play is confounding. Indeed, non-motorised transport, which requires public infrastructure (pathways, sidewalks, safe storage of cycles) does not have the support of any "operators," hence is rarely treated in an even handed way. We suspect the reasons for these difficulties are lack of political will—governance—and a lack of both public and private resources to adapt to new boundary conditions—social and economic sustainability.

Why do people move around so much? Many studies point to the pivotal role of land use: "If people could just live near work [my reading, 'want to live or can afford to live near work'] then transport distances would be reduced." Unfortunately, very few communities have solved the land use regulation problem because doing so would destabilize governance. Robert Cervero, in *The Transit Metropolis*, reviews the relatively modest successes of a number of cities around the world.[16] The two notable highlights, Singapore in Asia[17] and Curitiba in Brazil,[18] are justly held up as models for transportation planning, yet neither has been replicated elsewhere. Other cities he cites—Zurich and Ottawa—each made progress combining both good public transportation and land use rules, but both are still overwhelmingly dominated by cars for most trips. But do residents of those cities really own fewer cars and travel less in them than residents of other cities? In short, what is the quantitative bottom line from experience in these regions, in terms of modal share, total travel, total pollution, and total fuel use?

There is one final element of this conundrum that makes action difficult. In its most narrow form, sustainability means not leaving unpaid cost for future generations to pay. The U.S. NRC study (Transport for a Sustainable Environment) identified only a limited number of externalities as truly intergenerational in this sense: CO_2 and disruption of natural habitat. To this may be added the long-term damages to human health and ecosystems of pollution. Additionally, one could argue that the fixed infrastructure laid down in one era is very difficult to change in another short of war or natural catastrophe; rarely after such events do planners pause to ask how to improve the infrastructure just destroyed. In short, decisions and actions whose consequences are largely irreversible are closely related to effects that are unsustainable.

Now add the arrow of time. Economic growth usually means more cars and more transport activity in an irreversible spiral: How many metropolises find it impossible to restrict car use or impose land-use controls once cars are widespread, in contrast to Curitiba and Singapore, which acted relatively early on?[19] Normally, it is impossible to move homes, jobs, buildings, and roads and guide-ways overnight to a new configuration that would reduce travel; moving them piecemeal takes decades, during which other forces are likely to intervene to sideswipe the plan. The reverse—building suburbs connected by superhighways—transformed most cities in North America and Europe within two or three decades. While few oppose reducing congestion now (”getting the other guy off the road") or pollution ("get rid of his black smoke"), real action still faces the classic commons problem. Collective benefits are not felt by the individual who has to make the investment to reduce the pollution or incur the cost of not driving. And few individuals behave in a way that reflects concern for problems that face their descendants. Hence some elements of the transport conundrum echo the usual problem of the commons or the lack of real concern for damages that accrue to the future. Politicians can make some inroads against the first set of concerns, but it is more difficult to convince individuals to make sacrifices on behalf of others not yet born.

THE FRAMEWORK FOR DEVELOPING RESPONSES: AS IF KEEPING SCORE ON TRANSPORT DEVELOPMENTS MATTERED[20]

In order to develop sensible, sustainable plans and policies in transport, it is first necessary to understand where one stands and where one is heading. This issue—keeping score on transportation and environment—is not simply one of counting accurately (bottom-up statistics). It also rests on untangling the components of changes over time and across the population and the vehicles they use (top-down decomposition). It is vital to both allocating political credit for success and for fixing blame and fixing the problem when a policy or technology does not yield the intended benefits.

The IEA has developed the ASIF equation, expanding an idea of Ehrlich and Holdren[21] to cover transport impacts in a more general (and thus complete) way (Schipper and Lilliu 1999; Schipper and Fulton 2001):

$$\mathbf{G = A * S}_{i} \mathbf{* I}_{i} \mathbf{* F}_{i,j}$$

where **G** is the emission of any pollutant summed over sources (modes) i; **A** is total travel activity, in passenger kilometers (or ton-km for freight), across all modes. $\mathbf{S}_i$ converts from total passenger (or freight) travel to vehicle travel by mode. $\mathbf{I}_i$ is the energy intensity of each mode (in fuel/passenger or ton-km), and is related to the inverse of the actual efficiency of the vehicle, but it also depends on vehicle weight, power, and, of course, driver behavior and traffic. $\mathbf{F}_{i,j}$ is the fuel type j in mode i.

What matters for transport and environment is that each of these components be exposed to transport policies as well as feedback from other components. Not all components respond the same to a given stimulus, say a fuel tax increase or a kilometer road-use fee. And not all actors—vehicle operators, travelers, or shippers—will respond to the same stimuli in the same way, either. Each component (and not simply those related to fuel) affects emissions, too. For example, congestion drives up emissions; so does short trips in motor vehicles taken with cold engines. If some car trips are replaced by less energy-intensive modes or non-motorized transport, the savings are more than proportional to the kilometer not traveled by car.

The key purpose of the ASIF identity is to show policy makers how the components of transport and emissions fit together, and make sure that the potential—and actual—impacts of their actions on each component are noted. Modes are linked, too: safe cycle storage encourages cycling to collective transit nodes (bike and ride); measures to give buses or cycles priority lanes often take road or parking space from cars, which discourage car use, and so forth. ASIF helps remind analysts of some of these linkages. In the end ASIF is only an identity, but it has a powerful effect identifying underlying factors and rates of change.

WHERE CAN INTERVENTIONS TAKE PLACE? WHERE SHOULD THEY TAKE PLACE?

The ASIF framework affords a way of linking policy and technologies to particular problems that are associated with any of the ASIF components or their interactions. The matrix in Table 1 was proposed by Schipper and Lilliu-Marie (1999). It shows passenger transportation as it relates to carbon emissions, but very similar matrices could be drawn for other pollutants and for freight transportation.

A key interaction to guard against is a rebound effect, by which changes in one term of ASIF lead to changes in the opposite direction in another term. The most common of these, increased car usage with lower fuel costs (or indeed increased usage of any mode if costs fall), is small in high-income countries but can be very important in lower income countries.[22] Perhaps the most perverse of these effects can arise when an alternative “clean” fuel is available at substantially lower variable costs than the traditional fuel, for example, LPG or CNG for cars and taxis or even diesel in place of gasoline. Indeed, it has been strongly suggested that the low price of diesel fuel stimulates more fuel use from the resulting extra driving than is saved because diesel cars use roughly 10 percent less energy per kilometer on the road than gasoline cars.[23]

Equally important is to think about the stakeholders who are concerned about possible initiatives. Their relative strengths vary from region to region, and their responses may vary too. The ability to balance these stakeholders and develop strong policies is the key element of governance required for dealing with transport problems. This is shown by the “Governance Matrix” of Table 2, also from Schipper and Marie 1999.

Table 2 suggests that there are important groups who would be opposed to fiscal or regulatory measures. Vehicle manufacturers are not opposed to improved fuel economy *per se*, but, because of fears about market acceptance, are reluctant to commit themselves or their products to significant improvements. The challenge for analyst is to anticipate political opposition, economic difficulties, and other unforeseen problems and incorporate them into sensitivity analysis to gauge the real costs of any development. For developing countries, an additional political issue arises if a policy encourages use of a technology or product that must be imported. Conversely, the fact that some vehicle technologies are poor or old and outmoded in some countries may have more to do with trade and industrial policies than with any problems of local technical competence. India, where older models of British and Japanese cars were produced for decades, comes to mind immediately, as do the former Soviet bloc countries. Whether such policies are simply protectionist or a result of perception that newer technologies are too expensive, they cannot be put aside easily to make way for progress. Thus Table 2 suggests many profound positions that must be understood on a local level and met squarely in the political sphere, i.e., with political sustainability.

WHAT IS IN THE WAY?

There are many factors in the way; many that run deeper than the problems indicated in Table 2. Addressing them will take a long-term commitment to fuse transportation issues with progress on other social fronts, such as improving all four of the elements of transport sustainability.

TABLE 1 Interaction Matrix:Which Policies Affect Which Components of Travel-Related Emissions?

Component/ Option	**A** (Activity)	**S** (Modal Share)	**I** (Vehicle intensity, characteristics, load factor)	**F** (Fuel Mix)
Vehicle Fuel Economy Technology	None except small rebound in driving caused by lower fuel costs	Slightly encourage modes with lower running costs	All	Affected by fuel (e.g. diesel has lower fuel intensity)
Overall Fuel Taxation	Slight restraint, elasticity low	Favors modes with low fuel intensities	Encourages improvement in all comps.	Neutral
Carbon Taxation	Slight restraint	Favors low carbon modes	Same as above	Favors lower carbon fuels
Kilometer Pricing (including congestion pricing, etc.)	Significant restraint. Depends on extent, costs, time of day, etc.	Favors modes with small footprints per passenger (i.e., bus, rail)	Little effect unless permits small vehicles selectively	Little effect unless cleaner fuels exempt
Fuel Quality Improvements	Small impact if fuel prices rise	Small impact away from most fuel intensive modes, but potentially important when affecting fuels used in vehicles used by lower income people such as buses or two-wheelers	Usually small improvement in engine performance	Can improve the attractiveness of otherwise "dirty" fuels (e.g., diesel or gasoline) over alternative fuels (natural gas or alcohol)
Alternative Fuels: development, pricing	Little effect unless price of fuel forced up	Little unless "clean fuel" modes given priority	Little, unless clean fuel more efficient	Potentially large (subsidies, taxes on dirty fuels)
Transit Development	Increases activity among low income, distance for all	Encourages its own use if supported by policies	Could take some hi-occupancy car	Could be developed to use natural gas, electricity
Non-Motorized Transport Initiatives	Increases among those with low activity	Reduce other shares, but could take some passengers from collective modes	None except where short, fuel-intensive car trips are replaced	None
Land Use Planning	Supposedly would reduce total activity	Could increase transit share	Little	Little

SOURCE: Schipper and Lilliu-Marie 1999

TABLE 2 The Governance Matrix: Who Cares About Each Policy?

Actor/ Option	National and Local Government	Vehicle Makers	Consumers, e.g., Households, Taxi Drivers, etc,	Stakeholders and Lobbies
Vehicle Fuel Economy	Local: None except through procurement. National: influence through fuel prices, standards, taxes.	Hold the technologies.	Choose vehicles and how to drive them.	Mainly automobile industry opposing regulations to encourage or mandate. Less opposition to taxation.
Fuel Taxation	Set by national or state governments.	Mixed position; accept if alternative to regulation, but often defend status quo, especially through their industry associations	Oppose.	Opposed in past by many groups.
Registration, yearly, or Special Fees	Set by national or local governments.	Oppose when aimed at new vehicles.	Oppose.	Opposed: by principal transport industries (e.g., airlines opposed landing fees, etc.).
Kilometer Pricing (including congestion pricing, etc.)	Local and national favor for different reasons.	Few have thought through what significantly lower utilization/year would mean for sales and planning.	Would oppose unless congestion benefits clear.	Probably opposed, particularly by truckers and other transport professionals.
Cleaner Fuels	Set standards.	Usually accept because of beneficial impacts on vehicles.	Mixed, depending on costs.	Often opposed by national oil companies and refiners, or transporters who have to pay the extra costs.
Alternative Fuels: development, pricing	R&D, testing, pricing, introduction into market.	Mixed reaction; Could favor.	Suspicious unless price differential.	Lobbies for fuels develop quickly.
Transit Development	Crucial for planning, financing, running.	Some taking proactive stand (e.g., Volvo).	Urban interested; suburban not.	All sides of issue.
Land Use Planning	Local gov. implements, but can be based on national laws.	No view.	Take both sides.	Usually real-estate interest, property owners organize to oppose.

SOURCE**:** Schipper and Lilliu-Marie 1999

Serious Inadequacies in the Existing Analytical and Advisory Policy-Making Infrastructure

Lack of good data is of course no excuse for inaction, but it is a good reason to move carefully. But recent experience in many of the worst cities of the world revealed amazing inadequacies of even the most elementary data:

- The number of vehicles *in use* by type and fuel is not known in many countries. In India, for example vehicles are counted once, when they are first registered, but not through any yearly fees or census;
- Distances driven are generally not known, nor is the total traffic by vehicle type.
- There are almost no real figures on fuel economy of each vehicle;
- Non-motorised transport (and some informal transport, such as jitneys) is rarely counted accurately, and often believed to be significantly underestimated; and
- Emissions tests are rare, so emissions inventories are from simulations or norms, not from real measurements that reflect fuel quality, traffic, driver behaviour, and ageing of vehicles.

These uncertainties may seem academic, yet the quantities that are uncertain form the basis for the ASIF breakdown. Without such information, authorities cannot discern good news from bad. Not knowing existing pollution per km or total kilometers of travel, one cannot evaluate the benefits of an improvement in pollution per km or a reduction in travel. Lacking direct tests, it is impossible to say how much pollution a CNG bus or a combination of filter and low sulphur diesel will emit relative to the present base line. Worse, one cannot take credit for reductions from what would have been since there is no real base line. In some cities, notably Mexico City, traffic and travel surveys have improved knowledge greatly, but dynamic monitoring efforts are only just getting started in the Ministry of Environment.[24] A similar effort has been underway in Sao Paulo (OD surveys) under the Secretariat dos Transportes Metropolitano.

There are, of course, established centres of expertise and sources of information within academia/public interest groups, government agencies and the private sector (consultants, companies, etc.) capable of providing the sort of information and expert input that will be needed by policymakers trying to design and implement cost-effective transport interventions.[25] But a careful look at this institutional and information infrastructure reveals some serious shortcomings in the depth and coverage of existing information and databases relating to the key aspects of the problem, such as vehicles in use, vehicle usage, fuel economy, and emissions of most kinds:

- The actual components of ASIF belong to different authorities or constituencies. For example, estimates of vehicle km are done by road authorities, estimates of mobility are done by transport ministries, estimates of total emissions are made by the air quality authorities, and estimates of emissions/km usually made by the environmental testing authority or a local university. Fuel deliveries are usually recorded by energy or fiscal authorities. Getting all of these levels (and in many cases regions) of authority to sit down and work out numbers is difficult almost anywhere;
- The explanatory power of “models” used by analysts, policy makers and investors to understand the situation and devise optimal strategies where little is really known about the present situation, for example, data on vehicle use, fuel economy, and so on, as key input data;

- The issue coverage and expertise of existing institutions—particularly among those operating in the public interest and servicing developing countries where human and financial resources for developing baselines and monitoring the impacts of policies and technologies have been almost non-existent;
- The lack of strong advocacy for non-motorised transport, since it does not represent any particular economic or political interests other than a large share of the poor;
- The fact that since multi-lateral organizations and donors assess problems and design solutions via individual projects, they miss huge opportunities for significant synergies, as transport externalities must be addressed from a *systemic* perspective as they have national, regional and urban dimensions, are shaped by cross-cutting drivers, and have impacts well beyond transport per se.[26]

The net result is a very limited information pool, inadequate understanding, and scattered institutional capacity to support the sort of significant multi-national interventions, aimed at both technology and in the policy sphere, that are now recognised as necessary to have a real impact on the transport challenge. This means authorities are poorly informed and unable to obtain relatively fresh information on what is going wrong . . . or what is going right!

Lack of Detailed Understanding of Local Policy Context Undermines Effective Intervention by International Bodies

The problems these "infrastructural" shortcomings pose for the transport policy-making process are compounded and greatly exacerbated by another feature of the current situation that is by far the most serious of all the weaknesses in current approaches to assessing the transport problem and devising solutions. Even when a solution appears to be solely technological, one size rarely fits all. For elementary improvements in vehicle technology, this is appropriate. But each region has its peculiarities that affect both technology and governance.

Below the national level—in virtually all developing countries and many OECD countries—very little *timely*, systematic analysis of transport trends is being carried out.[27] As a result, the information available is too aggregated or broad to generate the insights and understanding necessary to design optimal, second, or even third-best policies.[28] Each of the foregoing examples showed why what might seem like best practices can not be applied easily.

Some regional public authorities, donor agencies, and well-meaning NGOs responded to the transport "crisis" with actual and proposed standards, taxes, regulations, and an array of one-off, ad hoc interventions. But most of these were designed with little reference to the reality of the *local* underlying cause-effect relationship of the transport externalities and system problems they were trying to address. The "forced" conversion of buses to CNG or ethanol under political pressures in many cities, and Mexico's "Hoy no Circulan" are two good examples. To be sure, these interventions may have some measure of success. But they may also prove to be an expensive waste of time and public money that allow the real problems to increase as they "creep" further and further into the warp and weave of the lives and livelihoods of everyone living in or close to urban areas. One important source of waste is not poor advice per se but the inability of authorities to follow the impacts of their interventions and discern success from failure in time to make corrective changes, in time to avoid great losses.

Even worse, the overall result of these interventions may be profound changes in the transportation system—generated via the wrong market signals being sent—that are decidedly suboptimal from a resource allocation, economic development, and environmental protection perspective. Given the shortcomings described, their efficacy cannot be assessed until its too late to take corrective action. Yet given the enormous lead times required to change transport trends and the enormous costs (environmental and economic) involved, authorities can ill afford long-term mistakes caused by inability to measure and see where the system is going. The good news is that Mexico City recovered from "Hoy no Circulan," Los Angeles and Mexico City concluded their ethanol bus programs and moved on, and other cities learned lessons in designing their own behavioural strategies, or simply avoided the widest pitfalls and loopholes.

Thus to a large degree, characteristics of technology performance, behavior, and lifestyles and in the impact of national or local policies and corporate or local, non-governmental initiatives to affect transportation are simply too poorly known to draw lessons, spot winning technologies, correct undesirable trends, or reinforce successful initiatives. For policymakers and donor agencies, this means it is almost impossible to design optimal interventions or to measure the added value of an intervention—while trends need to build up for a decade or longer before they emerge in a well-understood way. By such time, it is often too late to change policies or change technologies except at very large cost.

Political Difficulties: Divided Markets and Divided Responsibilities

One of the paramount problems of governance in transportation is that of divided responsibilities. Consider these examples of sensitive local situations where either markets (i.e., economic competition) or responsibilities (political competition) are divided:

- *The role of "paratransit" is a sensitive issue in many large cities because paratransit is both a competitor and a complement to organised public transit.*

In most third-world cities, informal transportation (or paratransit) coexists with formally organized municipal buses, trams, and metro (rail) systems in a relationship that may not be totally sanctioned by authorities. In Mexico City, around 30,000 "collectivos" (mini-buses and vans, akin to jitneys in the U.S. and similarly around the world) have managed to garner about 30 percent of all trips in that region. These riders come mostly from people who otherwise would have been regular transit riders, but some would have been car users as well. Politically the collectivos are "tolerated," yet represent a chaotic, uninsured and sometimes unsafe mode of transport that nevertheless delivers a much desired service. Unquestionably the informal paratransit drivers are a strong political force. In Brazil, the informal paratransit has been brought into the system in some cities, tolerated in others, yet officially hated in most. Given this tension, little effort has been made to clean up the vehicles or organise the routes to fit with bus and metro systems. Indeed, cleaner and more efficient vehicles are virtually unavailable in Mexico City today, making the existing aging fleet old and polluting. (By some estimates, the Collectivos consume more gasoline than the buses from the two public companies consume diesel!) Any transport solution must fit this kind of local circumstance squarely into the picture. At present the antagonism between all parties makes exploiting synergies impossible.

- *Fierce competition between collective and individual modes has arisen in many cities, always as a function of peculiar local conditions.*

In Delhi (and other Indian cities) the most important mode of motorised transport is the two-wheeled scooter, most of which have dirty two-stroke engines. They compete directly with buses for much of the mobile middle-class. Because they are so numerous they are a significant source of air pollution and congestion. Further, they consume as much as 66 percent of all gasoline in metropolitan areas! Although most manufacturers are switching to clean, four-stroke engines (and even CNG for the three-wheeled taxis), these vehicles will remain a huge source of air pollution for many years. If bus fares are raised to permit acquisition of modern, comfortable vehicles with improved motors and clean fuel, one result could be further erosion of the bus market and a worsening of both air pollution and traffic. Yet if bus fares do not rise, bus operators (public, contract, and private) will stick with old, polluting vehicles based on ancient designs in which bus bodies are placed on truck chassis.

Divided Responsibilities

In some regions, political parties divide authorities. In both Sao Paulo and Mexico City, the mayor is of a different party than the national or state government. This tends to impede progress. Divided responsibilities separate those pushing technologies from those who use them. Indeed, new technology may be the least important component of the solution unless its acquisition and use is carefully adapted to these kinds of local conditions. In Brazil, for example, there are enormous potential gains to be made by improving bus technologies. But the owners of buses are rarely the operators. Whether owned by contractors to large cities (as in Sao Paulo), or by speculators, buses are resold after only a few years in service to the original purchaser. Most make their ways from larger to smaller cities. Hence few original purchasers are interested in expensive buses that they may not be able to resell. In El Salvador, virtually all buses were purchased used, primarily from the United States. And in both El Salvador and Brazil, small private operators dominate the bus business, few of whom can afford to buy more expensive, modern buses. While technologies to both improve fuel economy and drastically cut emissions in buses in both countries seem attractive, the present organization of the bus market presents a formidable barrier, even in the cities of Brazil with the most advanced systems, like Curitiba.

Divided responsibilities arise where transport crosses geographical or administrative borders and often undermine technological and behavioural solutions. New York City Metropolitan Transit Authority operates one of the most important bus systems in the world. With long north-south streets on Manhattan and wide boulevards in Brooklyn and Queens, it would seem a logical place for dedicated bus lanes. Yet MTA cannot easily develop bus paths, as it is technically a State entity, while the City of New York controls the streets. This kind of divided responsibility plagues other cities, too, such as Delhi, Sao Paulo, and Mexico, where two or more regional or even national authorities have to agree on a strategy because vehicles and people cross borders constantly. Experts in all three cities say authorities rarely agree.

First Costs: High and Divided

Money is a barrier to almost all social investments. The problem is particularly acute for transportation because the payoff to the public sector are so long-term. Thus even modest costs will be seen as high costs because the apparent payoff is so slow to realise. This is a classic problem for metro systems, which are extremely expensive but over decades could transform transport patterns profoundly. But as with most investments involving externalities, the payoffs to private investment are usually negligible. As previously noted, private bus and van owners and operators are usually small businesses or individual operators with little capital. Users of private vehicles—cars and two-wheelers—buy what is available, so if national governments have not required clean engines and clean fuels, the results will be pollution. Since the free infrastructure must be shared by public and private vehicle users, travellers and freight, there is rarely a simple or politically acceptable way of charging for road use, which further drains away potential funds that could be useful for infrastructure investments (including busways), electronic road-pricing schemes, signal timing, or other investments that could reduce traffic.

THE GOOD NEWS: POLICIES AND TECHNOLOGIES ARE BEING DEVELOPED

Lest this review appear unduly pessimistic, it is only aimed at being realistic. Recognizing barriers and failures is as important as crowning successes. Lessons learned help guide future actions. Indeed, actions are being taken in key areas. Removing lead from gasoline, lowering the sulphur content of fuels, raising vehicle pollution controls, imposing some controls in traffic, and working through the governance process to bring transport operators as well as private citizens, NGOs, fuel companies, and vehicle producers into a dialogue are all underway in some locations. At the same time, a larger array of smaller projects and collaborative initiatives among stakeholders emanating from multi-lateral agencies, private donors, NGOs, and the private sector and all targeting transport's environmental and economic externalities.[29]

Compared to the scale of the problem, these moves are very limited. Some even backfired. But they are at least indicative that the public, politicians, the policy-making system, and even major private sector players are beginning at last to engage seriously with the transport dilemma and starting to look for answers. This upward trend in demand for action emanating from the public and the public sector can only accelerate in the future.

Mexico City's "Hoy No Circulan"

This policy dictated that a car could not be driven one day per week, the day depending on the last number of the license plate. Newer cars with modern clean exhaust systems were exempt. The World Bank's study showed that the policy appeared to stimulate a significant uptake of used cars with license plates covering the "fifth day" in Mexico city, by those who could afford them.[30] This led to more driving and fuel use, not less, since more cars were available.

Low Sulfur Diesel in Europe and the United States

Pioneered in Sweden (as "city diesel"), very low sulfur diesel has been appearing increasingly in bus fleets in Paris, London, and more recently in US cities. The City of New York's Metropolitan Transit Authority soon will have switched all of its diesel fuel to very low sulfur diesel. It has also embarked on an ambitious environmental program to acquire several hundred compressed natural gas (CNG) buses, plan for an equal number of diesel hybrid electric buses (with significant savings of fuel and emissions), and add particulate filters to its diesel buses.

CNG Buses

These buses have become popular in many cities in Europe and the U.S. In the developing world, cities like Delhi, Jakarta, and many cities in China have begun to convert to them. The conversion of all public buses to CNG before April 1, 2001 in New Delhi, India, was ordered by the Indian Supreme Court. But as of May 2001, only a few hundred have been converted. When buses were ordered off the streets on April 2, some of the few that did appear were attacked and burnt by angry riders. But a useful side effect of this order is the wave of conversions of three and four-wheeled taxis, the former from gasoline, the latter from either gasoline or diesel, to natural gas. The three-wheeled, two-stroke taxis were a source of horrendous pollution; the natural gas vehicles are no doubt burning more cleanly than those that were replaced. The real issue the Indian authorities have finally confronted is the difficulty of making choices and carrying them out in ways that meet all four tests of sustainability.[31]

Car-Free Days

The City of Bogota, Columbia, which declared car-free Sundays and introduced its Millenia 2000 bus-way. It is reported now to carry several hundred thousand people per day. It has also upgraded its cycle paths significantly, introducing an important complement to NMT (see http://www.terra.com.co/proyectos/transmilenio/index.htm).

A Voluntary Agreement on CO_2 Emissions from New Cars

In Europe, manufacturers and the EU adopted such a pact, with Japanese and Korean importers agreeing to go along. The agreement targets a 25 percent reduction in sales-weighted new car CO_2 emissions by 2008. A similar agreement was reached in Japan in late 1998. Data from the manufacturers and ECMT show that through 1999 and 2000, these test emissions are headed downward.[32]

Phase Out of Two-Stroke Motors

Honda Motor Co. pledged to phase out two stroke motors for its two-wheelers (scooters, mopeds), and the industry in India is slowly doing the same thing. A series of inspection and maintenance clinics is being developed in India to improve operation and reduce pollution from the millions of existing vehicles.

Thus there have been some important actions that pry open the future with policies and with technologies. Most of these actions are being watched closely, but not all produce cleaner air and other results that are unambiguous beyond the uncertainties of measurement. This creates problems for governance: how to place proper credit or blame for the results of such initiatives?

Longer-term efforts are being made. Sao Paulo is developing its long-range plan, “PITU,” and Mexico City is commencing—again—on a long-range vision.[33] Bangalore, India, has laid out a long-term strategy for bus-ways currently awaiting international funding of the first stage. Jakarta is developing a master plan of its own. Many other cities in Latin America besides Curitiba sport important new busways. Even Los Angeles, stung by the huge costs and low-ridership of its Metro and light rail lines, implemented a traffic signal synchronization scheme along two of its major bus corridors with measurable results—higher bus speeds, more passengers, and likely less fuel consumption and pollution. All of these achievements came about because authorities at different levels and in different regions—as well as in different parts of the same authority—began to work together to build sustainable governance for transportation.

At the same time, a number of very bold and important experiments are underway to test both technologies and behavior, both individual and governance. RATP, the Paris transportation company, is running buses on low-sulfur diesel, natural gas, LPG, and even electric batteries, as are many other cities.[34] The World Bank, the Global Environmental Facility, and UNDP are fostering experiments with advanced buses powered by fuel cells and diesel hybrid engines. Toyota and Honda are selling limited numbers of hybrid automobiles with very low emissions and low fuel consumption, and many companies have announced limited numbers of fuel-cell cars for sale by 2003. Cycle paths are being extended in Paris and other European cities, as well as in Shanghai and other cities in Asia and Latin America. Even Bangkok is trying, with its people mover. And the World Business Council for Sustainable Development has convened a large and far-reaching study of Sustainable Mobility, funded by fuel and transportation companies, that is engaging much of the Third World in local dialogues to diagnose the problems before imposing “solutions.” The first decade of the new millennium should be filled with experiments and signals about what works, and what does not, providing valuable insights into what might contribute in the longer term to the four pillars of sustainable transport.

THE WAY FORWARD: A NEW PARADIGM FOR TRANSPORT PLANNING AND IMPLEMENTATION[35]

What is the way forward? City authorities must take the lead:

- *Cities must take a long-range, systematic approach, including strengthening transport system governance.* Any urban transport initiative plan must be part of a systematic or comprehensive plan in order to succeed. The plan must include a long-range vision of where both the region and its transportation system is headed, and how that direction might be changed. Issues of governance and transport system management (including regulation and licensing of operators) are as important as technical issues. The various policies affecting transport must be harmonized so that they work together, for example to encourage use of mass transit and discourage single-occupant car travel. Improving integration of transport and land-use planning is also very important. Improvements in single or isolated elements of a transit system or transport plan rarely have strong effects, while the systematic approach allows synergies to strengthen the system and improve transportation.
- *Focusing only on technology without paying attention to other aspects of transportation represents a narrow approach.* Technologies gain strength in the battle against pollution and congestion as other systems that reinforce them are also strengthened. As long as competing, “dirtier” modes pay a “correct” share of their external costs—however difficult that is to determine—then the incentive to use improved technologies will be highest. And technologies must be used properly and maintained, not simply installed. This requires good management and monitoring of pollution from vehicles. People are adept at exploiting the weaknesses—and strengths—of technological systems. Policies must erase incentives for people to drive, pollute, and congest more, even if actual emissions from vehicles are reduced by technology.

- *Focusing on behavior and management without careful attention to technology is an equally narrow approach.* Policies and management strategies must be in tune with technological innovation and technologies that support the policy goals, and recognize technologies (including automobiles!) as part of the landscape. Rapidly evolving transport technology can speed up traffic and reduce pollution, yet charge each user for road space during congested times. GPS systems could make paratransit—small busses and vans—easily available to those who need them without creating endless swarms of hovering vans that mark many airports.
- *National governments must help.* Fuel and vehicle standards need to be set firmly by national governments. Although local variations may be necessary, both fuels and vehicles are manufactured and traded within and between countries. The scale of production is usually too large to be adjusted to each locality. If the U.S. and California are any guide, authorities are willing to move to the most stringent levels of quality if they meet demands of a large market (i.e., California), rather than fragment into too many individual markets. And only national governments can negotiate standards with large multinational corporations and other countries.
- *The private sector must be involved.* Vehicles and fuels are made largely by the private sector. Indeed, some publicly owned fuel companies are among the most notorious for the slowest responses to environmental demands. Bringing in the private sector to develop, produce, and sell the technologies needed for clean transport is a key step towards sustainable transport. Getting these actors to move ahead on their own with enthusiasm, however, is not so easy.
- *Political sustainability must be developed.* Regardless of the present attractiveness of policies or technologies, a path must be developed that is relatively robust to changes in the political winds for the party governing a city, or indeed acceptable to more than one party should there be divided political responsibilities. The private sector will not act with full strength if it believes that rules will be changed once the next politicians take over.

STRATEGIC QUESTIONS AND ISSUES TO CONSIDER

This paper is based on several presumptions that are worth emphasising as the basis for future discussions.

- Do the four elements of sustainable transport (economy, environment, equity, and governance) fit together? How well a match must there be among efforts addressed at all these elements for real progress to occur?
- How well do the components of ASIF need to be known and monitored for success with technologies and policies?
- How do technologies, short-term behavioural change, economic forces, and urban planning fit together to affect the ASIF components?
- How can governance be harnessed to provide better solutions to tomorrow's problems? That is, how do public (i.e., local and national government, international organisations, lenders, and NGOs) and private-sector roles blend for sustainable transportation?
- What is the best mode for intervention: technological experiments or policy trials?
- Is the program proposed here too ambitious or too limited? Are there serious omissions?

CLOSING THOUGHTS: OPTIMISTIC OR PESSIMISTIC VIEW?

Problems of traffic, transport, and pollution have emerged very rapidly in the cities of developing countries, even as plenty of examples of what to avoid could have informed urban policy makers. One reason why so many cities may have sped ahead beyond an optimal point is the true lack of quantitative measures, as in the components of the ASIF notation. Authorities simply may have missed the danger signs. Another is the incentive to continue the process of individual motorization and let that lead to new forms of cities, rather than let city development lead to appropriate transport.

The good news, however, is that authorities are reacting at an earlier stage of development outside of the developed countries than was the case in those countries themselves. Consider that Europe introduced lead-free gasoline in the 1990s—a time when their per capita GDP lay not far from where it was in the U.S. when authorities were putting lead into gasoline. Euro-4 fuel (and engines to match) is not far away for major countries of Latin America and Asia—at per capita incomes around those at which the debate over automobile air pollution first began in Southern California. And the time lags between the introduction of technology in wealthy countries and first appearance in developing countries is getting shorter. In short, clean air technologies are being developed with an eye to world markets, rather than just a few countries with strong regulations. And at this writing, fuel economy agreements in Europe and the likelihood of policy initiatives in the U.S. mean that carbon emissions are once again within reach of being tamed. In short, technology is not standing still; it is getting both less costly and better.

Two enormous barriers stand in the way. The first is the political will (in both developed and developing countries) to change rules and/or prices to make cleaner and more fuel efficient (or carbon-saving) technologies move faster through development and into every vehicle on the road. These developments can reduce the importance of the **IF** terms (energy intensity and fuel type) in the ASIF equation remarkably over as little as 20 years, or one generation of vehicles. Thus the technological problems of un-sustainable transport probably can be solved.

The second barrier is the political will to deal with the **AS** components (person, freight, and vehicle travel) of the equation. No matter how clean, enormous flows of traffic and ever expanding cities will always themselves cause problems to present generations, while leaving even worse problems to future generations. In developed countries, this may mean less motion, but not necessarily less access to people, goods, and services. In the developing countries this must mean more access to the same ends, without the endless chase to be like Americans, Europeans, or Japanese. What is working so hard against the developed countries is generations of habits built up around individual motorized transport. What is pressing hard against the developing countries is the huge and rapidly growing scale of the challenge, exacerbated by swollen urban population and inadequate infrastructure to deal even with last year’s problems. The developed countries are wealthy and innovative, so that deep cuts will work their way slowly but surely through the problem. The developing countries are growing and changing so rapidly that even modest cuts in some forms of emissions rapidly become the norm as vehicles are replaced, and citizens can grow into new patterns of mobility and access before they get mired in the old ones.

NOTES

1. Braudel, F. The Wheels of Commerce. In *Civilization and Capitalism, 15th–18th Century. Vol. 2*, Berkeley, Calif: University of California Press. 1992.
2. The Dutch government repeatedly backed away from ambitious plans for intercity road pricing; the government of Stockholm, which had worked out a detailed transportation package in the early 1990s, saw its work fall through because of political differences.
3. The World Bank has threaded environment, economy, and equity into their important book, *Sustainable Transport: Priorities for Policy Reform*. Washington, D.C., The World Bank, 1996. More recently it commenced a major effort in its "Urban Transport Review," http://wbln0018.worldbank.org/transport/utsr.nsf.
4. A recent World Bank/IEA hosted Roundtable (http://www.back-to-work.com/clearingtheair.html documented this phenomena in New Delhi and Mexico City—where policies designed to address years of neglect of the transport challenge either had the opposite effect (leading to increases in traffic and emissions) or took so long to implement that any benefit was overwhelmed by problems elsewhere. Valuable years were lost. This is a subtle but terribly important reason why urgent action is needed—once the problems (and failed solutions) get out of hand, trends are even harder to break.
5. IEA, 2000. World Energy Outlook. Indeed, the IEA presents a case of intervention for OECD countries in which the growth in emissions from transport is brought to near zero after 2010.
6. This is the principal recommendation of Schipper, Marie, and Gorham 2000, *Flexing the Link between Carbon Emissions and Transportation* (World Bank). See also *www.iea.org/flexing.html*. A more complete version is available as Schipper and Lilliu-Marie, 1999. *Transportation and CO_2 Emissions: Flexing the Link—A Path for the World Bank*. Paper No. 69. Washington: World Bank Environment Division.
7. Former U.S. Vice President Al Gore made many statements about urban sprawl; for example, during the 2000 Presidential Campaign.
8. CEC (Commission of the European Communities), 1995a. *Towards Fair and Efficient Pricing in Transport—Policy Options for Internalising the External Costs of Transport in the European Union*, Green Paper COM(95) 691 final, Brussels, Belgium.
9. ECMT, 1998. *Efficient Transport for Europe: Policies for Internalisation of External Costs*. Paris, France: OECD
10. TRB, 1997. *Special Report 251: Toward a Sustainable Future: Addressing the Long-Term Effects of Motor Vehicle Transportation on Climate and Ecology*. TRB, National Research Council, Washington, D.C.
11. IEA, 2000. *The Road from Kyoto: Current CO_2 and Transport Policies in the IEA*. Paris: International Energy Agency.
12. World Bank, 2001. "Urban Transport Review." (http://www.worldbank.org/html/fpd/transport/ut_over.htm).
13. Ranjan Bose, Daniel Sperling, Mark Deluchi, Lorien Redmond, Lee Schipper, and Geetam Tiwari, *Transportation in Developing Countries: Greenhouse Gas Scenarios for Delhi, India*. Pew Center on Global Climate Change, Washington, D.C., 2001. Hongchang Zhou, Deborah Salon, Daniel Sperling, and Mark Delucchi, *Transportation in Developing Countries: Greenhouse Gas Scenarios for Shanghai*, China. Pew Center on Global Climate Change, Washington, DC, 2001.

14. Fulton, L. and Schipper. L., 2001. Making Urban Transit Systems Sustainable Around the World: Getting Many Birds with One Bus? Presented at Cities of Tomorrow, Gothenburg, Sweden, Aug. 23–24, 2001.
15. Presented at the OECD Workshop on Sustainable Transport, Vancouver BC, Canada, and published by the OECD, Paris. See http://www.ecoplan.org/vancouvr/enhome.htm.
16. Cervero, R., 1998. The Transit Metropolis. Washington, D.C:, Island Press.
17. Ang, B. W., and Tan, K. C. 2001. Why Singapore’s Land Transportation Energy Consumption is Relatively Low. *Natural Resources Forum* 25 (2) 2001.
18. Rabinowitch, J., and Leitman, J. 1993. *Environmental Innovation and Management in Curitiba, Brasil*. Washington D.C: UNCP/UNCHS World Bank Urban Management Programme, Working Paper #1.
19. There is an interesting counter example in Stockholm, Sweden. “Slussen,” the elaborate set of ramps that is one of only two connections between Northern Stockholm, Gamla Stan (the old town) and Soedermalm (the southern part of Stockholm) was built in 1936 when Sweden still used the left side of the road for driving. The authorities at the time realised that they had to build a symmetrical set of ramps or forever face the spectre of huge costs should they decide to switch to right-hand drive, which they did in 1967. By contrast, did the authorities of Los Angeles think about reversibility when they removed the “Key System” trolley lines, or did the authorities of Paris worry when they took away the rail that originally went around Paris? Instead, both cities had to re-invest billions of dollars decades later to try to reverse some of the impacts of these decisions, much of which went to rebuilding parallel structures!
20. This discussion is taken from Schipper, L. and Fulton, L. 2001, Driving a Bargain? Using Indicators to Keep Score on the Transport-Environment-Greenhouse Gas Linkages. Presented at the 75th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2001.
21. Ehrlich, Paul R., and Holdren, John P., 1971. Impact of Population Growth, *Science*, Vol. 171, pp. 1212-1217, 26 March.
22. See the entire issue of *Energy Policy* (Vol. 28, July 2000), which addresses rebound effects.
23. Schipper, L., Fulton, L., and Marie, C., 2001. Diesels in Europe: Analysis of Characteristics, Usage Patterns, Energy Savings and CO_2 Emission Implications. *Jour. Trans. Econ. Policy*.
24. Comision Ambental Metropolitana, 1996. *Inventario de Emisiones a la Atmospfere en la ZMVN*. Mexico City: CAM. Also Secretaria de Medio Ambiente, Recursos Naturales y Pesa y Secretaria de Salud: *Programa para Mejorar la Calidad del Aire en el Valle de Mexico 1995-2000.* Mexico City: Departamento del Distrito Federal and Gobierno del Estado de Mexico.
25. Norway’s Institute for Transport Economics, Sweden’s “SIKA,” India’s Transportation Research & Injury Prevention Programme, Indian Institute of Technology in Delhi, the Indonesian NGO Pelangi, the Federal University of Rio de Janeiro’s COPPE all have important programmes in transport policy related to the environment.
26. To some extent the *Global Overlays* now being produced by the World Bank have begun to develop ways of recognizing environmental benefits beyond either those of any given project or beyond those accruing only to the local environment.
27. Even in Curitiba, Brazil, the city with the most far-reaching bus system in the world, it is virtually impossible to measure the overall balance of car use, fuel use, and emissions in the city, and thus impossible to give a bottom-line fuel and emissions balance for the city. (Source *MS Thesis,* R. Marston de Texiera, University of Sao Paulo, 1998).

28. Most analyses of developing countries hearken back to data provided by the IEA. While the IEA data for developing countries are still too aggregate for analysis of key transport trends, the present “Energy Indicators” effort covering many IEA member countries, has matured to include key parameters of transportation activity. This work is now reaching out to cover developing countries, and economies in transition in more detail, particularly India, China, Brazil, etc.
29. Including the World Business Council for Sustainable Development Industry Collaboration on Transportation, the World Bank’s “Clean Air Initiative” with local governments in Latin America and Asia, the W. Alton Jones Foundation Clean Bus project involving the IEA, and local and national governments in Asia and Latin America, plans for dedicated bus-ways in El Salvador and Bangalore, India, etc.
30. Eskeland, G. S. and T. Feyzioglu, *Rationing Can Backfire, The Day “Without a Car” in Mexico City,* The World Bank, Policy Research Department, Public Economics Division, December, 1995.
31. Bose, R. K. and Nesamani, N.K. 2001. *Urban Transport, Energy and Environment: A Case Study of Delhi*. Delhi: Tata Energy Research Institute.
32. ECMT, 2001. *Monitoring of* CO_2 *Emissions from New Cars*. Paris: OECD.
33. Governao do Estado de Sao Paulo, 1999, *Plano Integrado de Transportes Urbanos para 2020*. Sao Paulo: Secretaria de Estadodos Transportes Metropolitanos.
34. RATP, 2000. *Bilan des Experiments des Bus Ecologiques*. (Results of Experiments with Ecological Busses). Paris: RATP.
35. This discussion follows Fulton and Schipper, Making Urban Transit Systems Sustainable Around the World: Many Birds with One Bus? In *Transportation Research Record: Journal of the Transportation Research Board, No. 1791*, TRB, National Research Council, Washington, D.C., 2002, pp 44–50.

Toward Zero Emissions for Transportation Using Fossil Fuels

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THE CASE FOR HYDROGEN AS A MAJOR ENERGY CARRIER

The hydrogen (H_2) fuel cell is receiving considerable attention as the fuel and engine option of choice for the automobile in the long term. The world's major automakers are racing to develop the technology—a quest bolstered in early 2002 by the Bush Administration's announcement of Freedom CAR (Cooperative Automotive Research), a collaboration between U.S. automakers and the U.S. government aimed at developing fuel cell cars and the associated H_2 fuel infrastructure.

A transition to H_2 as a major energy carrier alternative to gasoline and diesel fuel and the fuel cell as an alternative to the internal combustion engine would be very costly and would require many decades. So these technologies must offer benefits that exceed the huge costs involved. Yet the societal costs of a business-as-usual future in which the automobile continues to be dominated by hydrocarbon-fueled internal combustion engine vehicles (ICEVs) are also arguably huge. Concerns about oil supply insecurity, air pollution damages, and climate change motivate serious consideration of introducing H_2 as a transport fuel.

Concern about oil supply insecurity in light of growing dependence on oil from the politically volatile Persian Gulf,[1] the primary driver of energy policymaking in the 1970s, has again come into focus as a result of the events of September 11, 2001. The valuation of the risk of being dependent on this insecure source of oil is difficult, but a conservative estimate for the United States is likely to be the cost of maintaining a military capability for safeguarding access to Persian Gulf oil, some $20 to $60 billion per year (private communication from Michael O'Hanlon, Brookings Institution, September 2000). The cost of this "insurance policy" aimed at preventing disruption of oil flowing from the Gulf can be converted into an external marginal cost of $0.35 to $1.05 per gallon ($15 to $44 per barrel) assigned to all oil consumed in the United States—or $0.70/gallon as a mean estimate, calculated by dividing the total cost of maintaining this military activity by 20% of Persian Gulf exports,[2] to reflect the fact that the United States accounts for 20% of gross oil imports at the global level. Table 1 shows that the mean estimate of the oil supply insecurity cost accounts for more than one-fifth of the lifecycle cost for typical new cars—comparable to the contribution from direct expenditures on gasoline. Figure 1 also shows contributions at high and low estimates of these costs.

Because of the large and growing role of the automobile as an oil consumer,[3] technologies that reduce its oil dependence would be effective in mitigating this risk. This could be accomplished by introducing cars fueled with H_2, which can be provided from a wide range of primary energy alternatives to oil. But many other options could also address such concerns—for example, advanced internal combustion engine/hybrid electric vehicles (ICE/HEVs) that offer double the fuel economy of today's ICEVs (see Table 1) and synthetic middle distillate fuels that can be produced from remote natural gas resources (so called "gas liquids") in various remote regions outside the Middle East (Weick and Landrum, 2001). Such options could begin to make significant contributions long before H_2 fuel cell vehicles could be launched in the market.

Despite remarkable progress in reducing automotive air pollutant emissions in recent decades, recent studies suggest that environmental damage costs from air pollution—mainly chronic mortality health impacts caused both by direct emissions of small particles and the formation of small particles in the atmosphere from gaseous precursor emissions of SO_2 and NO_x—might be comparable to a substantial fraction of direct consumer expenditures on automotive fuel in densely populated urban areas—not only for typical new gasoline-fueled cars but also for alternative advanced liquid hydrocarbon-fueled internal combustion engine cars, as indicated by the comparison of lifecycle costs, including environmental damage costs, for various combinations of car engines and fuels presented in Table 1. Health damage cost estimates are uncertain, however—with costs at one standard deviation from the median estimates presented in Table 1 higher and lower by a factor of four (see Figure 1).

The wide range of uncertainty makes air-quality regulatory policy-making difficult—but nevertheless the trend has been toward ever tighter regulations as more has been learned about these impacts. H_2-fueled cars, especially H_2 fuel-cell cars, offer the advantage in such circumstances that fuel cycle-wide air-pollutant damage costs would be a small fraction of direct fuel costs even if high estimates of damage costs turn out to be valid (see Figure 1). A shift to H_2-fueled vehicles could free automakers from the historical process of continually having to make large investments in new emission-control technologies as regulations tighten.

Climate concerns are usually invoked as the most compelling reason to introduce H_2 as an energy carrier. But climate change damages from anthropogenic greenhouse gas (GHG) emissions are highly uncertain. The ExternE studies of the European Commission suggest that at the 95% confidence level the value of carbon lies in the range \$14 to \$510 per metric tonne of carbon (tC) and in an "illustrative restricted range" of \$66 to \$170 per tC if only discount rates in the range of one to three percent are considered (EC, 1997). In the present study a base case carbon valuation of \$120/tC is assumed, which is at the middle of the latter range. This valuation is consistent with the cost of achieving deep reductions in GHG emissions via the least costly approaches for decarbonizing fossil fuels.[4] There are reasonably good prospects that if decarbonization of fossil fuels to extract the contained energy and sequestration of the separated carbon dioxide (CO_2) in geological media proves to be a viable strategy for climate change mitigation, the carbon tax[5] needed to induce sequestration might not be higher than this in the longer term.[6] When this seemingly high carbon valuation is applied to automotive fuels, the resulting cost per car is less than both the estimated value of oil supply insecurity and the median estimate of health damage costs for hydrocarbon-fueled ICEVs (see Table 1).

Consideration of the climate-change mitigation challenge in a broad context highlights the desirability of evolving an energy economy in which H_2 is a major energy carrier. Scrutiny of IS92a, a global energy scenario introduced by the Intergovernmental Panel on Climate Change (IPCC) in the early 1990s, is helpful in understanding the potential importance of H_2. IS92a is often referred to as a 'business-as-usual'(BAU) scenario representing a plausible course for global energy under a public policy that gives no consideration to climate-change concerns.[7]

A summary of the global energy and CO_2 emission features of IS92a for 2050 and 2100 is presented in Table 2, along with actual data for 1997. This table shows that under IS92a, global CO_2 emissions climb from 6 gigatonnes of carbon (GtC) in 1997 to 13 GtC in 2050 and 20 GtC in 2100. Moreover, despite the projected continued "electrification" of the energy economy,[8] electricity's share of CO_2 emissions declines from 31% in 1997 to 29% in 2050 and 25% in 2100. Electricity's share declines because of the expectation that even under business-as-

TABLE 1 Projected Base Case Societal Lifecycle Costs For Automobiles with Alternative Fuel/Engine Options[a]

Alternative fuel/engine options *{gasoline equivalent fuel economy (in mpg) and fuel price [in $/gallon of gasoline equivalent (gge)]}*	**PV of lifetime AP and GHG damage costs for fuel cycle**[b]			PV of OSI costs[b]	PV of AP + GHG + OSI costs	PV of lifetime fuel costs[c]	Retail cost of drivetrain (*incl. fuel storage*)	*Cost of Aluminum-intensive frame*	**Total societal lifecycle costs**				
	AP	GHG	Total environmental costs						Without external costs	AP only	GHG only	AP + GHG	AP + GHG + OSI
Current gasoline SI ICEV (27 mpg, $0.95/gal)	2640	1429	4069	2654	6723	2828	2837	0	5665	8305	7094	9734	12388
Advanced Lightweight ICEVs													
Gasoline SI ICEV (45.6 mpg, $0.95/gal)	1162	846	2008	1571	3579	1674	2837	936	5448	6609	6293	7455	9026
H_2 (NG) SI ICEV (52.6 mpg, $2.21/gge)	524	746	1270	0	1270	3381	2837+2500	936	9654	10178	10400	10924	10924
Advanced Lightweight ICE/HEVs													
Gasoline SIDI ICE/HEV (58 mpg, $0.95/gal)	1097	683	1780	1235	3015	1316	2837 + 1342	936	6432	7528	7114	8211	9446
CNG SI ICE/HEV (62 mpg, $1.19/gge)	644	515	1160	0	1160	1552	2837 + 1556	936	6881	7525	7397	8041	8040
H_2 (NG) SI ICE/HEV (63 mpg, $2.21/gge)	458	623	1081	0	1081	2823	2837 + 2780	936	9376	9834	9999	10457	10457
Diesel CIDI ICE/HEV (67 mpg, $0.83/gge)	1150	590	1740	1069	2809	996	2837 + 1863	936	6632	7782	7222	8372	9441
FT50 (NG) CIDI ICE/HEV (67 mpg, $0.88/gge)	1122	596	1718	535	2253	1058	2837 + 1863	936	6694	7816	7290	8412	8947
Lightweight Fuel Cell Vehicles													
Gasoline FCV (38 mpg, $0.95/gal)	338	1019	1357	1886	3243	2009	2837 + 5097	936	10879	11217	11898	12236	14122
Methanol (NG) FCV (56 mpg, $1.56/gge)	248	668	916	0	916	2238	2837 + 3220	936	9231	9479	9899	10147	10147
H_2 (NG) FCV (82 mpg, $2.21/gge)	257	479	736	0	736	2169	2837 + 2459	936	8402	8659	8881	9138	9138
H_2 (NG) FCV (82 mpg, $2.46/gge) w/$CO_2$ seq.[b]	119	106	225	0	225	2411	2837 + 2459	936	8644	8763	8750	8869	8869
H_2 (coal) FCV (82 mpg, $2.24/gge)[c,d]	366	881	1247	0	1247	2200	2837 + 2459	936	8432	8798	8798	9679	9679
H_2 (coal) FCV (82 mpg, $2.48/gge) w/$CO_2$ seq[b,c,d]	215	99	314	0	314	2435	2837 + 2459	936	8667	8882	8766	8981	8981
H_2 (wind electrolytic) FC (82 mpg, $3.46/gge)[e,f,g]	68	114	182	0	182	3394	2837 + 2459	936	9626	9694	9740	9808	9808

NOTES TO TABLE 1:

[a] From Ogden, Williams, and Larson (2002) except for the H_2 from coal and wind entries, which were developed for the present analysis. The indicated automotive fuel economies [for the US Environmental Protection Agency (EPA) urban/highway driving cycle] and cost estimates [from Table 2 of Ogden, Williams, and Larson (2002)] are for vehicles of comparable performance. Upstream emission (well-to-tank) emissions of air pollutants (APs) and greenhouse gases (GHGs) are based on Argonne National Laboratory's GREET1.5 Transportation Fuel-Cycle Model for all cases except for the following, which were developed to be consistent with the GREET framework: (*i*) a case has been added involving geological sequestration of the CO_2 byproduct of H_2 manufacture (see Table 3) for FCVs fueled with H_2 derived from natural gas; (*ii*) cases have been added involving coal-derived H_2 for FCVs without and with sequestration of the separated CO_2 (see Table 4); (*iii*) a FCV option has been added involving use of electrolytic H_2 derived from wind power coupled to compressed air energy storage (CAES). For the sequestration cases, it is assumed that electricity consumed at H_2 refueling stations (17.5 kWh_e/GJ H_2) is provided by the US average mix of electricity supplies for 2015 as projected in GREET but with coal electricity (54% of all electricity) provided by coal IGCC plants with sequestration—for which CO_2 emissions are as indicated in Table 4, and for which SO_2, NO_x, and PM_{10} emissions equal the measured emissions for the coal IGCC plant at Buggenum, The Netherlands (Williams, 2000). To estimate upstream emissions, the GREET upstream emissions are scaled by the ratio of the GREET fuel economy to the new fuel economy. Direct AP emissions from the vehicle are estimated from GREET for currrent gasoline ICEVs and for CNG hybrid vehicles. Internal combustion engine vehicles and ICE/HEVs fueled with gasoline, Diesel or Fischer-Tropsch liquids are assumed to satisfy Tier II standards for AP emissions (spark ignited engines satisfy Tier II, bin 3 and compression ignition engines Tier II, bin 4). Vehicle emissions from H_2 ICEVs and ICE/HEVs and from FCVs are from Thomas et al. (1998b); the latter are near zero for gasoline and methanol FCVs and zero for H_2 FCVs.

[b] AP damage costs ($ per kg) are median estimates based on ExternE studies of the European Commission adjusted for US population densities (Ogden, Williams, and Larson, 2002). GHG emissions are assigned a value of $120/tC (see main text). The cost assigned to oil supply insecurity is $0.70/gallon of gasoline equivalent for oil-based transport modes (see main text). The present value (PV) of lifecycle external costs is calculated for a 3%/year discount rate (DR) (in accordance with guidelines established for the ExternE studies) and is thus 0.853 times the PV evaluated for DR = 0%/year.

[c] For cars driven 12,000 miles/year for 10 years, assuming DR = 8%/year, so that the PV of the fuel cost = 0.671 times the PV for DR = 0%/year.

[d] Production costs for coal-derived H_2 are from Table 4 with coproduct electricity valued at 5.0¢/kWh [the generation cost for a NGCC plant with CO_2 vented, if carbon emissions are valued at $120/tC (see Table 5)]: $5.69/GJ with CO_2 vented and $7.36/GJ with CO_2 sequestered. The H_2 producing plants are assumed to be sited 100 km from the city gate. Bringing H_2 to the city gate entails costs of $0.35/GJ for H_2 transmission + $0.55/GJ for H_2 recompression (Ogden, 2002). To this $8.98/GJ H_2 is added for distribution and refueling stations (Table 3), so that the costs seen by the consumer at the refueling station are $15.57/GJ, HHV ($2.24/gge, LHV) with CO_2 vented and $17.24/GJ, HHV ($2.48/gge, LHV) with CO_2 sequestered.

[e] GHG and AP emissions upstream of the coal-to-H_2 plant are from the GREET model: the discounted value of damages from upstream emissions are $0.092/GJ of coal for GHGs (64.6% CH_4, 35.3% CO_2, and 0.2% N_2O) and $0.559/GJ of coal (43.7% NO_x, 25.2% SO_x, 28.6% PM_{10}, and 2.4% VOCs) for APs. The CO_2 emissions for the coal conversion facility are from Table 4. The only AP emissions taken into account for the coal-to-H_2 plant are NO_x emissions (all other AP emissions are assumed to be negligible). For H_2 manufacture without CO_2 capture and sequestration [where the synthesis gas not converted to H_2 is burned to provide coproduct electricity in a steam turbine power plant (see Table 4)], it is assumed that NO_x emissions are 43 ppmv (dry) at 3% O_2 (typical for natural gas steam-electric power plants), or 6.9 gr NO_x/GJ of coal, for which the discounted value of damages = $0.081/GJ of coal. For H_2 manufacture with CO_2 capture and sequestration [where the synthesis gas not converted to H_2 is burned in the gas turbine combustor of a combined cycle power plant to provide coproduct electricity (see Table 4)] it is assumed that NO_x emissions are 25 ppmv (dry) at 15% O_2 (typical for natural-fired gas turbines) or 4.7 gr NO_x/GJ of coal, for which the discounted value of damages = $0.056/GJ of coal. Discounted lifecycle GHG emission cost s for the electricity (17.5 kWh_e/GJ H_2) consumed at refueling stations are $0.32/GJ H_2 (based on 178 grC-equivalent/kWh—GREET value for 2015 power mix) and $0.056/GJ H_2 (based on 31.3 grC-equivalent/kWh—value if coal in power mix is provided by IGCC with sequestration) with CO_2 vented and sequestered, respectively. Discounted lifecycle AP damage costs for electricity consumed at refueling station emissions are $1.73/GJ H_2 with CO_2 vented and $0.068/GJ with CO_2 sequestered.

[Notes to Table 1, *continued*]

[f] Cost parameters for the wind/CAES system are based on the discussion in the text. A wind electric generation cost of 2.9 ¢/kWh is assumed—the cost projected for Class 6 wind resources in 2020 (EPRI/OUT, 1997). It is assumed that the wind/CAES system provides baseload electricity that is transported 300 km via a high-voltage transmission line at an estimated delivered cost of 4.0 ¢/kWh to an urban center where it is be used to make H_2 for transport applications in an 83%-efficient 500 MW_h city-gate electrolysis plant. The estimated H_2 cost = $15.0/GJ for the least-costly advanced H_2 production technology described in Table 6. To this $8.98/GJ H_2 is added for distribution and refueling stations (Table 3), so that the cost to consumers = $24.0/GJ, HHV ($3.46/gge, LHV).

[g] Emissions for the wind/CAES system arise from burning 0.32 GJ of natural gas in the CAES combustor per GJ of H_2 produced. Direct + upstream GHG damage costs = $0.49/GJ of H_2 (4.82 kgC-equivalent/GJ of H_2). Upstream AP damage costs = $0.294/GJ of natural gas ($0.094/GJ H_2). The only AP emissions considered for the CAES plant are NO_x (other emissions are assumed negligible). Assuming NO_x emissions are 25 ppmv (dry) at 15% O_2 (typically realized for natural gas-fired gas turbines), NOx emissions for the CAES plant are 38.4 gr/GJ of natural gas, for which the discounted damage cost is $0.53/GJ of natural gas ($0.17/GJ H_2). Assuming all coal power in the GREET power mix for 2015 is replaced by wind/CAES power, GHG and AP damage costs for electricity consumed at refueling stations are $0.046/GJ H_2 (from emissions of 25.8 grC-equivalent/kWh of electricity) and $0.059/GJ H_2, respectively.

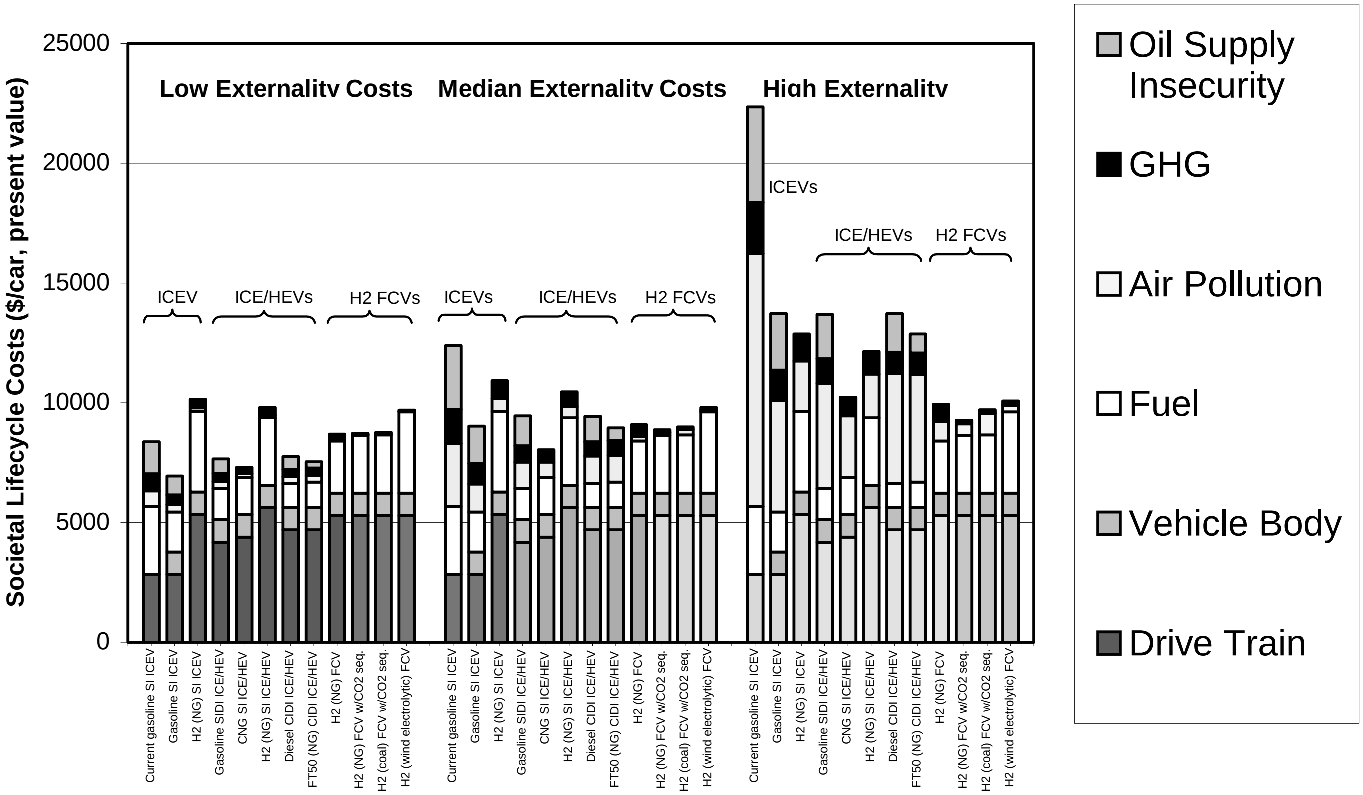

FIGURE 1 Lifecycle costs for cars with alternative fuel/engine options and low, median, and high estimates of externality costs.[9]

TABLE 2 Business as Usual Projection for Global Energy

	Actual	IS92a projection	
	1997	2050	2100
Population (*billlion*)	5.87	10.0	11.3
Electricity generation (*TWh/y*)			
Coal	4,818	11,517	15,480
Oil	1,244	1162	531
Natural gas	2,246	2558	915
Synthetic liquids/gases from coal	-	819	3,017
Hydroelectric	2,574	5,848	7,660
Solar	192	5,838	20,405
Biomass		951	1,381
Nuclear	2,266	8,140	18,695
Subtotal	13,340	36,833	68,084
Electricity generation per capita (*kWh/y*)	2,273	3,683	6,025
CO_2 emissions, power sector			
GtC/y	1.9	3.8	4.9
% of total global CO_2 emissions	31	29	25
Fuels used directly (*EJ/y, HHV basis*)			
Coal	43.2	128.9	132.7
Oil	142.7	142.6	94.6
Natural gas	63.0	114.8	37.3
Synthetic liquids/gases from coal	0	68.5	276.5
Synthetic liquids/gases from biomass	0	79.5	126.5
Subtotal	248.9	534.3	667.7
Fuels used directly per capita (*GJ/y*)	42.4	53.4	59.1
CO_2 emissions, fuels used directly (*GtC/y*)	4.3	9.4	14.9
Primary energy requirements (*EJ/y, HHV basis*)			
Coal	97.9	356.4	718.1
Oil	156.9	155.2	100.0
Natural gas	88.5	143.3	46.7
Biomass	-	128.4	205.2
Hydroelectric power	32.3	58.7	71.7
Solar	-	58.6	191.0
Nuclear power	25.5	81.7	175.0
Total primary energy requirements	401	982	1508
Primary energy used per capita (*GJ/y*)	68.3	98.2	133.5
Total CO_2 emissions (*GtC/y*)	6.2	13.2	19.8

SOURCE: Global data for 1997 are from EIA (2001a). The IS92a projection is the "business as usual" global energy scenario presented in Intergovernmental Panel on Climate Change (IPCC, 1994). Energy quantities are presented on a higher heating value basis.

usual conditions there will be continuing "decarbonization" of the power sector as a result of growing roles for renewable and nuclear energy sources—which account for 71% of electricity in 2100,[10] up from 38% in 1997.[11] Another important reason for the declining power-sector share of CO_2 emissions under BAU conditions is an increase in the carbon intensity of "fuels used directly" (i.e., other than for stationary power generation) in the latter half of the century as a result of the expected peaking of global production of conventional oil and natural gas before the middle of this century[12] and growing roles for synthetic fuels.

For fuels used directly in IS92a, CO_2 emissions rise from 4 GtC in 1997 to 9 GtC in 2050 and 15 GtC in 2100. Thus, even if power generation could be completely decarbonized, global CO_2 emissions would be 2.4 times higher in 2100 than in 1997. Among activities for which fuels are used directly, CO_2 emission growth for the transport sector stands out under IS92a, growing 1.65%/y between 1997 and 2100 from 1.2 GtC/y to 6.8 GtC/y—far more rapidly than emissions from the power and other sectors (which grow 1.0%/y in this period).

If society should eventually decide to stabilize atmospheric CO_2 at 550 (450) ppmv, cumulative emissions between 1990 and 2100 would have to be no more than about 1150 (700) GtC, (compared to 1500 GtC for IS92a), and, by 2100, annual emissions would have to be reduced to about 5 (3) GtC/y (Wigley, Richels, and Edmonds, 1996; Hoffert et al., 1998; Pitcher, 2001). Thus even if the power sector could be completely decarbonized by 2100, stabilization at 450 to 550 ppmv would require reducing emissions for fuels used directly in 2100 three- to five-fold relative to IS92a—a daunting challenge. Of course, scenarios can be imagined that involve greater electrification of the energy economy during this century than envisioned for IS92a. But without fundamental breakthroughs that can provide low-cost electrical storage at small scales (e.g., batteries), the scope for expanding electricity's share of total energy beyond that projected in IS92a is limited.[13]

The preceding analysis highlights the importance of energy supply technologies and strategies characterized by near-zero emissions of air pollutants and greenhouse gases for transportation and other activities that used fuels directly.

This paper explores alternative options and concludes that producing hydrogen from fossil fuels with CO_2 capture and sequestration in geological media is especially promising in addressing the challenges posed by fuels used in automobiles. A companion paper (Ogden, Williams, and Larson, 2002) shows that, when mass produced, the fuel-cell car powered with such H_2 is potentially competitive on a societal lifecycle cost basis—offering (by a wide margin) the lowest externality costs of any advanced automotive option, with the societal lifecycle cost being quite insensitive to the valuation of these externalities (see Figure 1).

OUTLOOK FOR TRANSPORT FUELS CHARACTERIZED BY NEAR-ZERO EMISSIONS

The options for realizing near-zero emissions in the transport sector are shifting to biomass-derived transport fuels or to H_2 that is produced without releasing CO_2 to the atmosphere. The options for H_2 production with zero or near-zero CO_2 emissions include: (1) H_2 derived from fossil fuels (natural gas, coal, and other low-quality fossil fuel feedstocks) with CO_2 capture/sequestration; (2) H_2 derived electrolytically from water using non-carbon-based electricity supplies; and (3) H_2 derived from water via complex thermochemical cycles using non-carbon heat sources. In what follows each of these options is discussed in turn.

Biomass Fuels

Biomass can be converted to clean transport fuels by various routes, including biological processes (e.g., ethanol from woody biomass via enzymatic hydrolysis—the main focus of the U.S. Department of Energy's biofuels development effort) and by the synthesis gas route (e.g, methanol, synthetic middle distillates, or dimethyl ether). The growing of biomass on a sustainable basis leads to no net buildup of CO_2 in the atmosphere, because CO_2 released in combustion is balanced by CO_2 extracted from the atmosphere during photosynthesis. Biomass-derived energy can be provided from residues of agricultural and forest product production and from biomass grown on plantations dedicated to growing biomass for energy.

Modern clean fluid fuels derived from biomass will certainly come to play significant roles in markets that use fuels directly. Futhermore, biomass can become a major energy option in land-rich countries such as the United States and Brazil. Yet, biomass by itself cannot come close to solving the "fuels used directly" problem. Analysis carried out for the World Energy Assessment (WEA) concluded that the practical global potential for biomass production for energy (residues plus plantation biomass) over the long term is 100-300 exajoules per year (EJ/y) (Turkenburg, 2000). This WEA analysis suggests that the biomass energy option offers only a modest potential to improve upon IS92a in terms of greenhouse gas emissions from energy over the longer term, because that scenario already involves, for 2050, the use of 128 EJ/y of biomass (compared to 655 EJ/y of fossil fuels) and, for 2100, 205 EJ/y (compared to 865 EJ/y of fossil fuels)—see Table 2.

Hydrogen as an Energy Carrier in Transportation

Although H_2 can be used in ICEVs, most interest in H_2 as an energy carrier relates to interest in fuel cells for transportation, because H_2 is the energy carrier of choice for use with fuel-cell vehicles (FCVs). Fuel-cell technology is approaching commercial readiness for transportation applications (Ogden, Williams, and Larson, 2003). Fuel-cell buses are expected to be commercialized in various countries during this decade; and a race is underway among all the world's major automakers to commercialize fuel-cell cars.

When H_2 is used in FCVs its conversion generates only water as a byproduct of energy conversion, so that H_2 FCVs are true zero-emission vehicles. Although H_2 is often perceived as a dangerous fuel, it can be used safely if procedures are developed that respect its physical and chemical properties (see Box A).

Compressed gaseous storage is the only viable option at present for storing H_2 onboard vehicles, which poses a challenge because compressed gaseous H_2 storage systems have only one-tenth the volumetric storage density of gasoline. But cars can be made much more fuel efficient than today's typical internal combustion engine cars—for example, ICE/HEVs are expected to have double the fuel economy of today's typical cars and H_2 FCVs triple the fuel economy of today's cars (see Table 1). Their expected high fuel economy makes it possible to design H_2 fuel cell cars that provide adequate range between refuelings without compromising passenger or trunk (storage) space;[14] designing for adequate range between refuelings would be more difficult for less fuel-efficient H_2 ICE/HEVs (see Table 1).

Because a H_2 supply infrastructure for transportation is not in place anywhere in the world, some automakers and their suppliers are pursuing market-launching FCV fueling strategies based on methanol (MeOH) and gasoline as energy carriers delivered to the car[15]—despite the fact that H_2 FCVs would be less costly to own and operate than either MeOH or gasoline FCVs (Ogden et al.,1998, 1999; Ogden, Williams, and Larson, 2002).

Currently, fuel cell cars are much more expensive than today's cars. However, inherent materials and fabrication costs are not high for the currently favored proton exchange membrane (PEM) fuel cell, for which large reductions in cost are expected as a result of production at large scales and learning-by-doing (experience) effects, as well as continuing incremental

BOX A Hydrogen Safety

Hydrogen is widely perceived to be an unsafe fuel, because it burns or detonates over a wider range of mixture with air than other fuels, and very little energy is required to ignite H_2 mixed with the minimum amount of air needed to completely burn it. Although H_2 is flammable in air over a wide range of mixtures, when used in unconfined spaces (as will be typical in transport applications), the lower limits for flammability and detonation matter most. In this regard, H_2 is comparable to or better than gasoline. Gasoline and natural gas can also be easily ignited with low-energy ignition sources such as electrostatic discharges—like those that result from a person walking across a rug. Moreover, in dilute mixtures with air, the ignition energy for H_2 is essentially the same as for methane. In another regard, H_2 has an advantage over gasoline: in case of a leak in an unconfined space, H_2 will disperse quickly in the air because of its buoyancy, whereas gasoline will puddle.

An important safety issue for H_2 is leaks—prevention, detection, and management, particularly in confined spaces. Areas where H_2 is stored and dispensed have to be well ventilated; this means providing vents at the highest points in ceilings. Considering all these issues, a major study of H_2 safety (Ringland, 1994) concluded that "H_2 can be handled safely, if its unique properties—sometimes better, sometimes worse, and sometimes just different from other fuels—are respected."

technological improvements. Ogden, Williams, and Larson (2003) estimate that with manufacture in large factories (300,000 vehicles/year), costs for H_2 PEM fuel-cell cars could fall to market-clearing levels[16] by the time one to two million fuel cell cars have been produced—sometime near the middle of the next decade. They argue that the buildup of cumulative production to the levels needed to "buy down" the technology cost should be carried out in centrally refueled fleet markets with H_2 fueling—avoiding altogether the more technically challenging and more costly market-launching based on MeOH or gasoline FCVs.

Fossil Energy-Derived Hydrogen with CO_2 Capture/Sequestration

As will be shown, fossil fuel-derived H_2 is likely to be much cheaper than H_2 from any other primary energy sources—even taking into account the costs of preventing release to the atmosphere of the CO_2 coproduct of H_2 manufacture. This upbeat outlook for fossil fuel-derived H_2 arises from considerations that: (1) much of the chemical energy in a fossil fuel can be recovered without releasing CO_2 to the atmosphere if the CO_2 coproduct of H_2 manufacture is sequestered—e.g., in deep geological media; (2) the cost penalty associated with disposal of the CO_2 coproduct of H_2 manufacture is likely to be relatively modest; and (3) the global capacity for secure geological storage of CO_2 might be vast.

In what follows, the production of H_2 is described for 1 gigawatt hours (GW_h) plants based on commercially available or ready technology, alternatively considering natural gas and coal as feedstocks, both with venting of the CO_2 and with CO_2 capture and sequestration. The calculations are carried out for natural gas and coal prices of \$3.67/GJ and \$0.92/GJ, respectively—average prices projected for U.S. electric generators in 2020 (EIA, 2001b), assuming an annual capital charge rate of 15% and an 80% average capacity factor for energy production facilities. For the carbon capture/sequestration cases, it is assumed that the CO_2 is transported 100 km[17] to a deep saline aquifer disposal site and disposed of in an aquifer 2 km below the surface. The disposal cost estimation procedure is outlined in Box B.

Hydrogen from Natural Gas

H_2 production technology is well established worldwide for applications in the chemical process and petroleum refinery industries. Where natural gas is readily available, it tends to be the preferred feedstock for H_2 manufacture. Widely used commercial processes for making H_2 from natural gas at large scales are described here. The overall energy balances and production costs, as developed by Foster Wheeler (FW) in a study carried out for Statoil and the Greenhouse Gas R&D Programme of the International Energy Agency, are presented in Table 3.

The process of making H_2 from natural gas (mostly methane) begins with the production of synthesis gas via steam reforming [$CH_4 + H_2O_{(g)} \rightarrow CO + 3\ H_2$], a highly endothermic reaction that takes place in the presence of a catalyst at high temperature and pressure.[18] The synthesis gas is then cooled in the FW plant design to 320°C and delivered to a water-gas-shift reactor, in which CO is reacted with steam in the mildly exothermic water-gas-shift reaction [$CO + H_2O_{(g)} \rightarrow CO_2 + H_2$]. The shifted synthesis gas, which exits this reactor at 392°C and contains 77% less CO than the gas entering, is then cooled to 40°C (condensing out water) and delivered to a pressure swing adsorption (PSA) unit that adsorbs gases other than H_2 in a set of adsorbing beds. The H_2 exiting the PSA unit at 22 bar as a 99.9%-pure product accounts for 87% of the H_2 generated in the reformer and shift reactor. The rest of the H_2 (along with some unconverted CO and CH_4 recovered from the adsorber beds when the pressure is reduced) is used as process fuel gas. The H_2 product is then compressed to 60 bar, cooled to 40°C and delivered to a pipeline. The energy content of the H_2 product is 81% of the energy content of the natural gas from which it is derived (HHV basis), and the production cost for a plant with a H_2 output capacity of 1 GW H_2 is \$6.33/GJ (see Table 3).

The process designed by FW for the case where CO_2 is separated out for pipeline transport to a suitable disposal site begins in the same manner, but in this case the synthesis gas exiting the (high-temperature) shift reactor is cooled to 180°C and fed to another (low-temperature) shift reactor for further CO conversion; the synthesis gas exiting the low-temperature shift reactor at 207°C contains 98% less CO than the synthesis gas entering the high-temperature shift reactor. In this case the shifted synthesis gas is again cooled (condensing out water) and delivered to a "wet" CO_2 removal plant based on aMDEA (activated methyl diethanol amine), a chemical solvent in which CO_2 accounting for 85% of the carbon in the natural gas feedstock is absorbed to form a weakly bonded intermediate compound. The CO_2–deficient synthesis gas exiting the aMDEA unit is then passed to a PSA unit where H_2 at 99.9% purity (accounting for 71% of the H_2 generated in the reformer and shift reactors) is recovered, compressed to 60 bar, and delivered to a pipeline as product. The CO_2 is released in a regenerator via heating to about 120°C, regenerating the original aMDEA solvent. The CO_2 is then compressed to 112 bar and delivered to a pipeline for transport to a suitable geological disposal site. Taking into account all energy penalties associated with separating out CO_2 and compressing it to 112 bar for disposal, the energy content of the H_2 product is 78% of the energy in the natural gas from which it is derived, and the production cost is \$8.04/GJ, 27% higher than for the case where CO_2 is vented to the atmosphere (see Table 3). The cost of H_2 for the CO_2 capture/sequestration case contains a 5% contribution for the CO_2 disposal cost (see Box B).

Notably, the plant-gate cost for H_2 with venting of the CO_2 is \$0.91/gallon of gasoline-equivalent energy (gge)—not much higher than the average U.S. wholesale (refinery gate) gasoline price of \$0.88/gallon in 2000. But getting H_2 to consumers at motor vehicle refueling stations from the H_2 production facility via pipelines adds considerably to the cost seen by the

TABLE 3 Producing H_2 from Natural Gas (*1000 MW_t of 60-bar H_2 Output Capacity*)[a]

	CO_2 vented	CO_2 sequestered
First law efficiency (η_{1st}), HHV basis (*%*)	81	78
CO_2 Emission Rate (*kg C/GJ H_2*)	17.56	2.74
CO_2 Sequestration Rate (*t CO_2 /h*)	-	204
Capital investment except for CO_2 disposal (*$ million*)		
Equipment and installation subcontracts:		
Reformer	48.65	67.90
Purification	23.65	58.08
CO_2 compression	-	35.67
Other	123.95	174.67
Subtotal	196.25	336.32
Engineering, const. management, commissioning, training	9.13	16.94
Catalysts and chemicals	8.75	9.00
Client's costs	24.00	28.00
Contingency	23.81	39.03
Total installed capital cost	261.94	429.3
Production cost (*$/GJ*)		
Capital (*excluding CO_2 disposal*)	1.56	2.56
O&M (*except for CO_2 disposal*)	0.24	0.39
CO_2 disposal (*@ $6.73/t CO_2*)	-	0.38
NG input (*for NG @ $3.67/GJ*)	4.53	4.71
Total	6.33	8.04
Cost with a carbon tax (CT) = $115/tC	**8.35**	**8.35**
Cost w/ CT = $49.5/tC	7.20	8.18
Delivered Cost of H_2 from Natural Gas (*$/GJ*)		
Production cost	6.33	8.04
Central H_2 plant buffer storage cost *($/GJ)*, storage capacity = 1/2 day's output of H_2 plant[b]	1.63	1.63
H_2 pipeline distribution system[b]	1.29	1.29
Refueling station[b]	6.06	6.06
Total cost of delivered H_2[c]	$15.3/GJ ($2.21/gge)	$17.0/GJ ($2.46/gge)

[a] Based on a study (Foster Wheeler, 1996) prepared for Statoil and the IEA GHG Programme except that: the FW results are presented here with all energy quantities expressed on a HHV basis; the annual capital charge rate and system capacity factor are assumed to be 15% and 80%, respectively (compared to 12.4% and 90% in the original FW study), so that the annual H_2 production rate is 25.2 million GJ/year; the CO_2 disposal cost is estimated to be $6.73/t CO_2, the cost of transporting CO_2 100 km and disposal in an aquifer 2 km below ground (see Box B). For these systems all energy requirements for H_2 production are provided from natural gas. 85% of the CO_2 in the feedstock is recovered, compressed to 112 bar, and transported by pipeline to the disposal site at a disposal rate of 57 kg CO_2/GJ H_2. The natural gas price is assumed to be $3.67/GJ, the average natural gas price projected for U.S. electric generators in 2020 by the Energy Information Administration (EIA, 2001b).

[b] High auto density case (1600 cars/mi^2) developed by Ogden (1999)—equivalent to ½ the cars in the Los Angeles area being H_2 FCVs; refueling stations dispense H_2 at 345 bar to FCVs at a rate of 10^6 scf/day.

[c] The retail fuel price in $/GJ is presented on a HHV basis; the retail price in $ per gallon of gasoline equivalent energy (gge) is presented on a LHV basis.

BOX B Estimating CO_2 Disposal Costs

The CO_2 disposal cost C_D (in \$/t CO_2) is

$C_D = C_{PT} + C_{DW} + C_{SP}$, where

C_{PT} = cost of pipeline transmission,
C_{DW} = cost of disposal wells, and
C_{SP} = cost of surface piping near disposal wells.

Ogden (2002) has developed a CO_2 disposal cost model for CO_2 sequestration in deep saline aquifers, when CO_2 is made available at the energy conversion plant at a pressure of 150 bar. She has verified via consultation with industrial experts that the major cost items such as CO_2 pipeline costs are consistent with current industrial practice. For all cost components, capital costs are converted to annualized costs assuming a 15% annual capital charge rate and annual O&M costs equal to 4% of the capital cost.

Pipeline transmission. Ogden estimates for a CO_2 flow rate of Q (tonnes/day) and pipeline length L (km) that the capital cost per unit length (\$/m) is Cost (Q,L) = \$700/m x $(Q/Qo)^{0.48}$ x $(L/Lo)^{0.24}$, where Qo = 16,000 tonnes/day and Lo = 100 km. Assuming disposal at L = 100 km, the corresponding annualized cost is C_{PT} = \$3.51/t CO_2 (\$5.27/t CO_2) for the 1,000 MW_h H_2 from coal plant described in Table 4 (H_2 from natural gas plant described in Table 3).

Disposal wells. Ogden estimates the capital cost per disposal well as $Cost_{well}$ = \$1.52 million + (\$1.22 million/km) x [depth (km)]. Assuming wells are 2 km deep, the capital cost per well is \$4.0 million, and the annual cost per well is \$0.752 million/well. Thus if N wells are required, C_{DW} = (N wells)*(\$0.752 million/w)/(Q*0.80*365 d/y). The number of wells N = Q/q_w, where q_w is the injection rate per well, assumed to be the lesser of the injectivity (the maximum rate of injection based on various reservoir parameters such as reservoir thickness and permeability) and a maximum rate of 2,500 t/d dictated by engineering constraints. For all the cases considered here (reservoir thickness of 50 m and permeability of 40 millidarcies or more) the engineering constraint determines the injection rate. For the H_2 plant described in Table 4 for coal (Table 3 for natural gas), N = 4 (2), so that C_{DW} = \$0.96/t CO_2 (\$1.05/t CO_2).

Surface piping costs. The amount of and costs for surface piping near the wells depend on the number of wells. For the coal (natural gas) plant described in Table 4 (3a), 37 (12) km of piping is required, and the corresponding capital costs are \$9.0 million (\$3.1 million) so that C_{SP} = \$0.55/t CO_2 (\$0.41/t CO_2).

Thus C_D = \$5.02/t CO_2 (\$6.73/t CO_2) for H_2 from coal, Table 4 (H_2 from natural gas, Table 3).

consumer (assuming H_2 is stored onboard vehicles as a gas compressed to 345 bar), increasing the retail H_2 cost to \$2.21/gge with CO_2 venting and \$2.46/gge with CO_2 sequestered (see Table 3); for comparison, the retail price of gasoline in the United States was \$1.14/gallon[19] in 2000.

The high retail H_2 cost is not necessarily a “show-stopper,” however, because H_2 fuel-cell cars will typically be more fuel efficient than alternatives [e.g., 82 mpgge vs. 27 mpg for a typical new gasoline car or 46 mpg for an advanced gasoline ICE car (see Table 1)], so that the fuel cost per mile would be 3.0¢/mile for a fuel cell car powered by H_2 from natural gas with CO_2 capture/sequestration—roughly midway between the 3.5 ¢/mile fuel cost for today’s typical new (27 mpg) gasoline car and the 2.1¢/mile cost for an advanced (46 mpg) gasoline ICE car.

Separating out and sequestering the CO_2 does not contribute much to fuel costs. As shown in Table 3, the retail cost of natural gas-derived H_2 is 11% more for the case where 85% of the carbon in the natural gas feedstock is separated out as CO_2 in H_2 manufacture and transported to a geological disposal site where it is injected into storage wells. This penalty could be reduced or possibly eliminated in some cases if there were opportunities for using the separated CO_2 for enhanced oil or coal bed methane recovery (see the section below on the outlook for disposal of CO_2).

Hydrogen from Coal

Interest in coal stems from several considerations. First, coal is a much more abundant resource than natural gas. At the global level, estimated ultimately recoverable coal resources amount to about 200,000 EJ—enough to support total global fossil energy use for 580 years at the current rate; for comparison, estimated ultimately recoverable conventional natural gas resources amount to about 17,000 EJ[20] (Rogner, 2000). Second, coal is much less costly than natural gas and is expected to become cheaper still: in 1999 the average price in the United States paid by electric generators for natural gas was 2.2 times the average coal price, and the Energy Information Administration projects that this ratio will increase to 4.0 by 2020, as a result of an expected natural gas price growth rate of 1.6%/year compared to an expected 1.0%/year rate of decline for the coal price in this period (EIA, 2001b). And third, as will be shown, the prospective costs for coal-derived H_2 at large scales appear to be more promising than for natural-gas derived H_2–especially for cases involving CO_2 disposal.

What follows is a presentation of findings of a study (Chiesa, Kreutz, and Williams, 2002)[21] exploring the technology and estimating the cost of making from coal H_2 plus byproduct electricity, both with CO_2 vented and with CO_2 captured and sequestered (see Figure 2).[22] Although the focus is on H_2 production for transportation applications, cases for which only electricity is provided via a coal integrated gasifier combined cycle (IGCC) power plant, both with CO_2 vented and with CO_2 captured and sequestered (see Figure 3) are also presented. The technologies involved in H_2 production and coal IGCC power generation with CO_2 capture/sequestration are very similar (compare Figures 2 and 3).

Making H_2 from coal without CO_2 capture/sequestration involves (see Table 4): (1) gasifying coal in oxygen[23] and steam at 70 bar to produce synthesis gas (mostly CO and H_2); (2) cooling and humidifying the synthesis gas (for downstream water-gas-shift reactions) and scrubbing it of water-soluble contaminants; (3) reacting the cooled synthesis gas with steam in a high-temperature water-gas-shift (WGS) reactor equipped with an H_2S-tolerant WGS catalyst; (4) cooling the partially shifted synthesis gas; (5) reacting this cooler synthesis gas with steam in a low-temperature shift reactor; (6) cooling the shifted synthesis gas to 25 ^{o}C, removing the H_2S using a glycol solvent, and condensing out much of the water from the cooled synthesis gas; (7) converting the recovered H_2S to elemental sulfur (in a Claus plant); (8) passing the H_2S-depleted synthesis gas through a PSA unit in order to separate out from the synthesis gas relatively pure H_2 (85% of the potential H_2[24] in the synthesis gas); (9) delivering the purified H_2 exiting the PSA unit at 60 bar via pipeline to distributed users; and (10) burning the "purge gas"[25] from the PSA unit in a boiler for electricity generation in a steam turbine.[26] For this process the "effective efficiency" of converting coal into H_2[27] is 70.3% (see Table 4).

For the case where CO_2 is sequestered, the initial processes would be the same. But after H_2S removal, the H_2S-depleted synthesis gas would be delivered to a chamber where another glycol solvent (e.g., Selexol) would remove CO_2. After it absorbs the CO_2, this solvent would be regenerated (mainly by pressure reduction) to release the CO_2, which would then be dried (to 20-50 ppm moisture), compressed to 150 bar, and sent via pipeline to an appropriate geological disposal site. The CO_2-depleted synthesis gas would be delivered to a PSA unit for H_2 purification. As before, the purified H_2 exiting the PSA unit at 60 bar would be delivered via pipeline to distributed users. But in this case the purge gas released on depressurization of the PSA beds (undiluted by CO_2) would be compressed and burned in the combustor of a combined-cycle power plant to produce more coproduct electricity than would be feasible when CO_2 is not separated out for disposal. For the CO_2 capture/sequestration case, the effective efficiency of converting coal into H_2 is 67.7% (see Table 4). Although the plant for manufacturing H_2 from coal with CO_2 capture/sequestration sketched in Figure 2 and described in Table 4 has not been built, no new technology is involved: all components have been widely used in other applications—so the technology can be described as "commercially ready."

The total cost of producing H_2 from coal is estimated to be seven to eight percent less than for H_2 produced via steam reforming of natural gas (compare Tables 3 and 4). These cost relationships are for the coal and natural gas prices of \$0.92/GJ and \$3.67/GJ, respectively, assumed here for 2020. For 1999 prices (\$1.2/GJ for coal and \$2.5/GJ for natural gas) natural gas-derived H_2 would be less costly with both CO_2 venting and CO_2 capture/sequestration. The natural gas price at which H_2 would be the same for natural gas and coal is about \$3.3/GJ when the coal price is \$0.92/GJ.

Very few analyses have been published on the costs of making H_2 from coal. However, the H_2 cost calculations presented in Table 4 can be partially benchmarked by a comparison of the costs of electricity generation in this table with CO_2 venting and CO_2 capture (4.57 ¢/kWh and 5.76 ¢/kWh, respectively) with the costs for the same electric conversion technologies developed in a recent report prepared for the Electric Power Research Institute and the Office of Fossil Energy of the U.S. Department of Energy (4.53 ¢/kWh and 5.71 ¢/kWh, respectively—see Table 5). This good agreement is relevant to the H_2 production analysis because, as noted earlier, the technologies for H_2 production and coal IGCC power generation with CO_2 capture/sequestration are very similar (compare Figures 2 and 3).

The finding that coal-derived H_2 may well be competitive with natural gas-derived H_2 at 2020 coal and natural gas prices warrants discussion in light of the greater capital intensities[28] and lower conversion efficiencies[29] for the coal systems. Making H_2 from coal is more capital-intensive than from natural gas because of the high capital costs for the gasifier, the air separation unit (for O_2 manufacture), and the sulfur removal equipment. But this capital intensity is offset by the much lower feedstock cost for coal.

The finding that the incremental cost for CO_2 separation/sequestration is about the same for natural gas (\$1.7/GJ of H_2–see Table 3) and for coal (\$1.6/GJ of H_2—see Table 4) is counterintuitive, because the amount of CO_2 that must be sequestered per unit of H_2 produced is twice as large for coal as for natural gas. But the relatively high pressure of the synthesis gas in the coal system compared to the natural gas system contributes to cost lowering. The partial pressure of CO_2 in the synthesis gas for the natural gas case is so low that chemical (amine) solvents must be used, whereas less-costly physical (glycol) solvents can be used at the high partial pressures for coal. Moreover, because the efficacy of CO_2 scrubbers requires limiting the gas velocity through the scrubbers, the much higher volumetric flow rate (in *actual* m^3/h) for the natural gas cases requires using more scrubbers in parallel, which leads to higher relative cost per unit of CO_2 removed (private communication from Paolo Chiesa, September 2001).[30]

TABLE 4 Producing Electricity and H_2 from Coal at 1000 MW_h and 60 bar[a]

	Electricity only,[b] with CO_2:		H_2 + electricity,[c] with CO_2:	
	Vented	Seq.	Vented	Seq.
Coal input rate (*MW_{th}*)	984	1046	1550	1554
CO_2 emission rate	grC/kWh		kgC/GJ_{H2}	
	195.3	15.9	36.33	2.62
CO_2 disposal rate (*t CO_2/h*)	-	300.6	-	445.9
Electric power balance (*MW_e*)				
Gas turbine output	321.2	319.4	-	58.9
Steam turbine output	184.7	173.1	143.5	107.1
Syngas expander output	7.2	9.9	-	-
Air separation	- 26.6	- 28.2	- 41.8	- 41.9
Extra O_2 compressor	- 16.2	- 17.2	- 25.5	- 25.6
Gasification auxiliaries	- 9.3	- 9.9	- 14.7	- 14.7
CO_2 compressor (→ *150 bar*)	-	- 25.0	-	- 37.0
Purge compressor for PSA unit	-	-	-	- 8.6
N_2 compressor	- 29.6	- 27.3	-	-
Other auxiliaries	- 6.2	- 7.1	- 6.4	- 5.2
Net power output	425.2	387.7	55.1	33.0
1st law efficiency (η_{1st}), HHV basis (*%*)[d]	43.19	37.07	68.07	66.47
Eff. Efficiency (η_{eff}) of H_2 production (%)[d]	-	-	70.30	67.68
Plant capacity factor (*%*)	80	80	80	80
Capital cost by component (*$\$10^6$*)				
Coal storage, preparation, handling	41.40	43.19	56.87	57.00
Air separation unit	75.03	78.07	126.35	126.63
Extra O_2 compressor	15.47	16.02	20.60	20.65
Gasifier	94.21	98.29	129.43	129.72
Water gas shift reactors	-	26.36	34.72	34.79
Glycol H_2S removal	60.82	63.45	83.56	83.74
Selexol CO_2 or CO_2/H_2S removal	-	27.19	-	35.89
PSA H_2 separation	-	-	42.91	42.91
Gas turbine	105.23	105.45	-	26.62
HRSG and steam turbine	119.87	113.81	97.93	77.53
N_2 compressor	16.49	15.71	-	-
CO_2 drying and compression	-	30.45	-	45.09
Subtotal, overnight construction cost[e]	528.5	617.99	592.4	680.57
Interest during construction[e]	84.7	99.0	94.93	109.06
Total installed cost[e] (*$\$10^6$*)	613.2	717.0	687.3	789.6
Energy production cost by component	Electricity (*¢/kWh*)		H_2 (*\$/GJ*)	
Capital (*ACCR = 15%, CF = 80%*)	3.09	3.96	4.09	4.69
O&M (*4% of "overnight" capital/y*)	0.71	0.91	0.94	1.08
Coal input (*@ \$0.92/GJ*[f])	0.77	0.89	1.43	1.43
CO_2 disposal[g]	-	0.46	-	0.62
Electricity credit[h] (*P_E = electricity price in \$/kWh*)	-	-	-15.29*P_E	- 9.15*P_E
Cost with carbon capture but excluding (including) CO_2 disposal cost and assuming NGCC value (5.0 ¢/kWh) for electricity byproduct of making H_2	4.57 (4.57)	5.76 (6.22)	5.70 (5.70)	6.74 (7.36)
Cost (including CO_2 disposal cost) w/ CT = \$92.0/tC	**6.37**	**6.37**	9.08	7.63
Cost (including CO_2 disposal cost) w/ CT = \$48.3/tC	5.51	6.30	**7.55**	**7.55**

NOTES:

[a] Energy balances/material flows (Chiesa, Kreutz, and Williams, 2002) were calculated using GS power generation and chemical process software developed at the Dipartimento di Energetica, Politecnico di Milano, Milan,

Italy. All cases involve the Texaco O_2-blown gasifier with quench (at 70 bar) and high sulfur (S) coal (3.9% S, dry coal basis). CO_2 recovery cases involve CO_2 compression to 150 bar for pipeline transport to a sequestration site.

[b] Technology w/o CO_2 separation/recovery is an IGCC with a steam-cooled gas turbine; glycol solvents are used to recover H_2S, which is converted to S. Technology with CO_2 separation/recovery is the same IGCC except that shift reactors are added where steam reacts with CO to form CO_2 and H_2, and Selexol (a glycol solvent) is used to remove simultaneously H_2S and CO_2 from the shifted synthesis gas; 92.7% of C is recovered as CO_2 for disposal.

[c] Technology without CO_2 separation/recovery involves: gasifier plus shift reactors; a glycol solvent to recover H_2S, which converted to S; pressure-swing-adsorption (PSA) unit to separate out H_2; steam turbine fueled by PSA purge gas. For the "sequestration" case, a glycol solvent is used to remove H_2S, which is recovered and converted to elemental sulfur; Selexol is used to remove CO_2 from the shifted synthesis gas for disposal; a pressure-swing-adsorption (PSA) unit is used to purify the H_2; a PSA purge gas compressor is used to compress the purge gas for use in a combined cycle providing coproduct power; 92.7% of coal C is recovered as CO_2 for disposal.

[d] η_{1st} = (electricity + H_2 output)/(coal input); η_{eff} = (H_2 output)/(coal input – coal saved), where the coal saved is the coal avoided by not having to produce the electricity coproduct in a stand-alone facility. The power generation efficiency assumed in calculating coal saved is for the least costly electricity option with zero carbon tax.

[e] The installed capital cost includes interest during construction (assuming a 10% interest rate and a 4-year construction period). Costs for CO_2 separation and compression are included but not the cost of CO_2 disposal (pipeline plus disposal wells and surface facilities), which are treated separately below.

[f] The $0.92/GJ coal price is the projected average price for US electric generators in 2020 (EIA, 2001b).

[g] The CO_2 disposal cost C_D (in \$/t CO_2) is $C_D = C_{PT} + C_{DW} + C_{SF}$, where C_{PT} = cost of pipeline transmission, C_{DW} = cost of disposal wells, and C_{SF} = cost of surface facilities near disposal wells. The following cost estimates are for aquifer disposal at a site 100 km from the energy conversion facility, based on Ogden (2002). For a 15% annual capital charge rate, annual O&M costs of 4% of capital cost, and an 80% capacity factor. These costs are $C_D = 3.51 + 0.96 + 0.55 = \$5.02$/t CO_2 for coal H_2 and $C_D = 4.31 + 1.07 + 0.52 = \$5.90$/t CO_2 for coal electricity.

[h] The electricity value P_E depends on the carbon tax. P_E equals the cost of the electricity from the least-costly option—assumed to be a natural gas combined cycle power plant (see Table 5) when the carbon tax is $120/tC.

TABLE 5 Performance and Electricity Generation Cost for Alternative Fossil Fuel Power Plants as Estimated by the Electric Power Research Institute[a] (*CO_2 vented vs. CO_2 captured*)

Technology	Emissions (*grC/kWh*) with CO_2:		Efficiency (*%, HHV basis*) with CO_2:		Busbar cost (*¢/kWh*) with CO_2:							
					Vented				Captured			
	vent-ed	captured	vented	captured	Capital	O&M	Fuel	Total	Capital	O&M	Fuel	Total
NGCC[b]	92.2	10.9	53.6	43.3	1.16	0.28	2.46	3.90	2.20	0.73	3.05	5.98
Coal IGCC[c]	196	20.0	43.1	37.0	3.04	0.72	0.77	4.53	3.95	0.86	0.90	5.71

NOTES:

[a] Based on PE&CG and WITS (2000) except that: (*i*) coal/natural gas prices are assumed to be $0.92/$3.67, respectively (compared to $1.18/GJ/$2.56/GJ, respectively, in the original report), average prices projected for U.S. electric generators in 2020 (EIA, 2001b); (*ii*) the annual capital charge rate and capacity factor are assumed to be 15%/y and 80%, respectively (compared to 13.8%/y for coal and 12.2%/y for natural gas and 65%, respectively in the original report), to make the calculations consistent with those in Tables 3 and 4.

[b] Natural gas combined cycle (NGCC) unit based on GE Frame 7H gas turbine with steam-cooled turbine blades; output: 384.4/310.8 MW_e; capital cost: \$540/\$1026 per kW_e; fixed O&M (FOM) cost: $10.81/$17.70 per kWh-y; variable O&M (VOM) cost: 0.13/0.48 ¢ per kWh—with CO_2 vented/captured.

[c] Coal integrated gasifier combined cycle (IGCC) unit based on GE Frame 7H gas turbine with steam-cooled turbine blades; output: 424.5/403.5 MW_e; capital cost: \$1420/\$1844 per kW_e; FOM cost:$28.86/$32.98 per kWh-y; VOM cost: 0.31/0.39 ¢ per kWh—with CO_2 vented/captured.

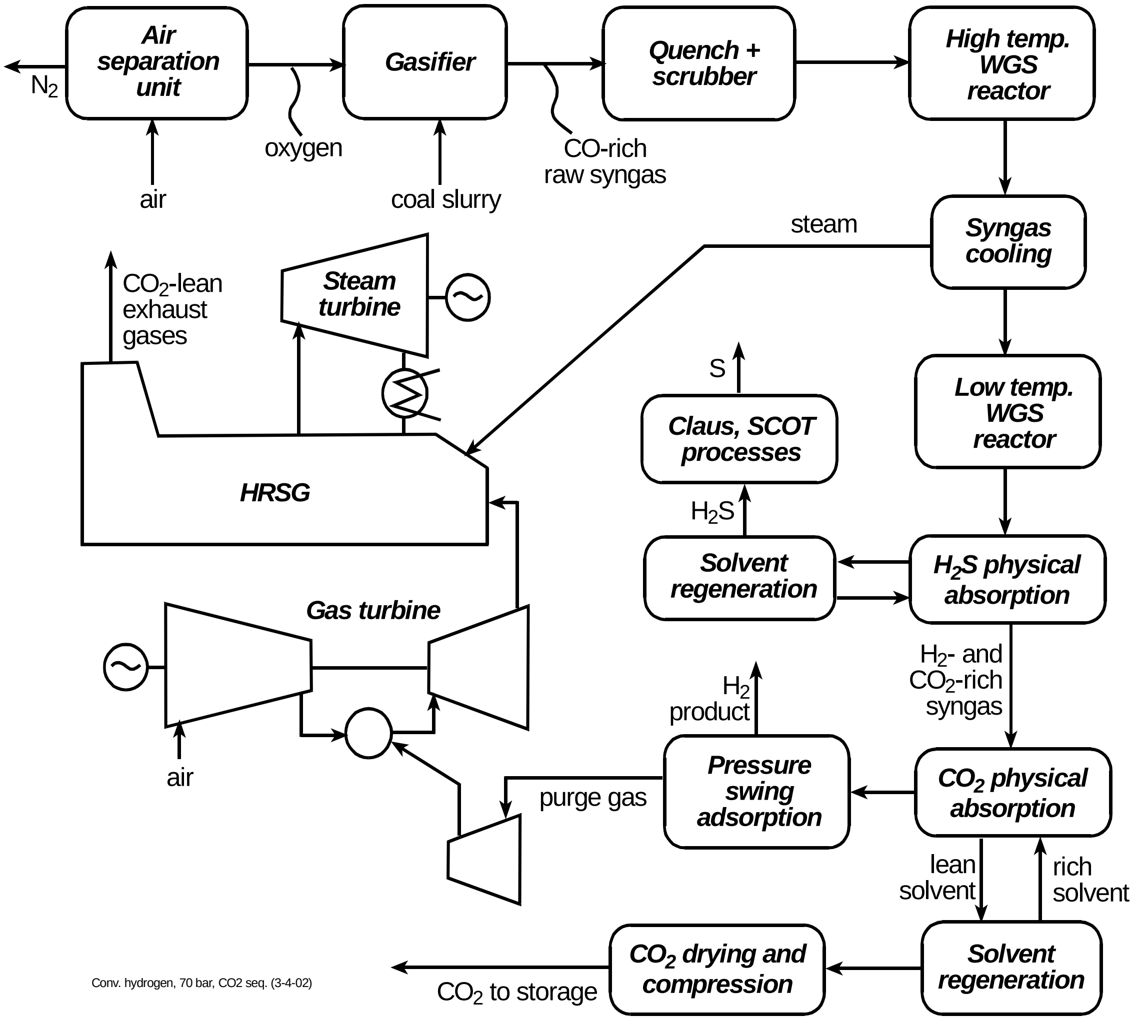

FIGURE 2 Production of H_2 from Coal with Near-Zero CO_2 Emissions Using Commercially Ready Technology

The analysis presented in Table 3 is for H_2 production from natural gas based on steam reforming technology, for which practical operating pressures are of the order of 25 bar. As noted above, the low incremental cost for CO_2 sequestration with coal systems compared to natural gas systems is due in large part to the high synthesis gas pressures that are practically realizable with gasification systems. An alternative approach for making H_2 from natural gas is autothermal reforming, where the heat needed for reforming is provided by burning in place some natural gas in oxygen instead of through a heat exchanger. For such systems the synthesis gas pressures can theoretically be 100 bar or more (Dybkjaer and Madsen, 1997/1998). With such high operating pressures, it might be feasible to close at least partially the “incremental cost gap for sequestration” between natural gas and coal that arises when H_2 is produced from natural gas via steam reforming. However, the economic viability of autothermal technology relative to

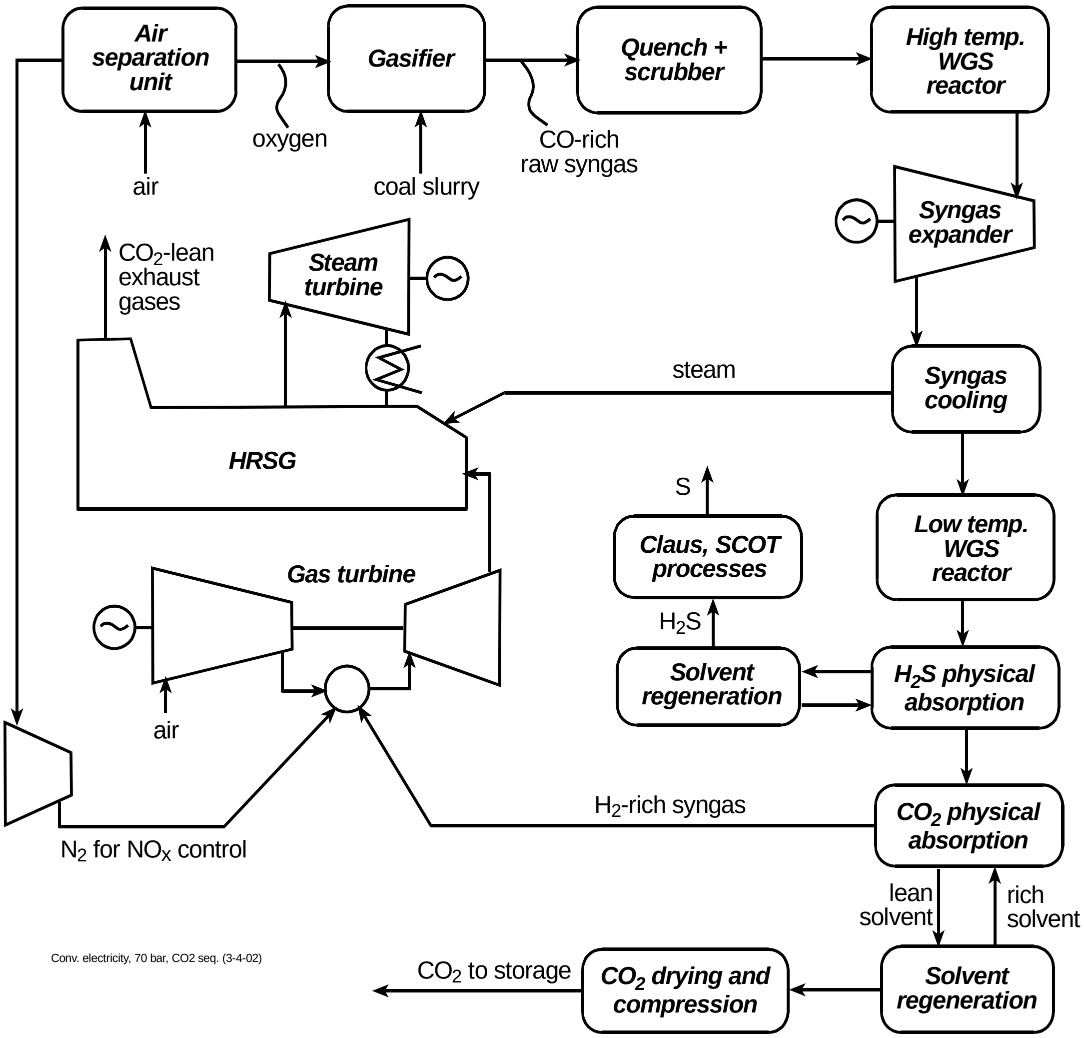

FIGURE 3 Production of Electricity from Coal with Near-Zero CO_2 Emissions Using Commercially Ready Technology

steam reforming technology in large plants depends on the availability of relatively low-cost oxygen (Dybkjaer and Madsen, 1997/1998). Any advanced technology (such as ion transport membranes for oxygen from air as an alternative to cryogenic separation) that would reduce the cost of oxygen would be helpful to coal gasification-based H_2 production as well as to natural gas autothermal-reforming-based H_2 production.

There are many other advanced technologies that might also improve the economics of H_2 production from coal—including gasification at higher pressures (e.g., up to 120 bar) (Chiesa, Kreutz, and Williams, 2002), co-sequestration of H_2S along with CO_2[31] which would make it possible to avoid the costs associated with sulfur recovery (Chiesa, Kreutz, and Williams, 2002) and use of various membranes for separating H_2 from CO_2 and other gases (Kreutz and Williams, 2002).

The lifecycle environmental damage assessment for coal presented in Table 1 is incomplete, because it does not include estimates of damage costs for acid mine drainage and land degradation resulting from coal mining. If H_2 production from coal were to become widespread, tough regulations or tax measures aimed at keeping such damages to low levels would be needed. It is very likely that such policies would not hamper the coal industry much in evolving a coal future characterized by near-zero air emissions. Coal resources are so abundant that if environmental regulations were to impede coal mining activities in some areas,[32] new mining activities would instead be pursued elsewhere where compliance with tough environmental rules could be readily achieved. Moreover, the historical record indicates that the U.S. coal industry has been able to adjust quickly to tough new environmental rules (Williams, 1999a).

Carbon Price Required to Induce CO_2 Capture/Sequestration

An energy carrier manufacturer will not be willing to capture/sequester CO_2 unless so doing is economically worthwhile. In some instances there will be economic opportunities for enhanced hydrocarbon resource recovery via CO_2 injection into geological reservoirs where the CO_2 would be sequestered (see "Outlook for CO_2 Disposal" below). But if CO_2 capture/sequestration were to become a major activity of the fossil energy industry, most CO_2 sequestration would be associated with disposal options for which there are no resource recovery opportunities. Sequestration would be considered only if climate change concerns led to the levy of a carbon tax (or the equivalent[33]) The minimum tax needed is one such that the cost of energy (H_2 or electricity) with CO_2 capture/sequestration is equal to the cost with CO_2 venting—an equality that defines the cost of CO_2 emissions avoided.

For the technologies investigated here the minimum carbon tax is \$115/tC for natural gas-derived H_2, \$49/tC for coal-derived H_2, and \$92/tC for coal IGCC-derived electricity for the systems described in Tables 3 and 4. For the H_2 cases these taxes are for the situation where there are energy markets for H_2 produced with CO_2 venting. To help put these carbon taxes into perspective, consider that a \$50/tC carbon tax is equivalent to a tax of 12¢ a gallon on gasoline.

The carbon tax required to induce CO_2 capture/sequestration for coal-derived H_2 is much lower than for natural gas-derived H_2 for the same reasons that the incremental cost of CO_2 capture/sequestration is less. For the coal case, the required carbon tax is much less for H_2 than for electricity in large part because, whereas the water-gas-shift reactors are key to H_2 manufacture so that their costs are charged to H_2 production, these costs are charged to carbon in the electricity case, because they are needed only for mitigating climate change.

The levy of a \$50/tC carbon tax would be adequate to induce CO_2 capture/sequestration for coal-derived H_2, but not for natural gas-derived H_2. Rather, the producer of natural gas-derived H_2 would choose to vent CO_2 and pay the carbon tax. For the assumed coal and natural gas prices and with a \$50/tC carbon tax in place, natural gas-derived H_2 with CO_2 venting would still be competitive with coal-derived H_2 with CO_2 captured/sequestered,[34] even though the CO_2 emission rate for the natural gas case would be nearly 7 times as large.

Electrolytic H_2

An alternative to making H_2 from fossil fuels with CO_2 sequestration is to make it by breaking apart water molecules using electricity from either nuclear or renewable electric supply sources.

Consider that among renewables, wind power is the closest to being cost-competitive with fossil-fuel-based power, with generation costs of \$0.04-\$0.05/kWh today in areas of good wind resources; moreover, wind power costs are expected to continue to fall; one recent forecast is that, for good (Class 6) wind resources, costs will fall to \$0.029/kWh[35] by 2020 (EPRI/OUT, 1997). A large wind farm providing power at this price coupled to a compressed air energy storage (CAES) unit could provide baseload electricity at a relatively modest incremental cost (Cavallo, 1995). Such baseload electricity from a remote wind farm in turn could be transported via a high-voltage transmission line at low incremental cost to an urban center where it might be used to make H_2 electrolytically for transport applications. It is estimated that the cost of such baseload electricity delivered 300 km to a "city gate" would be about \$0.04/kWh[36,37]—less than the cost of electricity from a coal IGCC plant with venting of the CO_2, as estimated in Tables 4 and 5. With advanced electrolytic conversion equipment that could become widely available by 2020, the cost of H_2 derived from wind power at \$0.04/kWh would be \$15-\$16GJ in a large city-gate plant (see Table 6). Neglecting the damage costs from GHG emissions associated with the wind power system,[38] the cost of the electrolytic H_2 so produced with advanced electrolytic technology would be twice as costly as H_2 produced from coal with CO_2 sequestration using commercially ready technology (compare Tables 4 and 6). From the perspective of the H_2 fuel cell car owner, lifetime environmental damage costs for the wind H_2 case would be \$130 less per car than for H_2 from coal with CO_2 captured/sequestered, but this advantage would be dwarfed by the direct economic cost disadvantage (~ \$960 per car) arising from the higher retail H_2 price (\$3.5/gge for wind vs. \$2.5/gge for coal)—see Table 1.

The prospects are not bright that advanced technology will one day help electrolytic H_2 emerge as the economic winner. Even assuming advanced electrolysis technologies the economics of electrolytic H_2 production from any carbon-free electricity source would always be unattractive unless there are "fatal flaws" associated with the option of sequestering the CO_2 byproduct of making H_2 from fossil fuels. Consider the electricity price required for breakeven. Assuming baseload (80% capacity factor) electricity, the electricity price for a carbon-free source would have to be ~ 1.8 ¢/kWh in order for electrolytic H_2 based on advanced electrolytic technology to be competitive with H_2 from coal with CO_2 capture/sequestration using commercially ready technology (Table 4). It is unlikely that electricity prices less than 2 ¢/kWh will be routinely achievable with either nuclear or renewable electric technologies—at least over the course of the next several decades. Offpeak hydroelectric power prices are typically this low or lower, however, and variable nuclear costs might plausibly become low enough to put nuclear offpeak prices in the targeted range as well (see, for example, Table 9). However, offpeak pricing strategies would be appropriate only for the situation where H_2 production is a minor activity relative to electricity generation, so that power generation could shoulder capital and other fixed charges. But in a GHG emissions-constrained world, H_2 is likely to be required in the late 21st century at levels far in excess of the level of power generation,[39] so that fixed charges must be allocated to H_2 production.

So, for the long term, electrolytic H_2 generated via either nuclear or renewable electric sources is not promising economically and neither would be considered as a major energy option in this century unless the CO_2 sequestration option proves to be unworkable. It might be considered in the longer term (more than a century into the future), when geological storage capacity limits for CO_2 are approached.

TABLE 6 Performance and Costs for Centralized H_2 Production Using Advanced Electrolytic Technologies[a]

	Capital cost/performance targets			Plantgate cost breakdown *($/GJ, HHV basis)*					
Electrolyzer technology				Electrolysis				H_2 compression[h]	Total
	Capital cost[b] *($/kW$_h$)*	Pressure *(bar)*	η[c] (%)	Capital[d]	O&M[e]	Electricity[f]	O_2 byproduct credit[g]		
Alkaline or PEM (*low P, T*)	300	2	83	1.78	0.36	13.39	- 1.70	1.16	15.0
Alkaline (*high P, low T*)	400	31	80	2.38	0.48	13.89	- 1.70	0.16	15.2
Solid oxide (*low P, high T*)	900	2	111	5.35	1.07	10.01	- 1.70	1.16	15.9

NOTES:

[a] For H_2 produced at a scale of 500 MW_h and compressed to 60 bar. Based on Ogden et al. (1998b).

[b] Current costs for alkaline and solid oxide electrolyzers are \$600/kW_h and \$1350/ kW_h, respectively (Odgen *et al.*, 1998b).

[c] $\eta \equiv$ [H_2 output (HHV basis)/electricity input]. Some high-temperature heat is an input to the solid oxide electrolyzer, so that in this case $\eta > 100\%$.

[d] Assuming a 15% annual capital charge rate and an 80% capacity factor.

[e] Assuming that the annual O&M cost for electrolyzers is 3% of the capital cost.

[f] Assuming baseload low-carbon electricity costing \$0.04/kWh (see note f, Table 1).

[g] Byproduct O_2 is generated at a rate of 8 t O_2 per t H_2 or (0.056 t H_2 per GJ H_2) and is assumed to have a value of \$30.4/t O_2 (see Table 7).

[h] The electricity required to compress H_2 from 2 [31] to 60 bar is 12.74 kWh_e/GJ_h (0.046 kWh_e/kWh_h) [2.47 kWh_e/GJ_h (0.0089 kWh_e/kWh_h)]. For low pressure (high pressure) electrolysis, the compressor capital cost is assumed to be \$2000/kW_e (\$1000/kW_e). The annual capital charge rate and capacity factor are assumed to be 15%/y and 80%, respectively. The annual O&M cost for compressors is assumed to be 3%. The electricity cost is assumed to be \$0.04/kWh.

TABLE 7 Cost of Making O_2 in a Cryogenic Air Separation Unit (ASU)[a] (*\$/t O_2*)

Capital cost	16.48
O&M cost	3.79
Electricity cost	10.14
Total cost	30.4

NOTES:

[a] For O_2 produced @ 3200 t/d, the maximum rate for a single-train ASU. The capital cost (including a 16% increment over the overnight construction cost for interest during 4-year construction period) = \$102.65 million (\$32,080/t/d) and the required electricity = 253.5 kWh/t O_2 (Kreutz and Williams, 2002).A 15% annual capital charge rate, an 80% capacity factor, an annual O&M cost = 4% of the overnight construction cost, and \$0.04/kWh electricity are assumed.

Hydrogen Production via Complex Thermochemical Cycles

An alternative to electrolyzing water to produce H_2 is to dissociate water using heat. To do so directly temperatures of the order of 4000 ^{o}C[40] would be needed. This cannot be accomplished at present because no known materials can contain the reactions. But various multiple-step processes have been proposed for making H_2 from water thermochemically at much lower temperatures, using either nuclear heat—heat that can be provided by a high-temperature helium gas-cooled reactor (Yoshida, 1983; Yalçin, 1989)—or high-temperature solar heat that can be provided with collectors that concentrate sunlight (Steinfeld and Palumbo, 2001).

In contrast to electrolytic processes, thermochemical processes for H_2 manufacture are far from being commercially available. A recent assessment (Brown et al., 2002a) of 115 thermochemical cycles for making H_2 from a nuclear heat source and alternative reactor concepts for providing the needed heat singled out: (1) the UT-3 (or Ca-Br) process[41] under development in Japan (at the University of Tokyo = UT) and the sulfur-iodine (S-I) process[42] being developed in the United States (at General Atomics) as warranting focused development, and (2) the high-temperature helium gas-cooled reactor as the most promising reactor that could be commercialized over the next decade or so that would be suitable for use with these processes.

For such processes, a series of reactions takes place in multiple vessels, water and heat are consumed, and both H_2 and O_2 are produced; the rest of the chemicals are recycled. Overall thermal efficiencies for converting heat into H_2 that are of the order of 50% (Yoshida, 1983). Table 8 presents an estimate of the cost of H_2 produced via the S-I process at a scale of 1200 MW_h, for an estimated process efficiency of 50% (HHV basis) in converting nuclear heat into H_2. The cost presented in Table 8[43] is 80% higher than the cost of H_2 from coal with sequestration of the separated CO_2 (see Table 4)—the least costly option for making H_2 from fossil fuels and sequestering the coproduct CO_2 assuming current technologies, but also assuming fossil fuel prices projected for 2020 by the Energy Information Administration.

For two reasons, there is probably not much room for closing the cost gap between H_2 from nuclear heat and H_2 from coal with CO_2 sequestration. First, there is probably little potential for improving the assumed process efficiency of 50%. [General Atomics researchers estimate that potential efficiencies are in the range 45-55% (Ken Schultz, private communication, April 2002)].[44] Second, the estimated cost of nuclear heat (which accounts for two-thirds of the total H_2 cost—see Table 9) is based on optimistic projections about future nuclear energy costs.[45] For the electricity-generating version of the assumed modular helium reactor (MHR), the projected capital cost is about \$1300/kW_e (see Table 9). For comparison, a survey in the late 1990s of costs for new nuclear power plants [light water reactors (LWRs)] in 18 countries indicates that installed costs range from \$1,700 to \$3,100/kW_e (Paffenbarger and Bertel, 1998).[46] Moreover, the cost goal for the next generation of LWRs is \$1,500/kW_e.[47] Also the operation and maintenance (O&M) cost projected for the electric plant in Table 9 might prove to be optimistic, as it is 70% less than the average O&M cost for U.S. nuclear plants in 1998 [1.40 ¢/kWh_e (Ryan, 1999)].

Aside from such cost considerations, in a world where nuclear technology is deployed for electricity or H_2 production at scales large enough (~ 10^4 GW_t or more by 2100) to make a substantial impact in coping with climate change, the nuclear weapons link to nuclear power would come into sharp focus as a result of uranium supply constraints during the second half of this century and a likely shift to breeder reactors—a link that may be difficult to make acceptably weak by deploying proliferation-resistant reactor/fuel cycle systems (Williams et al., 2000).

TABLE 8 Estimated Cost of Thermochemical H_2 via S-I Process (Heat from Nuclear MHR)[a] (*$/GJ$_h$*)

Capital[b]	4.35
O&M[c]	1.75
HTGR heat[d]	$C_{MHRheat}/0.50$
Credit for byproduct O_2[e]	- 1.70
Subtotal	$4.40 + C_{MHRheat}/0.50$
Total production cost for $C_{HTGRheat}$ = $4.56/GJ[f]	$13.51 ($1.95/gge)

NOTES:

[a] For H_2 production at a rate of 1,200 MW_h (4320 GJ/h) using the heat output from a cluster of four 600 MW_t modular helium reactors (MHRs), with the MHR heat output converted at 50% efficiency (HHV basis) into H_2 via the Sulfur-Iodine (S-I) thermochemical process (Brown *et al*., 2002a; private communication from Ken Schutlz, General Atomics, April 2002). The byproduct O_2 amounts to 8 t O_2/t H_2 or 0.056 t O_2/GJ H_2.

[b] For the Nth plant, the overnight construction cost for the S-I process capital cost is projected to be $315/$kW_t$ (Brown *et al*., 2002a; private communication from Ken Schultz, General Atomics, April 2002). Assuming a four-year construction period and a 10% interest rate, the total capital required is 16% more—$365/kWt ($101,500 per GJ_t/h) of heat input or $203,000 per GJ_h/h of H_2 output. A 15% capital charge rate and plant operation at 80% annual capacity factor are assumed.

[c] The annual O&M cost is projected to be 7% of the overnight construction cost (private communication from Ken Schutlz, General Atomics, April 2000).

[d] $C_{MHRheat}$ is the cost of heat (in $/GJ) from the MHR.

[e] It is assumed that the byproduct O_2 is worth the cost of producing it at an air liquefaction plant. From Table 7, the estimated value is $30.4/tonne.

[f] The cost of nuclear heat is assumed to be 1.64 ¢/kWh_t (see Table 9) or $4.56/$GJ_t$. The contribution of nuclear heat to the cost of H_2 is $9.11/$GJ_h$.

TABLE 9 Estimated Cost of Electricity or Heat from a Nuclear MHR[a]

	Electricity (*¢/kWh*$_e$)	Heat (*¢/kWh*$_t$)
Capital cost	2.80	1.00
Fixed O&M	0.38	0.18
Variable O&M	0.06	0.03
Fuel cost	0.91	0.43
Total cost	4.15	1.64

NOTES:

[a] The 4-module MHR generates heat at a rate of 2,400 MW_t that is converted either into electricity @ 47.7% efficiency (4 x 286 = 1,144 MW_e installed capacity) or delivered to a S-I thermochemical H_2 plant—see Table 8 [Brown *et al*., 2002a: private communication from Ken Schultz, General Atomics (GA), April 2002].

[b] The projected overnight construction cost for the N^{th} GT-MHR is $1126/$kW_e$; the same plant without the turbogenerator but with the addition of a heat exchange loop for connection to the hydrogen process plant would have a projected overnight construction cost of $844/$kW_e$ or $403/$kW_t$ (Brown *et al*., 2002a; private communication from Ken Schultz, GA, April 2002). Assuming a 4-year construction period and a 10% interest rate, the total capital required (including interest during construction) is 16% more—$1306/$kW_e$ for power and $467/$kW_t$ for heat. A 15% annual capital charge rate and plant operation at 80% annual capacity factor are assumed.

[c] The estimated fixed O&M cost is $30.4 million/y, including $1.13 million/y for decommissioning (private communication from Ken Schultz, GA, April 2002).

[d] Variable O&M cost estimates are from Ken Shultz, GA (private communication, April 2002).

[e] Nuclear fuel cost = $1.2/$GJ_t$ (private communication from Ken Schultz, GA, April 2002)

In light of its relatively high cost and concerns about the nuclear weapons link at high levels of nuclear energy development, thermochemical H_2 would not be considered seriously unless geological sequestration of CO_2 associated with fossil energy-derived H_2 proves to be unworkable. The option might be considered in the longer term (more than a century into the future) when geological storage capacity limits for CO_2 are approached.

OUTLOOK FOR CO_2 DISPOSAL

What are the prospects for safe disposal of CO_2? The options include CO_2 storage in both the deep ocean and porous geological media. Although ocean disposal has received the most attention, environmental concerns and other large uncertainties in its prospects have led to a shift of focus in recent years to geological (underground) storage of CO_2—in depleted oil and natural gas fields (including storage in conjunction with enhanced oil and natural gas recovery), in uneconomic (e.g., deep) coal beds [in conjunction with enhanced coal bed methane (CBM) recovery], and in deep saline aquifers (Williams et al., 2000; Bachu, 2001).

CO_2 injection for enhanced recovery of oil (Blunt, Fayers, and Orr, 1993), natural gas (van der Burgt, Cantle, and Boutkan, 1992; Blok et al., 1997), and CBM (Byrer and Guthrie, 1999; Gunter et al., 1997; Stevens et al., 1999; Williams, 1999b) might become profitable foci of initial efforts to sequester CO_2.

There are about 74 enhanced oil recovery (EOR) projects worldwide, mostly (66) in the United States, where in 2000 oil production via EOR reached 216,000 barrels per day (4% of total U.S. oil production), a byproduct of which is the sequestration of 30 million tonnes of CO_2 annually. Most of the injected CO_2 comes from natural reservoirs of CO_2,[48] but 5 million tonnes per year comes from anthropogenic waste CO_2 sources (Stevens, Kuuskraa, and Gale, 2000).

In western Canada, where natural reservoirs of CO_2 are not available, natural gas rather than CO_2 injection is mostly used for EOR. However, recent analysis indicates that for oil prices of about $20 per barrel recovery of CO_2 from flue gases of coal power plants and use for EOR in the region would often be profitable (Edwards, 2000). It follows that EOR in the region based on CO_2 recovered from synthesis gas would typically be even more profitable, because separation of CO_2 from synthesis gas would be less costly. Indeed, one project launched in 2000 involves transporting for EOR applications byproduct CO_2 from a North Dakota (United States) plant making synthetic natural gas from coal to the Weyburn oil field in Saskatchewan (Canada); the 300 km pipeline carries 1.5 million tonnes of CO_2 annually to this EOR site.

Another potential option is CO_2 injection for enhanced recovery of methane from beds of unminable coal. Large amounts of methane are trapped in the pore spaces of many coals. Injection of CO_2 into such coals can sometimes lead to efficient methane recovery because typically CO_2 is twice as adsorbing on coal as is CH_4; it can therefore efficiently displace the CH_4 adsorbed on the coal (Gunter et al., 1997). As CO_2 moves through the reservoir it displaces CH_4; the limited experience to date indicates that very little of the injected CO_2 shows up in the production well until most of the CH_4 has been produced (Gunter et al., 1997), so that the prospects for permanent sequestration of the injected CO_2 appear to be good. Of course, CO_2 sequestration in the coal bed would prevent subsequent mining of the coal. However, deep or otherwise unminable coal beds for which coal mining is uneconomic might prove to be attractive for CBM recovery and CO_2 sequestration, because large amounts of the coal in the ground are unminable.[49] Unlike EOR, enhanced recovery of CBM via CO_2 injection is not commercially established technology, although an independent CBM producer has been carrying out a commercial pilot application of CO_2 injection for enhanced CBM recovery in the San Juan Basin of the United States since 1996 (Stevens et al., 1999).

Sequestration of CO_2 in depleted oil and gas fields is generally thought to be a secure option if the original reservoir pressure is not exceeded (van der Burgt, Cantle, and Boutkan, 1992; Summerfield *et al*., 1993). One estimate of the prospective global sequestering capacity of such reservoirs associated with past production plus proven reserves plus estimated undiscovered conventional resources is 100 and 400 GtC for oil and gas fields, respectively (Hendriks, 1994); other estimates are as low as 40 and 90 GtC for depleted oil and gas fields, respectively, plus 20 GtC associated with enhanced oil recovery (IPCC, 1996). The range of estimates is wide because reservoir properties vary greatly in suitability for storage, and because oil and gas recovery may have altered the formations and affected reservoir integrity; moreover, much of the prospective sequestering capacity will not be available until these fields are nearly depleted of oil and gas.

Deep saline aquifers are much more widely available than oil or gas fields. Such aquifers are present in all sedimentary basins, the total area of which amounts to 70 million km^2 (two-thirds onshore and one-third offshore)—equivalent to more than half of the 130 million km^2 of land area of the inhabited continents. Some sedimentary basins offer better prospects for CO_2 storage than others (Hitchon et al., 1999; Bachu and Gunter, 1999; Bachu, 2001). To achieve high storage densities, CO_2 should be stored at supercritical pressures,[50] which typically requires storage at depths greater than 800 m.[51] The aquifers at such depths are typically saline[52] and not effectively connected to the much shallower (depths less than ~ 300 m) freshwater aquifers used by people. Up until a few years ago it was generally thought that closed aquifers with structural traps would be required for effective storage. The potential global sequestering capacity in such traps is relatively limited—about 50 GtC (Hendriks, 1994), equivalent to less than 10 years of global CO_2 production from burning fossil fuel at the current rate. However, a growing body of knowledge (Bachu, Gunter, and Perkins, 1994; Holloway, 1996) indicates that many large, regional-scale open aquifers with good top seals (very low permeability layers) can provide effective storage, if the CO_2 is injected sufficiently far from aquifer boundaries that it either never reaches the boundaries, or if it does, the leakage rate would be sufficiently slow as to be of little consequence with regard to climate change, because of the extraordinarily slow rates of CO_2 migration in such reservoirs (typically of the order of 1 cm/year)—a phenomenon called "hydrodynamic trapping" of CO_2 (Bachu, Gunter, and Perkins, 1994). For large aquifers, the CO_2 will eventually dissolve in the water ("dissolution trapping" of CO_2). For sandstone reservoirs containing certain clay minerals (but not carbonate reservoirs), the CO_2 will, after dissolving in the water, eventually precipitate out as a carbonate mineral ("mineral trapping" of CO_2) (Gunter, Perkins, and McCann, 1993).

If structural traps are not required for effective storage, potential aquifer storage capacity might be huge; estimates range from 2,700 GtC (Omerod, 1994) to 13,000 GtC (Hendriks, 1994). For comparison, estimated remaining recoverable fossil fuel resources (excluding methane hydrates) contain 6,000 to 7,000 GtC (Rogner, 2000). The notion that large aquifers with good top seals can provide effective sequestration is a relatively new idea that has contributed to the growing confidence in the scientific community that long-term sequestration of a significant fraction of the next several hundred years of global CO_2 production from human activities might be feasible (Holloway, 1996; Socolow, 1997; PCAST Energy R&D Panel, 1997).

There is a growing base of experience with CO_2 disposal in aquifers. One large project being carried out by Statoil involves recovering the CO_2 contaminant in natural gas from the

Sleipner Vest offshore natural gas field in Norway gas at a rate of 1 million tonnes of CO_2/year and its injection into and sequestration in a nearly aquifer under the North Sea (Kaarstad, 1992). A prospective large aquifer disposal project expected to commence within 10 years will involve recovery of more than 100 million tonnes/year (equivalent to 0.5% of total global emissions from fossil fuel burning) from the Natuna natural gas field in the South China Sea (71% of the reservoir gas is CO_2) (IEA,1996).

There is also a rapidly growing number of smaller acid gas disposal projects. In Alberta[53] there are 31 such projects[54] that involve recovery of CO_2 along with H_2S from natural gas fields and injection of these acid gases (characterized by a wide range of relative concentrations) underground for storage, in aquifers as well as in depleted oil and gas fields. Underground disposal of CO_2/H_2S is pursued in these projects as a less costly strategy for responding to sulfur air emission regulations than the alternative of recovering H_2S from the natural gas and converting it to elemental sulfur (Longworth, Dunn, and Semchuck, 1995; Wichert and Royan, 1997).

The long history of experience with EOR, the growing body of experience with aquifer disposal, and extensive historical experience with underground gas storage are contributing to the growing scientific confidence in the reliability of geological media for storing CO_2. However, more research, field testing, modelling, and monitoring are needed to narrow the uncertainties relating to CO_2 storage in geological media.

Regulations that have been evolving for underground gas storage provide a good basis for defining issues associated with formulating regulations for CO_2 storage (Gunter, Chalaturnyk, and Scott, 1999). Public acceptability issues are paramount. Fuel decarbonisation with CO_2 sequestration is unfamiliar to most people as a strategy for dealing with the climate change challenge. The scientific community has a major responsibility to inform the public debates on the various issues relating to safety and environmental impacts. Much can be learned from both natural events (Holloway, 1997) and from the extensive historical experience with use of CO_2 injection for enhanced oil recovery and with underground gas storage (Gunter, Chalaturnyk, and Scott, 1999). But more research is needed to clarify the issues.

MOVING FORWARD

The present analysis shows that if H_2 FCVs can be successfully launched in the market and if geological CO_2 sequestration proves to be a viable option on a large scale, the prospects are good that most of the needed H_2 would be derived from fossil fuels—even in a GHG-emissions-constrained world—although there are still many uncertainties relating to geological sequestration of CO_2 that must be resolved.

A relatively modest carbon tax of about $50/tC would be an adequate incentive to induce producers of H_2 from coal to capture/sequester the CO_2 coproduct of H_2 manufacture, whereas with a tax of this magnitude the producers of H_2 from natural gas would prefer to vent CO_2. Because such high carbon taxes would be needed to induce sequestration for natural gas-derived sequestration, there is no compelling reason to build large centralized H_2 production facilities based on natural gas for a long time to come, in light of the fact that with CO_2 venting, costs of H_2 delivered to consumers will be comparable for centrally produced H_2 and distributed H_2 production at refueling stations (Ogden, 1999). Although it is not practical to consider CO_2 capture/sequestration for distributed H_2 production,[55] distributed production of H_2 from natural gas with CO_2 venting would help mitigate climate change if the H_2 were used in fuel cell cars, because lifecycle GHG emissions for such cars powered with this natural gas-derived H_2 would be lower than for all the fluid hydrocarbon-fueled ICE/HEV options considered in Table 1. In contrast, significant climate-change-mitigation benefits relative to fluid hydrocarbon-fueled ICE/HEV options arise for coal-derived H_2 only with CO_2 capture/sequestration (see Table 1). This consideration and the strong scale economies associated with manufacture of the oxygen needed for coal gasification (see Table 7) indicate that the appropriate scale for H_2 manufacture from coal is at large central plants such as those described in Table 4. Thus in the longer term, the H_2 supply infrastructure might be made up mainly of distributed production of H_2 based on natural gas, e.g., at refueling stations—the option being considered by many prospective H_2 suppliers (Ogden, 1999)—and centralized production based on coal.

For the United States, the building of large new plants to make H_2 from coal is constrained by the "NIMBY" problem[56] that is making it virtually impossible to build large new green-field energy conversion plants anywhere. However, the construction of new energy capacity at brown-field sites might not be so constrained. Consider that in the United States 56% of power generation in 2000 was based on coal. Over the next couple of decades most U.S. coal-fired power plants will have reached a nominal retirement age (~ 40 years). The coal power industry is addressing this prospect by planning to make modest investments that would enable plant-life extension for old coal steam-electric plants to 60+ years. But this strategy might not be an adequate response to growing concerns about health damage costs from small-particle air pollution, which in the case of coal steam-electric plants, are associated mainly with sulfate and nitrate particles created in the atmosphere from gaseous precursor emissions of SO_2 and NO_x (Williams et al., 2000). Consideration might instead be given to an alternative "repowering" strategy that would involve replacing old steam-electric generating capacity with gasification-based electricity plus H_2 production facilities built at the same sites to serve both central-station power and FCV applications. This repowering strategy would make it possible to reduce to very low levels health damage costs associated with small-particle air pollution, because such plants can be made as clean in terms of air pollutant emissions as natural gas combined cycle power plants (Williams et al., 2000).

A "thought experiment" developed in Box C to illustrate such a strategy with CO_2 capture/sequestration shows that if coal power plants were so modified: (1) they could serve nearby H_2 markets for fuel cell vehicles with only very modest net increases in the amount of coal consumed relative to what is currently consumed to meet electricity needs, and (2) at the national level such a strategy could meet the H_2 fuel needs of about half of the light-duty vehicle fleet if all light-duty vehicles were powered by H_2 fuel cells. A policy for inducing such a change might be to levy on power plants at their nominal retirement age a "retirement tax" on air pollutant and GHG emissions of sufficient magnitude to make it worthwhile for plant owners to pursue this "scrap-and-build" strategy.[57] The gasification plants deployed under this strategy might be designed to produce initially only electricity, with a growing share of H_2 in the plant's output as the demand for H_2 grows. A public policy might be crafted to provide appropriate incentives for suppliers to build coal conversion plants with this flexibility.

Even under optimistic assumptions about progress in the development H_2 fuel cell vehicles, spurred by strong public-sector support for "buying down" costs of H_2 fuel cell vehicles, there would be virtually no demand for H_2 from large coal plants before the end of the next decade (Ogden, Williams, and Larson, 2003). Yet, as discussed, there are many technological opportunities for improving gasification-based H_2 production technology and thereby potentially reducing the cost of H_2. In the absence of significant demand for H_2 as an energy carrier, such innovations might be pursued in the interim in conjunction with H_2 use at petroleum refineries, where H_2 demand growth is rapid, spurred by the growing demand for clean hydro-carbon fuels (e.g., for hydro-desulfurization) as well as the ongoing shift to heavier crudes.

These significant non-energy markets for H_2 might in many instances be served cost-effectively by making H_2 via gasification of low-cost petroleum coke and other petroleum residuals, especially if the CO_2 coproduct of such H_2 plants could be used for EOR wherever there are attractive EOR sites near refineries—a strategy that offers promise in light of the low cost of CO_2 capture in H_2 manufacture via gasification (Williams, 2002).

BOX C Thought Experiment: Electricity + H_2 from Coal with Near-Zero Emissions

To illustrate the significance of widespread deployment of near-zero-emitting technologies such as those described in Table 4, imagine a hypothetical energy future for the United States, where, in response to a levy on 40-year old coal power plants of a "retirement" tax[58] made up of a carbon plus air pollution tax adequate to make the total cost of making electricity via gasification less than the operating cost for coal steam-electric plants: (i) all U.S. steam-electric coal power plants are replaced by gasification-based plants that produce both electricity and H_2 with near-zero CO_2 emissions for distribution to H_2 FCV refueling stations "in the vicinity of the power plants," and (ii) the CO_2 coproduct is sequestered in appropriate nearby geological reservoirs. The time by which this transformation would take place is not specified, but energy-related activity levels projected for the year 2020 by the U.S. Energy Information Administration (EIA, 2001b) are assumed. To quantify "in the vicinity," it is assumed that power plants are distributed like cars and that the amount of extra H_2 produced at each plant is enough to support 0.73 miles of FCV driving per kWh of electricity generated—the ratio of total light-duty-vehicle (LDV) driving to total power generation.[59] It is also assumed that these FCVs have an average fuel economy of 82 mpgge (see Table 1) and are driven on average 14,700 miles per year (U.S. average for 2020, as projected by the EIA).

It is assumed that a typical plant would produce 392 MW_e of electricity. Under the above assumed conditions, a plant of this size would produce coproduct H_2 at an output capacity scale of 140 MW_h,—enough H_2 to support about 136,000 FCVs within a 24-mile radius [if the FCV density were 78/mi^2 (the average for LDVs in the US in 2020)]. These fuel cell vehicles would be served by 28 refueling stations (each providing daily 10^6 scf = 342 GJ of H_2 to FCVs). The annual CO_2 sequestering rate for each such a conversion plant would be 2.5 million tonnes of CO_2.

At the national level, all coal-fired power generation plus 49% of all LDVs (equal to coal's projected share of power generation) would be characterized by near-zero emissions of both air pollutants and GHGs. The oil displaced by H_2 FCVs would be equivalent to 30% of oil imports projected for 2020; because the efficiency of power generation (37.1%) would be higher than projected by the EIA for coal plants in 2020 (33.5%) and because FCVs would have fuel economies much higher than the 21.5 mpg the EIA projects for LDVs in 2020, total coal use would be only 8% more than what the EIA projects for coal power generation in 2020. Total US CO_2 emissions would be 1.32 Gt compared to *the* projected level of 2.09 GtC for 2020. The total annual US CO_2 sequestration rate would be 0.61 GtC (2.2 Gt CO_2). [For comparison, the Mt. Simon Sandstone aquifer underlying the Appalachian, Illinois, and Michigan Basins (800 to 3000 m below the surface) in the midwestern states (where much of U.S. coal electric generating capacity is located) has an estimated potential CO_2 storage capacity in the range 40 to 200 GtC (Gupta et al., 1998).]

The finding that the cost of carbon capture is low for H_2 produced via coal gasification (the same would hold for H_2 derived from petroleum residuals as well as coal) underscores the economic attractiveness of pursuing early demonstrations of CO_2 disposal in applications that do not offer enhanced resource recovery opportunities, in conjunction with H_2 manufacture via gasification of petroleum residuals. Carrying out such demonstration projects would require a carbon management policy that would make these activities economically attractive to private investors. Several "megascale" experiments[60] might be carried out in conjunction with H_2 production from petroleum residuals at refineries during the next two decades, to test the viability of CO_2 sequestration in various geological media (e.g., depleted oil and gas fields, deep beds of unminable coal, deep saline aquifers) (Williams, 2002). Such activity could thus help both to commercialize promising advanced gasification-based H_2 production technologies[61] and to provide a broad base of understanding of the risks and benefits of geological sequestration of CO_2 while waiting for the establishment of fuel-cell vehicles in the market.

The value of finding out soon via appropriate experiments and demonstration projects if the fossil fuel decarbonization/CO_2 sequestration concept will be viable in wide applications can be gleaned from consideration of the cost implications of a *hypothetical* outcome that this concept is *not viable*, but where climate-change concerns motivate a shift to alternative carbon-free H_2 supplies. Suppose that under such circumstances coal-derived H_2 technology is not developed and that policymakers introduce a carbon tax large enough to enable H_2 generated from nuclear energy via complex thermochemical cycles or renewable electrolytic H_2 to compete with H_2 derived from natural gas with CO_2 venting. The required carbon tax would be ~ $410/tC in the case of nuclear thermochemical H_2 and ~ $650/tC in the case of renewable electrolytic H_2. If such carbon taxes were levied in an energy economy characterized by 1999 levels of U.S. energy use (97 Quads/y) and CO_2 emissions (1.52 GtC/y), retail expenditures on energy would have been ~ $1200 billion/y and ~ $1550 billion/y, respectively—2-3 times the actual U.S. retail expenditures on energy in 1999 ($560 billion/y). By way of contrast, if geological sequestration of CO_2 proves to be a viable option for wide application, the ~ $50/tC carbon tax required to induce CO_2 sequestration for coal-derived H_2 (see Table 4) would increase retail expenditures on energy only 13% (to $630 billion/y) at 1999 U.S. energy use/CO_2 emission levels.

It is too soon to tell how the public will react to CO_2 sequestration technologies and strategies for fossil fuels—which are still largely unfamiliar to most people. The nuclear experience with pubic attitudes regarding radioactive waste disposal is not encouraging. However, CO_2 is not radioactive and would not be harmful as long as leakage rates can be kept low, and there seem to be good prospects for that. One hopeful consideration is that if carbon capture/sequestration efforts were focused on technologies such as those described here that offer near-zero emissions of air pollutants as well as CO_2—thereby offering technology as clean as renewable energy—the prospects for getting broad public support would be much better than for the "band aid" approach of removing CO_2 from stack gases of fossil-fuel power plants that many regard as environmentally unacceptable.

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NOTES

1. For example, the Energy Information Administration (EIA, 2002) projects (Reference Case) that Persian Gulf oil production will increase from 21.2 million barrels/day in 2000 to 39.6 million barrels/day in 2020, and that Persian Gulf production as a share of world consumption will increase from 28.1% to 33.4% in this period.
2. If expenditures on this military activity were instead divided by actual U.S. oil imports from the Persian Gulf (0.9 billion barrels in 1999), the estimated marginal cost of oil insecurity would be 50% higher. However, the actual U.S. oil imports from the Persian Gulf is probably an inappropriate measure of the volume of imports at risk. Even if U.S. oil imports from the Persian Gulf could be reduced to zero in favor of more imports from other regions and other oil importers were thereby forced to become more dependent on Persian Gulf oil, U.S. oil security would not become significantly enhanced thereby, because oil supplies are fungible. Accordingly, it is assumed here that these military expenditures are instead charged against 20% of Persian Gulf exports (1.35 billion barrels in 1999), corresponding to the US share of total gross global oil imports in 1999. [In 1999, gross oil imports amounted to about 54 million barrels/day at the global level (EIA, 2002b), of which the United States accounted for about 11 million barrels/day.]
3. For example, in 2000 U.S. light-duty vehicles consumed 15.8 EJ, compared to 23.5 EJ of US oil imports; for 2020, the Energy Information Administration projects (Reference Case) that, in 2020, when imports will be 37.0 EJ, light-duty vehicles will consume 22.5 EJ (EIA, 2001b).
4. Society should be willing to pay for avoiding environmental damages no more than the cost of the least costly mitigation technologies and strategies.
5. Or, equivalently, the price of carbon credits in carbon trading markets in a world where a "cap and trade" policy is adopted as an alternative to a carbon tax as the policy for mitigating climate change.
6. For H_2 production via commercial steam-reforming technology, it is estimated in Table 3 that a carbon tax of $115/tC would induce the producer to capture and sequester CO_2. The corresponding costs for CO_2 removal and sequestration are estimated to be about $90/tC for a coal IGCC power plant and $50/tC for making H_2 from coal in Table 4. In all cases the costs of CO_2 disposal are estimated as indicated in Box B.
7. But IS92a should not be regarded as a "high emissions scenario." Several of the 40 long-term scenarios generated for the IPCC's Special Report on Emissions Scenarios are characterized by CO_2 emissions in 2100 that are much higher (up to 37 GtC/y) than for IS92a (~ 20 GtC/y) (IPCC, 2000).
8. In IS92a, electricity generation grows 1.6%/y, on average during 1997-2100, compared to 1.0%/y for fuels used directly.
9. For selected engine/fuel combinations from Table 1, lifecycle costs are shown with high and low estimates of externality costs as well as the base case values presented in Table 1. The high and low values of air pollutant damage costs are estimates at 1 standard deviation from the median (base case) value (a factor of 4 higher or lower than the median damage cost estimates). The high and low values of greenhouse gas damages are at 0.5 and 1.5 times the median valuation ($120/tC). The high and low estimates of the oil supply insecurity cost correspond to U.S. military expenditures to insure access to Persian Gulf oil of $60 billion/y

and \$20 billion/y compared to \$40 billion/y for the base case. Source: Ogden, Williams, and Larson (2002).

10. Projected carbon-free electricity for 2100 is 39% nuclear, 16% hydroelectric, and 45% new renewables.
11. In 1997 carbon-free electricity was 45% nuclear, 51% hydroelectric, and 4% new renewables.
12. Although there is no imminent danger of running out of conventional oil and gas, productive capacity is expected to be constrained after about half of remaining exploitable conventional resources have been used up—in large part as a result of the tendency to exploit the largest fields first.
13. Recently the IPCC Special Report on Emissions Scenarios (SRES) explored the global energy future with 40 scenarios. For these scenarios, electricity's share of final energy in 2100 ranges from 16% to about 60% (a 42% average for the 40 scenarios), compared to 29% for 2100 in IS92a and the actual 16% share in 1997 (see Table 2).
14. Ogden, et al. (1998; 1999) designed a H_2 fuel-cell car that, relative to today's typical cars, would have lower aerodynamic drag, less rolling resistance, and reduced weight—without compromising performance and interior space requirements. [The aerodynamic drag, rolling resistance, and vehicle weight parameters assumed for these analyses are comparable to those for cars being developed under the Partnership for a New Generation of Vehicles] It's estimated gasoline-equivalent fuel economy is 2.2 liters/100 km (106 mpg). H_2 would be stored onboard as a gas compressed to 345 bar in cylinders with an aggregate storage capacity of 3.75 kg of H_2—providing a range of 680 km between refuelings. State-of-the-art system storage densities for canisters (carbon-fiber-wrapped tanks with aluminum liners) are 7.5% H_2 storage by weight, so that the loaded storage system weight is 50 kg. It is assumed that the H_2 is stored in 3 cylindrical canisters, each of which is 103.4 cm long and has an outside diameter of 28.3 cm. The total storage system volume is 195 liters. Such volumes can be stored onboard cars without compromising passenger or storage space if the car is redesigned "from the bottom up" to accommodate such storage volumes.
15. For MeOH or gasoline fuel cell cars, the liquid energy carrier is converted onboard the vehicle into a H_2-rich gas that the fuel cell can utilize.
16. From ~ \$2800/kW for automotive fuel-cell engines manufactured one-at-a-time by hand today to ~ \$65/kW for mass-produced fuel-cell engines that would make H_2 fuel-cell cars competitive with gasoline hybrid electric cars (Ogden, Williams, and Larson, 2002).
17. For disposal sites located more than about 100 km from the energy conversion site, the flows of CO_2 from several conversion facilities would be combined for transport distances beyond about 100 km. Consider, for example, that for sequestration at 100 km the CO_2 disposal cost for coal-derived H_2 in Table 4 is \$5.0/t CO_2 (see note g, Table 4). If instead the sequestration site were 500 km away, with the outputs of three plants combined for the 100-250 km leg and the outputs of six plants combined for the final 250 km, the disposal cost would increase to \$12.6/t CO_2 and the cost of coal-derived H_2 would increase 13% relative to the cost presented in Table 4.
18. Temperatures and pressures ~ 850 ^{o}C and ~ 25 bar at the reformer exit, respectively.
19. Exclusive of retail taxes, which average about \$0.42/gallon.
20. Estimated ultimately recoverable, unconventional natural gas resources at the global level are estimated to be 33,000 EJ (Rogner, 2000), but such gas is likely to be more costly than conventional natural gas.

21. Aspen Plus (commercial) software was used for the chemical process analysis; GS (Gas/Steam) software developed at the Dipartimento di Energetica, Politecnico di Milano, Milan, Italy, was used to investigate the complex power cycles and to provide an independent check on heat and mass balances; a self-consistent data base was developed from published studies for costs of system components; a uniform approach for treating the various indirect costs was developed.
22. Typically some electricity is generated as a byproduct of H_2 manufacture for the most cost-effective system designs. The ongoing shift to competitive electricity markets should facilitate the deployment of such facilities by making it possible for H_2 producers to sell their electricity co-product into the electric grid at competitive prices—which is assumed for the H_2 production analysis (see note h, Table 4).
23. Partial oxidation of the coal in the gasifier provides the heat needed to drive the endothermic reactions involved in gasification.
24. The potential H_2 is defined as the sum of the CO plus H_2 in the synthesis gas.
25. The purge gas is made up of the residual H_2 along with small amounts of CO and CH_4 (diluted with CO_2 and H_2O) released at atmospheric pressure when the PSA beds are depressurized.
26. Much more electricity could be produced if the purge gas could be burned in the combustor of a combined cycle power plant; however, the heating value of this purge gas is too low (because of its high CO_2 content) to use a combined cycle for power generation, so that the purge gas is instead burned at atmospheric pressure for power generation in a less energy-efficient steam turbine (producing 154.4 MW compared to 183.9 MW from the combined cycle used when CO_2 is separated out for sequestration—see Table 4).
27. The effective efficiency is defined by η_{eff} = (H_2 output)/(coal input – coal saved), where the "coal saved" is the amount of coal that would otherwise have to be consumed in a stand-alone facility to produce the amount of electricity generated as a co-product of H_2.
28. For the CO_2 capture/sequestration cases, the capital intensity for H_2 derived from coal is 1.8 times the capital intensity of the system for making H_2 from natural gas (compare Tables 4 and 3).
29. For the CO_2 capture/sequestration cases, the efficiency of converting natural gas to H_2 is 78% (see Table 3), compared to an effective efficiency of 67.7% for coal (see Table 4).
30. It is to be stressed, however, that these judgments relating to natural gas are preliminary, because the analysis presented here for natural gas systems is based on modeling by others (FW, 1996) and is not based on a full set of self-consistent assumptions and models in making inter-technology comparisons, as is the case for all the coal systems presented in Table 4.
31. If co-sequestration of H_2S and CO_2 proves to be a viable option without posing significant environmental risks, this option would significantly reduce the net incremental cost of CO_2 capture/sequestration (Chiesa, Kreutz, and Williams, 2002).
32. For example, if the environmentally damaging and controversial technique of mountain-top decapitation, which has become a prominent strategy for coal mining in West Virginia, were to be banned.
33. In a cap and trade system for CO_2 emissions management, the price would be determined by the market price of traded CO_2 emissions credits.
34. Compare lines in Tables 3 and 4 for production costs with CT = $49/tC.
35. Assuming a 15% annual capital charge rate.

36. It is estimated that for wind power at \$0.029/kWh the cost of baseload wind power (wind farm + CAES) would be \$0.036/kWh for CAES based on storage in salt dome caverns. Transmission via a 1 GW_e HV AC line (including ohmic losses) would bring the city-gate cost of this baseload power to \$0.04/kWh. Calculations of the lifecycle cost for such a wind power/CAES system providing electricity to make H_2 with advanced electrolysis technology for use in FCVs are presented in Tables 6 and 1.
37. Plausibly, electricity generation costs could also be this low for advanced nuclear power technologies—see, for example, Table 9.
38. The non-zero GHG emissions associated with wind power-generated H_2 indicated in Table 1 are due to the assumed use of natural gas for firing the turbines used with the CAES unit: some 0.3 GJ of natural gas is required to produce each GJ of H_2 electrolytyically from wind power, so that *direct* GHG emissions of the CAES plant would be 4.0 kgC/GJ H_2 (compared to 2.6 kgC/GJ H_2 for coal-derived H_2 with CO_2 sequestered—see Table 4).
39. Note in Table 2 that fossil fuels used directly in 2100 under IS92a amount to 541 EJ/y and account for 15 GtC/y of CO_2 emissions. For comparison electricity generation in 2100 amounts to only 245 EJ (68,000 TWh/y).
40. At a more modest but still challenging temperature of 2500 ^oC only 10% of the water is decomposed.
41. The UT-3 process is based on the following reactions aimed at decomposing water thermochemically:
    $CaO + Br_2 \rightarrow CaBr_2 + ½ O_2$ (at 700-750 ^oC)
    $CaBr_2 + H_2O \rightarrow CaO + HBr$ (at 500-600 ^oC)
    $Fe_3O_4 + 8 HBr \rightarrow 3 FeBr_2 + H_2O + Br_2$ (at 200-300 ^oC)
    $3 FeBr_2 + 4 H_2O \rightarrow Fe_3O_4 + 6 HBr + H_2$ (at 550-600 ^oC)
42. The S-I process is based on the following reactions aimed at decomposing water thermochemically:
    $H_2SO_4 \rightarrow H_2O + SO_2 + ½ O_2$ (850 ^oC),
    $2 HI \rightarrow H_2 + I_2$ (450 ^oC),
    $2 H_2O + I_2 + SO_2 \rightarrow H_2SO_4 + 2 HI$ (120 ^oC)
43. The estimated costs for nuclear H_2 (Table 8) and nuclear electricity and heat (Table 9) are based on component cost estimates developed under the U.S. Department of Energy's Nuclear Energy Research Initiative (Brown *et al.*, 2002a; personal communication from Ken Schultz, General Atomics, April 2002). Details relating to the development of these component cost estimates will be presented in a General Atomics report to NERI (Brown *et al.*, 2002b) that will probably be released in the fall of 2002.
44. A conversion efficiency of 50% measured as the ratio of the HHV of H_2 divided by the heat input can be restated as an efficiency of 41.5% measured as the ratio of the maximum amount of work that can be extracted from the H_2 (the change in the Gibbs Free Energy associated with use of the H_2 in an ideal fuel cell) divided by the heat input in making the H_2. The latter efficiency can be appropriately compared to the Carnot efficiency $\eta_{CARNOT} = 100*(900 – 120)/(900 + 273) = 66.5\%$, the theoretical maximum efficiency for this process. Thus the targeted efficiency for the S-I process is $100*(41.5/66.5) = 62.4\%$ of the theoretical maximum.
45. In order for the cost of nuclear H_2 to break even with the cost of H_2 from coal with CO_2 sequestration, the cost of nuclear heat would have to be reduced from 1.64 ¢/kWh to 0.52 ¢/kWh, assuming an overnight construction cost of \$315/kW_t for the S-I thermochemical H_2

plant (as is assumed in Table 6). If in the distant future it were possible to reduce the thermochemical H_2 plant cost to \$210/kW$_t$, (Brown *et al.*, 2002b), the breakeven nuclear heat cost would be 0.89 ¢/kWh. Because there would be little room for reducing the fuel and O&M costs, nuclear heat cost reduction to 0.89 ¢/kWh would have to come largely as a result of reducing the nuclear capital cost by about a factor of four—which would be difficult to realize.

46. Note that the 1300 MW$_e$ Advanced Boiling Water Reactor (ABWR), a recent variant of the light water reactor developed by GE/Toshiba/Hitachi, which *has been* built, *is* in operation in Japan, and *has been granted* design certification in the United States, has an overnight construction cost of \$1582/kW$_e$ (according to the OECD's Nuclear Energy Agency) (Taylor, 2001). The corresponding total capital required is \$1835/kW$_e$, assuming a 4-year construction period and interest during construction at a 10% interest rate.
47. Although both the MHR and next-generation LWR costs are projections, one can have much more confidence in the latter than the former because of the extensive industrial experience with LWRs and the dearth of experience with the MHR (although a demonstration MHR plant was built and operated at Fort St. Vrain, Colorado, 1979-1989).
48. Most EOR projects in the United States are in the Permian Basin of Texas. Most of the CO_2 for these projects is transported by pipeline from natural reservoirs of CO_2 in Colorado, New Mexico, and Wyoming (e.g.,via an 800 km pipeline from the M^{c}Elmo Dome in western Colorado—which contains 0.5 Gt CO_2).
49. For example, 90% of the nearly six trillion tonnes of U.S. coal resources deposited at depths less than 1800 m is unminable with current technology, either because the coal is too deep, the seams are too thin, or mining would be unsafe (Byrer and Guthrie, 1998).
50. The critical point for CO_2 is 74 bar and 31 ^{o}C.
51. Because the hydrostatic pressure gradient is typically about 100 bar per km.
52. Deep aquifers (~ 800 m or more below the surface) tend to be saline because the contained water is fossil water that has been there over geological time—time sufficient for the water to come into chemical equilibrium with the minerals in the host rock. Dissolved salts typically make the water brackish and often even briny.
53. Recently an acid gas disposal project was launched in Texas (Whatley, 2000). The CO_2/H_2S ratio in the acid gas is 2.65 by volume, and CO_2 is injected at a rate of 6,200 tonnes/y into an aquifer at a depth of 1700 m.
54. Canadian acid gas disposal projects began in 1989; since then the number of projects has grown rapidly: to 6 by 1995, 22 by 1998, and 31 by 2000 (private communication from Stefan Bachu, August 2001).
55. As shown in Box B, there are substantial scale economies associated with pipeline transport of CO_2.
56. NIMBY = not in my backyard.
57. Retirement taxes would make it possible to induce radical technological innovation in targeted areas when the levy of justifiable large externality taxes for the entire energy economy is not politically feasible.
58. See the discussion in the main text of the "retirement tax" concept.
59. For its reference forecast the US Energy Information Administration (EIA, 2001b) projects for 2020 that the total amount of LDV driving will be 3631 billion vehicle miles and total power generation will be 4983 TWh.
60. A typical scale for needed H_2 productive capacity at refineries would be ~ 100 million

standard cubic feet (400 MW_h) of H_2 produced daily, for which the annual CO_2 disposal rate would be in excess of 1 million tonnes of CO_2 per year, if the H_2 were produced via gasification of petroleum coke (Williams, 2002).

61. Gasification technologies launched in the market using as feedstocks petroleum residuals could subsequently be adapted to coal.

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Is the Barrel Half Full or Half Empty?

Implications of Transitioning to a New Transportation Energy Future

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U.S. motorists were reminded twice recently (in the spring of 2000 and again in the spring of 2001) that gasoline and diesel fuel prices can escalate rapidly. The escalation of motor fuel prices served as a reminder for some of the energy crises of the 1970s. While there were no price controls and long lines at service stations this time, there was uncertainty about how high fuel prices would go.

Beginning in 2000, the Office of Transportation Technologies in the U.S. Department of Energy (DOE)began an examination of the long-term availability of petroleum supplies for U.S. motor vehicles as well as the projected demand. Included in this analysis was a forecast for the future energy demand of automobiles and trucks, as well as several strategies for the use of alternative fuels and the introduction of new propulsion system technologies into the vehicles. The analysis was extended for fifty years to determine the effects on oil and energy demand as well as greenhouse gas emissions as these fuels and vehicle technologies permeated the fleet of vehicles over time. The study participants included staff from several national laboratories, contractors, and the department. This paper summarizes the major findings of the first phase of the study. Forecasts of world petroleum supply and demand are reviewed. The implications (with attention devoted to energy issues and greenhouse gas emissions) of U.S. transportation energy demand under various technology strategies are then examined.

FOCUS OF THIS PAPER

The study that this paper summarizes presents the case for an inevitable transition from conventional oil—the leading energy source for the world economy and virtually the sole source of energy for motorized transport—to other energy sources. The transition will most likely begin in earnest within the next two decades. By 2050, or shortly thereafter, unconventional energy sources will predominate. The coming energy transition will have great significance for the global economy and will be a pivotal event for the world's transportation systems. It will have long-lasting implications for the global environment and especially the outlook for global climate change. It could lock the world into a high greenhouse gas future or break the link between climate change and energy use, depending on the choices we make in the very near future.

This paper calls attention to a coming transition that will be of significance to the world economy and major importance to the world's transportation systems. A transition from conventional oil will present the world's transportation systems with the opportunity to choose among alternative futures. This paper demonstrates that plausible, alternative paths exist, and that the choices available may have very different implications for energy and environmental outcomes. The issue we raise is the importance and urgency of better understanding the nature of the coming energy transition, the choices we face, and their consequences. We believe the transition is inevitable and the consequences are important. Not to decide will be to decide, and the choices made, or not made, are likely to be very important.

Because the thrust of this paper is about the anticipated transition in the transportation sector from conventional petroleum to other fuels or new vehicle technologies, there is considerable discussion here about the world oil supply. Two other issues are likely to have considerable influence on the direction we as a nation take during this transition: one is greenhouse gas emissions and the other is criteria pollutants. The former is examined in this paper; the latter is not. An explanation is appropriate.

Greenhouse gases, such as carbon dioxide, trap solar heat in the atmosphere, raising its temperature. The precise consequences of increasing GHG emissions are not well understood, but the potential adverse consequences include major changes in precipitation and temperature patterns, increased catastrophic storm activity, and higher sea level. While comprising only about 5 percent of the global population, the U.S. is responsible for nearly one-fourth of the global annual CO_2 emissions. Transportation accounts for one-third of all carbon dioxide emissions in the U.S., and about one-fourth worldwide. U.S. passenger cars and light trucks account for nearly two-thirds of the net carbon equivalent emissions from transportation, and CO_2 emissions from transportation fuel use are expected to grow faster than any other sector. Carbon emissions vary greatly by fuel type and by the propulsion system that is used in the vehicle. If, as it appears likely, reduction or stabilization of greenhouse gas emissions continues to be a global concern, then understanding those differences will be important in our choices of fuels and technologies in the future. The calculation of carbon emissions is also a rather straightforward process.

Air quality, especially in our major cities, is another important transportation emissions issue. Over the past four decades, the combination of steadily more demanding emissions regulations, improved fuels, and continued advances in pollution control technology have enabled significant strides in reducing total air emissions from motor vehicles and improving air quality. However, at the end of 1999, over 100 million people in the U.S.—nearly 40 percent of the country's population—still lived in non-attainment areas. It is recognized that some vehicle technologies and fuels are inherently cleaner than others, and that the cleaner ones may have greater value in meeting the stricter bins of the new emissions standards, but they may be more costly as well. Forecasting future criteria emissions levels and the relative capability of each fuel/propulsion system to meet or exceed those future standards is complex and was beyond the resources for this study. Nevertheless, the criteria pollutant issue is recognized as important.

LIMITATIONS OF THIS PAPER

Anyone who embarks on a 50-year projection does so with the full recognition that the world will likely be much different than forecast. The early speculation about nuclear energy being too cheap to meter is called to mind. On the opposite end of the spectrum, the ubiquitous personal computer was inconceivable in 1950. Yet, in 1950 if the forecast had been "two cars in every garage," then the forecast would have been fairly prescient. And, the forecast would have been a simple extrapolation of current trends, as unimaginable as it would have been thought in 1950.

Thinking about the world in fifty years is a valuable exercise if only to illuminate the potential impacts of decisions we might make in the interim. Despite our inability to accurately forecast for decades into the future, we can make some assessment of the consequences that our choices today could have for future generations.

This paper does not estimate costs for new transportation technologies. This is not to say that costs are unimportant, indeed they are fundamental to understanding the choices we will make. Rather this paper reports on the first phase of the Department of Energy's 2050 study. Given the interest in this study, the authors considered it important to provide the initial findings to a broad audience, along with the appropriate caveats. The second phase of the 2050 study (ongoing and co-funded by both the U.S. Department of Energy and Natural Resources Canada) will explicitly examine the costs of both technologies and fuels, including oil price feedbacks though the World Energy Supply Model.

This study does not fully explain the dynamics of a transition away from oil use in transportation or predict the outcome. It does not analyze how the shift from conventional oil to other energy sources will affect the balance of power in world energy markets or improve or worsen oil dependence for the United States. It is not the intent of this paper to prove that catastrophe looms, or to provide a blueprint for the "best and brightest" future. We do not pick the winning energy source(s) and we do not prescribe panaceas. The goal of this paper is more limited.

WORLD PETROLEUM SUPPLY

After the energy crises of the 1970s, higher oil prices had the simultaneous effects of expanding supply by encouraging new petroleum exploration and tempering demand by increasing the efficiency of oil use. In some nations, notably the U.S., there was particular concern about imported oil because of its implications for energy security. By the late 1970s, the Alaska pipeline was completed and substantial oil reserves were being exploited in Mexico and the North Sea. Higher oil prices also encouraged new oil exploration. New technology enhanced the process and lowered the cost of finding oil and extracting it. New oil discoveries have made significant short-term contributions to oil supplies, and fuel substitution has made large inroads in oil use—although alternative fuels have made only a small contribution in the transportation sector.

The latest U.S. Geological Survey (USGS) assessment[1] places the world's ultimate supplies of conventional oil (mean estimate) at about 3 trillion barrels (sum of the bars shown in Figure 1), with some 700 billion barrels as yet undiscovered.[2] Since the discovery of oil at Titusville, Pennsylvania, in 1859, the world has recovered and used about 850 billion barrels of oil—nearly half of the known petroleum resources and about one-fourth of the estimated total conventional oil resources on earth. Geologists have observed that when oil fields and even regions reach the halfway point of depletion, oil production generally begins to decline. U.S. crude production peaked in 1970 when approximately half of the nation's oil resources had been produced, and has declined steadily since. Even the addition of oil from the Alaska North Slope has not changed this long-term decline in U.S. oil production. When the world reaches the point at which half the total resources of conventional petroleum has been consumed, a long-term decline will begin. The question of when that point might be reached will be largely determined

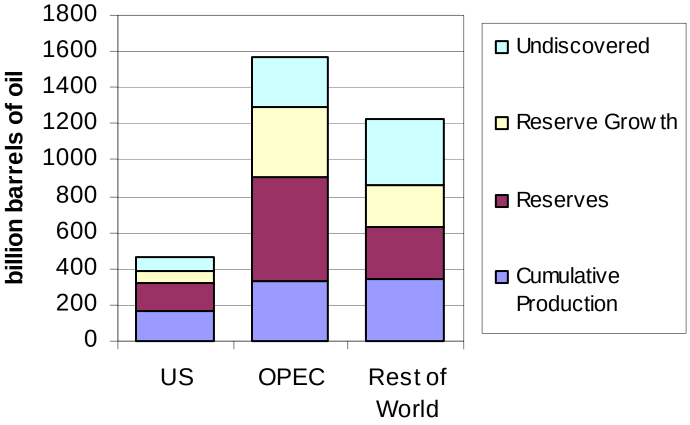

FIGURE 1 World ultimate conventional oil resource.

by how fast the demand for oil continues to increase, and that demand will be determined principally by the transportation sector.

World Transportation Energy Demand

Today, transportation accounts for 40 percent of world oil consumption at nearly 75 million barrels of oil per day (mbpd). The U.S. and world transportation systems are almost entirely dependent on fuels derived from conventional petroleum. According to the International Energy Agency (IEA) statistics, fuels derived from oil supplied 96 percent of the energy to move people and goods worldwide.[3] The 29.6 mbpd consumed in transportation in 1997 was 75 percent more than the 16.9 mbpd used in 1973, implying an average annual growth rate in oil use by transport of 2.4 percent. The 12.7 mbpd increase in transportation oil consumption accounted for over 80 percent of the increase in world oil consumption from 1973 to 1997. Clearly the transportation sector drives the demand for oil; the IEA projects that between 1997 and 2020, world demand for transportation use oil will grow at twice the rate of that for non-transportation oil use.

The U.S. accounts for one-fourth of the world oil consumption, with approximately 13 mbpd going toward transportation. Light vehicles (8 mbpd) are the largest portion at 60 percent of the transportation share. Focusing on passenger vehicles, there are three factors that affect transportation energy demand: the number of vehicles, the number of miles that they travel, and the fuel economy of the vehicles.

Vehicle Population

The motorization of the world has been a major development over the last fifty years. The U.S. accounted for a remarkable 70 percent of the world's light vehicles in 1950, but only 30 percent by 1998 after the world's total number of light vehicles increased ten-fold to 700 million. Because vehicle ownership is correlated with income, forecasts of the future vehicle population can be estimated with a simple model of world vehicle ownership as a function of income (GDP), combined with population projections from the World Bank. Using this approach, the total number of light vehicles is likely to increase by a factor of 3 to 5 over the next fifty years, resulting in two billion to three and a half billion light-duty vehicles worldwide. Other analyses have yielded similar results, notably Gately (3.1 billion in 2050) and the World Business Council for Sustainable Development (1.25 billion in 2025).[4,5]

As income rises, most of the world vehicle population growth is expected to occur in emerging economies where the levels of vehicle ownership are presently very low, as illustrated in Figure 2. In China, for example, the ownership rate is about 12 vehicles per 1000 persons, which is less than the level reached by the United States in 1913. Since the size of the future vehicle fleet is highly dependent on assumptions regarding population and income growth, a midrange forecast of 2.7 billion is used in this analysis. This forecast reflects an ownership rate for the world as a whole that grows from 100 vehicles per thousand people to 300 vehicles per thousand people in 2050. As a reference, this compares to an estimated 780 vehicles per thousand persons in the U.S. in 1998.

Vehicle Miles of Travel

Vehicle miles of travel (VMT) are a second determining factor in the demand for transportation fuels. Growth in VMT in the U.S. has outpaced growth in the vehicle population, rising at about 2.5 percent over the last decade. Consequently, VMT per vehicle has risen at a rate of 1 percent per year over the same period, reaching 11,800 miles per year in 1998.[6] This analysis assumes that total U.S. VMT grows at a slower rate (1.9 percent) in the decade from 2001 to 2010, and then the rate declines linearly to 1 percent by 2050. VMT per vehicle for the world is estimated to be much smaller than in the U.S., although there are no reliable statistics available. However, it is plausible to expect that travel, as a function of per capita income, will increase and perhaps approach current U.S., European, or Japanese levels in many world regions by 2050.

Vehicle Fuel Economy

Nearly all transportation modes, including air, rail, and highway, became much more energy efficient after the energy crises in the early 1970s. However, low fuel prices during the past 15

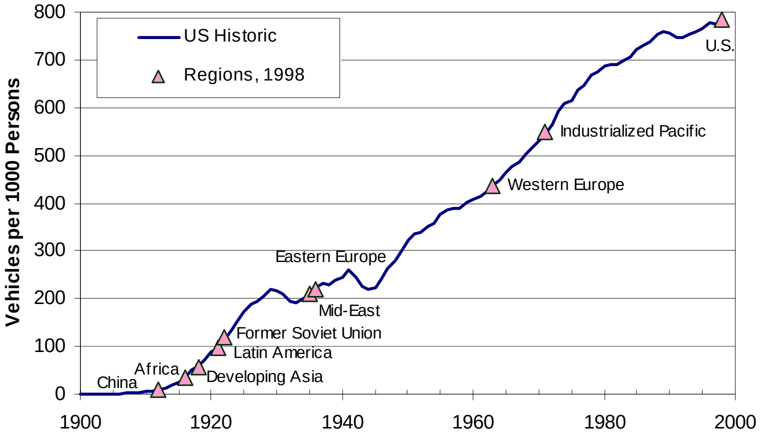

FIGURE 2 World vehicle ownership rates.

years have virtually eliminated demand for improved fuel efficiency in cars and light trucks. New car fuel economy has not improved for more than a decade. In addition, light trucks (pickups, vans, minivans, and sport utility vehicles) that are less efficient than cars are increasingly used in place of automobiles. The fuel economy of new light vehicles (cars and trucks combined) rose from about 14 miles per gallon (mpg) in 1973, peaked in 1987 at 26 mpg, and has since declined more than 2 mpg as the share of trucks has increased to nearly 50 percent of light vehicle sales.

The Oil Gap

World oil consumption has been increasing at a rate of 2.2 percent per year since 1993, and reached 75.6 mbpd in the first half of 2000. Although the U.S. currently accounts for one-fourth of world consumption, growth in oil use in the U.S. has been less than that in the rest of the world for the last 40 years. The Energy Information Administration (EIA) projects that world oil demand will grow between 1.1 percent and 2.7 percent per year through 2020.[7] The midrange forecast of demand growth of 1.9 percent implies that oil consumption in Asian countries will be equal to that in the U.S by 2020. China, India, and South Korea will more than double their oil consumption over this period. Similarly, demand in Central and South America is expected to double, with Brazil accounting for much of that growth.

The date the world reaches the point of peak conventional oil production will depend on the ultimate resource quantity, demand growth rate, and the production decline rate. Using the most current USGS world resource estimates, the EIA developed a set of illustrative production curves for 2 percent demand growth and various decline assumptions for oil production. EIA's own methodology applies a maximum world reserve to production ratio (R/P) of 10. As shown in Figure 3, for a mean resource estimate, this results in peak production in 2037, followed by a precipitous 6 to 8 percent initial decline. The more traditional exhaustion pattern used in this study applies a 2 percent per year decline, which results in an earlier production peak in 2016, but a more gradual decline. The two projections result in similar petroleum production in 2050.[8]

Because of the time required for investments in capital replacement, oil production is unlikely to decline sharply. Therefore, the analysis presented here further assumes that conventional oil production will level off slightly and peak around 2020, then begin a long-term decline. The dashed line in Figure 4 illustrates such a production path. Whether this particular projection is accepted or not, there is considerable consensus that world oil production will be declining early in the 21st Century. Even the USGS's most optimistic assessment of remaining conventional oil resources, matched with the EIA's Low Economic Growth Case for world oil demand, implies that 50 percent of the world's total endowment of oil will be used up before 2040. Pessimistic assumptions and high economic growth would put the 50 percent exhaustion point at 2010.

This analysis assumes that the demand for world oil products will continue to grow at 2 percent per year. After 2020, however, conventional oil production is assumed to peak once 50 percent of ultimate resources have been produced and begin a continual decline. As shown in Figure 4, the gap between continuing demand growth and declining production could be around 50 billion barrels of oil equivalent (145 mbpd) by 2050, or almost twice current production of conventional oil. In the Base Case, the gap is filled by conventional hydrocarbon fuels derived from unconventional fossil energy sources. If the price of the fuels from unconventional fossil resources is not markedly greater, the substitution may occur with little change in energy

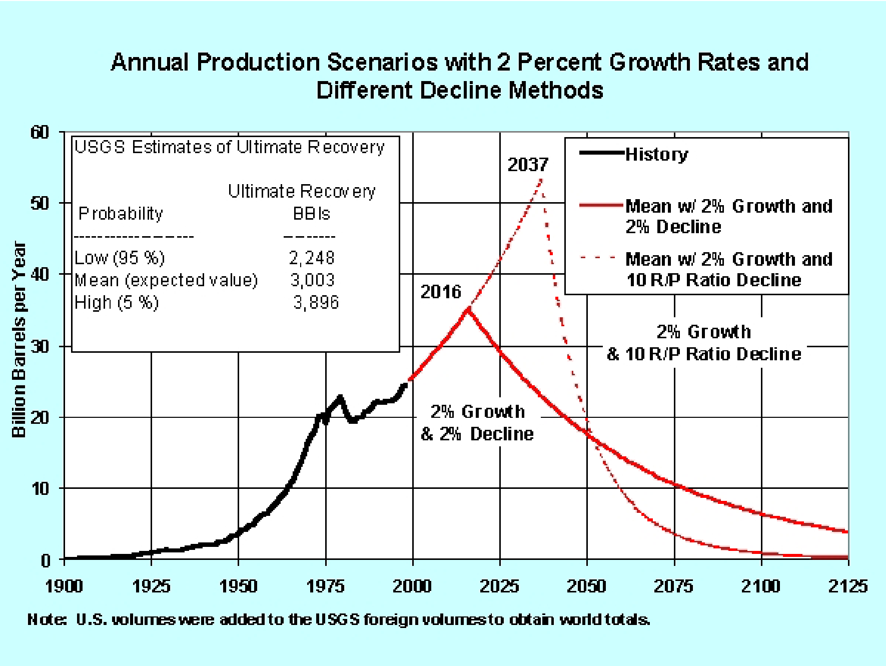

FIGURE 3 Illustrative world conventional oil production paths.
NOTE: Production paths ignore price feedbacks and are illustrative only.

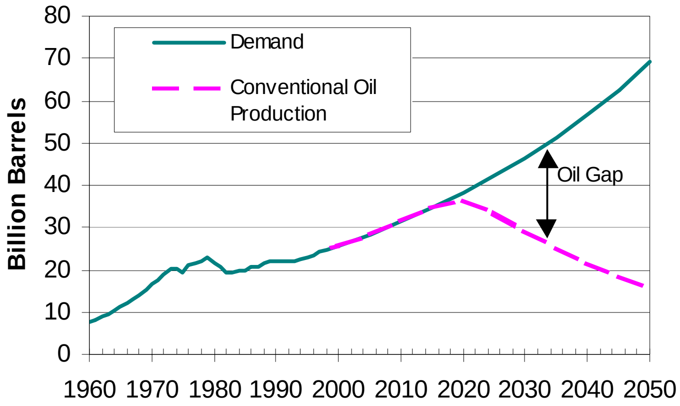

FIGURE 4 The world oil gap.

efficiencies or transportation demand. Otherwise, a tightening of conventional petroleum supply will raise fuel prices, which will stimulate some combination of reduced (or slower growth in) travel demand, higher vehicle efficiencies, and substitute fuels.

A question may now arise whether the discovery and development of new oil fields not adequately accounted for in current estimates could change the prospects for the peak in world oil production. For example, estimates of oil reserves in the Arctic National Wildlife Refuge (ANWR) range from 6 to 16 billion barrels of oil, while estimates of a recent Caspian Sea discovery range from 8 to 50 billion barrels of oil.[9, 10]While the potential for developing large new fields can be significant in the short run, it is unlikely to dramatically affect the long-term prospects for oil supply. The USGS addresses this issue with its high value for undiscovered oil estimated at 1,200 billion barrels compared to a mean estimate of 700 billion barrels. With world demand growth of 2 percent per year, the additional 500 billion barrels – equivalent to 10 to 60 Caspian Sea discoveries—would delay the peak production by only 5 years, assuming a symmetric 2 percent decline. Domestically, the oil contained in a 6 to 16 billion barrel field of oil (for instance, ANWR), which represents 0.3 to 0.8 percent of estimated remaining reserves worldwide, would fuel the U.S. light-duty vehicle fleet for about three to eight years. While this is not insignificant, this supply, over a projected 20-year life of the oil field, would be equivalent to a light-duty vehicle fuel economy improvement of about 2.5 to 6.7 mpg—except that the oil field will be exhausted after twenty years while the vehicle fuel economy improvement would continue to save oil.

IS THE BARREL HALF FULL OR HALF EMPTY?

Determining whether we should be concerned about the future availability of petroleum can be a confusing issue. Knowledgeable people can have diametrically opposed views. Consider these two statements from Scientific American:

> "Global production of conventional oil will begin to decline sooner than most people think, probably within 10 years."
> —Colin J. Campbell and Jean H Laherrère, The End of Cheap Oil,
> *Scientific American*, March 1998

> "There's plenty of cheap oil, says the U.S. Geological Survey."
> —Eric Niiler, Awash in Oil, *Scientific American*, September 2000

So is there plenty of oil or are we running out? The appropriate answer to both questions appears to be: "Yes." We are indeed awash in oil, but we are also awash in the demand for oil. In this study, estimates of crude oil reserves and resources have been reviewed. The latest U.S Geological Survey does increase by 20 percent its earlier estimate of worldwide crude oil reserves. But that simply pushes back by about ten years the estimates of when half of the reserves of crude oil will have been consumed and world crude oil production will begin an inevitable decline.

Filling the Gap

While conventional oil resources are nearly half depleted, the total fossil fuel resource base is vast. As shown in Figure 5, the total resource base conceivably could be 100 times larger than

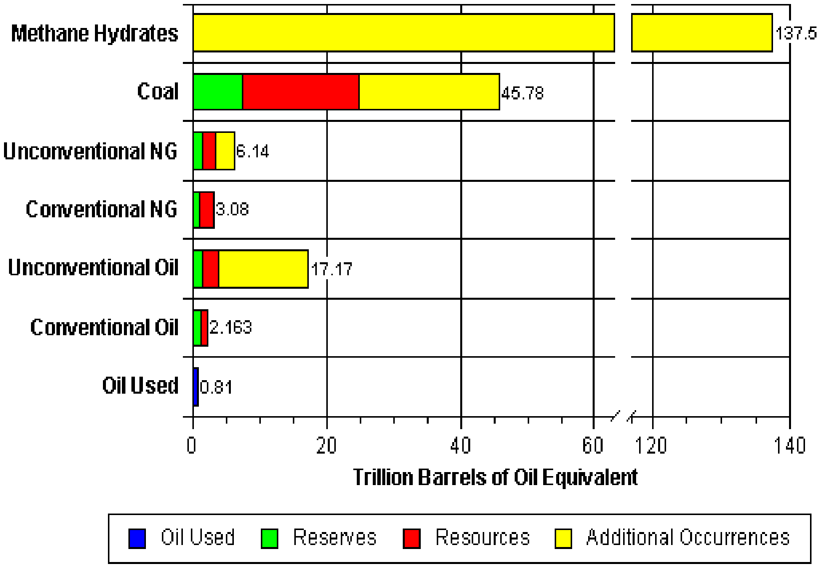

FIGURE 5 World fossil fuel potential.
SOURCE: H. H. Rogner, "An Assessement of World Hydrocarbon Resources," Annual Review of Energy and Environment, 1997.

the base of conventional oil, though estimates vary widely. Also, resources[11] (occurrences that have not been accurately measured and may not be economically recoverable with today's level of technology and fuel prices) could be twice as large as reserves, which have been measured in known reservoirs and can be economically extracted. Additional occurrences with unknown degrees of assurance and unknown or speculative economic significance could be 10 times as large, though quantities are highly uncertain.[12] Estimates of unconventional petroleum resources, in the form of heavy oil, oil sands (sometimes called tar sands), and oil shale are many times larger than conventional oil resources.

With unconventional fossil energy resources estimated at 10 to 100 times conventional oil resources, the world could conceivably continue to use liquid fossil fuels far into the future, but the issues of greenhouse gas emissions, air and water pollution, solid wastes, and oil spills would need to be addressed. For example, producing crude oil from oil sands and oil shale requires large strip or open-pit surface or underground mines that disturb the natural environment. Processing and upgrading to crude oil produces solid and liquid tailings, toxic heavy metals, and gaseous wastes that require after-treatment and/or long-term storage. These challenges add to the familiar environmental problems associated with oil use.

Converting conventional natural gas to liquid (GTL) fuels could be a more desirable path, and could enable liquid fuel production to continue to increase for about another decade after conventional crude oil supplies begin to decline.[13] However, because the known reserves of inexpensive natural gas (flared, stranded, and remote) are outside the U.S., the first liquids made from natural gas would likely be imported. At higher fuel prices, liquids from natural gas could be produced domestically. Estimates of the total U.S. natural gas resource base are highly uncertain. USGS estimates, which are based on geological assessments, have been criticized as overly pessimistic. Meanwhile, the more optimistic estimates, such as those by the Gas Technology Institute (GTI), are based on econometric analysis. The latest USGS estimate puts the total U.S. remaining resource (including proven reserves, reserve growth, and undiscovered resources of conventional and unconventional natural gas) at 1400 tcf (trillion cubic feet). The U.S. currently consumes 21.5 tcf of natural gas annually, and imports 3.5 tcf from Canada (a tcf of natural gas is approximately one quad of energy or 0.5 mbpd of oil). The DOE EIA projects that demand will grow at 3 percent annually beginning in 2001, with growth slowly declining through 2020. If this projection is extrapolated, half of the remaining U.S. resource estimated by the Potential Gas Committee could be consumed before 2030. Figure 6 illustrates this production path with production declining after half the remaining resource is depleted. If this assessment is accurate, significant use of GTL fuels in highway vehicles would likely result in imports of natural gas and or GTL fuel.

On the other hand, if methane hydrates could be successfully developed, liquid fuels from natural gas could support the world economy for a very long time. Although large-scale GTL production might help reduce local air pollution,[14] it would not reduce greenhouse gas emissions unless environmentally acceptable methods were developed to sequester the carbon produced in fuel conversion. Further, the environmental impacts of methane hydrate extraction and processing are unknown. Alternately, developing and using competitive, yet dramatically more efficient vehicle technologies and cleaner, renewable fuels, could provide an option that reduces these environmental impacts by reducing demand for fossil fuels.

Left to market forces, the conventional oil gap likely will be filled with the cheapest liquids from fossil fuels, referred to here as synthetic fuels, that are currently under development and which would be compatible with existing infrastructure. Unconventional petroleum would likely be the first of these to enter the market. For example, heavy crude oil requires enhanced oil recovery methods and currently accounts for 8 percent of world oil production. In Venezuela, the cost of producing a barrel of oil from heavy crude is around $10.[15] In Canada, ongoing research in producing crude oil from oil sands has decreased production costs from $26 per barrel in 1976 to under $10 in 1996.[16] While oil prices fell to $10 per barrel in late 1998, the marginal cost of production of a barrel of conventional oil is below $10, with costs in the Middle East as low as $2-$3.[17] Countries in OPEC and the Former Soviet Union control nearly 90 percent of world heavy crude resources, with more than half in Venezuela. A significant fraction (35 percent) of estimated oil sands resources are located in North America.[18]

With the world's economies dependent on petroleum for virtually all of its transportation, additional production may be necessary in the near term to avoid economic disruption. Even in the long term, development of unconventional petroleum resources may prove to be the most economic alternative. However, conservation could play an important role in meeting transportation energy demand. Developing and using dramatically more efficient vehicle technologies and cleaner, renewable fuels could provide an option that stretches the availability of petroleum resources while improving environmental impacts by reducing the demand for fossil fuels.

ALTERNATIVE FUTURES: ADVANCED VEHICLE TECHNOLOGIES AND ALTERNATIVE FUELS

This study combines the previously described projections of rising world oil prices, the number and type of vehicles, and the vehicle miles of travel to construct a baseline projection, called the

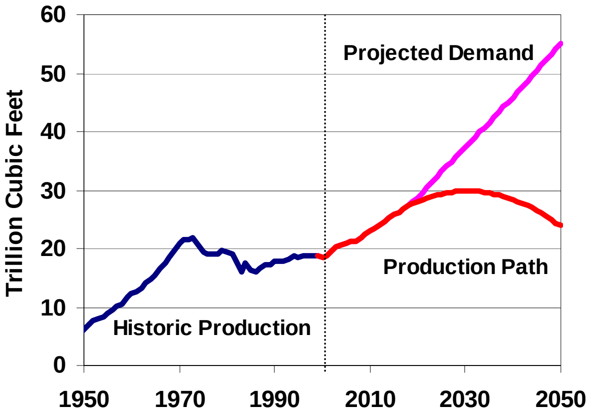

FIGURE 6 Illustrative U.S. natural gas production path.

Base Case. Total energy use, oil use, and carbon emissions are calculated for the projected travel. Six alternative strategies are then developed by postulating various levels of new light vehicle fuel-economy improvements, alternative fuels use, and advanced vehicle technologies. The vehicle population, VMT, and energy use are calculated using the Potential Oil Worksheet (POW). This spreadsheet model includes a 20-year light vehicle stock model with age specific use and scrappage rates, and is calibrated to actual vehicle data from the Federal Highway Administration.

The following assumptions are made about the availability of energy resources. Half of conventional oil is produced domestically in 2000, but oil is assumed to be virtually 100 percent imported by 2050. Methanol is 75 percent imported in 2000, transitioning to 100 percent imported by 2050. CNG is assumed to be mostly domestic, with only 20 percent imported in 2050. Electricity, hydrogen, and ethanol are assumed to be domestically produced, while fossil liquids are assumed to be entirely imported.

There is no attempt in examining alternatives to define a “best” strategy because each produces a mixture of impacts on oil use, greenhouse emissions, and other impacts, and because the costs have not been evaluated. The intent in analyzing the several strategies is to provide a perspective about the range of potential outcomes from pursuing different technologies (vehicles/fuels).

Base Case

The Base Case is a 50-year projection in which the growth in transportation, and the fuels needed for it, reflect 1) continued population and economic growth, 2) modest, but steady, increases in fuel prices, and 3) a declining rate of growth in vehicle miles of travel (VMT). VMT is projected to continue the current trend toward slower growth. The modest fuel price increases over the forecast period are presumed to provide little incentive for increasing the vehicle fuel economy beyond about the 28 mpg for new cars and 20.7 mpg for light trucks[19]. Consequently, the Base Case is one in which vehicle fuel economy remains stagnant; new technology provides performance, not efficiency, improvements.

The resulting light-duty vehicle fuel use projections are illustrated in Figure 7. In the Base Case and in the strategies examined, new light truck sales remain at the 1999 market penetration of nearly 50 percent. Therefore, the stock of light trucks grows after 2000. As a result, although passenger car energy use is currently greater than light trucks, the situation is soon reversed, so that by 2050 light trucks consume one-third more energy than cars. With transportation energy demand continuing unabated, the oil gap discussed earlier would need to be filled with *synthetic fuels* from fossil sources, such as liquids from natural gas. This analysis assumes that carbon emissions per barrel of alternative liquids would be 20 percent higher than for conventional oil, due to conversion losses. This Base Case provides a reference forecast against which various alternatives for meeting future transportation energy use requirements can be compared. Several alternative approaches will be illustrated in the paper. The following six strategies are not exhaustive, of course, but provide some insight for the energy and greenhouse gas impacts of pursuing various alternatives.

The Base Case assumption of no improvement in vehicle fuel economy may appear pessimistic to some given the recent introduction of hybrid electric vehicles (HEVs) (e.g., Toyota Prius, Honda Insight), the ambitious goals of the Partnership for a New Generation of Vehicles, recent announcements of light-truck fuel economy improvement targets by DaimlerChrysler, Ford, and General Motors, and the potential for Congress to increase Corporate Average Fuel Economy standards (CAFE). However, over the past 20 years, stagnant light-duty vehicle fuel economy levels have coexisted with significant technological improvements, and there appears to be no *market* reason why this situation could not continue for the foreseeable future. Technologies may instead enable manufacturers to meet *current* (CAFE) standards despite the continuing shift to larger vehicles with better performance. Although some analysts might prefer more optimistic fuel economy as a base, the only intent with this Base Case is to present a plausible baseline with which to compare alternative strategies.

The levels of oil use and carbon emissions shown in Table 1 for the year 2050 reflect the results of continuing to remain dependent on petroleum to this extent. Carbon emissions track oil consumption to 2020, and then rise more rapidly as synthetic fuels are substituted for conventional oil. Total carbon emissions more than double from 2000 to 2050, leading in the opposite direction from reducing greenhouse gas emissions.

The Base Case also assumes that no alternative fuels (other than synthetic fuels) are used, apart from the small amounts being used today. Alternative strategies are used to project the impacts of significant increases in the use of natural gas, biofuels, hydrogen, or electricity.

Strategies

Strategies are used here to explore “what if” situations, such as what would be the energy and carbon emissions impacts if various vehicle technologies and alternative fuels were to achieve widespread commercial success. The following strategies are defined in terms of vehicle efficiency improvements and/or alternative fuel substitutions for oil and presumed market penetrations for advanced vehicle technologies. One strategy includes vehicle travel reductions that may be due to telecommunications, land use change, or mode shifts. Historically, efforts to reduce the use of personal vehicles have achieved only modest success, since significant travel reductions entail large-scale lifestyle modifications. However, advances in electronics and telecommunications and/or shifting environmental and social priorities could facilitate more substantial reductions over a 50-year period than we have witnessed to date.

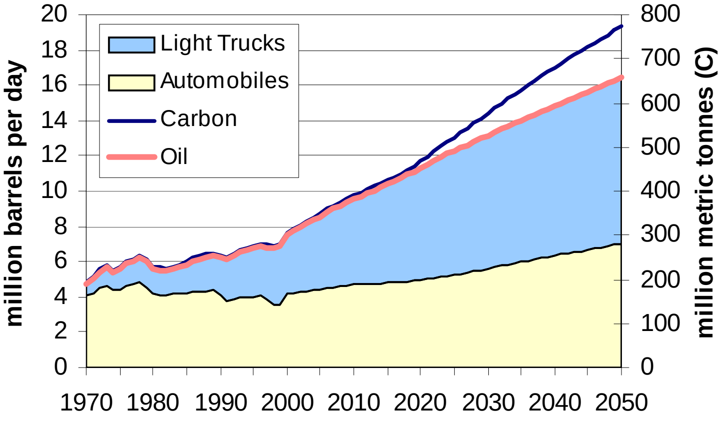

FIGURE 7 Base case light vehicle energy.

TABLE 1 Base Case Projected U.S. Light Vehicle Situation in 2050

	Year 1990	**Year 2000**	**Base Case Year 2050**	**Year 2050 Ratio to 2000**
Oil Use (million barrels per day)	6.2	7.5	16.4	2.19
Carbon Emissions (million metric tons)	255	306	773	2.53

In the strategy definitions and descriptions, the level of the increase in light vehicle fuel economy is represented by the “times” symbol – ×. For example, 2× means that the fuel economy has been doubled (or increased by 100 percent). The notation of 1.5× means that fuel economy has been increased by 50 percent. For ease of reference and comparison, each of the strategy titles includes the increase in fuel economy for the total *fleet* of light vehicles (not new vehicle sales) in 2050, for example, the 1.4× in Strategy 1 means that the total fleet of light vehicles on the road in 2050 would be 40 percent more efficient that today’s fleet of vehicles.
It is presumed that light trucks achieve 75 percent of the stated fuel economy improvement given for cars. This assumption reflects the fact that historically new technology in truck applications has been used to enhance performance capabilities, such as improved torque, rather than fuel economy.

The individual strategies are described and discussed first, then a summary comparison is made.

Strategy 1: Enhanced Conventional Vehicles (1.4× Fleet Fuel Economy)

What would be the effect of a non-trivial increase in vehicle fuel economy? In this strategy, new light vehicle fuel economy increases by 50 percent over the forecast period, resulting by 2050 in new cars averaging 42 mpg and new light-trucks averaging 29 mpg (EPA test values). In a market situation, these increases might be consistent with a fairly high cost of synthetic fuels from fossil sources. Alternatively, the fuel economy gains could be attributed to voluntary or mandated increases in the CAFE standards. Here, the fuel economy increases occur through incremental improvements (e.g., weight reduction, engine/transmission enhancements, aerodynamics, etc.) consistent with the "enhanced conventional vehicle technology" pathway. The introduction of some of these efficiency improvements begins immediately (year 2000) and continues steadily throughout the forecast period. Therefore, it should be noted that any delay in increasing the fuel economy of cars and light trucks will result in a corresponding delay in the energy and carbon emission effects of those improvements. While petroleum and synthetic fuels (from conventional or unconventional sources) continue to be used, this strategy does not assume that there is any increase in the use of alternative fuels beyond the present niche markets.

Annual energy savings grow as a result of new vehicles becoming more efficient each year and the cumulative effect of more efficient cars and light trucks in the total stock of vehicles as time passes. Figure 8 shows the energy and carbon emissions impacts of this strategy. By 2050, energy (as well as oil consumption) and carbon emissions are almost 30 percent lower than the Base Case. This level of energy use and carbon emissions, however, is still an 80 percent increase over the level in the year 2000. The fuel economy improvement is more than offset by the growth in VMT, despite the expected slowdown in its rate of growth. As a result of VMT growth and the continuing shift of the vehicle sales from cars to trucks, automobile fuel use remains flat after 2030, while light truck energy use continues to grow through 2050.

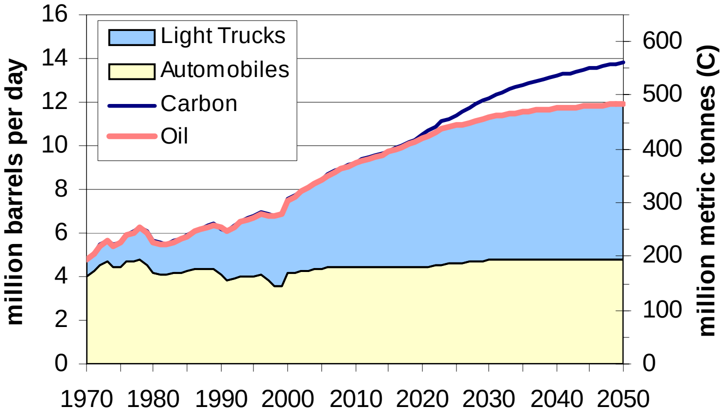

FIGURE 8 Energy use and carbon emissions in Strategy 1.

If the reader believes that fuel economy improvements are likely to occur over the next 50 years, then this strategy could be viewed as a "base case" for comparison with the following strategies.

Strategy 2: Hybrid Electric Vehicles and Electricity (1.7× Fleet Fuel Economy)

What would be the effect of electricity providing a substantial amount of transportation energy and the vehicles becoming more efficient? In this strategy, the fleet is transformed by large numbers of efficient hybrid vehicles, half of which are grid-connected hybrids that, on average, obtain 50 percent of the energy they use from electricity from the grid. Vehicles with a 100 percent improvement in efficiency over current vehicles (2×) resulting from the use of hybrid drivetrains and incremental improvements in materials, structural design, tires, and aerodynamics are introduced in 2005, gradually increasing to 100 percent market penetration by the year 2030. Trucks achieve 75 percent of the fuel economy increase of cars. By 2050, hybrids make up essentially 100 percent of the light vehicle fleet, and half of these are grid-connected, thereby allowing electricity to fuel 25 percent of the miles driven.

The doubling of new vehicle fuel economy in this strategy, along with a substantial use of electricity produces significant reductions in energy use and greenhouse emissions. By 2050, energy use is over 40 percent lower than the Base Case, with oil use still lower (nearly 60 percent less). As shown in Figure 9, energy use levels off and falls after 2015. However, without sustained improvements in energy efficiency, energy consumption is again on the rise by the end of the analysis period because of the continued growth in vehicle stock and VMT. Carbon emissions are only 43 percent of the Base Case by 2050, yet they are still more than 40 percent higher than carbon emissions in the year 2000.

Strategy 3: Travel Reductions Plus Efficiency (1.8× Fleet Fuel Economy)

What would be the effect of reducing travel in conjunction with more efficient vehicles? In Strategy 3, 2× hybrid vehicles are introduced just as they are in Strategy 2 and obtain the same level of market penetration, but none are grid connected. But this time, in addition to the efficiency improvements, vehicle travel grows more slowly than in the Base Case, resulting in a 15 percent reduction in total VMT by 2050. These reductions might be realized through a combination of modal shifts, changes in land use patterns, telecommuting, e-commerce, and other uses of telecommunication.

By 2050, the fleet is composed almost entirely of 2× vehicles, and the average per-vehicle VMT is reduced from 16,622 to 14,138 miles, producing over a 50 percent reduction in energy use, oil use, and carbon emissions relative to the Base Case (see Figure 10). However, compared to the year 2000, carbon emissions are still 20 percent greater in 2050.

Strategy 4: HEVs with Accelerated Use of Biomass (1.8× Fleet Fuel Economy)

If a substantial amount of renewable fuels are introduced along with very efficient vehicles, what would be the effect? Strategy 4 combines HEVs with the same efficiency as those in Strategy 2 and adds an emphasis on renewable fuels, in this case cellulosic ethanol. This approach might be especially desirable if the need to combat global warming is viewed with greater urgency. As in Strategy 2, 2× hybrids are introduced into the light vehicle market in year 2005. Again, by 2030, 2× gasoline hybrids obtain 100 percent penetration of new vehicle sales. As shown in Table 2, biomass ethanol blends are introduced in 2005. By 2050, ethanol provides 45 percent of fuels used in gasoline vehicles, in blends up to E-85.

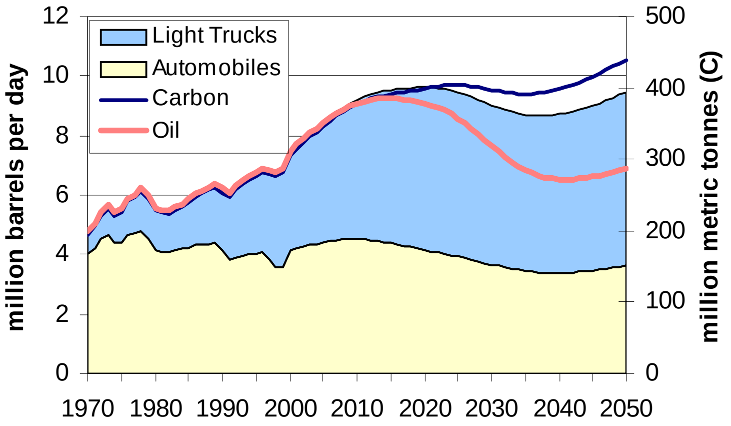

FIGURE 9 Energy use and carbon emissions in Strategy 2.

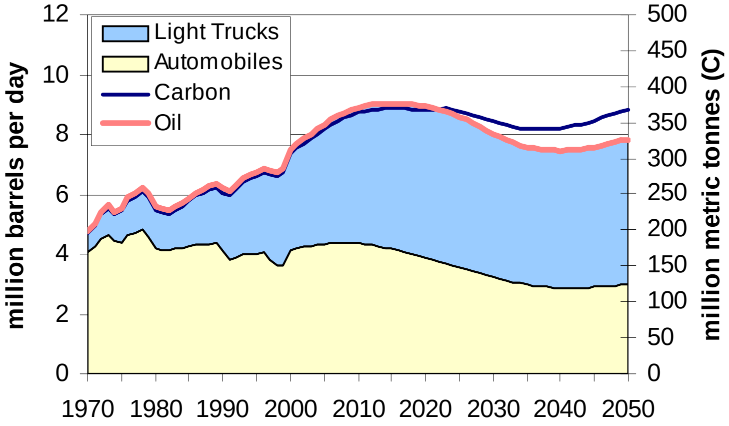

FIGURE 10 Energy use and carbon emissions in Strategy 3.

TABLE 2 Strategy 4 Ethanol Production and Blends

	2010	**2020**	**2030**	**2040**	**2050**
Ethanol (quads)	0.283	0.846	1.69	3.00	5.00
Percent Blends	1.5%	4.8%	12.5%	28.2%	45.0%

It is recognized that agricultural lands are at a premium, so the production of 5 quads of ethanol in 2050 are assumed to be from four sources:

1. Cropland: 44 percent of the ethanol, using 10 percent of current total U.S. cropland, including Conservation Reserve Program acreage;
2. Grassland: 19 percent of the ethanol, using 10 percent of current grassland;
3. Agricultural waste: 25 percent; and
4. Waste wood: 12 percent.

As shown in Figure 11, this strategy yields reductions in energy and oil use similar to Strategy 2, but larger carbon reductions. By 2050, energy use is 44 percent below the base case, and both oil use and carbon emissions are nearly 60 percent below the Base Case because of the substantial shift to a non-petroleum, renewable fuel. Carbon emissions in 2050 are only 6 percent above today's levels. However, this strategy makes it apparent that even with substantial vehicle fuel economy improvements combined with a renewable fuel, it would take many years to return to today's greenhouse gas emissions in the transportation sector.

Strategy 5: F-T Diesel HEVs and Hydrogen FCVs (2.2× Fleet Fuel Economy)

Would the widespread use of much more efficient diesel hybrids combined with the introduction of fuel cell vehicles using hydrogen have a significant impact? This strategy reflects a more radical shift to new fuels and technologies in response to perceptions of a strong need to move away from oil use. Here it is assumed that usable resources of natural gas will be greatly expanded by the development of technologies enabling the eventual use of methane hydrates. By converting natural gas to Fischer–Tropsch (F–T) diesel and hydrogen, the world might then have a supply of clean hydrocarbon fuels, possibly for centuries to come, although as indicated earlier North American natural gas supplies would not support greater transportation use resulting in reliance on imports. However, no carbon sequestration was assumed in this analysis. Because of the cost of these fuels, and because F–T diesel will still produce both conventional pollutants and greenhouse gases, there remain important issues of energy efficiency, pollution minimization, and carbon emissions management. It is recognized that older diesel vehicles emit large amounts of particulates and that the EPA has concluded diesel exhaust is carcinogenic. New diesel engine exhaust is cleaner and future diesels will have to be cleaner still if this technology is to see widespread use. Low sulfur fuel and Fischer-Tropsch processes are currently seen as the enabling technologies.

This strategy applies a progression of vehicle introductions from 2× vehicles in year 2005 to 3.5× by 2040, and uses cleaner distillate fuel (F–T diesel) and hydrogen from natural gas for fuel cells. Some car and light truck hybrids use diesel rather than gasoline, allowing for higher fuel economy. Methane hydrates may emerge as a new energy source after 2020, but without hydrates there is insufficient domestic natural gas to support this strategy. This strategy leads to extensive use of F-T diesel fuels for distillate, comprising up to 50 percent of the diesel fuel supply by 2050. Tables 3 and 4 summarize the fuel efficiency and market penetration of these vehicles.

Conversion of methane to hydrogen for fuel cell vehicles begins around 2015 and develops about as fast as the fleet of hydrogen fuel cell vehicles can expand. Initially, this is based on reformation of methane to hydrogen at the refueling station. After 2015, with this level

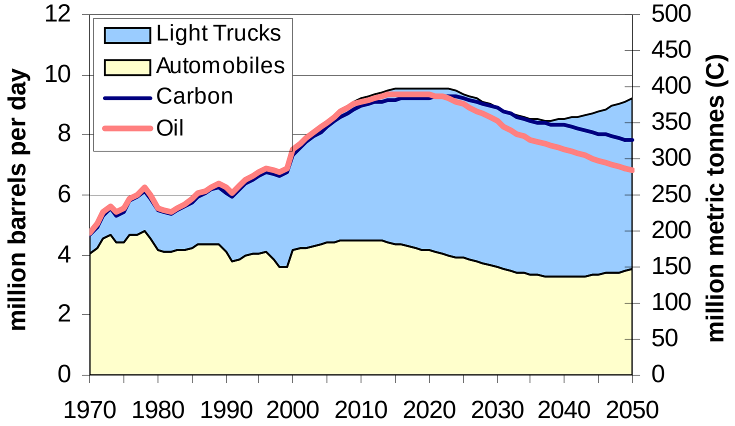

FIGURE 11 Energy use and carbon emissions in Strategy 4.

TABLE 3 Strategy 5 Vehicle Efficiency, Factor Improvement over Current Efficiency

	2010	2020	2030	2040	2050
HEV Gasoline	2.0	2.0	2.0	2.0	2.0
HEV Diesel	2.5	2.5	2.5	2.5	2.5
FCV Hydrogen		3.0	3.0	3.5	3.5

NOTE: Light trucks get 75 percent of the stated improvement.

TABLE 4 Strategy 5 New Sales Market Penetration by High-Efficiency Light Vehicles (Percent)

Vehicle Type	**2010**	**2020**	**2030**	**2040**	**2050**
Cars					
HEV Gasoline	20.0	45.0	50.0	30.0	30.0
HEV Diesel	0.0	7.5	30.0	40.0	40.0
FCV Hydrogen	0.0	7.5	20.0	30.0	30.0
Light trucks					
HEV Gasoline	20.0	40.0	50.0	30.0	30.0
HEV Diesel	0.0	12.5	30.0	40.0	40.0
FCV Hydrogen	0.0	7.5	20.0	30.0	30.0

of demand, a commitment is made to a hydrogen infrastructure with centralized reforming and distribution.

This strategy results in over a 50 percent reduction in energy use from the Base Case—similar to Strategy 3. However, this strategy substitutes hydrogen from fossil sources, and produces larger oil use reductions—nearly 75 percent over the Base Case. Strategy 5 reduces year 2050 carbon emissions by about 55 percent from the Base Case, but even that decrease leaves carbon emissions 15 percent higher than in the year 2000 (see Figure 12). The drop in carbon emissions is equal to the energy reduction because domestic natural gas is the source for the alternative fuels used, and no carbon sequestration is included.

Strategy 6: Three Fuel Future (2.8× Fleet Fuel Economy)

Could the U.S eliminate oil by light-duty vehicles over the next 50 years? Strategy 6 illustrates one possible path toward the elimination of fossil liquid fuels in light vehicles after 2050. By switching to three domestic fuels (biomass ethanol, electricity, and hydrogen), this strategy also significantly reduces reliance on imported fuels. A future with light vehicles using three very different fuels (a liquid, a gas, and electricity) would require a dramatic shift from what exists today. Given the higher fuel and infrastructure costs, resource limitations, and storage considerations of two of the three alternatives, fuel switching would have to be combined with very aggressive fuel economy improvements in order to make this alternative feasible. In this strategy, the stock of light vehicles in 2050 is comprised of fuel cell vehicles operating on hydrogen, very efficient HEVs operating on ethanol, electric vehicles (EVs) operating on electricity, and enhanced conventional vehicles. The combination of low carbon fuels and high vehicle fuel economy also minimizes carbon emissions.

The assumptions for market penetration for this strategy are multiple combinations of new technologies, so for clarity they are provided in Table 5. HEVs operating on ethanol, fuel cell vehicles running on compressed hydrogen, and electric vehicles that plug into the grid each achieves a small share of the new vehicle market by 2020 and, in combination, grow to 100

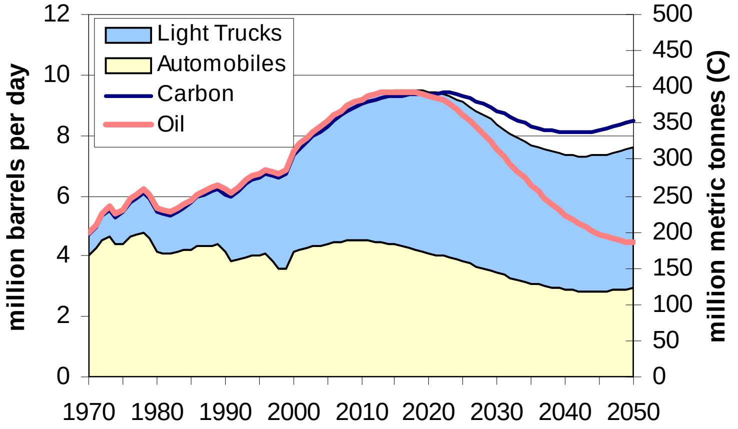

FIGURE 12 Energy use and carbon emissions in Strategy 5.

TABLE 5 Strategy 6 Vehicle Market Penetration (Percent)

Vehicle Type	Fuel Economy	2010	2020	2030	2040	2050
Enhanced Conventional	1.5×	8.0	10.0	0.0	0.0	0.0
	2.0×	0.0	10.0	0.0	0.0	0.0
HEV Gasoline	2.0×	5.0	15.0	10.0	0.0	0.0
	3.0×	0.0	7.5	15.0	10.0	0.0
HEV ETOH	2.0×	5.0	15.0	10.0	0.0	0.0
	3.0×	0.0	7.5	20.0	35.0	35.0
EV	3.15×	2.0	5.0	10.0	10.0	10.0
FCV Hydrogen	3.0×	0.0	10.0	15.0	10.0	0.0
	3.5×	0.0	0.0	20.0	35.0	55.0

percent of new vehicle sales by year 2050 (the 2020 penetration would be a remarkable achievement and clearly could occur only with an aggressive policy environment or the willingness of vehicle manufacturers to assume strong market risks). Each vehicle system achieves at least three times the current fuel economy (3×) on a total fuel cycle basis by 2050. Conventional vehicles are eliminated from the market as early as 2030. Again, light trucks achieve 75 percent of the stated fuel economy improvement.

The hydrogen in 2050 could come from reforming domestic natural gas, the electrolysis of water with electricity (renewable or nonrenewable), or from biomass or coal. This strategy assumes the reforming of natural gas. The electric utility mix of fuels follows the projections in the AEO’00 reference case out to 2020. After that, a greater fraction of electricity is assumed to be generated from renewable resources; it is noted, however, that the policy environment that would allow this strategy should also be expected to move the electric utility sector strongly in the direction of more efficiency and renewable resources well in advance of 2020.

This strategy, as would be expected, produces the greatest energy, oil, and carbon reductions of the strategies examined (see Figure 13). The very high fuel economy of the total vehicle stock results in a 64 percent reduction in energy use over the Base Case. Oil use is nearly eliminated through substitution of alternative fuels, with only small amounts of gasoline still used in ethanol blends (15 percent gasoline by volume). Carbon emissions are reduced by 80 percent over the Base Case are about 50 percent *below* current emission levels. Since the market penetration of 3.5× fuel cell vehicles is still increasing in 2040 and 2050, the fuel economy of the total vehicle stock would continue to rise after 2050, resulting in further reductions beyond the 50-year period of analysis.

Summary of Results

As shown in Table 6, all but Strategy 1 reduce oil use by more than 50 percent compared with the Base Case of stagnant vehicle fuel economy. All but Strategy 1 reduce carbon by 40 percent or more relative to the Base Case. However, as shown in Table 7, Base Case carbon emissions are 2.5 times the current level, and three times a hypothetical Kyoto accord 1990 level minus 7 percent. Only Strategy 6 reaches the 7 percent below 1990 light vehicle greenhouse gas emissions by 2050 *if* transportation assumed its share of carbon emissions reduction.

The levels of fuel economy achieved by all vehicles on the road are shown in Table 8. These values take into account the difference between tested and on-road mpg, as noted earlier. Table 9 shows the overall oil reduction percentage and how it is split between efficiency improvements and the substitution of alternative fuels. Strategy 6 has the largest oil reduction from both efficiency and alternative fuels.

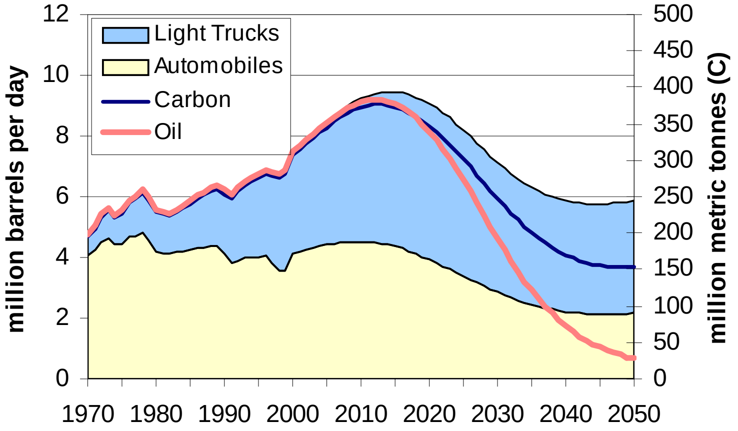

FIGURE 13 Energy use and carbon emissions in Strategy 6.

TABLE 6 Light Vehicle Strategy Results: Reductions Relative to Base Case, Year 2050 (Percent)

Scenario	Description	Year 2050 Results Energy, mbpd	Oil,* mbpd	Carbon, Million Metric Tons
Base Case	Stagnant fuel economy	16.4	16.4	773.0
Strategy:		Percent Reductions Relative to Base Case		
1	Enhanced Conventional Vehicles (1.4×)	27	27	27
2	HEV and Electricity (1.7×)	42	58	43
3	Travel Reduction and Efficiency (1.8×)	52	52	52
4	HEVs with Accelerated Biomass (1.8×)	44	58	58
5	F-T Diesel HEVs and FCVs with H_2 (2.2×)	54	73	54
6	Three Fuel Future (2.8×)	64	96	80

* Includes fuels from unconventional petroleum.

TABLE 7 Light Vehicle Strategy Results: Carbon Emissions in 2050

Base Values, U.S. Light Vehicles in 2050		**MMTC**		
	1990 Minus 7%	237		
	2000 Estimate	306		
Strategy Values, 2050			**Ratio to:** **1990 minus 7%**	**Ratio to:** **2000**
Base Case	Stagnant Fuel Economy (1.0×)	773	3.27	2.52
1	Enhanced Conventional Vehicles (1.4×)	561	2.37	1.83
2	HEV and Electricity (1.7×)	439	1.86	1.44
3	Travel Reduction and Efficiency (1.8×)	369	1.56	1.20
4	HEVs with Accelerated Biomass (1.8×)	325	1.37	1.06
5	F-T Diesel HEVs and FCVs with H_2 (2.2×)	353	1.49	1.15
6	Three Fuel Future (2.8×)	155	0.65	0.51

TABLE 8 Light Vehicle Fuel Economy in 2050

		Total Stock Fuel Economy (mpg)*			
Scenario		**Cars**	**Light Trucks**	**Light Vehicles**	
Base	Stagnant Fuel Economy (1.0×)	22.5	16.4	19.0	1.0×
1	Enhanced Conventional Vehicles (1.4×)	33.3	21.4	26.2	1.4×
2	HEV and Electricity (1.7×)	43.4	26.5	33.0	1.7×
3	Travel Reduction and Efficiency (1.8×)	45.0	27.0	33.8	1.8×
4	HEVs with Accelerated Biomass (1.8×)	45.0	27.0	33.8	1.8×
5	F-T Diesel HEVs and FCVs with H_2 (2.2×)	54.0	33.1	41.1	2.2×
6	Three Fuel Future (2.8×)	73.0	41.6	53.2	2.8×

*Includes on-road degradation factor of 20 percent for all vehicles, excluding electric.

COST CONSIDERATIONS

While purchase and operating costs are very important determinants of commercial viability, cost projections for any developmental technologies over a 50-year horizon are problematic at best. The results of a cost analysis are heavily dependent on projections of vehicle incremental costs and fuel prices. While research goals can be used as a starting point for *cost* projections, market forces will largely determine consumer *prices*. The varying demand for conventional and alternative fuels under the strategies examined here would result in different prices, which would

TABLE 9 Light Vehicle Oil Reductions from Efficiency and Substitution (Percent)

	Strategy	Oil Reduction Relative to Base Case		
		Efficiency	Alternative Fuel*	Total
1	Enhanced Conventional Vehicles (1.4×)	27	0	27
2	HEV and Electricity (1.7×)	42	15	58
3	Travel Reduction and Efficiency (1.8×)	52	0	52
4	HEVs with Accelerated Biomass (1.8×)	44	14	58
5	F-T Diesel HEVs and FCVs with H_2 (2.2×)	54	10	64
6	Three Fuel Future (2.8×)	64	32	96

* FT diesel and other synthetic fuels are not included in alternative fuel.

in turn affect demand. Due to these complicated feedbacks, this analysis, in the current stage that is reported here, has not considered the costs or monetary benefits of the strategies explored, nor made any attempt to pick technologies that would be the “winners” in terms of energy use or GHG emissions. As noted at the beginning of this paper, costs are being addressed in the second phase of the Department of Energy 2050 study.

CONCLUSIONS

The world’s energy system and especially its transportation systems are facing a transition from the predominant energy source of the century: conventional oil. The transition will most likely begin within the next twenty years, if it has not begun already. How and to what fuels this transition is made will have major implications for the world’s economy and for the global environment. A transition to unconventional petroleum could lock in a future of high greenhouse gas emissions from the world’s transportation systems. Transitions to alternative, non-fossil energy sources present uncertainties and risks.

- The best estimates of world conventional oil resources (coupled with projected demand) indicate that half of the world’s conventional crude oil will be consumed by 2010 at the earliest or 2040 at the latest.
- U.S. dependence on petroleum has been growing as U.S. oil production has steadily declined since 1970, when approximately half of all our petroleum resources had been extracted.
  - Even the additions from Alaskan North Shore fields failed to halt declining production.
  - With more than half of U.S. ultimate resources of conventional oil exhausted, U.S. production is unable to meet the energy needs of our transportation sector.
  - Until a transition to other energy resources is well underway, and perhaps even then, U.S. dependence on imported petroleum is likely to increase.
- The transition to unconventional energy resources will be a pivotal event for the world’s transportation systems. The world’s transportation systems are currently more than 95 percent dependent on conventional petroleum fuels. World demand for petroleum products is outpacing the discovery of new conventional petroleum resources.
  - Economic and population growth, especially in the developing economies, are driving a continually increasing demand for faster and more convenient and flexible forms of transportation.

  - U.S. transportation demand is expected to more than double by 2050.
  - World transportation energy demand is projected to increase by a factor of five over the same period.

There are several possible energy futures for the U.S. and world transportation systems. The choices have very different implications for investments in infrastructure, needed technological developments and, probably, environmental and economic consequences. All present significant technological challenges. A number of alternative strategies have been sketched in this paper.

- A strategy that is likely to be beneficial under any plausible strategy is increasing energy efficiency. A 2.5 mpg fuel economy improvement for light-duty vehicles that lasts for 20 years is the equivalent of finding a new oil field containing 6 billion barrels of oil.
- High-efficiency light-duty vehicles (2.5 to 3 times more efficient than today's vehicles), coupled with the use of alternative fuels (e.g., biomass ethanol, F–T distillate, or electricity) could reduce U.S. transportation use of oil to below current consumption levels and restrain the growth of carbon emissions.
- Although we have not evaluated the costs and benefits of alternative strategies and are not able to make statements about which are preferable, it is clear that alternatives with very different economic and environmental implications exist.
  - As shown in Strategies 4 and 6, biomass ethanol, from a combination of sources representing no more than 15 percent of current cropland, could provide significant oil displacement and carbon emissions reduction.
  - F-T diesel fuel from natural gas has substantial oil substitution potential, but would have little carbon emission reduction benefit, unless carbon emissions could be sequestered during the conversion process. However, high-efficiency diesel engines using the ultra-low sulfur fuel could achieve significant carbon emissions reductions.
  - Grid-connected hybrid vehicles might achieve greater use of electricity in transportation than battery-powered electric vehicles. Either can provide significant local air quality benefits, energy efficiency improvements, and reduced oil use, as illustrated in Strategies 2 and 6.
  - Dramatic reductions in oil use and carbon emissions might be achieved with widespread commercialization and market success of high fuel economy technologies, such as hybrid and fuel cell vehicles, utilizing low carbon fuels, such as cellulosic ethanol, electricity and hydrogen.
- Reductions in travel demand, if achievable, could help reduce demand for petroleum, relieving pressure on world resources and extending the period of conventional oil's dominance.

How such reductions might be achieved is not clear, but advances in electronics and telecommunications, or changes in cultural priorities might lead to much greater telecommuting, virtual travel, or changes in land use patterns and shifts in the modal structure of transport.

Because completing a transition to a new and different vehicle technology or fuel systems will require 20 to 30 years, it is not too early to begin serious analysis of energy transitions for the world's transportation systems. Research and development of advanced vehicle and fuel technologies are needed to create desirable alternatives to power the world's transportation systems. Even, new tools for modeling and analysis are needed to better understand the costs and benefits not only of end states, but also of complex, lengthy, and expensive transition processes.

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Transportation Transitions

What Can We Learn from the Ongoing Fuels Transition?

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This paper draws attention to the ongoing and dramatic transition in transportation technologies for both vehicles and fuels by examining the ongoing transitions in conventional vehicles and fuels. Additionally, the paper tries to answer the following three posited questions. How will the ongoing fuels transition influence, limit, or accelerate other transportation transitions? What does the ongoing transition tell us about the opportunity to achieve successful, or even useful, niche markets in the U.S.? What does an examination of the factors behind this ongoing transition reveal about effective policy mechanisms needed to bring about a significant change?

There has been much of discussion of the effects of "transitions" in the transportation sector at previous Biennial Conferences on Transportation, Energy, and Environmental Policy at Asilomar, CA and at other venues. There appear to be two drivers for this intense interest in seeking some sort of "radical market transition" in the transportation sector. The first is the observation of transitions in other sectors of the economy that have brought apparent benefits, such as telecommunications. The second is the desire to shift the ongoing development of the U.S. transportation system to an alternative path that will presumably lead to better outcomes, such as reduced environmental impact, "sustainable" energy use, or "livable cities."

In these discussions of transportation transitions, little attention has been given to the ongoing and dramatic transition in transportation vehicles and fuels technologies. Apparently, most of the participants in these "transition" discussions are comfortable not examining transitions in conventional vehicles and fuels, paying little or no attention to them, as they pursue the more interesting topics of "sustainability," "paradigm shifts," and "socially equitable transportation futures." In as much as this 2001 Asilomar conference intends to "create an informed high-level discussion that *unravels ideology, facts and beliefs*," we believe that an examination of one of the ongoing, real-world transportation transitions would be informative and timely.

The purpose of this paper is to focus on and explore the ongoing transition in transportation fuels and fuels industry. We have chosen the "conventional fuels" industry as our focus because: 1) it is in fact going through a significant "transition;" 2) this is the industry that will have to be even further changed, or displaced, if many of the other apparent goals of the transition seekers are to be attained; and 3) once this ongoing transition is completed, it will become that much more difficult to achieve additional change for a variety of reasons.
This last issue was well captured in a recent article in *The Economist,* which observed,

> it seems pretty plain that oil [i.e., conventional fuels] will be dislodged only by something that is equally cheap, easy to use and efficient—and less polluting. Even if such a thing can be found, oil could be around for decades yet, *so great are the sunk investments in infrastructure, so strong the power of incumbency, so impressive the advances in fossil-fuel technology*—and quite possibly, so vast the remaining deposits. [Emphasis added.]

As we force, directly and indirectly, the conventional fuels industry through its transition, we certainly will have increased its sunk investments as well as advanced its technology base. It would appear that this can only enhance its "powers of incumbency," thereby making displacement that much more remote a possibility.

However, we have come to neither praise nor bury the conventional fuels industry. Our goal is to discuss the elements of the transition in this industry and the factors driving it. To be useful in the context of the discussions at the Biennial Conferences on Transportation, Energy, and Environmental Policy, we also explore three questions that bear on the broader, longer-term perspectives of this conference. These questions are as follows:

- How will the ongoing fuels transition influence, limit, or accelerate other "transportation transitions,"
- What does the ongoing transition tell us about the opportunity to achieve successful, or even useful, niche markets in the U.S., and
- What does an examination of the factors behind this ongoing transition reveal about effective policy mechanisms needed to bring about a significant change, such as another "transition"?

WHAT CHANGES DEFINE THE ONGOING TRANSPORTATION FUELS TRANSITION?

Conventional (i.e., petroleum-based) transportation fuels and vehicles have been undergoing, and continue to undergo, significant changes to address many environmental problems. The vast majority of these changes were to vehicles' engine and exhaust after-treatment designs. Beginning in 1970, motor vehicles were required to limit fuel evaporative emissions. These regulations were followed by limits on emissions of volatile organic compounds (VOC), oxides of nitrogen (NO_X), and carbon monoxide (CO) in order to reduce air pollution known as smog. As vehicle manufacturers gained experience with controlling engine-out and after-treatment emissions, emission requirements became more stringent during the 1980s and 1990s to combat the continued growth in emissions from increases in numbers of vehicles and vehicle travel. These vehicle emission requirements are summarized in Table 1.

Fuel Quality Changes for Emission Control

Parallel to these vehicle technology changes, fuels were changing as well. Removal of tetra-ethyl-lead from gasoline was required to enable proper operation of the catalyst after-treatment systems. Lead removal began in 1975 and was largely completed in the U.S. by 1990, when gasoline was reformulated to deliver sufficient octane and performance without the use of lead.

TABLE 1 Vehicle Emission Control Requirements

Year	Action
1966	Minimal California emissions controls
1968	Minimal Federal U.S. emission controls
1971	Evaporative emission controls
1974	CAFE standards first established for 1975
1975 to 1981	Initiation of Clean Air Act controls; 1975 hydrocarbons (HC) and CO controls, delayed to 1976, then 1978 by Congress; then HC emission requirements were delayed to 1980 and CO emission requirements to 1981 by Congress
1977 to 1981	Clean Air Act Amendments, 1977 NO_x controls, delayed to 1981 by Congress
1983	Inspection and maintenance (I&M) programs established in 64 cities
1985	Emissions controls established for diesel trucks and buses for 1991 and 1994
1989	EPA establishes volatility limits (Rvp) to reduce evaporative emissions
1990	Amendments to the CAA, set new HC, CO, NO_x, and particulate emission standards, more stringent test procedures, expanded I&M programs,
1990	EPA limits on-road diesel sulfur level to 500 parts per million (ppm) Sulfur (S) beginning in October 1992 vehicle technology and clean fuel programs, transportation management provisions
1991	EPA promulgated lower HC, NO_x for 1994
1992	EPA sets emission limits for CO at cold temperatures
	Federal Low Emission Vehicle
	California LEV, ULEV, SULEV, PZEV, ZEV
2004-2010	Tier 2, more stringent exhaust emission requirements on NO_x VOC, and CO
2007	Heavy-duty, on-road diesel emission standards for NO_x VOC, and CO
2010 (?)	Off-road engine emissions standards for NO_x VOC, and CO

In the late 1980s, oxygenated gasoline was introduced—through States' requirements—during the wintertime in severe CO non-attainment areas to reduce CO emissions under certain engine operating conditions. In 1992 the Federal Clean Air Act Amendments (CAAA) of 1990 required additional areas of the country to have oxygenated gasoline during the winter driving season. The CAAA also created a new reformulated gasoline (RFG) with additional requirements for certain ozone non-attainment areas of the country. RFG is required to meet a complex set of performance requirements for controlling VOC, NO_x, and toxics emissions along with a maximum benzene level and a minimum oxygenate requirement. The RFG program started in 1995 with more constraining requirements established in 1998 and 2000. California has it's own requirements even more stringent than the Federal reformulated gasoline requirements, that took effect in 1996 with further reductions in 1998, 2000, and 2003. Diesel fuel sulfur level was regulated in 1993 to help enable proper operation of emission control equipment. California placed additional reformulation requirements on diesel fuel to meet its unique emission requirements goals.

Future gasoline formulation changes are tied to the Federal Tier 2 vehicle emission requirements and have been limited to the maximum sulfur levels for gasoline for both conventional and reformulated gasoline to 30 parts per million (ppm) average and 80 ppm maximum. Additional gasoline reformulations could also occur with controls on gasoline toxics levels and changes associated with the RFG oxygenate requirement and MTBE controversy. On-road diesel vehicles will face more stringent emission requirements beginning with model year 2007 vehicles. These emissions requirements will necessitate diesel fuel sulfur levels be reduced to a maximum of 15 ppm. Additional reformulation requirements to diesel fuel—similar to those already adopted in California—may be adopted by other States as part of their implementation plans to control NO_x emissions. Table 2 lists changes to transportation fuels to help reduce vehicle emissions.

Integration of Vehicle and Fuel Technology

These changes to both vehicles and fuels are the result of the integration of vehicle and fuels design in order to facilitate vehicle emission equipment. This integration in design first began with the removal of lead as a gasoline additive. The Federal Tier 2 exhaust emissions requirements, which take effect in 2004, require the lowering of fuel (gasoline and diesel) sulfur levels to enable the after-treatment equipment to perform efficiently and with the requisite longevity.

Going beyond sulfur reductions to benefit emissions after-treatment, vehicle manufactures have established distillation (or driveability) index (DI) specifications for gasoline. DI is related to gasolines gas-phase combustion characteristics in the engine as they relate to the fuel distillation profile. The first 20 percent of gasoline’s distillation profile effects cold and hot starting characteristics, while the middle portion of the distillation profile effects fuel economy and acceleration performance, and the last 20 percent of the distillation profile effects emissions and fuel economy. Equation 1 presents the relationship of DI relative to its distillation profile.

TABLE 2 Motor Fuel Changes

Year	**Action**
1974 to 1990	Lead removal from gasoline
1989, 1992	Oxygenated gasoline requirements
1993	Low sulfur diesel (500 ppm S)
1995, 1996, 1998,	Reformulated gasoline [1995, 1996 (CARB)]
2000, 2003	1998, 2000, 2003 [(CARB3)-RFG]
1993	California diesel reformulation, sulfur, aromatics, and cetane
1995 to 1998	Low-Rvp gasoline requirements for State Implementation Programs
2004 to 2008/9	Low sulfur gasoline
2006 to 2010	Ultra-low sulfur diesel
2002/3?	Gasoline toxics controls, (MSAT)
2002?	Reformulated diesel? Texas and other states?
?	Gasoline Distillation Index (DI) control

Equation 1

$$(\text{Driveability/Distillation Index}) = (1.5 \times T_{10}) + (3 \times T_{50}) + T_{90} + (20 \times \text{oxygen weight, percent})$$

where T_{10}, T_{50}, and T_{90} are the temperatures (°F) at which 10, 50, and 90 percent of the gasoline is evaporated.

A lower DI number is seen as beneficial to vehicle performance and emissions. However, lowering the DI number requires replacing the higher boiling components from the gasoline pool with lower boiling components. A significant reduction in DI would represent a high level of vehicle/fuel integration, but would also drive significant further changes in refining operations. The National Petroleum Council (NPC) has estimated the cost of reducing gasoline DI by 50 degrees Fahrenheit (°F) to be U.S.$11 billion. The cost is high because it requires that 10 to 15 percent of the gasoline volume be replaced with lighter lower boiling molecules. These lower boiling gasoline components would require expensive cracking of the larger, less volatile gasoline-blending components. Whether this degree of vehicle and fuel technology will occur in the ongoing transition is yet to be determined.

Increasing the Use of Nontraditional Inputs

The basis of the petroleum fuels industry has been to upgrade crude oil into marketable lighter products. Crude oil is made up of a mixture of many different hydrocarbon molecules ranging in size from a few to many hundreds of atoms. The smaller or lighter molecules boil at a low temperature while the largest molecules are still liquids at temperatures above 1000 °F. The first stage of upgrading crude oil to marketable product begins with distillation of the crude oil into the product of decreasing boiling ranges, which corresponds directly to molecular weight and density. The highest (800 °F) to lowest temperature (less than 90 °F) boiling range material is residual oil, distillate, kerosene, gasoline, petrochemical feedstocks, liquid petroleum gases (butane, propane), to ethane and methane, respectively.

Motor gasoline is the petroleum product of greatest demand in the U.S. and subsequently provides the refiner with the highest gross revenues. However, the demand for motor gasoline is much higher than can be derived from the simple distillation of crude oil. Approximately fifteen percent of a barrel of crude yields gasoline via distillation, while U.S. demands require approximately fifty percent of the crude oil to fulfill motor gasoline demand. To make up the difference refiners rely on a number of processes downstream from distillation to break up larger, higher boiling point molecules of less valued crude products such as residual oil into more valuable gasoline and distillates. This molecule breaking process usually employs extreme temperatures and pressures along with catalytic reactants and sometimes the input of expensive feedstocks such as hydrogen. Additionally, lighter or smaller molecules such as propane and butane are reconfigured and combined through alkylation and polymization to produce higher boiling point gasoline blending components with more desirable product properties. Over the last century, with the advent of a mobile society, the U.S. refining industry has invested heavily to develop a very complex system of refineries with ability to process many types of crude oils into products the consumer market demands.

Nontraditional inputs to U.S. refineries are arriving because of the energy policies of other countries. Both Venezuela and Mexico have promoted the investment in upgrading facilities at U.S. refineries to use some of their less desirable crude oils. Additionally, Canada has invested heavily in processing their tar sands to provide refinery feedstocks to the U.S. market.

During the last three decades changes to the refinery industry in terms of environmental facility requirements and environmental product quality requirements mentioned above have led the industry to develop products using additional inputs that are non-crude based, such as hydrogen, ethanol, and methanol. The addition of hydrogen to the refining process has enabled the refiners to produce a greater volume of higher quality product from less desirable crude oils. California refineries are an example of how stringent environmental requirements for product and facilities have pushed the industry to further upgrade their facilities. California refineries have invested heavily in complex downstream processing units and the addition of hydrogen and oxygenates, which enable them to meet the more stringent product quality constraints. PADD V refineries consume over two times the hydrogen as in PADD III refineries and eight times that consumed in PADD I refineries. Oxygenate are used to meet clean fuel requirements and mandates economically, extend gasoline volume, and address DI and octane.

Looking to the future, the refinery industry will continue to evolve to become even more complex and capable of producing products of higher environmental quality while using feedstocks of increasingly poor quality or that are non-crude based. This evolution of the industry will most likely lead to advances that will enable use of a number of alternative forms of feedstocks— such as natural gas, synthetic gases, biomass, and petroleum residual products—to provide the refineries with power, steam, and hydrogen, ultimately enabling the production of cleaner products.

Changing the Way Petroleum Products Are Marketed

Recently, retailing of conventional transportation fuels have moved from mom-and-pop retailers to high volume, convenience markets (C-marts) retailers to hypermarkets (COSTCO, Wal-Mart, etc.). The entry of ultra-large C-marts and hypermarkets represents a revolution in gasoline and diesel fuel marketing in that the petroleum product sale is secondary to other product sales and income sources. Because they have other income sources, these hypermarkets compete effectively against the traditional convenience store and “service station” gasoline outlets. Hypermarkets can offer deep discounts on gasoline, while earning income on sales of other products. These hypermarkets, being less reliant on gasoline sales than conventional convenience stores, can withstand longer periods of very low margins, such as low gasoline prices. While their “deep pockets” provide the financial capability to compete effectively with traditional fuel retailers, they also could have positive implications for alternative fuels for niche markets.

Industry Consolidation and Reconfiguration

Over the last decade the U.S. refining and petroleum marketing industry has been plagued with low product margins resulting in lower profits. These low product margins could be attributed to the excess of refining capacity in the early to mid-1990s relative to total product supplied. In order to increase profits, the refining industry has cut costs by selling or closing the least profitable refineries while increasing capacity at their most profitable and capable refineries. Figure 1 shows the trend of the decline in the number of operating refineries while the average and total capacity has increased. The reason for this trend toward larger refineries is economics.

The economy of scale in refining capital investment (fluid process technology) is defined by the "six-tenths rule." That is, the cost of investing at larger refineries is only six-tenths the power to the size ratio. So a refinery that has approximately three times the distillation capacity only requires twice the investment costs for a given change in input or product quality, i.e., lower per barrel costs.

The economies of scale are difficult to overcome when product margins are pennies per gallon. Survival in petroleum refining and marketing is defined as being able to compete on price for less than a cent per gallon as mentioned above. Since the margins on the sale of product are small, survival requires increasing the amount of product sold. This can be done two ways: by making enormous investment to increase capacity and probably decreasing your competitiveness at the margin or by acquiring lower cost refining assets through merger or formation of joint ventures with competing interests. Joint ventures and mergers in the refining and marketing end of the petroleum industry have enabled companies to consolidate operations by sharing assets and reducing redundancies in operations. These efficiencies of scale allow refiners and marketers to trim operating and investment costs, the prime variable in undercutting the competition on price, and to gain additional market share. Table 3 displays the mergers and joint ventures that have occurred over the last decade.

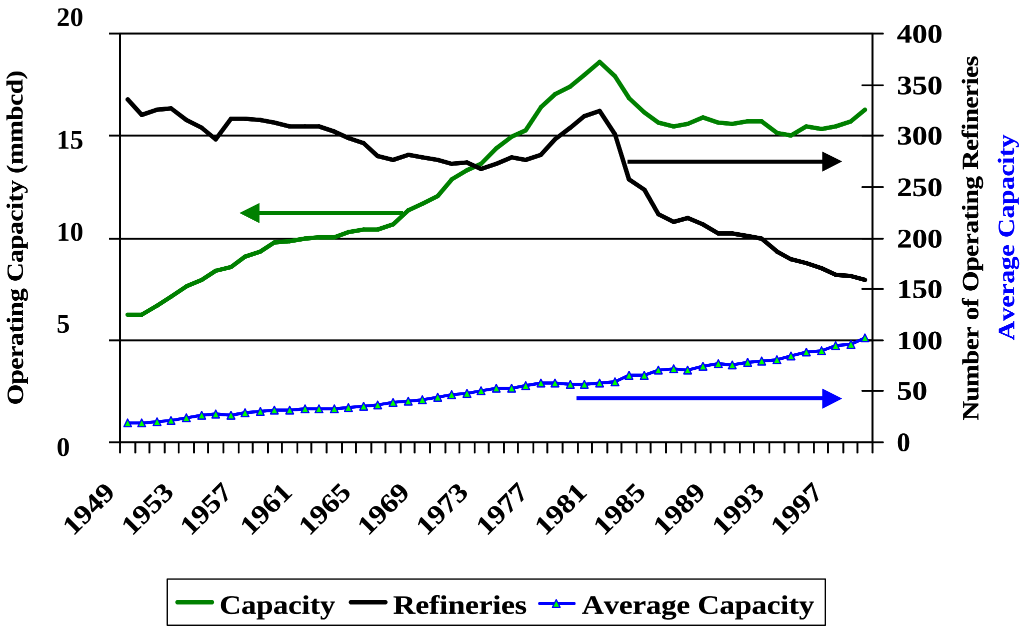

FIGURE 1 U.S. refining capacity and number of operating refineries.

Sunk Costs Are Increasing

The refining industry will continue to require tens of billions of dollars of investments over the next decade to upgrade facilities to produce cleaner fuels. These are investments simply to stay in business, not expand production. Table 4 lists these investments by regulatory requirement. These environment regulation only investments are on the order of at least one half of the value of the U.S. refining industry's net property, plant, and equipment value of approximately U.S.$40 to 50 billion. Additional investments may be required in the marketing and delivery system of the fuel also. These investments will drive the refining industry towards a more complex and capable system and enable petroleum-based fuels to more rapidly and cost effectively adjust to future environmental requirements.

TABLE 3 Mergers and Joint Ventures

Mergers
BP, Amoco, ARCO
Exxon, Mobil
Valero, Ultramar Diamond Shamrock (pending)
Phillips, Tosco (pending)
Chevron, Texaco (pending)
Joint Ventures
Texaco, Aramco, Shell
Amerada Hess, PdVSA
Marathon and Ashland Oil
Phillips, PdVSA
Mobil, PdVSA

TABLE 4 Investment by Regulation

Regulation	**USD**
MTBE Phase-out	$2B
Low Sulfur Gasoline	$8B
Ultra Low Sulfur Diesel	$8B
Mobile-Source Air Toxics	?*
Off-road Diesel Sulfur	?*
Reformulated Diesel	?*
DI Control	**up to $11B
Heavy Crude Upgrading	$250M+/per facility

* pending or probable
** uncertain

WHAT IS DRIVING THE ONGOING TRANSPORTATION FUELS TRANSITION?

There appear to be four major factors that are driving the ongoing transition in the conventional fuels industry:

- *Traditional environmental constraints*, including the need to reduce ozone, toxics, and particulate matter levels,
- *Advancing vehicle and fuel technology*, including emission control and driveability on the vehicle side, and hydro-processing and bio-processing on the fuel side,
- *Economics* of increasingly competitive markets and globalization, and
- *National energy policy*, not in the U.S., but in energy rich countries that are economically motivated to exploit not only conventional oil resources, but to use remote or unconventional light and heavy energy resources.

One could add a fifth factor to this list, that of *national development goals in the less developed countries*, that depend on easy (relatively low infrastructure cost) to import or produce, and use, petroleum products to fuel economic expansion. However, this is not so much contributing to the transition of the conventional fuels industry, as to its geographic expansion and the displacement of less oil dependent transportation systems.

The above factors are discussed in more detail below, but it is worth noting what the list does not include as drivers of the transition.

- As a practical matter, global environmental concerns over climate change have not had a direct effect, except as they have caused increased demand for diesel fuel in lieu of gasoline to fuel more efficient light duty vehicles.
- Domestic energy policy or, as many people see it, the lack of one, has had no real effect, either positive or negative. While current National Energy Policy initiatives may lead to greater infrastructure development for transportation fuels, that development will not be distinguishable from the ongoing transition.
- The push for greater fuel diversity and reduced oil dependency such as expressed in the 1992 Energy Policy Act has been largely unsuccessful and what impacts it has had have shown up in vehicle design and not in the fuels industry transition.
- Interest in sustainability has been paid much lip service, but it is hard to identify how it has affected the fuels industry transition, unless one wants to attribute efforts to promote bio-fuels, like ethanol, to it. A more correct reading would attribute bio-fuels growth to one aspect of agriculture policy and certain traditional environmental drivers.

Returning to what appear to be the real drivers of the transition in the transportation fuels industry, we have really nothing more than the same four factors that have been driving change in the transportation sector, and fueling discussions at these Biennial Conferences on Transportation, Energy, and Environmental Policy, for the past twenty years.

Environmental needs have been a dominant feature of the fuels industry transition since the removal of lead more than 25 years ago. As pollution from the transportation sector has grown and its subtleties have been better understood, more has been demanded in terms of fuel quality changes to meet these environmental needs. Rarely, throughout this process, has the validity of this driver been questioned effectively and it is likely to continue to be a major force in this transition for the foreseeable future. On the other hand, some have claimed that the environmental needs are so great that displacement of the conventional transportation fuels industry is necessary. That was a key premise behind the unsuccessful 1990 CAAA proposal to force a shift to "clean (and presumable non-petroleum) fuels." This call for a wholesale shift, a "radical market transition," gets repeated periodically but unsuccessfully, largely because it has been an economically unattractive means of reducing pollution, and was not required to meet the environmental goals that were established.

While one can debate whether *advancing technology* of conventional fuels will be adequate to meet ever increasingly stringent demands, those advances in technology have been substantial and a driver in reshaping the industry. These fuel technologies have allowed ethers to be produced and used economically, increased the use of natural gas as a conventional fuel feedstock (either in hydrocracking or gas-to-liquids (GTLs)), provided a basis for near elimination of sulfur with reduced volume and cost impacts, and enabled significant vapor pressure and toxics reduction through hydrocarbon restructuring, and is allowing economic upgrading of very heavy (high carbon to hydrogen ratio) feedstocks for conventional fuels production. Information technology has played a role in allowing improved inventory, blending and process control, producing both economic and environmental benefits of conventional fuels.

From the vehicle side, technology advances have required greater integration of vehicle design and fuel formulation. While refiners have, to varying degrees, resisted this, these technology advances have brought about the need for near-zero sulfur fuels and reduced variability in gasoline formulation. Those needs have in turn helped drive the fuels industry transition.

The e*conomics* of increasingly competitive markets and globalization have caused a significant restructuring of the conventional fuels industry as discussed above. Smaller players (companies or facilities) cannot afford the high level of stay-in-business investment required and either close or merge. Reduced trade barriers and increasing similarity of product specifications made product trading more viable and attractive. Increasing intercontinental shipments of petroleum products (aided by information technology in commodity markets) and an increasingly sophisticated domestic pipeline system means everyone is, in fact, competing with everyone else; very few geographically isolated (and protected) markets exist.

Along with these increasingly competitive markets have come reduced inventory levels and increasing product price volatility. The last few years of wide swings in gasoline and diesel fuel prices are not aberrations, but indicators of what is likely to become an expected characteristic of an economically competitive fuels market. Under these circumstances, "large" and "technologically sophisticated" become requirements, not just desirable attributes. This need to be large and sophisticated, and to be able to survive in a volatile price world, has also translated to the fuel retailing level.

National energy policy, not in the U.S., but in energy-rich countries, is playing an increasingly important role in the fuels industry transition. While policy has been one of essentially free market determination, countries with both light (natural gas) and heavy (crude and tar sands) hydrocarbon resources are making explicit decisions and the related investment to get their resources to the conventional fuels market. Venezuela, Mexico, and Canada have made investments at home and in the U.S. to enable their heavier feedstocks to complete with conventional crude oil. The volume of this very heavy product used in conventional fuel production already exceeds 1 million barrels/day. Middle Eastern and African nations are signing contracts to bring about gas-to-liquid developments that are targeted at U.S. and European markets. Most of these developments envision the GTL product to be used as a premium blendstock in making clean diesel fuel. Volumes on the order of hundreds of thousands of b/d are envisioned over the next five years and such blending has already taken place in the California diesel market. It is evident that “energy policy” can and does affect fuels transitions, but it appears that it has to be proactive or interventionist in nature, backed up with either financial or resource commitments. Energy policies based on setting goals and providing very modest or passive incentives (EPAct), or R&D-based policies, have not had any significant, observable effects to date.

Concluding Thoughts

To better understand where this leads us vis-a-vis the question of “managing transportation transitions,” we return to the three questions posited earlier.

- *How will the ongoing fuels transition influence, limit, or accelerate other “transportation transitions”?*

The most probable answer is: *The Economist* was right, increasing pressure on the conventional fuels only leads to further entrenchment of the existing industry.

Incumbency is powerful and the ongoing fuels industry’s investments in advanced technology and increasing economies of scale are increasing its powers of incumbency. Causing something else to happen (e.g., moving to a hydrogen pathway) just becomes more difficult and unlikely because it is not in the economic interest of these powerful, relatively homogeneous players.

An alternative interpretation is that a small number of relatively homogeneous, large, economically powerful players with an advanced technology base will find it easier to switch pathways—making the socially desirable transition—all that easier when they finally “see the light.” We have not seen the evidence for that but it is a plausible argument, at least from a technical point of view.

- *What does the ongoing transition tell us about the opportunity to achieve successful, or even useful, niche markets in the U.S.?*

We believe the only supportable answer is: Niche markets do not lead to alternative pathways and transitions.

Niche-market players will never be competitive and niche-market technologies become successful only when they are “mainstreamed” by the existing industry in their conventional fuels production system. The successes (hydrogen, alcohols, and GTLs as blendstocks) and the failures (neat alternative fuels, EVs) prove the point.

- *What does an examination of the factors behind this ongoing transition reveal about effective policy mechanisms needed to bring about a significant change?*

None of the four factors that are driving the fuels transition are either new or unexpected, but only one, environmental demands, represents a U.S. policy mechanism per se, that has been used to bring about change.

Achieving environmental goals remains a widely supported public policy and the fact that it has driven significant improvements in fuel quality and the associated massive investments in the conventional fuels industry seems perfectly logical. What is equally important to note is that it has not driven any significant shift in the mix of products or the technical operation of the industry.

Among the other three factors, competitive market economics and advancing technology are largely external to the policy process, at least as it has been applied to the fuels industry in this country. The government has been involved in the market economics through subsidies and in technology development to a small degree, but this has been designed to economically aid the industry, not cause any change per se. Finally, within the U.S. context, we have had several attempts and no success (unlike the energy exporting countries discussed) in energy policy aimed at shifting the resource base for conventional fuels.

Overall, this suggests that pushing for a transportation fuels transition to achieve environmental goals can be successful. However, that policy approach must be based on achieving widespread public support for the environmental goal and attainment of the goal by the existing industry without causing major changes to existing infrastructure.

Regarding the other factors that have not been tried, arguments can be made that massive technology efforts or massive subsidies (or taxes) could work to bring about a transition, but real world evidence in a contemporary U.S. context is completely lacking.

A Strategy for Introducing Hydrogen into Transportation

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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 the 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 be maximized 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.

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 U.S. 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 U.S. 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 the ultimate goal—low CO_2 emissions and/or petroleum independent 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 mode into which to introduce hydrogen *first*.

HYDROGEN AS A TRANSPORTATION FUEL

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, but now forgotten study of a 'hydrogen economy' (Dickson, et al., 1976).

The emphasis on LDVs is evident in U.S. 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 (U.S. 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" (p. 4–48).

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 U.S. (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" (U.S. Department of Energy, 2000 p. 4–48).

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 (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.

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 large 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 considered. 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]

TECHNOLOGICAL CHANGE

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 analyze 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 research and development 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.

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 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 to 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.

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, U.S. 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).

GUIDELINES FOR INTRODUCING HYDROGEN FUEL

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]

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 trade-offs 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.

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.

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.

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 onroad, 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 relatively distant from people and property will tend to expose the public to fewer risks, all other things being equal.

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.

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.

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, for which customers place orders from more or less standard designs. By law,[5] freight vessels that sail from point to point within the U.S. must be domestically built, but all others, including ocean-going vessels, are built elsewhere, typically in Asia, at lower cost (about 20% to 30% of the U.S.-built cost). Marine engines are produced by about two dozen firms worldwide, but sales are almost exclusively by European and Japanese firms. Large (up to 60MW) 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 LNG tankers are now in service, and they have sailed without incident for over twenty 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).

Large differences exist in the elasticities of demand and substitution among different freight modes. In the U.S., 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

TABLE 1 Simple Cross-Modal Comparison

	Transportation Mode			
Feature	**Passenger Automobiles**	**Commercial Aircraft**	**Long-Haul Freight Trucks**	**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 hours/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 hours/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 hours/day over 250 days/year.	Refueled at commercial docks, most operations in harbors with tugs or at sea. Virtually 24-hour 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 ~10GJ/mo. (80,000 U.S. gal./mo.).	40 large commercial airports in the U.S., with an average size of ~5,200 GJ/mo. (38,000,000 US gal./mo.).	Approximately 1,500 truckstops and fuel centers in the U.S., with an average size of ~85 GJ/mo. (600,000 US gal./mo.).	About 30 bunker fuel providers (refiners) in the U.S., 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.

SOURCE: Pollution data from Davis, 2001, Chapter 4

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 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 U.S. (Corbett and Fishbeck, 1997), which could provide the U.S. with unique leverage in this case. Howver, this is balanced by the fact more than 90% of the cargo ships calling on U.S. ports are foreign-registered, often in developing countries. The net effect for environmental regulations is that the U.S. 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 above 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.

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 the 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 insufficient because inadequate incentives 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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NOTES

1. The authors are not committed to this assumption, but observe that it it currently driving considerable research and development 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.
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).
5. Section 27 of the Merchant Marine Act of 1920, commonly referred to as the Jones Act.
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.

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The Market for Fuel Cell Auxiliary Power Units for Heavy-Duty Diesel Vehicles

First Widespread Application of Fuel Cells in Transportation?

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Introducing fuel cells into market niches may be a promising near-term commercialization strategy. DaimlerChrysler and BMW are investigating the use of fuel cells for vehicle auxiliary power, and several manufacturers are exploring mild-hybrid vehicle applications that may also be appropriate for fuel cells. This paper addresses what could prove to be the first major commercial market niche for fuel cells in vehicles – their use as auxiliary power units (APUs) in heavy-duty vehicles. The use of fuel cell APUs is especially compelling because it not only reduces energy and environmental impacts, but has the potential to reduce costs and improve driver safety (by reducing noise and vibration for sleeping drivers). Thus, unlike many technologies that benefit either the public or private interests, APUs have the potential to serve both.Widespread idling of main and auxiliary heavy-duty truck engines consumes significant amounts of diesel fuel, emits large amounts of pollution, accelerates engine wear and tear, and causes considerable noise and vibrations. Many heavy-duty long-haul trucks idle during driver rest periods for long periods (up to 40 percent of engine run time). Other local vehicles may idle during and between deliveries. The engines power climate control devices (e.g., heaters), sleeper compartment accessories (e.g., refrigerators, microwave ovens, and televisions), and auxiliary equipment. Main and auxiliary engines idle for power take off operations [1] and refrigeration units[2]. This paper explores how APUs might be attractive in trucks. We assess the potential market for heavy-vehicle fuel cell APUs, addressing APU performance requirements, driver acceptance issues, implementation barriers, and costs. The analysis yields several qualitative generalizations. First, the potential APU market is significant. It includes line-haul trucks which idle during rest periods, delivery trucks with long idle times, power take off operations, refrigeration units, recreational vehicles, and emergency equipment. Second, reliability and durability requirements are clear, but performance demands, APU power output, size, and weight, will vary with application. Third, in addition to cost, potential barriers include driver convenience, comfort, culture, fuel availability, truck design limitations, and competing products. Not surprisingly, costs are likely to be a pivotal factor. Quantitative cost-effectiveness assessments and market penetration estimates are hindered by the lack of knowledge of truck operations (e.g. idle duration, location, and fuel consumption) and uncertainties in future fuel cell costs.

The principal motivation for the use of auxiliary power units in trucks is to ease the cost, noise, and pollution associated with idling of large diesel engines. But the considerable uncertainty about the location, duration, power generation, and fuel consumption of truck idling makes it difficult to quantify the costs and benefits of reducing this idling.

Line-haul truck drivers spend considerable time resting in their trucks, for comfort, cost, safety, and legal reasons. In the U.S., truck driver rest periods are required by tightly-enforced federal safety laws. The Federal Motor Carrier Safety Administration of the U.S. Department of Transportation regulates the amount of hours a truck driver may load and unload, wait, drive, and rest (FMCSR 395). Rest requirements are complex and are a function of the daily time spent on duty, the daily time spent off-duty, and the number of days worked consecutively. In general, no driver may drive for more than 10 hours following 8 consecutive hours off duty.

Truck drivers often idle their engines in order to power climate-control devices (e.g., heaters and air conditioners) and sleeper compartment electrical appliances (e.g., refrigerators, microwave ovens, and televisions). Collectively, these are often referred to as “hotel” accessories. Engines are also idled to prevent start-up problems in cold weather, drown out noise, and maintain brake system air pressure. The extent of idling is highly uncertain and varies with season, freight operations, single or team driving, and routes (Stodolsky et al., 2000). Although no statistical data are available, numerous estimates have been made of typical idling duration. Approximately 2000 hours annually is a baseline estimate of idling duration of the main line-haul truck engine. Idling estimates are unavailable for auxiliary diesel engines, which are idled to power refrigeration equipment and other systems.

Idling of heavy-duty diesel engines has a variety of adverse effects. One concern is environmental. Idling leads to excess air pollution, noise, greenhouse gas emissions, and petroleum consumption. Recent studies indicate that a significant amount of pollution is emitted during long-duration idling (Brodrick et al., 2002b; and McCormick et al., 2000). Some truckers avoid truck stops because of the poor air quality generated by the concentration of idling trucks. Safety is another concern, though not well documented. The noise of the idling engines may affect the quality of driver rest and hence safety, although some drivers report that engine noise drowns out outside noise and improves their sleep (Brodrick et al., 2001). Idling noise is often a nuisance to the surrounding community.

Engine idling has adverse economic consequences for drivers and truck owners. Engine idling raises costs by increasing fuel consumption, accelerating engine wear, and decreasing productivity (i.e., requiring more frequent fueling and maintenance). Cost data are poor, most of it collected from pre-1995 long-haul vehicles (TMC, 1995a; TMC, 1995b). Estimates of annual diesel fuel consumption resulting from idling are between 838 million to 2 billion gallons (Stodolsky et al., 2000; Van den Berg, 1996), with the lower value being the most scientific estimate. Numerous studies are underway to update the fuel consumption and emissions data.

Attractive alternatives to truck idling include auxiliary power units (APUs), auxiliary climate control devices (for heating and cooling), truck stop electrification (similar to electrical hookups for recreational vehicles at campgrounds), and truck stop multi-systems (e.g., air electric, heating/cooling, and other hotel accessories supplies) (Stodolsky et al., 2000).

APUs are the most flexible strategy, but currently available APUs have not gained much market acceptance, according to preliminary analyses reported in Stodolsky et al. (2000) and Brodrick et al. (2001). An industry source, Jones (1999), estimates the market penetration of all types of auxiliary power and heating units is approximately five percent (Jones, 1999). Truck drivers largely reject batteries for cost and performance reasons, noting that overnight use puts too much stress on the vehicle’s batteries, leading to shortened battery life, high replacement costs, and unscheduled down time. Reasons for low market penetration of other options are unclear. Some truck drivers report that available auxiliary diesel-powered generator sets are heavy, expensive, and/or noisy. Others reject direct-fired heaters and coolers because they cannot power other accessories such as televisions and refrigerators. Many of the drivers who reject APUs do so based on experience with the early APU systems. In general, many users of contemporary APUs seem to be satisfied with their performance and costs.

The lack of market penetration of currently available idling alternatives does not appear to reflect a lack of interest by fleets and individual owner operators. The effects of idling are widely addressed by the trucking industry (Abrams, 2000; Abry, 1999; Jones, 1999; Leavitt, 2001; TMC, 1995a). The trucking industry reports that most fleet managers track fuel economy and idling closely and follow developments in idling alternatives. Similarly, fleet drivers and owner operators are increasingly aware of options to reduce idling. A pilot survey of 233 truck drivers found that 70 percent of owner-operators were aware of developments in alternatives to truck idling, as were 50 percent of company drivers (Brodrick et al., 2001). It appears that the market is primed for the introduction of enhanced idling alternatives.

Idling alternatives can be either on-board or shore-based. Examples of on-board systems are APUs, generators, deep-cycle batteries with inverters, and climate control devices. APUs are typically diesel-powered engine-compressor-alternator systems which, when integrated into the truck, provide direct current (DC) power, battery charging, fuel warming, and sometimes chilling. Generators produce 110-220 Volt electricity to run AC-powered devices. Direct-fired heaters are self-contained, diesel-fueled heating units. Several portable air chilling systems are currently under development. In contrast, shore power is non-portable power supplied via a connection to the main electrical grid. Truck stop electrification is a method of providing shore power to trucks. An integrated truck stop system, which provides power, Internet, heating, cooling, telephone, and cable in addition to power, is being demonstrated in cooperation with the Northeast States for Coordinated Air Use Management.

Although on-board and shore-based idling alternatives have focused on over the road long-haul applications in the past, they could be designed for other truck applications, such as, local delivery trucks, construction vehicles, and recreational vehicles (RVs). Moreover, a single APU system could be designed to power individual or combinations of components. The development of 42 Volt electrical systems will facilitate vehicle electrical components common to all applications (e.g., fans and compressors) being powered by on-board APUs. In Table 1, potential truck applications are categorized based on the type of trucking operation and components powered by the APU. Each application is identified as best suited to on-board or shore-based power.

Regulatory actions may hasten the introduction of idling alternatives into these various markets. Levinson (2001) presents a comprehensive discussion of the growing number of anti-idling laws and regulations. Recent bans on idling, such as those in the eight-county Houston, Texas, area, as well as government incentive funds for idling alternatives, such as the $1,500 APU purchase subsidy provided by California Air Resources Board, are designed to encourage interest in idling APUs. An emerging APU technology is the fuel cell APU. Truck APUs may be the first widespread use of fuel cells in transportation. This paper explores the potential market for fuel cell truck APUs, addressing APU performance requirements, driver acceptance issues, implementation barriers, and costs.

TABLE 1 Truck Applications Suited to On-Board (OB) and Shore-Based (SB) Power

Truck Operation Component	**Line-haul**	**Delivery**	**Construction**	**RV**	**Bus**	**Emergency**
Hotel Accessories Power truck lights, climate control, TVs, refrigerators, etc.	OB or SB	-	-	OB or SB	OB	-
Engine Maintain engine heat and avoid cold-start problems	OB or SB	-	OB	-	OB	-
Air Pressure Maintain air system pressure and as general practice during delivery operation	OB SB	OB	OB	OB	OB	-
Power Take Off Power additional systems, (e.g. mixers) and external power applications (e.g. work lights, tool outlets, lift gates etc.)	-	OB	OB	-	-	OB
Refrigeration Power refrigeration units	OB	OB	-	-	-	-
Electrical Systems Power pumps, fans, and compressors currently powered by the main engine	OB	OB	OB	OB	OB	OB

TRUCK APU MARKET

The size of the potential truck APU market is difficult to quantify precisely. The U.S. Department of Commerce’s Vehicle Inventory and Use Survey (VIUS) is the most comprehensive survey of U.S. trucking, but neither this nor any other study includes idle time and idling duty cycle data. For lack of better data, distance is a logical operational parameter to use as an indicator of idling. This is based on the premise that trucks that travel far are likely to have overnight stays and hence idle during rest periods. These trucks would include “truckload carriers” that haul an entire trailer full of a commodity for a long distance, making a single pick up and a single drop off. These are the typical tractor-trailer combinations seen on the highway system, with sleeper cabs. Specialized carriers, some car haulers, and household goods movers, are also operations that are likely to travel long distances. According to VIUS, over 400,000 Class 7 and 8 vehicles predominantly drive greater than 500 miles from their home base (1997), and hence are likely to idle during driver rest periods. As indicated in Figure 1, almost half of these trucks are basic enclosed vans carrying dry freight. The next most common van types are insulated refrigerated vans and trailers (21 percent) and basic platform vehicles (12 percent) (VIUS, 1997). The majority of vehicles with refrigerated vans and trailers (over 80,000 vehicles) have a second engine solely to power refrigeration. This engine could potentially be replaced by an APU.

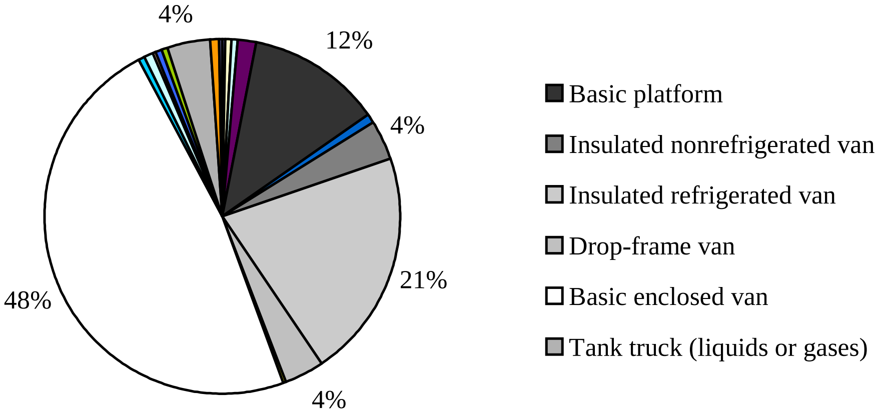

FIGURE 1 Body types of long-haul, Class 7 and 8 vehicles (adapted from VIUS, 1997).

Of these 400,000 trucks, the ones most suited to APUs are those that idle for long periods. Older studies by estimate vehicle idling for line-haul trucks to be around 1600 hours per year (El-Sharif, 1995; Van den Berg, 1996). An Argonne National Laboratory (ANL) study used a base case of 1,830 hours per year, assuming a truck idles 4.5 hours per day for 218 nonwinter days and 10 hour per day for 85 winter days (Stodolsky et al., 2000). These estimates are consistent with Freightliner LLC fleets (Brodrick et al., 2001) and have been utilized in various papers and reports (Brodrick et al., 2002a; NYSTA, 2001; Jones, 1999), but do not reflect the large range that is likely to prevail. A trucking industry publication reports that heavy-duty trucks idle between 1,040 and 2,080 hours per truck year (Landline Magazine, 2001). ANL's range of 1,000 to 5,000 hours used in their calculations represents the large range of idling times that is likely in reality (Stodolsky et al, 2000). No data are available on the idling of refrigeration unit engines, but they tend to idle a large amount of time when perishables are in the trailer.

Other potential market niches are local delivery operations with long idle times and auxilary power needs. Some Class 6, 7, and 8 delivery trucks idle approximately four to 10 hours per day, but may never idle during driver rest periods. Beverage, farm, tanker, dump, and port delivery trucks are examples of trucks with local operation and potentially long cumulative idling times. Basic platform trucks and basic enclosed vans may also have driving patterns suited to APU use. Additionally, refrigerated trailers, recreational vehicles, and power take-off operations (such as mixers) may be APU candidates. Table 2 presents a breakdown of the number of each type of truck. As with line-haul trucks, the distribution of idling times across these 1.4 million trucks is unknown, making it impossible to estimate the size of the APU target market.

There are also other possible market niches for truck APUs, such as recreational vehicles (which are often used as traveling homes) and power take-off operations. Emergency and contractor vehicles are other possibilities. These markets are currently being studied through Department of Energy-sponsored research. Thus far, the only APU market segmentation has been presented by the 21st Century Truck Initiative as shown in Table 3 (DOE, 2000). Four segments were created based on APU power required.

TABLE 2 Class 6, 7, and 8 Heavy-Duty Vehicles that Are Primarily Driven in Local Duty Cycles, Categorized by Body Type (VIUS, 1997)

Body Type[1]	Percent	Number of Trucks
Dump truck	21	302,501
Basic platform	15	215,424
Grain body	12	170,771
Basic enclosed van	10	143,746
Platform with added devices	7	104,599
Tank truck (liquids or gases)	7	100,892
Concrete mixer	4	64,876
Garbage hauler	4	58,621
Low boy or depressed center	4	50,742
Public utility	3	46,760
Beverage	2	34,540
Insulated refrigerated van	2	28,127
All others	9	123,338
Total	**100%**	**1,444,937**

1. A detailed description of the truck body types is provided in VIUS (1997).

TABLE 3 Truck Auxiliary Power Requirements for Tractor-Trailers (DOE, 2000)

Potential load	Power required (kW)
Base electrical loads, lights, battery charger, communications, computer	1 to 5
Hotel loads: lighting, simple HVAC, computer, appliances	3 to 5
Full truck electrification: all of the above, plus water and oil pumps, starter, cooling fans, transmission and hydraulic system, brake compressors, and fuel and air-handling systems	5 to 15[1]
Trailer refrigeration, other external power	Up to 30[1]

1. As discussed later, these estimates are less than other published estimates. In general, there is large variability in auxiliary power demands.

PERFORMANCE REQUIREMENTS

Market penetration of APUs will be determined by how well they meet the performance, cost, reliability, and durability demands of the truck consumers. Consumer demands and behavior will be a function of truck operation size (Nesbitt and Sperling, 2001). The U.S. truck market is composed of approximately 40 percent owner operators and 60 percent fleets. Owner operators, as the name implies, own the truck they drive as well as make the business decisions. In contrast, fleets hire drivers to drive fleet trucks and a fleet manager generally tracks costs and makes purchase decisions. Although fleet drivers will influence fleet purchases, the actual APU buyers will be owner operators and fleet managers.[3]

APU performance requirements include size, weight, and power. There is considerable debate about how sensitive the truck market is to APU size and weight. In general, the truck market can be characterized by applications that are sensitive to weight, volume, or neither. In a pilot survey, owner operators in the weight sensitive categories (those traveling at the maximum gross vehicle weight of 80,000 lbs.) reported that they would not tolerate an APU heavier than 100 lbs. (Brodrick et al., 2001). The truck already operated at maximum gross vehicle weight (limited by law) and would need to reduce payload (and hence profit) to carry the fuel cell APU. Consistent with this, truck manufacturers report that fleets often select options like aluminum rims to compensate for the added weight of additional technologies, such as exhaust after-treatment, which weigh as little as 50 lbs. In contrast, several owner operators that were volume sensitive had already added small diesel APUs that weighed over 300 lbs.

The acceptable volume of the fuel cell will be a function of the tractor length, swing clearance requirement, and accessories (such as tool boxes or pumping units) on the truck. The size and weight requirements will vary greatly by fleet. If a considerable cost savings were generated by the APU, it could be used to offset any loss in profit due to reduced payload or space.

APU power demand will differ based on truck application. The four categories and corresponding power demands identified by the 21st Century Truck Initiative were shown in Table 3 (DOE, 2000). Base electrical loads with appliances will likely necessitate a 5 kW APU system. If, however, full vehicle electrification (including pumps, transmission, fans, and hydraulic system, brake compressors, etc.) were desired, the necessary load will be higher. Refrigerated trailers require the highest level of power. In order to determine if these categories can be aggregated or disaggregated, duty cycles should be logged and used to characterize intermittent hotel-type loads (air conditioning and heating), constant power level, peak power, and continuously varying power.

More specific data on the range of power demand of truck cabins is available and indicates that current power demands may be higher than those in Table 3. However, many auxiliaries on trucks are currently gear or belt-driven, and the power required for future electrically-driven components may differ. The American Trucking Associations estimates power demand for air conditioning alone of 2.6 kW to maintain cab temperature at 90 °F ambient temperature and also gives a peak demand of 5.6 kW to cool down the cab under the same conditions (TMC, 1995a). Brodrick et al. (2001) estimate power demand for common accessory combinations may exceed 6 kW at peak demand. The power level for refrigeration units is also likely underestimated for some cases. According to the California Air Resources Board’s EMFAC model inventory, many of the refrigeration units on California are greater than 30 kW. This number is outdated, and surveys are being conducted to update it. Discussions with refrigeration dealers in Northern California indicate that sales of new units are commonly in the five to 25 kW range.

While power delivery requirement will differ with truck application, the reliability and durability requirements for all truck components, such as APUs, are consistent. According to Freightliner LLC, unlike passenger vehicle propulsion applications where engine service life is typically 5,000 hours, truck APU service life will likely be an order of magnitude longer. Commercial truck engines are rated for a 1,000,000-mile life before major engine service, which translates to approximately 25,000 hours (Gouse, 2000). If APUs were used continuously, the required service life could be as much as 2 to 3 times longer than the truck engine life. The available fuel cells in the one to 30 kW range are not yet manufactured to meet these requirements.

COST AND PAYBACK

The pivotal variable in purchasing any idling alternative will be cost. The cost of idling involves fuel consumption, as well as additional wear and maintenance on the engine. Table 4 contains a comparison of reported values for key variables that affect the cost of idling: duration, fuel consumption, and costs. The cost for additional wear varies greatly. Earlier calculations (El-Sharif, 1995; Van den Berg, 1996, DOE 1999) of the cost of wear and oil changes overestimate the costs of wear only. Engine wear was thought to be equivalent to 80 miles of driving per hour of idling. TMC estimates engine wear for contemporary vehicles is proportional to fuel consumption. For a truck which obtains 7 mpg, the wear would be equivalent to driving 7 miles. ANL applies this formula to estimate a total of $0.07 per hour cost for lubricant changes and $0.07 per hour cost for decreased time before engine overhaul (Stodolsky et al., 2000).

Variation in idling time, fuel consumption, and fuel costs estimates accounts for the large difference ($2,340 to $7,000) in annual truck idling costs presented in Table 4 below.

In calculating the cost savings possible with hydrogen-fueled fuel cells, Brodrick et al. (2002a) found fuel cost to be the key variable in determining payback period. The payback period of a hydrogen fuel cell, which cost between $6,950 to $8,950, ranged from 1.3 years for diesel consumption of 2.25 gallons per hour, to 6.5 years for diesel consumption of 0.6 gallon per hour. The true payback period is critical since trucking association's reports of truckers' willingness to pay suggest the fuel cell would need to have a two-year payback period.[4]

Owner operators and fleets are highly sensitive to fuel consumption, but it is unclear whether drivers accurately perceive their fuel consumption. In the UC Davis pilot survey, many drivers reported that their trucks consumed 1 gallon per hour of fuel during idle (a number widely reported in trade industry publications) but few could cite any evidence or explanation (Brodrick et al., 2001). Preliminary data indicates fuel consumption during idle may range from 0.4 to over 2 gallons per hour depending on accessory load, engine speed, and vehicle model year (Brodrick et al., 2002b). Based on informal discussions with large fleets, fleet managers appear to be much more knowledgeable about their fuel consumption. Either way, educational campaigns could shape the response to APUs, especially among smaller truck operators.

BARRIERS TO IMPLEMENTATION

A variety of factors beyond cost will influence an operator's decision to purchase an APU and the corresponding decision by a truck or equipment manufacturer to sell an APU. These include driver convenience and comfort, fuel availability, truck design limits, and competing products. There are differing opinions on the trucking industry's receptiveness to new technologies. Hydrogen fuel cells may cause safety concerns due to the stigma of hydrogen. No formal studies have been conducted to gauge truck driver and fleet reactions to hydrogen-fueled or other fuel cells. The reasons for low market penetration of current alternatives are unclear. Driver acceptance may depend on the type of fuel cell. For example, experience with selective catalytic reduction (SCR) systems, which require urea to be added, indicates that truck drivers and fleets many not be receptive to technologies that require an additional fuel, such as a hydrogen-fueled fuel cell. In contrast, a diesel-fueled fuel cell may be more appealing.

TABLE 4 Comparison of Reported Values for Idling Duration, Fuel Consumption, and Costs

	Idling time (hr/truck-yr)	Idling diesel consumption rate (gal/hr)	Diesel consumed (gal/yr)	Cost per idling hour ($/hr)	Fuel cost per truck year ($/truck-yr)	Wear cost per year ($/truck-yr)	Total cost per truck year ($/truck-yr)
Van den Berg, 1996; El-Sharif, 1995	1,611	1	1,611	$3.04	$1,804	$3,093	$4,897
Xantrex, 1998; Abry, 1999	2,500	1.5	3,750	$2.75	-	-	$7,000
Stodolsky et al., 2000	1,000 to 3,000	1	1,830	$1.89	$3,202	$256	$3,460
Landline, 2001*	1,040 to 2,080	1	1,560	$1.50	-	-	$2,340
Domenici, 2001	-	-	2,400	-	-	-	$4,000
Edison Electric, 2001	-	-	-	-	-	-	$5,307
Brodrick et al., 2001b	1,818 to 2,424	1	2,121	$1.65	$3,203	$297	$3,500
OIT, 2001	1,900	-	-	-	-	-	-

The availability of infrastructure to support the APUs will likely be one of the largest determinants of fuel cell APU success. Public agencies, such as California Air Resources Board, are strong proponents of hydrogen-fueled APUs. Hydrogen fuel-cell systems are attractive because they are currently available and could be adapted for truck APUs in the near-term; however, hydrogen refueling infrastructure is scarce. There is widespread disagreement on the length of time, costs, and market size that would be required to develop adequate infrastructure. The cost of adding adequate hydrogen fuel infrastructure would be a large determinant in the cost-effectiveness of hydrogen-fueled fuel cell APUs. The cost of hydrogen depends upon the production method, production scale, facility location, and distribution cost. In addition to fuel availability and cost, hydrogen fuel volume and energy value will be limiting factors due to the size and weight limitations of the trucks.

The trucking industry is clear that readily available fuel, such as diesel or propane, is the most desirable and would be embraced. The main issue with diesel and other fossil fuels is the feasibility of reforming the liquid fuel to produce a fuel cell quality reformate feed. The issues with reforming diesel fuel result from the often-high concentrations of sulfur, aromatics, and naphthenes found in diesel fuel. The specification of 15 ppm sulfur diesel will help, but diesel may still contain aromatics and heavy sulfur compounds that will make reforming the fuel for fuel cell applications a challenge. Also, the use of a reformer could add significant extra costs and increased weight. An alternative possibility is to have the reformation take place at the truck stop and have the truck carry only the reformed fuel.

Propane, natural gas, and synthetic fuels are other fuel options. All these also require reforming into a fuel suitable for the fuel cell. Of these, only propane is readily available. Many truck stops sell propane for sleeper accessories and some refrigeration units as well as for recreational vehicle users. However, as with diesel-fueled systems, propane reformation is only in the test stages and there are indeterminate issues with cost, weight, and performance.

The market for truck APUs will vary considerably based on whether APUs are sold as retrofit or as original equipment manufacturer (OEM) systems. Retrofit systems obviously require the least integration work. The incompatibility of fuel cell-produced electricity with belt-driven climate control components will likely be a primary inhibitor to add-on aftermarket units. A second criticism of retrofit systems is that the APU may hinder truck operation. For example, when battery condition monitoring is not interfaced with the APU control, engine start-up problems may ensue due to low battery charge. A more efficient OEM system would use an electrically driven climate control system compatible with fuel cell APU development. This would require a fundamental change to the current design approach in the truck industry as well as a large investment in research, development, and validation. An efficient approach may be to incorporate these design changes at the same time a 42 Volt electrical systems are incorporated into trucks.

The Electrification Alternative

APU market penetration will be a function of the availability of competing technologies, such as shore-based systems (i.e., truck stop electrification) and alternative APUs. In order to compare truck stop electrification and other APUs, more information will need to be gathered on where the drivers idle their trucks and for what purpose (i.e., short breaks or overnight stays). There are conflicting preliminary estimates of the amount of time trucks stop at truck stops. It is widely acknowledged that there is a truck parking space shortage. A Federal Highway Administration (FHWA, 1996) study reports that there is a projected shortage of 28,400 parking spaces in public rest areas and 84 percent of truck stop operators reported their facilities were full or overflowing at night. Parking shortages would reduce the market for electrification.

Few truck stops currently offer shore-based electrical services for trucks, but several initial truck stop electrification demonstrations are underway. Even if electrified truck parking is available, practical limitations restrict the flexibility of some truck operations and make them better suited to self-contained as opposed to external power sources. Freight movement has evolved to just-in-time, guaranteed delivery. In some cases trucks are rolling warehouses, whether on the highway, at a truck stop, or on a railcar or ship as part of an intermodal operation. In fact, Freightliner LLC estimates 30 percent of all freight is stored en-route as opposed to in the warehouse (Gouse, 2000). While the freight is under control of a motor carrier, the delivery location and hours of service regulations may require drivers to find rest areas in less traditional locations. Often, a loading dock schedule will assign a driver to be at the dock at an hour of the day or evening that is only reachable by being in the immediate location prior to their scheduled time.

Truck drivers may also reject using truck stop electrification for safety reasons. Some truck drivers reported avoiding truck stops because they were victims of solicitations by drivers, transients, and others that disturb their sleep. Therefore, even in mild weather, drivers may prefer to sleep locked up inside with their engine in idle mode and climate control functioning (Brodrick et al., 2001). It is unclear how many truck drivers actually reject truck stops due to such situations, but the safety concerns are clear. The recently published diary "The Hard Road" describes this scenario in graphic detail (Tower and McDonnel, 2001) and many truck drivers relayed anecdotal stories during a pilot survey conducted by UC Davis.

Lack of information on the performance requirements (e.g., power, size, and weight) and truck operation requirements (e.g., driving patterns and idling locations) hinders assessment of the practical and economic viability of idling alternatives. Multiple on-going studies will provide insight on the performance requirements and technology developments. Driver and trucking fleet attitudes (importance of payback and capital cost and acceptance of fuel cell technology), as well as, idling habits (e.g., duration, location, and fuel consumption of idling) will likewise be important determinants of the acceptance of new alternatives to truck idling. Comparatively little research is being conducted in this area.

CONCLUSIONS

There is a rapidly growing need to replace truck engine idling with a technologically and environmentally sound solution. Idling the main engine to provide electricity and climate control is costly, noisy, fuel inefficient, and environmentally damaging. Currently available solutions have not penetrated the truck market. Fuel cell APUs are a promising emerging technology that could be used in lieu of idling the main engine. The following is known about the market for fuel cell APUs:

- Over 400,000 line-haul trucks with long idle times and 80,000 long-haul refrigeration units are possible candidates for APUs. Additional candidates include an indeterminate portion of the more than 1 million Class 6, 7, and 8 delivery vehicles, refrigeration trailers, and power take-off operations. Introduction of 42 Volt electrical systems may facilitate incorporation of APUs in many vehicle applications which may not have long idle times, but do have accessory loads (e.g., pumps, fans, and compressors);
- The truck market can be further segmented into at least four groups based on APU power demand. APU power requirement estimates range from 5 kW to greater than 30 kW. However, it is less certain whether APUs in this size range will meet the start-up peak power demands of high energy heating and air-conditioning devices. If more were known about the size and weight demands, these parameters could be used to further segment the market;
- It is important to distinguish between owner operators, fleet drivers, and fleets. Drivers (i.e., owner operators and fleet drivers) will actually utilize the technology, but owner operators and fleet managers will make the actual purchase decisions;
- Consumer behavior with regard to APUs purchases is poorly understood. Payback periods of two years are required according to the trucking industry, but truck drivers report that initial costs may also influence APU purchases. Some truck drivers report economic and technical drawbacks to current APU systems, yet those who own modern systems are often satisfied;
- Market penetration of APUs will be determined by how well they can meet performance, cost, reliability, and durability demands. Reliability and durability requirements are clear, but performance demands (i.e., size and weight) vary with truck application;

- Fuel cell APU economic viability is highly uncertain due to lack of data on idle time, fuel consumption, infrastructure requirements, and APU costs. Fuel consumption appears to be a critical variable in determining payback periods;
- Various differences in truck operations will place widely differing values on the productivity gain or loss from using an APU versus long-term traction engine idling or truck stop electrification; and
- Consumer resistance, cost, infrastructure requirements, truck integration, and competing products are the likely barriers to implementation.

Despite significant gaps in knowledge, it is clear that the fuel cell APU has the potential to be the first widespread, commercial use of fuel cell technology for transportation applications. Cost and competition will likely be the key determinant of fuel cell APU success.

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Managing the Transition to Sustainable Transport Through Strategic Niche Management

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Present-day transport exhibits many problems. Worldwide, about 250,000 people die in road accidents every year. Emissions of pollutants from vehicles degrade air quality causing health hazards to humans and other living species. Emissions of greenhouse gases—especially CO_2—contribute to global warming. The continuously increasing numbers of vehicles gives rise to congestion, which causes time delays and reduced accessibility to many destinations and threatens the livability of cities and living quarters.

Since the 1960s these problems have been on the agenda of public authorities. Typically, these problems are split into behavioral and technological problems. Emissions are seen as technical problems because the vehicle technologies emit too much of hazardous substances. Congestion is primarily a behavioral problem caused by people traveling too much, traveling at the same time, and choosing an inefficient mode of travel.

These problem definitions strongly determine the search for solutions. Emissions are primarily made the problem of the vehicle industry, which is asked or forced through legislation to develop cleaner cars and other vehicles. Congestion is primarily tackled by making an appeal to people's responsibility to society via awareness campaigns, asking them to travel less or make more use of public transport.

Over the past decade, however, policy makers as well as many others have become more and more skeptical towards possibilities to influence people's travel behavior. At the same time, interest grew in technical options to tackle congestion problems. There appears to be a shift from the behavioral approach to the technological approach. This shift does not remain uncontested, however. A variety of actors, especially those concerned with the environment and the livability of cities, continue to emphasize that only a change of behavior of travelers can lead to fundamental (or sustainable) solutions for traffic and transport problems.

This opposing view can be seen as a call for a cultural or social fix instead of a technical fix. Proponents of the cultural fix paradigm view technology as part of the problem. The only way out is *not* to start with technology. Restricting mobility (through price mechanisms or by providing mobility quotas) is the way forward.

We argue for an approach aimed at stimulating both behavioral change and technical change. This approach is Strategic Niche Management (SNM). It consists of experiments; users in the experiments are real users. SNM is about the creation and management of spaces for experience to facilitate learning and institutional embedding, two key processes in transformation (conceptualized as socio-technical regime shifts).

SNM rests on two fundamental assumptions. The first assumption is that the introduction of new technologies is a social process that is neither an unavoidable deterministic result of an internal scientific and technological logic, nor a simple resultant of the operation of the market mechanisms. This assumption has been captured by the notion of co-evolution or co-production. The second assumption is that it makes sense to experiment with this co-evolutionary nature of technology. Such experiments can be envisaged as (part of) a niche in which technologies are specified and consumers are defined and concretized. Experiments make it possible to establish an open-ended search and learning process, and also to work towards societal embedding and adoption of new technology.

We will describe 3 experiments: a market test of converted electric vehicles (EVs) in the French town of La Rochelle, an experiment with individualized public transport using telematics called Praxitèle, and an experiment with sustainable community transport. The experiments are analyzed through the lens of SNM, focusing on what has been learned and what could have been learned through a different set up. We also evaluate SNM, compare it with other policy approaches, and point out the roles of private and public actors.

OPTIMIZATION VERSUS RENEWAL

In the past years a great range of technical options has been developed to tackle the societal problems related to traffic and transport. Some of those can relatively easily be fitted into the existing transport system while others require an extensive adaptation of the behavior of producers as well as suppliers and users of transport services.

To date we have two regimes in passenger transport: a private car regime and a public transport regimes, each with its own rules and constituencies:

- The *car regime* is based on the individual use of vehicles that are typically privately owned or leased. It is highly flexible. The average seat occupancy—even in rush hours—is low, just above one passenger per car. Especially during rush hour, there are many congested roads and highways. Fuel consumption is high, as are the land use requirements.
- In the *public transport regime* mobility is provided by professional suppliers. The vast majority of routes are fixed, with fixed stops along them. The seat occupancy is often very high (even above 100 percent) during rush hour, but mostly low at other times.
- The car regime is the dominant regime. In the EU, cars account for over 80 percent of all passenger kilometers traveled.

Regimes are not static, but are inherently dynamic. Within a regime, innovation takes place continuously. However, innovation tends to be conservative and incremental. Actors outside or on the margins of the regime are more inclined to take risks by attempting to introduce radical alternatives. An example of this is PIVCO, a Norwegian company who produced a plastic-bodied light-weight electric car, which challenged the main assumption of existing automobile manufacturers about what a car is and should do.[1] Such radical changes meet a range of barriers because they require complementary innovations and threaten the interests of powerful actors who tend to resist such changes. The latter point reflects a general characteristic of innovation processes, sometimes referred to by the term “path dependency.”

Although innovation tends to be incremental, the current problems of the traffic and transport domain seem to require more radical solutions. To explore this further, we will distinguish two main routes, notably “regime optimization” and “regime renewal” (or “regime shift”) which can be characterized as follows (Elzen et al. 1996, 1999):

- *Regime optimization* relates to attempts to make improvements within an existing regime. In the case of transport, regime optimization may concern improving the efficiency of either the public transport system or the car system;
- *Regime renewal* relates to a change in a system's architecture and rules; it consists of change beyond the level of system components. Examples are new transport modalities (e.g., door-to-door public transport concepts) or new forms of ownership (e.g., carsharing). A crucial distinction from regime optimization is that the behavior of various actors in relation to various relevant technologies changes considerably; travelers need to do different things to reach their destination.

Regime optimization is current practice. This is implied in a self-fulfilling prophecy that assumes that it is futile to try and change people's travel habits and their love for (using) their private vehicle. Innovations that do not fit the current pattern meet a lot of skepticism and have difficulty attracting funding.

Regime optimization in the past has led to a drastic reduction of per-kilometer vehicle emissions but has been very ineffective in tackling congestion. Measures (like new infrastructures) give temporary relief, but new (and old) problems pop up some time later or somewhere else. Regime renewal has much larger potential as it starts with what is considered desirable from the societal perspective.

A variety of innovations have been demonstrated that would fit the regime renewal perspective. The problem for such innovations is that these options do not fit the current regime, either on technical grounds (e.g., because of lacking infrastructures) or on societal and cultural grounds (e.g., "I am not going to share my car with others"). Small-scale introduction can sometimes be realized but innovations can only give substantial relief when applied on a large scale. Such upscaling to realize regime renewal requires interplay between a variety of new elements. Thus, the problem is not so much the development of new technologies but the alignment of various elements in a non-disruptive way.

THE IMPORTANCE OF EXPERIMENTS AND NICHES IN OVERALL TRANSFORMATIONS

History shows that while incremental change is the norm, but sometimes radical change does occur. Radical change can initially begin at the fringes, in so-called niches, from which it spreads in conjunction with other developments. SNM is directed at overcoming barriers to broader diffusion by exploiting niche dynamics.

SNM is based on a philosophy of "learning by doing" and "doing by learning." It aims at creating spaces for experience. It involves an element of protection, but protection should be temporary and be matched by selection pressures. The new technology is temporarily protected by various actors who believe in its long-term prospects and who are willing to invest time, money, and effort in "making it work" both in a technological and social sense. Such protected spaces are called *technological niches* or just *niches*.[2] These niches are experimental situations characterized by an approach of "learning by doing." By trying out a variety of changes an attempt is made to lower or overcome the variety of barriers.

Experimentation with new technology is nothing new. Across the world, a wide variety of transport innovations are so-called pilot or demonstration projects. All these experiments together for a specific technology (like EVs) make up a technological niche. A major problem is that many of such projects within the niche are once-off affairs; another is there may be little exchange of information between them. A deliberate strategy can then be followed to learn across these projects within a niche and, as a next step, to use this knowledge to define further experiments attempting to integrate findings. This requires the co-ordination of the activities of a wide range of actors. The (policy) approach targeting this coordination is called SNM (Kemp et al. 1998, Weber et al. 1999, Hoogma 2000).

From an SNM perspective, the general objective of experiments is to learn how new technologies and their societal embedding can be tuned towards another. That is why they are called *socio-technical* experiments. These learning processes have to be rather open. This contrasts with current practice where “pilot” and “demonstration” projects are usually defined more narrowly. In the case of a pilot or demonstration project, a specific technology is typically taken as a starting point and the objective is to fit it into the existing regime, as the general strategy consists of regime optimization. For regime renewal, however, more open learning processes are needed. This requires technology experimentation instead of demonstration.

Past experiments in the traffic and transport domain did not allow for these open learning processes. They were oriented toward technical learning and assessing the market, not toward exploring processes of co-evolution. Improving the design of experiments can increase the yield in terms of lessons learned about the potential and feasibility of the technology, the world in which it has to function, and the measures that need to be taken to mutually adjust the technology and the social environment in which it has to be produced and used. Especially the transport-demand side deserves more attention as one of the most “wasteful” characteristics of the car regime is the pattern of individual use of a single vehicle from door-to-door. Experiments should be organized so that the participants get a chance to develop new ideas and try them out. For example, users could be asked not only to fill out questionnaires but also to experiment with their mobility demand.

In the next section we will describe some experiments with transport innovations to explore what they may teach us about options for renewing the traffic and transport regime. We will do so by focusing on innovations that do not fit the car regime. We will focus on innovations which challenge actors’ assumptions about transport. These include people’s self-perceived need for having a vehicle capable to provide door-to-door services, and in the case of car companies, their assumption about what kind of company they are (a car manufacturer or a mobility provider), and about who their customers are and how they may be serviced. The experiments described show that experiments have a potential to change actors’ assumptions but that the lessons are not widely disseminated and acted upon (by public transport authorities, for example).

THREE TRANSPORT EXPERIMENTS ANALYZED THROUGH THE LENS OF SNM

This section describes three experiments with transport innovations offering sustainability prospects. The three cases are a market test of converted EVs in the French town La Rochelle, an experiment with a “self-service” EV short-term rental system near Paris, and an experiment with customized green community-transport.

Case 1: La Rochelle—Market Differentiation[3]

The La Rochelle experiment consisted of the practical testing of fifty EVs by real users under daily operating conditions. From late 1993 to late 1995, 50 electric vehicles were used by real users in La Rochelle. The vehicles consisted of 25 Peugeot 106s and 25 Citroën AXes,[4] which were leased at the price of 1,000 and 900 French francs a month respectively to private users and companies. The experiment sprang from the existing cooperation between the three main actors: French automaker PSA, EDF (the national electricity producer), and the Municipality of La Rochelle. A technological niche for EVs already existed before the experiment, created under guidance of EDF, which had been using EVs within its fleet since the 1970s. The aim of the La Rochelle experiment, however, was to investigate the household market. The main actor, PSA, was convinced that EVs were attractive for households and wanted to demonstrate that the technology was ready.

PSA provided the vehicles and selected the users. It also trained its dealers in the area to maintain the vehicles. EDF installed the necessary infrastructure for curbside recharging, at private parking lots and at service stations. The municipality provided incentives for EV use by reserving special parking places for them.

The users, all volunteers, were recruited through advertisements in the local media and direct mailings from PSA dealers to their customers.[5] PSA had defined the potential targets customers as follows: users of second cars who lived in households with more than one vehicle, who drove less than 10,000 km a year (and mainly in cities and seldom or never on highways), who did not use their car for holidays or weekend trips, and who made very few trips of more than 100 km. This group of potential users was estimated to be between one and two percent of the total market. In the actual experiment, however, the user group was biased toward professional men, employees, and senior executives, while retired people were underrepresented. In addition, the cars that were replaced by the EVs were not always second cars or cars that belonged to the low-range segment.[6]

To gain feedback about users' experience, the participants were monitored extensively during the original eighteen-month experiment. The three partners focused their monitoring and analysis learning about the following: EV driving, use patterns and recharging behaviors; the development of a perceived relationship between users and the vehicle; the evolution of the EV's status and image; and, the integration of EVs into the management of travelling needs, such as trip planning. After the initial eighteen months, PSA decided to extend the experiment by another six months and to replace the prototypes with series-produced vehicles that had been slightly modified based on user feedback.

The La Rochelle experiment was very well organized. A steering committee was established with different groups in charge of different tasks such as public relations, contact with users, feedback on vehicles, maintenance, and charging stations. This organization benefited from the strong commitment of the three partners, who shared a firm belief in the prospects of EVs. Their commitment was reinforced by the fact that the partners had already been co-operating for a long time. Also important was the fact that the partners saw the experiment as part of a step-by-step process for introducing technological innovation. Over the course of the experiment, new technological elements were incorporated one by one, the idea being not to come up with a futuristic car whose development would have been uncertain due to having to solve too many technical problems at the same time. This also explains why PSA chose to convert existing cars into EVs rather than building purpose-designed ones.

With fifty vehicles and a somewhat larger number of drivers, the user sample was large enough that the reactions of a given target group—owners of small second cars—could be assessed. Had the aim been to evaluate overall potential demand, a larger-scale experiment would certainly have been necessary. Nevertheless, the combination of low rental prices and the cost of maintaining the fifty vehicles was already quite an investment in terms of money and human capital.

The La Rochelle experiment lasted two years including the final six months during which series-produced vehicles were tested.

Learning[7]

PSA set up the La Rochelle experiment to learn about user needs for a particular market niche. It was less interested in gathering information about design and other issues, although it did implement design changes as a result of the experiment. The main issue was whether enough people were willing to buy the small electric passenger cars that PSA had been developing since the early 1980s. PSA considered user involvement crucial to the development of its EVs, so the process was targeted to produce first-order learning, that is, testing user acceptance of a specific vehicle. What did PSA find?

The general level of user satisfaction turned out to be high, and perceptions of the EV were positive, with limited driving range being the only drawback identified by the participants. As an unintended consequence the experiment also resulted in second-order learning effects—a new product identity took shape over the course of the experiment.

Users developed a new relationship to the EV in three phases. First, they discovered the electric vehicle and found that it was a “real” car that was pleasant to drive because of its silence, comfort, and cleanliness. Second came the stage of “maturity,” during which both the advantages and restrictions of the EV became clearer. This led users to modify travel planning by giving up long trips, avoiding random travel, and using the EV specifically as an urban vehicle. In the third phase, users came to define their vehicle as a different kind of car. For example, they began using the EVs mainly for short trips and their regular car for long trips. Also, household members tended to share use of the EVs more easily than was typically the case for traditional cars. By the end of the experiment, most users routinely recharged their vehicles at home. At first, users would precisely control the context in which their EV was used; many treated their EV too cautiously, recharging every day even when it was not necessary. Later, as they began to trust the EV more, they recharged less often.

The partners were satisfied with the technical choices that had been made during the development process, and the EVs exhibited few technical defects. However, users pointed out that some of the EV’s specific functions were underdeveloped. The reverse button and the charging cable came in for particular criticism and were modified before series production began. Half of the users who took part in the experiment decided to buy the EV they had tested, a clear indication of their satisfaction with and enthusiasm for EVs.

The experiment also yielded feedback regarding the battery chargers installed in and around La Rochelle. EDF proposed that ten changes be made to the normal chargers and fourteen to the fast chargers. The project findings showed that private users who owned a private parking place preferred to recharge at home, and that locating chargers near office buildings, public places, and restaurants increased their use. EDF also observed that users would need public charging places for psychological reasons—even drivers who recharged at home would find it reassuring to have other stations available.

Institutional Embedding and Material Investment

The three partners' efforts in La Rochelle since the early 1980s created a niche for the development of EVs. The fifty-car experiment contributed to the development of this niche by confirming initial expectations about the vehicle's technology, yielding lessons about its conditions of use, and strengthening the alignment of the network. The network developed was broad, including a variety of parties, but it lacked outsider involvement. PSA dominated the network, so that the interests of the car regime were protected. Lacking a strong environmental movement in France, no actor in the experiment had the objective of energy-efficiency high on the agenda, as EDF produces "CO_2-free" electricity in abundance from its nuclear plants.

The technical performance and reliability of the electric Peugeot 106 and Citroën AX led PSA to invest in small-scale production of these vehicles. Production began in November 1995. Three years later, thirty electric vehicles were being produced each day in the factory of Heuliez/France Design, a specialized small-scale car manufacturer.

Production numbers were expected to increase when sales grew, but sales remained far below projected results. The initial hope was to sell 2,000 cars per year, rising to 10,000 annually by the year 2000. However, actual sales were 1,300 in 1996 and just 800 in 1997, despite significant subsidies to EV buyers from both the national government and EDF. A PSA executive hypothesized that the 1996 production satisfied pent-up demand for the commercially produced EVs. In 1998 and 1999, sales increased again and by late 1999 about 6,000 battery electric vehicles, 80 percent of them PSA products, were on the road in France.[8]

These figures conceal a hidden shift. By the end of the period, almost the entire demand was from fleet customers. PSA sold scarcely any of its EVs to the individual customers that had been targeted in the La Rochelle experiment. This was apparently partly the result of a 1997 air-pollution law that empowered towns to restrict traffic to clean cars permanently if needed, and required government agencies, public bodies, and some large companies to increase the proportion of their fleet vehicles running on electric power, LPG or natural gas to 20 percent. This law supported the market niche for electric delivery cars, so in 1998 PSA acted on this demand by starting production of the Peugeot Partner and Citroën Berlingo delivery cars, based on the 106 and AX used in Rochelle.

Although PSA's sales have not met projections, Joseph Beretta, head of the EV group, commented:

> Our EVs may not make a profit—but they don't make a loss either....We have to earn money from our involvement with electric vehicles—so far we have invested around one billion FFr in electric- and hybrid-vehicle development. We currently have around 80 percent of the electric vehicle business in France, and we intend to remain the dominant company in this sector.[9]

In addition to deciding to start series production and the interest among test users in buying the EV that they had used, a third indication of institutional embedding resulting from the La Rochelle project was the huge interest it attracted among the public. Although the partners organized an active and intensive public relations campaign around the experiment, the extent of public interest in the project still surprised them. Many people visited La Rochelle and the project received wide media coverage, which increased the use of and interest in EVs in France. In addition, the EV users in La Rochelle have also strongly supported EVs locally and have formed a user club that has played an important role in promoting the technology. Similar clubs were also created in other cities.

Since the end of the La Rochelle experiment, PSA has become involved in three major programs or projects that can be considered as branches of the EV niche developed in La Rochelle. The first is Vedelic, a research program in the Poitou-Charentes region, where La Rochelle is located, aimed at developing a version of the Peugeot 106 model with lithium-carbon batteries. This project was developed to promote economic development in the region, to develop high-level industrial and university research, and to protect the environment. The region is seen as a strong contender for developing an innovative EV industry because many relevant research institutes and industries, including car and electronics companies, are already located there. Several government bodies are providing most of the project funding.

A second project has involved testing a plan for integrating rental EVs and scooters into the multimodal public transport system developed in La Rochelle starting in the early 1980s. This project aimed to test the feasibility of such a system and to identify types of use and potential customers, such as tourists, citizens interested in buying an electric vehicle, or households that occasionally need a third car. The rental system scheme would be extended with another experiment developed by the Liselec group, a partnership among PSA, a transport operator that will be in charge of the overall design of the system, and a third company that is providing computer management and telematics. PSA is the largest contributor to the project, which started in March 1997 with ten vehicles being tested on PSA sites and ended with a follow-up test in 1998.

The Liselec experiment aimed to provide self-service electric vehicles that could be accessed with smart cards. Five stations equipped with the necessary recharging infrastructure should be developed with five electric vehicles each (Peugeot 106 or Citroën Saxo, the successor of the AX model). The Liselec experiment is a step toward the development of the more innovative TULIP concept, which is comparable to the Praxitèle concept. The TULIP concept is a service that gives subscribers access to small (2.2-meter), two-seater EVs located in stations throughout the city. A central control station manages the system and handles booking, maintenance, and payments of fares. The stations are to be set up with a computerized parking-space management application and an automatic recharging system.

Third, Peugeot in England was one of the main partners in the 1996-97 Coventry Electric Vehicle Project, in which fourteen Peugeot 106 Electric cars and mini-vans replaced existing gasoline and diesel vehicles used by five organizations in the English Midlands. The project assessed the extent to which EVs could reduce urban air pollution, overall energy consumption, and emissions of greenhouse gases from the transport sector, as well evaluating the on-road costs of the 106E under real operating conditions.[10]

Peugeot had several reasons for participating, including market-testing of EVs in the UK, increasing its “green credentials,” and forging links with government bodies and fleet operators. According to one PSA executive, the main aim was to sensitize fleet operators to the potential benefits of electric vehicles.

Evaluation

Although the La Rochelle experiment was a success in some ways, it failed to result in the hoped-for result—fast-growing sales of the 106 and AX to private consumers as a second car for city use. Several explanations for this failure have been suggested, including PSA dealers’ lack of commitment to selling EVs, a lack of marketing effort,[11] and the possibility that PSA simply overestimated the market on the basis of too small an experiment and underestimated the positive bias that colored the views of those involved in the actual experiment.

All these factors are certainly valid, but we would like to propose another explanation. The users' positive assessments only emerged after having lived with the EVs for a relatively long period of time. This suggests that a second-order learning process occurred in which users gradually rethought how they used the car. Over time, users learned to recognize and appreciate some of the car's specific and interesting features, and changed their mobility patterns accordingly. However, this process was not captured by PSA, which did not make use of the "relationship" that developed among the users and was nurtured in user clubs. Instead, the company relied on its own assumptions about why users liked the cars. Evidence that contradicted the company's own beliefs about what the EV drivers liked and needed—for example, in the case of the charging stations—was not properly interpreted.

Case 2: Praxitèle—An Advanced EV Self-Service System[12]

Experimental Set-Up

The initiative for Praxitèle was taken by CGFTE, a national French public transport company. In 1989, CGFTE organized a discussion meeting with passengers to identify "the ideal transport concept." Among several alternatives, a concept based on self-service rental cars turned out to be a strong option. Such a system was believed to combine the advantages of cars and the advantages of public transport. A practical design should guarantee a parking place for the car user, be easy to operate, and use non-polluting vehicles.

After several feasibility studies and interaction with other French companies and ministries this idea was developed into the *Praxitèle* concept. Praxitèle is a self-service EV rental system. It is based on a fleet of small vehicles—Praxicars—located in specific areas—Praxiparcs. The whole system is supervised with the help of a central computer—Praxicentre.

The experiment, the first of its kind, started in October 1997 in the "new town" Saint-Quentin-en-Yvelines. The town is an outlying Paris suburb—about 15 km from the center of Paris—and has 140,000 inhabitants. It contains two expanding industrial zones and is considered the second most important business area in the west Paris region. It is linked to Paris by an extensive auto route system as well as a fast urban train (RER).

The Praxicars are fifty EVs—electric Renault Clios with a 70 km range. In the long term, a novel vehicle specifically adapted to city use (a small, lightweight energy-efficient EV) is planned. The vehicles are located in 15 (originally 5) different Praxiparcs located strategically within Saint-Quentin-en-Yvelines at railway and bus stations, shopping and business centers, hospitals, and so on. A car can be taken at any time from any of the stations, used freely as if it were a private car, and then returned to any of the stations.

The same car can be used by several drivers during a single day. This permits a significant reduction in the total parking space required in the city center. The only requirements a driver has to meet is that he or she possesses a valid driving license and registers as a member upon their first use of the system. From then on, members can use the car as they like, much as they would their own private vehicle. Each client is billed at the end of the month for the time the driver has actually used the service.

Praxitèle is designed to provide the missing link between private vehicles and public transport, seeking to combine the freedom and independence provided by the former and the environmental and economic sustainability of the latter. It is considered complementary to existing public transport and should stimulate the use of efficient mass transport systems for long trips. It attempts to make optimum use of the qualities of electric propulsion. The cars are charged automatically at the charging station via a non-contact inductive charger that needs no intervention from the driver when the car is parked.

The Praxicentre is linked to computer terminals installed at Praxiparks. These ensure management and recharging functions. They also ensure service payment and information on the availability of the Praxicars and on the Praxitèle fare. The terminal also provides information on other public or private transport options including taxis, for example, by enabling a call for a taxi when there is no Praxicar available.

Praxitèle users get into a Praxicar by means of a small card—Praxicard—which checks their contract terms and handles fare collection. This card resembles a credit card. It uses an electronic billing technique identical to the ones now developed for other public transport services.

The fleet of Praxicars is controlled by the Praxicentre. It informs users of the nearest available vehicle via the Praxi terminals or telephone. It uses new telecommunication and localization systems that are considered necessary for the success of such a system because one of the reasons for the failure of previous experiments with self-service cars was the lack of efficient fleet management. One key for the success of such a novel transport system is to centralize information about vehicles' condition (e.g., state-of-charge), parking space availability, and customers' accounts. This requires an effective means of communication to link the management center to each vehicle.

Each vehicle is equipped with a GPS system allowing the vehicle to locate itself with a precision of about 30 meters. In specific cases (for example when the user needs help or leaves the designated area), the location of the vehicle is transmitted in real time to the management center which intervenes if necessary. The Praxicentre also handles reservations and transfers to other types of transport (train, bus, and taxis). The information collected by the Praxicentre enables an efficient redistribution of empty Praxicars among the Praxiparks.

In the first version of the Praxitèle system, the vehicles were driven by their users. Plans are to automate vehicle operation in some instances when no one is on board—for example, in case of uneven distribution of vehicles across Praxiparcs. Still later, fully automated driving with passengers is being considered on dedicated tracks in accordance with the concept of an automated highway.

Project partners were CGEA Transport (CGFTE's parent company), Renault, EDF, Dassault Electronique (now Thomson CSF Detexis), and by the municipality of Saint-Quentin-en-Yvelines. The project budget was 30 million francs (just over €4.5 million), of which 50 percent was paid by the partners and the remaining 50 percent by the Ministry of Transport, other French agencies and the European Commission.

The participation by Dassault is interesting as it has no tradition in the transportation business. Dassault primarily produces military electronics but with the collapse of markets for military equipment since the early 1990s it started to look for new markets. Companies in such a position tend to be more open to innovative approaches in a new field where they face less established competition.

The broad objective of the Praxitèle experiment in Saint-Quentin-en-Yvelines is to demonstrate the usefulness and economic feasibility of an individual public transport system based on a centrally managed fleet of small electric vehicles. In the evaluation, focus will be on the following aspects:

- Technical feasibility of the vehicle and related infrastructure (e.g., to test the new inductive recharging system);
- Usefulness and reliability of the technical system for customer service in relation to the customers' requirements;
- Public acceptance of this new service; to find the best conditions for exploitation (fares, hours of service);
- The organization of the system and its operation; and
- Knowledge required for a development on other sites.

Results

The experimental phase of Praxitèle officially started on 16 October, 1997. By early 2000, the practical phase of the experiment has been concluded but the final evaluation had not been completed. Therefore, only preliminary conclusions can be drawn.

It is evident that a significant number of people are using the service. In May 1998, 400 members had registered; membership had doubled one year later. In the one-and-a-half years since the start of the experiment, 25,000 trips had been made. The average trip distance was eight kilometers; average trip duration was 15 minutes. In April and May 1999, the average use was about 500 trips a week, or about one-and-a-half trips per car per day.

Users indicate they are very satisfied with the service. A growing group of clients has become regular users as they learn how to use the system. They change their behavior toward transport, especially when they have no regular access to a private car. They particularly appreciate the freedom, the ease of use of the self-service system, and the availability of cars without worries about maintenance. They show responsibility when driving the cars and there have been few reports of vandalism and accidents. They value the fact that the cars are electric as an expression of their environmental concerns. They indeed only use the cars as intended—for short trips between the dedicated stations inside Saint-Quentin-en-Yvelines area.

The main problems encountered relate to the experimental and innovative features of the service. Continuous adaptations have been made during the experiment to solve technical problems that were encountered. Concerning economic aspects, it was evident from the beginning that in the current set-up it would not be economically feasible. The current costs of EVs, because they are not made as a mass product, are far too high; an economic break-even point was not expected with a scheme with less than a few hundred vehicles. The least the experiment has done is to prove there is a substantial demand for such a service. How this demand could be satisfied in a cost-effective way is as yet unclear as detailed economic evaluations have not yet been made.

Concerning policy issues, the service has no juridical status. However, its definition as a public service gives right to reserved parking places on the street. The experiment should help to define this status. The future of the service will depend on its acknowledgment as a public transport service, in conjunction with collective transport and mass transit.

Initially it was feared that the system would directly compete with taxis and there was even a threat of resistance from taxi driver unions. In practice, taxis have not experienced a loss of clientele. The self-service system is a complement to existing public transport systems that may have taken away some customers from taxis but may also have increased their client base by creating demand for a taxi in the case that there are no self-service vehicles available at a specific station when needed.

The managers of the project are satisfied that the technical feasibility of the system has been proven and that the more detailed results should help to define the conditions for successful implementations of the service. Larger scale projects are considered for other sites and a project has been proposed for Paris with some 2,000 cars. In the longer term, an operator should be able to offer to cities and public transport authorities a service based on such a self-service system. The experiment seems to demonstrate that there is a place for a self-service car system in urban transport. The experiment in Saint Quentin is a first step in this direction.

Evaluation

There were many goals for Praxitèle. The project aimed to demonstrate technical function, to investigate the public's acceptance of this new type of service, to find the optimal conditions for deployment, and to gather the knowledge required for replication of the project at other sites. The economic feasibility of the self-service system was not central to the Praxitèle project.

The project yielded many lessons about these goals. The technologies functioned well. The number of users was grew; membership doubled May 1998 to May 1999. The service was used in connection with public buses and trains. The most frequent users were non-car owners, but a substantial share of the users (44 percent) did own a car and 29 percent were using cars from family members. For both groups the self-service cars formed a convenient addition to the spectrum of existing modes of transport, but users did not question their mobility patterns. Interestingly, contrary to expectations, the majority of users were not employees of local companies or tourists but area residents for whom the system offered a useful addition to the spectrum of transport options. Second-order learning hardly occurred, either by users or service providers. The latter merely found confirmation of their expectations about the working of the system. Contrary to the provider's expectation, however, companies were less eager to stimulate their employees to use the service especially because of its experimental, and thus perceived temporary, character.

The project thus created a lot of learning, which could benefit follow-up projects elsewhere, but the transfer of the lessons is not secured through the set-up of a transfer mechanism. The project also suffered from a weak internal network. Several of the partners sat back and were little more than suppliers. The project did not develop an efficient communication policy because early difficulties caused by the complexity of the project made the partners aware that high winds blow on high hills. Users played a role in the creation of the service as the idea was born in discussions with them, but large commercial firms developed the project further.

Nonetheless, the central actors now seem confident that there is a future for the self-service systems with electric cars and are continuing with their plans for larger follow-up projects. In conclusion, the Praxitèle experiment did not launch the self-service system outside the initial technological niche, but it did potentially contribute to niche replication. The experiment did not pose a threat to either car or public transport regime actors: the service provided is seen as a complement to collective public transport and is not believed to lead people to abandon their car. The technological niche of self-service systems with electric cars is likely to become a market niche that may form a link between the regimes of car-based individual transport and collective public transport.

Case 3: Camden's Accessible Sustainable Transport Integration: Customizing Public Transport[13]

The Accessible Sustainable Transport Integration (ASTI) project involved the development and introduction into service of a small fleet of three electric and three CNG-powered minibuses accessible to all people with reduced mobility in the London Borough of Camden. Part of the experiment was the introduction of demand-responsive service using telematic technologies for vehicle positioning and route guidance, and scheduling software to optimize the use of these and other minibuses. The project was integrated into the development of transit operators' networks to allow the pooled use of the fleets and better distribution of resources. The ultimate aim of the ASTI project was not simply to develop a small fleet of electric and CNG minibuses, but to develop a better and more efficient community transport (CT) service. The trigger for the ASTI project was the opportunity to bid for funding from the European Commission's LIFE program. Camden Community Transport (CCT) and Camden Borough hurriedly put together an initial bid that narrowly failed to be funded, but their second attempt was successful.

ASTI was run by CCT, with a project manager appointed by the Camden borough. Overall, ASTI was part of a vision that aimed to provide a better public transport system for people whose options for travel were very limited. The two organizations had a strong pre-existing relationship focused on funding and providing CT services in Camden. ASTI's two prime sponsors, the borough's environment department and CCT, worked together to carry out the vision and to steer the project. They developed the concept, put together bids, and arranged for the involvement of other partners. They also obtained funding from the European Commission's LIFE program, the UK Department of Trade and Industry, and several private- and public-sector partners (see below). The total funding amounted to nearly 2.5 million ECU. ASTI's objectives included[14]

- Developing a small fleet of three electric and three CNG-fuelled minibuses and the refueling infrastructure required for these vehicles;
- Integrating satellite vehicle tracking and software for a real-time service optimization and dispatching system to assign trips for a service;
- Identifying and developing the most appropriate routes and services for the vehicles and optimizing vehicle/route combinations for efficient service with minimal environmental impact;
- Improving the quality of life for the elderly, disabled, and infirm by facilitating greater independence;
- Integrating procedural aspects of health, municipal, social, and transport organizations to improve community and health care; and
- Disseminating the results of the project so that relevant lessons could be applied across European cities to enhance the provision of transport while mitigating environmental impacts.

An implicit objective was to develop an environmentally beneficial service using cleaner drive systems and better fleet management, but actual environmental impacts were not monitored.

The vehicle design chosen for ASTI was strongly influenced by the specific function it needed to perform. Vehicles had to offer easy physical access to both ambulatory and wheelchair-bound users. Because no existing electric or CNG buses met this condition, it was decided to use a converted model of the same Iveco Ford van that CCT had been using in a diesel version. This van allowed for combinations of up to twelve seats, could accept wheelchairs, and had a hydraulic passenger lift at the rear entrance. In terms of project management, choosing this vehicle reduced uncertainty and meant that attention could be focused on the scheduling and operational changes required for electric and gas traction.

AC motors were chosen because of their relatively lightweight and sturdy construction. The AC controller developed by the British firm Wavedriver was used; it was actually an integrated AC drive and a high-rate charger and battery-management system. Proven, maintenance-free, lead-acid gel traction batteries were also chosen. With an overall weight of 4.5 tons (including one ton of batteries), the vehicle's range on one charge fell well short of the 130 km required for daily operation. However, a simulation of bus operations suggested that "opportunity recharging" during occasional layovers between trips could achieve the target of 130 km/day thanks to the Wavedriver system's quick-charge characteristics. For the CNG buses, Iveco Ford, working with the Motor Industry Research Association (MIRA) and British Gas, converted the diesel vehicles to run on CNG.

Evaluation of Project Design and Management

Because ASTI was an experiment involving three inter-related technologies, it created overlapping networks of business, technical, and research partners, along with a network of accessible-transport operators to develop the operational side of the PlusBus service. A three-person team consisting of one member each from CCT and the Camden borough, along with an external consultant, selected the partners; all three were well grounded in the CT world.[15]

The team faxed one hundred potential suppliers and received forty replies. They then carried out a type of competitive selection, but, unlike conventional tendering, this process was intended more to test potential partners' commitment than to push prices down (although prices had to be accommodated within the overall budget). The team then invited preferred suppliers or partners to meet with them, visit the site, and make their case regarding what they could bring to the project. A strong commitment to the project and its aims was considered crucial.

Once selected, the partnership network worked together very closely and arrived at joint agreements on key decisions. One aspect of ASTI that was particularly emphasized was the "openness" of the relationship among the partners in developing the design for the two types of vehicles and the ASTI system as a whole. The consultant commented that the private-sector partners "got a bit of a shock as they thought the community transport/voluntary sector would be a pushover." In practice, they found themselves subject to close scrutiny and binding conditions.

The partner network turned out to be strong, in part because ASTI was important to the partners for developing their core activities. For instance, because MIRA wanted to position itself on the European stage with respect to cleaner fuels, it viewed ASTI as a prestigious project that could establish and enhance its international reputation. For Wavedriver, ASTI provided its first serious on-road project and a chance to gain operating experience with its controller. Given that systems integration in EV design was still underdeveloped, the company hoped to find a large market for its systems. Two other partners were PowerGen, the UK's major electricity generator, and London Electricity, an energy supplier, both of which had an interest in developing new markets for electricity and electric appliances for purposes of load management.[16] British Gas, another partner, was also interested in developing new markets.

The team's hardest task was attracting an appropriate software company as a partner in the project. They approached a large number of GIS software companies, but none were particularly keen; they believed that the market for accessible transport was not worth bothering with and that other applications looked more lucrative. Signal Computing, the company that eventually joined the project, initially dismissed ASTI but later decided that accessible transport did represent a market worth developing because success there could lead to applications in mainstream transport.[17]

Among transport operators, the only notable absence was London Transport, which is responsible for accessible transport in London. LT did become involved via the follow-on project, PlusBus Interactive. Besides Sainsbury's supermarkets—with whom CCT had already contracted to provide transport services to and from their Camden branch—no other CCT clients chose to join ASTI. Also, the Camden and Islington Health Authority was initially represented, but this tentative link ceased after the individual involved left. The ASTI partners worked closely with local community and day-care centers through regular user forums and other meetings to ensure that the transport provided was responsive to user needs.

After the project concluded at the end of 1997, its elements became a permanent part of CCT's operations. The next stage is PlusBus Interactive, which studies the possibility of a control center that allows other transport operators to join in and pool their resources to improve integration and utilization of the shared fleet. This center would use the scheduling and control systems developed under ASTI. Further European funding was secured for PlusBus Interactive and London Transport, who did not take part in ASTI, is involved in this service.

Learning

ASTI resulted in a number of useful lessons concerning both vehicle technologies and the operational aspects of an integrated service. Regarding the technology, the experiences were generally positive. The driving range per charge of the electric buses proved less than anticipated, and this was somewhat aggravated by delays in installing a second charging station.[18] The lower range also appeared to be related to driving styles; this was addressed by retraining the drivers. The use of lead-acid gel batteries, the Wavedriver system, and the strategy of opportunity charging proved to be a successful combination that met the daily range requirements. Although this strategy had led to battery cell failures in the Oxford project because the batteries had not been sufficiently discharged, the ASTI buses did not appear to have been affected by this problem. However, heating was a problem on the electric ASTI buses; the batteries did not generate enough surplus heat. As the users were elderly and disabled, this was a serious issue. As for the CNG buses, fuel economy turned out to be to 20 percent better than predicted.

With reference to bus technology, ASTI showed that the technologies used were applicable to the CT sector. Representatives of other transport service operators, although impressed by CCT's electric minibuses, still believed that they were too expensive compared to diesel vehicles. They were, however, more hopeful regarding the CNG buses.

The project also established that accessible transport, rather than being merely of peripheral interest, could serve as a staging ground for developing demand-responsive technologies which were then able to diffuse into mainstream transport applications. This lesson was especially important for the telematics firm.

Both drivers and passengers were generally very positive about the buses. Users found both the CNG and electric minibuses quieter than the diesel vehicles they had replaced. This even led to new opportunities for passengers who could now chat with each other. The low emissions were also appreciated; as one CCT driver said:

> As my partner and child have developed asthma, it is a privilege and an honour to drive a vehicle that is, if only in a small way, cutting down on pollution.[19]

The results of the ASTI project have been widely disseminated, particularly in the CT press. Its service-integration aspects were well understood and have attracted wide support within CT groups and the social services departments of the municipalities that fund them.

However, municipal-transport operating departments and others that run accessible services have tended to perceive ASTI as a bus *technology* development project rather than as a bus *system* development project. This perception was illustrated at the mid-project ASTI Technical Seminar organized by MIRA in December 1996. The event attracted a number of non-CT attendees who were interested in applying the ASTI technology to their own organizations. These included representatives from several local authorities and their social-services departments, London Transport, and the above-mentioned Sainsbury’s supermarket chain. The questions asked by these representatives indicated that they generally viewed ASTI as an “electric bus” or “gas bus” project. The project's basic vision of exploring the ways in which information technologies could transform transport service for the mobility-impaired was not shared and possibly not even grasped.

Among policymakers, the issue of integrating the operations of parallel fleets of providers, which was central to the ASTI/PlusBus development, became increasingly important after the project. As increasing amounts of money are needed to provide a poor-quality, uncoordinated mix of accessible transport services, local authorities commissioned various studies on integrating ASTI-type innovations with existing transport systems. This interest was not an effect of the ASTI project but was clearly a related development.

Institutional Embedding

ASTI contributed to network development by strengthening links between the CT segment of the accessible-transport-services market and other providers of accessible-transport services. Diffusion of the ASTI fleet-management and trip-allocation technologies has already taken place by mechanisms that have sometimes been surprising. For example, the UK trend towards privatization of municipal services assisted the diffusion of ASTI/PlusBus technologies beyond the community transport sector.

One example is the London borough of Lambeth, which let out, via competitive bid, the whole of its Direct Works organization including all its education and social-services transport. In partnership with Ealing Community Transport, Camden Community Transport established a new CT group in Lambeth that provides transport services as subcontractors to a large utilities company. A CCT spokesman said:

> Our work on low-emission vehicles, global positioning, and transport management software which we have developed as part of the ASTI project can be applied to the transport problems of Lambeth.[20]

The movement of CT groups and their technologies towards more mainstream transport activities could create competitive pressures on conventional bus companies that may in turn adopt CT-type systems and innovations.

No benefits emerged from the investments made in the six ASTI minibuses beyond their continuing use in the PlusBus Interactive scheme. The electric and CNG buses were one-off conversions to a special design and thus quite costly, about 150,000 ECU for each electric bus. Moving to volume production of twelve or more vehicles of roughly standard design would cut the cost by about half. Beyond this, no economies of scale will be gained until mass production is involved, when orders would have to be in the thousands. Such numbers are not attainable in today's market for accessible vehicles, which is served by fragmented batches of van conversions, but operational integration could lead to more universal specifications, which could in turn result in mass production of accessible, alternative fuel minibuses.

Concerning expectations, the accessible-transport-services niche aspects of ASTI (i.e., the vision of using IT to integrate poorly coordinated transport for the mobility-impaired) appear to be widely shared. However, ASTI's telematics system was distinctive in that it was not developed simply to improve existing ways of offering accessible demand-responsive services, but rather to effect changes in how services were provided. Obviously, political and organizational boundaries become relevant as actors attempt to defend their own empires. For example, under-utilized school-transport vehicles are rarely integrated into CT schemes, although they obviously share the roads with CT service vehicles. Additional extensions of the ASTI CT services model to other transport domains are still in their infancy, but most observers expect the continued greening of the CT system via integrative IT improving overall resource use.

The ASTI experiment also helped solidify expectations around specific technological alternatives. For example, a number of technologies can be used to locate the position of a minibus. For demand-responsive services, this has always been an important issue. In cabs, radios have been used since the 1980s, so that if dispatchers want to know a vehicle's precise location, they use the radio to ask the driver. Such cheap, low-tech solutions may well be appropriate for smaller and less complex Dial-A-Ride and CT operations. But ASTI's use of a fully integrated package of satellite positioning and passenger booking has helped to clarify thinking about what type of system will best meet the needs of both operators and users.

Regarding expectations about CNG and electric-traction technologies, ASTI has apparently had little if any influence. Cost and performance remain the key barriers to electric traction. Electric buses may prove useful for CT services in some cases, but the prevailing opinion is that other alternative fuels (CNG in particular), low-sulfur diesel, or hybrids will be more appropriate solutions.

Evaluation

Overall, ASTI showed that both CNG and electric-bus technologies were viable for CT operations, although, as mentioned above, initial costs of the latter remain a substantial barrier. The alternative-drive technologies used in the project may also find mainstream application in taxi services; because the operational requirements of taxis overlap with those of CT, ASTI's experience with CNG/electric-traction would be relevant. CNG is already in limited use in straight commercial road-transport applications. However, many taxi companies are actively looking at LPG rather than CNG as a cheap, quick way to offer cleaner-fueled vehicles and thus to keep their vehicles running in city centers where other vehicles could be banned.

ASTI offered evidence of positive utility of both the concept and the operating economics of the IT software systems and integrated services, and the value of these systems appears to be gaining wide acceptance. The project probably speeded up adoption of satellite and booking/dispatching systems as well as their related software by demonstrating the benefits that can be achieved.

ASTI also showed that accessible transport services are an excellent pioneering application that does not require a large infrastructure investment. The IT technologies developed in the project could find mainstream application in developing general public-bus services. Vehicle tracking and real-time information systems are already being introduced in some areas. As new IT technologies are developed, it may be possible to reintroduce Dial-A-Ride to mainstream operations. These technologies could certainly transform present bus technologies and operational regime and increase the appeal and viability of bus services compared to the private car.

WHAT DO THESE CASES TELL US ABOUT SNM?

We now turn to the question: what do the cases tell us about Strategic Niche Management? Do they confirm the assumption about SNM being useful for stimulating co-evolution and system innovation (a regime shift)? A first look would suggest that they were not really influential; a second look reveals the lessons learned.

How Influential Were the Experiments?

The contributions of the projects to niche development appear to be small. Much has been learned about the functioning of technologies and their acceptance. In some cases the market potential of a new technology or concept was established thanks to the experiment, such as the ASTI fleet management software, the protective bicycle racks, and electric bicycles and motorcycles. In other cases, the experiments showed that there was not a real market, as for BEVs for private, individual use. The experiments did not make actors change their strategies and invest in the further development of a technology in a big way; efficiency improvements resulting in cost reductions were small (due to the small production scales); and there has not been a takeoff or significant upscaling. Even contributions to solving local problems was generally small: no spectacular results have been achieved here as the experiments were too small scale. The experiments were relatively isolated events. It seems it was difficult for actors to build bridges.

Perhaps more could have been done and achieved, but there are limits as to the transformative power of experiments. Only occasionally will an experiment be such a big success that it will influence strategic decisions. Experiments may tip the balance of decision-making, as it did in many cases, but won't change the world in a direct, visible way. We should therefore not evaluate experiments on the basis of its immediate economic success but on the basis of what has been learned and its contribution to processes of social embedding. Negative learning then becomes something useful. One also should accept that failures are inevitable in experiments and that it takes time for some of the lessons to be applied in ways that produce real benefits (either economic benefits or sustainability benefits). For instance, it took the Swiss carsharing cooperatives seven years before they achieved a membership of 5,000 people. We also are convinced that the knowledge about electric propulsion and lightweight, plastic-bodied vehicles obtained in the experiments with electric vehicles will be utilized in the future in hybrid-electric and internal combustion engine vehicles.

Failure should be accepted in the quest for success. A good example of this is the Praxitèle experiment with self-driven public electric vehicles. The experiment was terminated because it was not economically viable, but the public transport company CGEA is convinced that the system has economic potential as a supplement to existing public transport services and will introduce it in the coming years in various cities in France. Fortunately, not all experiments were failures on their own set of objectives, and the case for experimentation does not have to be forcefully made by us or anyone else, as many people are convinced that societal experimentation with technology is useful.[21]

It is important that the experiments are seen as learning exercises and projects that are occurring in the *predevelopment* phase of a transition or technological regime shift. In a predevelopment phase there is a great deal of experimentation in the form of trials, but no visible trail. This may lead people to conclude that change will come from other events and directions. But this would be a wrong conclusion. To get a feel of the future one should look at people's expectations, not at the results of experiments. There is a convergent view about the contours (but not the details) of future passenger transport, a view that is guiding strategies and investment by private and public decision-makers. All car manufacturers are convinced that alternative fuel vehicles will be on the road in the next five to 10 years. Some even think that in the future people will no longer own a car. Bill Ford, chairman of Ford Motor Company, the world's 2nd largest carmaker, has said that fuel cells will end the 100-year reign of the ICE and that we may witness an end to car ownership as the preferred method of personal transportation. In his words:

> The day will come when the notion of car ownership becomes antiquated. If you live in a city you don't need to own a car. [22]

Under this vision, Ford and other carmakers could own vehicles and make them available to fee-paying motorists when they need access to transportation.

It is unclear to what extent the rise of organized carsharing informed this vision, but it is likely to have played some kind of influence. Experiments influence the world (by changing the odds of certain futures) but do not bring particular futures about. Their influence is more indirect. It is only during the takeoff phase and especially the acceleration phase of a transition that we start to see the effects of explorations and niche projects.[23] This illustrates the importance of undertaking a *wide set* of explorations and designing experiments in ways that allow for second-order learning (about basic assumptions), besides first-order learning. As a last remark, regime transformations are associated not only with learning and adaptation but also with unlearning and undoing. The latter aspect (of dissociating old ideas, assumptions, and habits) proves to be very difficult but is central to a regime shift.

Practical Lessons of the Experiments for SNM

The cases bring out some practical lessons for conducting SNM. One important lesson is the importance of committed partners. In the ASTI case, partners were selected partly on the basis of their commitment to the project, which seems a good idea. The cases also show that ambitions should be balanced: they should be neither too high nor too low. Upscaling should be done in a gradual way.

The experiments with the use of more sustainable transport technologies and concepts also show that there are advantages of relying on a learning-by-doing approach, or *probe and learn* strategy. This offers flexibility to a project, and offers an opportunity to react to project outcomes and shifts in the environment. The cases also suggest that learning should be made the key aim of experiments rather than quantitative goals (the number of users or vehicles sold). This suggests that projects are best labeled as experiments (or learning experiments). Calling a project an experiment also has a disadvantage. Actors will perceive it as something temporary; this may undermine their support for it. This happened in the Praxitèle experiment.

When designing a new experiment, the actors should gather knowledge on and utilize previous relevant experience. They should carry out a niche analysis. Furthermore, the expectations of all partners need to be continuously articulated to ensure co-operation of partner activities.

Lastly and perhaps most importantly, experiments should be used to question underlying assumptions at all levels; these include technology options, technology diffusion strategies and effects upon patterns of mobility. Most of the experiments failed to do this, which meant that the potential for transformation was insufficiently utilized. The lessons do not contradict or invalidate our model of SNM, but rather provide further substance to it.[24]

SNM AS A TOOL FOR TRANSITION

In Section 2, we made a distinction between optimization and renewal of the transport regime. Renewal implies a drastic change of the current system, playing down the importance of the private car and developing a range of alternatives tuned to the specific needs of a variety of travelers. Such drastic changes are also called (technological) transitions.

Transitions take a long time. They are the outcome of myriad decisions over an extended period in a changing landscape. They are not a linear process but involve processes of co-evolution that give rise to new "configurations that work,"[25] combining old and new elements in novel ways. Technological transitions are associated with structural change at different levels—of companies, production chains, users, and government policies—and are connected with new ideas, beliefs and sometimes even new norms and values. Many of the elements involved in transitions cannot be managed. This raises the question: can regime shifts be managed? The simple answer to this question is no, at least not in a simple way. The best one can do is to "slightly bend" the direction of existing patterns, or to modulate ongoing dynamics. "Slight bending" in an initial phase, however, can lead to drastically different outcomes in the long run.

One way to influence innovation processes is through centralized planning. Historically there has been a lot of planning in transport. Infrastructures were built based on planning decisions. Planning has an important role to play in making the current transport regime more sustainable, by reducing the need for transport, providing for transfer places and special infrastructures for cycling and collective transport means to substitute for individual modes of travel. But there are limitations to a planning approach. When end states and best means to meet these are not clear, as in the case of sustainable travel, you can not use a planning and implementation approach. These cases give rise to a second approach—to try to bend the development process by judiciously applying economic and/or social incentives and disincentives, so as to make some possible paths more interesting and feasible. This is what policy makers have tried to do through for example the use of gasoline taxes.

A third approach, besides planning and changing the framing conditions, is to "float with the co-evolution processes and modulate them."[26] It is very close to the previous one, but is more directly oriented at dynamics, at learning and adaptation, and at the creation of visions and plans to guide private and public decision-making. Here policy makers engage in process management, exercising some leverage to socially beneficial developments and putting constraints on less desirable developments in order to bend these into more advantageous directions. The support given to EVs and rigorous future standards for vehicle emissions are examples of a modulation attempt, aimed at exploring a new path and bending an existing one. SNM is also an example of a modulation approach and in our view an important one. But can it really do the job?

The three cases provide little insight for evaluating SNM as a tool for transition. It is unclear whether the experiments will be instrumental in a regime shift: it is too early to tell. An alternative way to approach the problem is to ask the reverse question: can there be a regime shift without SNM? The answer is yes, if one defines SNM as a deliberate action to achieve a regime shift. However, if SNM is seen as the introduction of new technology in society in a "probe and learn" manner, benefiting from special circumstances offered by the local context, the answer is no. Historical studies of technology development offer support for this belief. Technological niches appear a necessary component of a regime renewal. They help to create a pathway to a new regime without which there will not be a new regime. Niches act as stepping stones. Of course, not all niches will be instrumental in this respect. There are four conditions for a regime shift to occur. First, the niche technologies must have ample room for improvement that allows for cost efficiencies and for branching out. Second, they also must have a synergetic relationship with other developments in technology and markets in order to find new users and capture new domains of applications. Third, the gap between existing domains of application and new ones should not be too big. Fourth, the rate of progress of the emerging technology system offering particular services should be larger than that of existing technologies with which it must compete.

Obviously it is difficult to tell beforehand whether these conditions pertain, but they provide a basis for decision making about technology systems that are eligible for support through niche management. Of course, the choices may be wrong in the sense that no new path gets created and the project fails to bear fruit. The attractiveness of SNM is that one finds this out in a bottom-up, non-distorting manner by carefully choosing a domain of application for which the technology is already attractive. The costs of discomfort are thus minimized (or carried by a local actor with a special interest) while useful lessons may still be learned. Here SNM as a probe-and-learn strategy differs from strategic planning or control policies based on the achievement of set goals in the sense that it is more reflexive and open-ended. It is aimed at the exploration and creation of new paths by building on developments at the local and supra-local level. SNM is thus *not about pushing possible winners but about testing and identifying* *prospective winners*. The pushing is done after a period of testing, and there is also an element of control, of limiting side effects. SNM thus combines elements of push and control.

The advantage of SNM is that it is targeted to specific problems and needs connected with the use of new technologies and practices. User experiences are used to inform private investment and government support policies. By carefully choosing an appropriate domain, the costs may be kept low. Windows of opportunity are exploited at the local level while at the same time a transition path may be created to a new and more sustainable system in a non-disruptive way. SNM will help actors to negotiate and explore various interpretations of the usefulness of specific technological options and the conditions of their application.[27] The outcomes of the experiments may be used to fine-tune government support policies and to change the frame conditions. This was done in the Mendrisio experiments with EVs described in Harms and Truffer (1998) and Kemp et al. (2000) where the large-scale test informed the expansion of the project to the whole of the canton. It was also done in the case of organized carsharing (described in Harms and Truffer, 1998b and the book *Experimenting for Sustainable Transport: The Approach of SNM* by Hoogma et al., 2001) in which Swiss authorities intervened to unite two carsharing organizations. In other cases, government intervention to stimulate the diffusion was limited. This very strongly suggests that technology experiments should be supplemented by niche management policies aimed at stimulating the diffusion and further development of niche technologies.

It should be noted that SNM is not a substitute for existing policies for sustainability, but a useful addition. One cannot do without policies that make sustainability benefits part of economic decision-making. Sustainability is a weak driver for change and path creation, far weaker than economic gain. The two things have to be reconciled: there should be an economic gain in activities that produce sustainability benefits. Subsidies and other types of positive rewards (such as prices) are a possible route for achieving this; taxes, standards and other penalties are another route. Infrastructure provision is a third route. All routes have a role to play, depending on the circumstances.[28] It should be noted that SNM is not so much an instrument to improve the effectiveness of such policies but a way to *improve the functioning of the variation-selection process* by increasing the variety of technology options upon which the selection process operates. SNM contributes to the goal of ecological restructuring by exploring options that go beyond the control of particular pollutants and the adoption of eco-efficiency solutions. It is an example of an "evolutionary" policy, aimed at deliberately shaping paths, creating circles of virtuous feedback through carefully targeted policy interventions, rather than at correcting perceived market failures. It thus helps to overcome the weakness of current environmental policies that have been found to have a marginal influence on innovation.[29] It is not a panacea and does not guarantee success, but this holds true for all instruments.

SNM AS A MODERN TOOL OF GOVERNANCE

Above we positioned SNM as part of a third model of governance, which we called *modulation policies*. Modulation policies are forward-looking, try to utilize the winds of change, and seek to exploit windows of opportunity. Such policies are especially suited when end goals are not clear and when there is uncertainty about the best ways to reach them. There are many types of modulation policies. SNM is just one possible policy but in our view an important one, as it helps to deal with uncertainty about the desirability and costs of new technologies and with opposition from vested interests that often stand in the way of something new. SNM may actually enroll companies vested in the status quo in the process of niche development. These companies should not be allowed to control the process, though, given their interest in the status quo. For radical change you need outsiders and entrepreneurs.

SNM is not something completely new. It has been attempted, *avant le mot*, by companies for radical innovations such as optical fibbers, cellular telephones, aspartame, and computer axial tomography scanners.[30] But although some attempts like the Californian Zero-Emission mandate could be labeled as de facto SNM policies, it is a new approach for policy makers. In our view there is a need for policy makers to go beyond demonstration projects and to promote user experiments with new technologies.

Different people and organizations may be interested in technology experiments and SNM for various reasons: to seize a business opportunity, to alleviate a local problem of unsustainability or simply to learn. Table 1 gives an overview of different actors' motivations to engage in technology experimentation.

The table shows that technology experiments allow for mutual benefits that help various parties to find a common ground to be involved in experiments. On the other hand, it shows that SNM involves difficult tradeoffs.

SNM is not something simple; it involves difficult decisions about the use of protection pressures (avoiding overprotection, finding a balance between protection and selection) and the choice of partners (strong actors versus outsiders). Suggestions for doing SNM are offered in Weber and Dorda (1999) and the forthcoming book *Experimenting for Sustainable Transport: The Approach of SNM* by Hoogma et al. (2001), but it may be clear that SNM can never be done in an instrumental mode only. It is a perspective that creates a specific kind of communication processes, with specific contents. It helps to better align the technical and social, and this is clearly missing in the three cases analyzed. Therefore we cannot be over optimistic about organizing regime shifts. But we also must not be over pessimistic. We can hold a position of moderate optimism at best.

TABLE 1 Actors' Reasons for Engaging in or Supporting Technology Experimentation

Type of actor	**Reasons to engage in or support technology experimentation**
Companies	• Learn about the current state of a technology either as suppliers or users, and inform company policies • Be prepared for a shift in market conditions creating a demand for a new technology • Influence public policy by offering a solution to an environmental, economic or other type of problem
Local authorities	• Learn about a new technology and about socio-technical arrangements that may solve a local problem (pollution, nuisance, employment, congestion, etc.)
State authorities	• Have society learn about new technology options and facilitate transition processes • Create business • Inform public policies to achieve socially desirable outcomes
Consumers and citizen groups	• Learn about their own consumption patterns and needs • Demonstrate to others sustainable life styles • Contribute to a reduction of environmental impacts
NGOs	• Demonstrate feasibility of sustainable lifestyles in order to get support for other

	policies • Experiments are vehicles for campaigns

AN AGENDA FOR SNM RESEARCH AND NICHE MANAGEMENT

Further work remains to be done with regard to SNM. More studies need to be conducted of the role of niches in technological regime shifts; historical studies may be used to this end. An unresolved issue is how to organize protection, by what means, and how the phase-out of protection should be done in an ordered, non-disruptive way. In general, one should utilize natural forms of protection offered by a local context but this may not be enough. One also needs sponsors and accompanying measures that change the overall frame conditions for economic decision making. This became most clear in the Bikeabout experiment, described in Hoogma et al. (2001) and a study by Colin Black for the EU-funded SNM project.

More research is also needed on the relationship between SNM, state policies, and planning. In general, SNM may be used to inform planning (both transport planning and town planning) while planning may be used to foster niche-development processes. These issues are unlikely to be resolved on the basis of careful thinking alone. Practical experience is needed to find answers and provide examples for decision makers. This is why we propose that decision-makers engage in niche management with niche management acting as a framework for long-term change and policy actions. So far technology experiments were largely oriented towards technology testing. We are arguing for experiments that are linked to visions and oriented towards co-evolutionary learning, in which users and other actors are encouraged to rethink their perceived needs and basic assumptions. There are signs that car manufacturers are currently reconsidering their business, we have already discussed this when we talked about Ford Motor Company. Public transport providers also seem to be changing their mental models, they become more client-oriented and more willing to provide door-to-door services. The vision of intermodal travel is widely shared but so far only a few steps are taken by societal actors to make this a reality. There is a need to further articulate this vision; acting upon this requires investment. SNM may help here. But this aspect—the link between vision and using SNM for further articulating the vision and exploiting it for short-term policies—is only weakly developed in this paper and the SNM book; it requires more work. One can think of the development of socio-technical scenarios based on the multilevel model of evolutionary change (See Geels 1999).[31] Such scenarios are best made in an interactive way, involving different stakeholders, to benefit from different types of knowledge and to make sure that the findings are utilized by decision-makers.

It is important that experiments are undertaken not as isolated events but are linked to long-term strategies for structural change, for instance as part of transition agendas.[32] This helps to bring more coherence in experiments and guarantees a better utilization of the results.

NOTES

1. One major automaker, Ford Motor Company, took up the challenge by simply buying PIVCO.
2. The concept of a “technological niche” should not be mixed up with a “market niche.” The latter refers to a subsection of a larger economic market with specific characteristics, like the

market for advanced sports cars. Technological niches usually precede market niches but a market niche may also fail to materialize. Thus, a technological niche represents a specific phase in an innovation process, preceding market development, whereas a market niche represents a specific type of market. Cf. Elzen et al. 1999.

3. This section is mainly based on B. Simon and R. Hoogma, The La Rochelle Experiment with Electric Vehicles, a case study for the project, Strategic Niche Management as a Tool for Transition to a Sustainable Transportation System (Maastricht: MERIT, 1998).
4. PSA developed two EV models because of the politics of balance between Peugeot and Citroën; these companies are competitors despite their tight organizational relation. The 106 and AX have mostly identical components, the main difference being the body design.
5. The users were 21 private individuals, including housewives; eight professionals; and 19 companies and administrations.
6. 86 percent of users had second cars; 64 percent had low-range segment cars, of which only 40 percent were bought new.
7. This section is largely based on PSA, EDF, Municipalité de La Rochelle, *Opération 50 véhicules électriques à La Rochelle – Bilan final de l'opération – Retour d'expérience*, 1996.
8. Schwegler, 2000.
9. T. Robinson, Developing Niches, *Electric & Hybrid Vehicle Technology '98* (Dorking: UK & International Press, 1998), 28-31.
10. B. Lane, Promoting Electric Vehicles in the United Kingdom: A Study of the Coventry Electric Vehicles Project, a case study for the project, Strategic Niche Management as a Tool for Transition to a Sustainable Transportation System (Milton Keynes: The Open University, 1998).
11. W. Blum, Editorial, *MobilE* Nr.3, 1994, 2 & 6.
12. Largely based on Simon 1998, Bleijs et al. 1998, and Carli 2000.
13. Based on S. Potter, Greening Transport for Disabled People. A Study of the Camden Community Transport's ASTI Project (Milton Keynes: The Open University, 1998), a case study for the EC DG-XII supported project Strategic Niche Management as a Tool for Transition to a Sustainable Transportation System.
14. A. Green and D. Charters, Camden ASTI Project: Electric and Natural Gas Fuels for Accessible Transport, *ASTI Technical Seminar* (Nuneaton: Motor Industry Research Association, 1996), 1.
15. The CCT coordinator, Ed Passant, had been active in debates over a number of strategic CT issues, and he was also an officer on the Executive of the national Community Transport Association (CTA).
16. PowerGen also had an interest in power control technology for EVs; after the start of ASTI, PowerGen acquired a 50 percent holding in Wavedriver.
17. V. J. Harvey, Community Transport for the Year 2000, *ASTI Technical Seminar* (Nuneaton: Motor Industry Research Association, 1996).
18. The delay led to inefficiencies in fleet utilization, as buses had to return to the depot for recharging whereas they could have been used for another service if a second recharging facility were available. The second recharging station was erected in 1997 in the south of Camden in addition to the station at the CCT depot in the north of the Borough.
19. Quoted in K. Claydon, ASTI Vehicles—Their Use in the Real World and User Acceptance, *ASTI Technical Seminar* (Nuneaton: Motor Industry Research Association, 1996).

20. Community Transport, Major New CT Project for London, *Community Transport* (Hyde, Cheshire: Community Transport Association, January 1996), 5.
21. This does not hold true for experimentation with technology that pose some kind of hazard, as for instance modern biotechnology does. In such circumstances experiments are often protested by people who fear experimental use will be followed by widespread application, before dangers are sufficiently known and addressed. In the past, the introduction of new technology often sparked protest from workers; nowadays the situation is different. A UK study on workplace industrial relations established that workers affected by technical change generally support its introduction, often strongly so, even to the extent that the introduction of new technology can act as a lubricant for less popular change in organization and working practices (W.W. Daniel and N. Millward (1993). Findings of the Workplace Industrial Relations Surveys, in J. Clark (ed.), *Human Resource Management and Technical Change,* Sage Publications Limited, London, 74-75).
22. *Wall Street Journal Europe*, Oct. 6, 2000.
23. For a discussion of transitions and transition management, see Rotmans et al. (2000).
24. Practical implications of the lessons of the 3 experiments and 10 other experiments studied in the EU project “Strategic Niche Management as a Tool for Transition towards a Sustainable Transportation System are described in the SNM workbook *Experimenting with Sustainable Transport Innovations. A workbook for Strategic Niche Management,* Seville/Enschede January 1999. See M. Weber, R. Hoogma, B. Lane and J. Schot (1999).
25. Rip and Kemp, 1998.
26. Kemp, Schot and Rip, 1998. The approaches are not mutually exclusive. Planning and policies that change the framing conditions will be *part* of the third approach, which is more inclusive. The distinction is not so much based on the instrument choice but on the management or governance philosophy.
27. Weber et al. 1999.
28. A discussion of the pros and cons of environmental policies and the circumstances in which they are best applied in offered in R. Kemp (2000), Technology and Environmental Policy: Innovation Effects of Past Policies and Suggestions for Improvement, in *Innovation and the Environment*, OECD, Paris.
29. A discussion of the pros and cons of different environmental policy instruments, especially the choice between the use of economic incentive and standards, is offered in Kemp (1997 and 2000), op cit.
30. Gary S. Lynn, Joseph G. Morone and Albert S. Paulson, Marketing and Discontinuous Innovation: The Probe and Learn Process, *California Management Journal* 38 (3), 1996.
31. Work of this nature is currently undertaken by Frank Geels, Peter Hofman and Boelie Elzen in two Dutch research projects: PRET and MATRIC.
32. The concept of transition agendas is described in Rotmans et al. (2000) and worked out for the case of an emission-low energy supply system.

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Assessment of European Initiatives to Reduce Fuel Consumption and CO_2 Emissions

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In 1998, the 15 member states of the European Union (EU15)emitted 3,328 million tonne CO_2 from anthropogenic sources (up 0.2 percent from 1990). The transport sector accounted for 28 percent of these emissions (up 15.3 percent from 1990). Per capita emissions fall in the range of 5.4 to 12.8 tonne compared to 20.6 tonne for the United States.

EUROPE AND THE KYOTO PROTOCOL

Under the Kyoto Protocol the European Union (EU) is committed to reduce its emissions of greenhouse gases by eight percent from 1990 levels by the period 2008 to 2012. The target covers emissions of six major greenhouse gases; this paper considers only carbon dioxide. The European Community is allowed under the Kyoto Protocol to redistribute its commitment among its 15 member states; it did so in a 1998 burden-sharing agreement. Some member states are allowed to increase emissions (by as much as 27 percent in the case of Portugal), while others are committed to reducing them (Germany and Luxembourg, by 21 and 28 percent respectively). Non-compliance by one or more member states will most likely have an impact on Community overall compliance. There is, as yet, no legal instrument that the Community can apply to a non-complying Member State. In a case of overall non-compliance, each Member State is obliged to meet the eight percent reduction target.

Only small amounts of fuels used in international aviation and maritime shipping are burnt in the air space and territorial waters of the country where the fuel was purchased. The Parties of the United Nations Framework Convention on Climate Change (UNFCCC) therefore decided to exclude emissions from such fuels from the national emission inventories. Instead, the International Maritime Organisation (IMO) and the International Civil Aviation Organization (ICAO), both UN bodies, were instructed to analyze ways to reduce carbon emissions from these fuels. For this reason, CO_2 emissions from aviation and maritime shipping in this paper are treated separately from emissions from land-based sources.

CURRENT TRANSPORT TRENDS AND CO_2 EMISSIONS

Between 1970 and 1997 demand for passenger transport in the EU grew faster than GDP. Passenger kilometers more than doubled, the average growth rate was 2.8 percent (Eurostat, 2000). Tonne kilometers of freight transport almost doubled, growing at an annual rate of 2.6 percent, which was slightly higher than that of GDP (2.5 percent).

During this period, cars and aviation gained mode share at the expense of rail, public transport, cycling, and walking. Motorized road passenger transport increased from 78.7 percent of the market in 1970 to 83.2 percent in 1995. Freight transport by road and short sea shipping increased by around five and two percent respectively per year. Rail lost not only market share (from 21 percent to less than nine percent), but also absolute quantity of freight moved (declining at about one percent per year).

The total final energy demand for transport rose from 850 to 970 million tonne oil equivalent (Mtoe) between 1985 and 1997 (+14 percent). The difference between growth in transport volumes and in energy demand was particularly marked in aviation but also large in road and sea transport. Rail, on the other hand, increased its energy demand despite continuing electrification of the network and diminishing demand for its services. Inland navigation experienced a large decline in energy efficiency if the Commission's figures are correct (Eurostat, 2000).

CO_2 emissions in the years 1985 and 1997 by sector in the EU15 are shown in Table 1. In 1997 transport was responsible for 27.5 percent of the emissions of carbon dioxide in EU15.[1] The transport share is rapidly increasing, approaching 40 percent in some member states. The 24 percent reduction for rail in Table 1 is an effect of electrification, as the resulting emissions from power stations are not reflected in the figures. The rail sector's overall demand for energy rose as previously mentioned.

There is no official forecast for transport growth in EU15. However, in a consultants' study for the European Commission (DG Environment) used the PRIMES model to establish baseline levels for 2010. Table 2 shows the results without including the possible effects of the CO_2 abatement agreement between the motor industry and the European Commission.

The PRIMES model was also used by the European Commission (1999a) in its *European Union Energy Outlook to 2020*. Motorized passenger transport was projected to increase by 1.6 percent per annum between 1995 and 2020 (equal to +48 percent), the fastest growth being in aviation and rail. The model assumes that future growth will be constrained by several factors. The most important assumption is the growth in average speed of travel will be limited by technological and safety considerations as well as congestion. Travel distance per capita is assumed to be limited to an increase of 1.4 percent per annum despite a growth in per capita income of nearly two percent. Rail is projected to grow considerably faster as a result of faster trains, large infrastructure investments, and improved connections between major European cities.

TABLE 1 Transport CO_2 Emissions in EU15 in 1985 and 1997 According to Eurostat Estimates

	CO_2 emissions in million tonne			Percent of total CO_2 emissions		
Transport Sector	1985	1997	Percent Change	1985	1997	Percent Change
Road	501.0	706.0	+40.9	16.8	23.1	+6.3
Rail *	11.1	8.4	-24.3	0.4	0.3	-0.1
Inland navigation	13.3	20.1	+51.1	0.4	0.7	+0.3
Aviation	62.5	106.8	+70.9	2.1	3.5	+1.4
Total transport	587.9	841.3	+43.1	19.7	27.5	+7.8
All sectors	2,984.3	3,059.3	+2.5	100.0	100.0	

* Emissions from electricity production not included.

Emissions from short sea shipping not included (no figures given by Eurostat).

SOURCE: Eurostat (2000).

TABLE 2 Baseline Trends in CO_2 Emissions from Transport in EU15

Transport Sector	1990 emissions	Estimated Baseline 2010	Change 1990-2010	Change in specific fuel consumption
	Mt CO_2	Mt CO_2	percent change	percent change
Passenger				
Cars	367	479	31	-2
Motorcycles	7	8	14	-6
Trains[1]	7	1	-89	-26
Buses	27	29	7	0
Aviation[2]	82	153	87	-27
Navigation[3]	11	14	24	-4
Total passenger	500	683	37	
Freight				
Trucks	222	296	33	-9
Trains[1]	2	1	-62	-20
Navigation	9	13	40	-4
Total freight	233	310	33	
Total (all)	734	993	35	

1. The reduction is mainly due to a continuing shift from diesel to electric trains.
2. Air passenger transport also includes airfreight. Figures include domestic and international aviation.
3. Not including international maritime transport.

SOURCE: AEA (2000) based on PRIMES.

Freight transport is also projected to grow annually by 1.6 percent. A large shift from road to rail is assumed to occur between 1995 and 2020. The consultants responsible for the PRIMES model and the Commission's services expect that rail will move from 17.5 to 23.1 percent of total tonne kilometers produced, while road transport will lose a similar share of the market. However, they provide no evidence to support their prediction, which contradicts current trends and would take place in an environment where heavy or bulky low value goods (which are a natural market for rail freight) make up a shrinking part of all goods and services.

The report does not anticipate any market penetration by non-fossil road fuels before 2020. Transport CO_2 emissions are thus projected to grow at the rate of energy demand and reach 40 percent over their 1990 level.

TAXATION OF FOSSIL FUELS IN EUROPE

In Europe, taxation of transport fuels in most member states applies only to road fuels. Fuel used by trains and commercial ships, barges, and aircraft are, with a few exceptions, excluded from fuel and electricity tax.

Table 3 shows the current excise duties on gasoline and diesel in the 15 member states as well as the EU minimum rate. The table shows a large variation. The United Kingdom is the only Member State that taxes diesel on a level with gasoline. In most member states the diesel tax is approximately two-thirds of the gasoline tax. Taking the difference in carbon content per litre of fuel into consideration, each kilo of CO_2 emitted from gasoline is taxed around 65 percent higher than the same amount emitted from diesel fuel.

According to the Mineral Oil Directive (92/81/EEC), alternative fuels should be taxed in line with the mineral fuel that they substitute. However, there is a provision under Article 8(4) whereby member states can seek the approval of the Commission and the Council to depart from the general rules in certain circumstances. Under this provision most member states have been authorized to apply lower tax rates on road fuels used for public transport. Electricity and diesel oil used by trains are only subject to taxation in a few member states. Some member states have also used this provision to exempt biofuels from taxation. The rule here is that such fuels should only be exempt from tax or enjoy reduced rates when produced under pilot programs. In some cases, however, zero rates have been applied for longer periods.

Harmonized energy taxes have been discussed for more than a decade by the EU. The Council has turned down several proposals for carbon and energy taxation. In 1997, the Commission presented a proposal for a new Directive on energy product taxes, which included a step-wise increase in the minimum excise duties. The taxes on gasoline and diesel would according to the proposal reach 500 and 393 Euro per 1,000 liters respectively in 2002 (European Commission, 1997). However, the Council of Finance Ministers (ECOFIN) has not been able to come to an agreement on this Directive.

Sales and Annual Vehicle Taxes

Ten of the current 15 member states enforce an excise duty on car sales and they all have differing systems of taxation. Most of them, however, have differentiated their taxes for differences in fuel consumption or factors that indirectly affect fuel consumption (such as cylinder capacity, power rating, and vehicle weight). Some use progressive rates. The sales or

TABLE 3 Current Excise Duties on Road Fuels in Member States of the EU

Country	Gasoline[1]	Diesel	VAT percent
Austria	408	283	20.0
Belgium	507[2]	290	21.0
Denmark	524	367[3]	25.0
Finland	552[4]	300[4]	22.0
France	571	374	19.6
Germany	593	409	16.0
Greece	297	245	18.0
Ireland	348	249	20.0
Italy	520	382	20.0
Luxembourg	372	253	15.0
Netherlands	402[5]	339[3,5]	19.0
Portugal	289	246	17.0
Spain	372	270	16.0
Sweden	528[6]	356[6]	25.0
United Kingdom	765[3]	765[3]	17.5
EU minimum rate	287	245	

1. Ordinary gasoline. High-octane blends are taxed higher in some member states.
2. Including energy charge.
3. Low sulfur.
4. Environment friendly.
5. Including “environmental fuel charge.”
6. Environmental Class 1.

NOTE: Euro per 1,000 liters; 1 Euro = 0.91 USD (August 30, 2001)

SOURCE: European Commission, DG Taxation (status July 2001) registration taxes are generally rather low (Greece and Denmark being exceptions), and therefore they have limited influence on the average specific fuel consumption of new cars.

All member states tax cars in use. The annual vehicle tax is often based on power rating, cylinder capacity, weight, or even fuel consumption or CO_2 emissions (Denmark, the UK, and to a certain extent Austria). The rates, however, are generally too low to significantly influence vehicle choice.

Sales and annual vehicle taxes may also have to be used for purposes other than improved fuel efficiency. Germany, for instance, has differentiated its annual vehicle tax for exhaust emissions with differing tax levels for cars meeting the requirements of the different existing and future EU emission standards. In addition, however, Germany grants cars that travel 100 km on three liters of fuel a total exemption from vehicle tax up to December 31, 2005, or to the point when the accumulated exemption reaches DM1,000 (Bundesministerium für Verkehr, 1998).

EU STRATEGY ON CLIMATE CHANGE

Where CO_2 emission abatement is concerned, the current European transport and environment policy is a patchwork. Fuel excise duties—levied at rates varying from €0 to 330 a tonne of CO_2—are supplemented by a variety of subsidies and tax exemptions for biofuels. In addition, a shift to rail and intermodal transport is encouraged.

In its Green Paper[2] on emissions trading the European Commission (DG Environment) strongly favored supplementing existing energy taxes with tradable CO_2 permits (European Commission, 2000b). The emphasis is on cost-efficiency. A year later the Commission presented a formal proposal for a European CO_2 trading scheme to enter into effect by 2005. This scheme would cover CO_2 emissions from power production, energy intensive industries, and large heat production plants. Fuels used in transport would not be included (European Commission, 2001c).

In the European Commission's recent Green Paper on a European strategy for the security of energy supply, issued by the Directorate General for Transport and Energy (DG TREN) in November 2000 (European Commission, 2000c), the message is different. This Green Paper provides a picture of what could be expected in terms of common policies in the absence of emissions trading. It emphasizes the importance of ensuring a growing market share for biofuels, "despite their high production costs" (p. 48). DG TREN's Green Paper calls for extended and harmonized tax breaks for biofuels in order to close the current price gap with competing products. The Green Paper on energy supply also highlights the importance from a CO_2 abatement point of view of re-balancing the modal split, but it does not say how this would be done. DG TREN's Green Paper does not discuss the cost-effectiveness of its abatement strategy and, surprisingly, does not mention that DG Environment launched a Green Paper on greenhouse gas emissions trading less than six months earlier (European Commission, 2000b).

Shift from Road to Rail

Policy documents from the Commission and the Transport Council often highlight the need to shift freight transport from road back to rail and multi-modal road and rail transport. The Community has launched a program for "revitalising Europe's railways," which includes a strategy for gradually opening the rail market to competition. In a White Paper on transport, launched in September 2001, the European Commission (2001b) comes back again to the issue of re-balancing modal split. It says infrastructure investments should be redirected to give priority to railways, and that all modes, starting with road transport, should internalise their externalities.

Mandatory Introduction of Alternative Road Fuels

Fossil fuels other than diesel and gasoline in road transport, kerosene in aviation, and middle distillates and heavy fuel oils in maritime shipping currently account for less than one percent of European transport fuel demand. Most of this is liquefied petroleum gas (LPG) (2.9 Mtoe in EU15 in 1997) and natural gas (0.3 Mtoe) used in road transport. These two combined equal 1.3 percent of the energy consumption in road transport (Eurostat, 2000a)

Ethanol and RME (rapeseed methyl ester) are currently the two most important biofuels used in European road transport. They are mostly used in low-blends with, respectively, gasoline and diesel. Quantified targets for renewable energy in the EU were set within the context of the ALTENER R&D program. The goals include a five percent market share for biofuels of total motor vehicle fuel consumption by 2005. In a more recent White Paper on renewable energy the European Commission (1997b) sets the target for 2010 at 18 Mtoe, compared to 0.5 Mtoe in 1995. The European Biomass Association (1998) thinks 11 Mtoe is more realistic.

In November 2001, the European Commission (2001e) proposed that alternative fuels (natural gas and hydrogen included) should make up 20 percent of the market for road fuels in 2020. Introduction of biofuels such as ethanol and RME should be given priority in a first phase. To promote an early introduction of biofuels, the Commission proposes that all member states should be committed to reach 2 percent in 2005 and 5.75 percent in 2010. To make this happen they would be allowed to apply reduced rates of excise duties on biofuels as well as on gasoline and diesel containing biofuels. However, the level of taxation of these products may not be lower than 50 percent of the normal rate of excise duty applied on a corresponding motor fuel.

Improved Specific Fuel Efficiency

The Commission’s abatement strategy is to a large extent based on the hope of improving the specific fuel efficiency of different types of vehicles. And indeed, the efficiency of most types of vehicles has improved significantly in the past few decades. This trend is expected to continue for the foreseeable future, even without government intervention, and in some cases even become stronger. The European Commission (1999b) believes that transport CO_2 emissions could be cut at low cost (less than €5 per tonne CO_2) by as much as 80 million tonnes below the baseline level predicted for 2010. An additional 70 million tonnes could be reduced at “medium cost” (€5 to 50 per tonne).

Voluntary Agreements with the Automotive Industry

Where passenger cars are concerned, the average fuel consumption of new cars stayed stable between 1985 and 1995 and has since declined by 6 percent. The decline, however, is to some extent the result of a shift to diesel powered cars. Without the increases in weight, engine size, and power rating since 1983 the average new passenger car would in 1997 have been around 20 percent more fuel efficient, according to the European Automobile Manufacturers Association, ACEA (cited in Keay-Bright, 2000).

In 1995, the European Council approved a Community Strategy to reduce CO_2 emissions from passenger cars (Council Conclusions 25/06/95). The Council foresees three interrelated policies which taken together would reduce CO_2 emissions to an average level of 120 g/km for newly registered cars. The three elements are

- A voluntary agreement with the car manufacturers to "commit the industry to make the major contribution" to the 120 g/km average standard and a related monitoring system for identifying the CO_2 emissions from newly registered cars;
- A CO_2 information and labelling scheme directed at consumers; and
- An increase in the use of fiscal instruments, both applied to fuels and to the fuel efficiency of vehicles.

The European Commission, however, failed to convince the automotive industry that 120 g/km can be reached in the foreseeable future. Instead, the European Commission and the European car industry represented by the ACEA in July 1998 finally reached an agreement on the reduction of CO_2 emissions from cars. In this agreement, ACEA commits itself to achieve the following:

- An average CO_2 emissions figure of 140 g/km by 2008 for all its new cars sold in the EU, as measured according to the EU's test procedure (Directive 93/116/EC);
- Bring to the market individual car models with CO_2 emissions of 120 g/km or less by 2000;
- An indicative intermediate target in the order of 165 to 170 g/km in 2003 as the basis for monitoring progress. ACEA underlines that this "does not constitute a commitment of any kind"; and
- Review the potential for additional improvements with a view to moving the new car fleet average further towards 120 g/km by 2012. This review will be undertaken in 2003.

The commitment is not legally binding. ACEA, however, has already fulfilled the second and the third of these commitments.

The European Commission later concluded agreements on CO_2 emissions from cars with the Japan Automobile Manufacturers Association (JAMA) and the Korean Automobile Manufacturers Association (KAMA) for their sales in the EU. JAMA and KAMA promise to meet the target value of 140g CO_2/km one year later (i.e., by 2009). The agreement with ACEA covers American-made cars as all major U.S. manufacturers have European subsidiaries.

Neither ACEA, JAMA, nor KAMA have made any decision on how the burden is to be shared among its members. The fact that they want to avoid a burden-sharing agreement means that each company is in effect committed to the same target—but in absolute or percentage terms? If the first is true it is obviously far easier for some manufacturers than for others. Keay-Bright's (2000) interviews with car manufacturers show that producers of large cars advocate a percentage target while manufacturers of small cars prefer an absolute target. The latter also argue that producers of larger than average cars, which generally yield greater profits, would be able to pass on the extra cost for advanced technology to consumers more easily.

Continuing "dieselisation" and a broad introduction of direct fuel injection in gasoline engines are important parts of the car industry's fuel efficiency strategy.[3] Currently only around one percent of new cars sold on the European market have direct injection gasoline engines.

Altering production to direct injection does not require entirely new engines. A different fuel injection system and some minor modifications of the engine are all that is needed. From a production point of view it would thus be feasible to carry out a major shift to direct injection over the next few years. However, for this to happen “zero-sulfur” gasoline must become available in all major markets. Down-sizing is not an element in the motor industry’s strategy.

In a communication to the European Council and Parliament on the implementation, the European Commission (2001d) reports that the specific CO_2 emissions from new cars in EU15 fell by 7.5 percent between 1995 and 2000. The details are provided in Table 4. Average emissions are weighted for sales.

Under the assumption that the automobile manufacturer associations continue average annual reduction rates in the same range as in the first reporting period, ACEA would meet the 2003/2004 intermediate target (165 to 170g), JAMA would be slightly above (i.e., would fail to meet the target) and KAMA significantly above. In order to meet the final target the annual reduction rate must be better 2 percent reduction per year. Up to the end of 2000, ACEA had achieved on average about 1.7 percent, JAMA 1.3 percent, and KAMA 0.6 percent per year (European Commission, 2001d). In order to meet the target of 140g/km in 2008, ACEA must achieve an annual average reduction rate of 2.1 percent.[4]

For all three associations, the CO_2 emissions reductions since 1995 for diesel cars have been considerably faster than for gasoline cars. In addition, the diesel segment has increased its share of total sales from 22 to 33 percent. For cars produced by ACEA members the average car mass and engine power increased by 7.9 and 14.3 percent respectively over the reporting period (ACEA, 2001).

Alternatively fuelled vehicles account for only 0.14 percent of the sales of ACEA members—or 17,283 cars in 2000 (down from 20,559 in 1998). Dual-fuelled cars are generally registered as gasoline or diesel cars (ACEA, 2001).

The motor industry claims it can fulfil its commitment to the EU without the incentive of higher fuel prices or a differentiated sales tax. For market acceptance the industry must then be able to keep incremental capital costs within a range where motorists would be fully compensated by lower running costs. The commitment by the motor industry is equal to a reduction in fuel intensity of close to 25 percent. A study by IEA (2000a) confirms that “available near-term ‘conventional’ technologies could be employed to reduce fuel intensity by as much as 25 percent in a cost-effective manner at current fuel prices” (p. 22). On the other hand, AEA (2000) believes that several of the technical measures identified by the motor industry would cost a great deal more than what is cost-effective at today’s fuel prices (including taxes).

TABLE 4 Average Percent Change Between 1995 and 2000 in Specific Fuel Consumption of New Passenger Cars in EU15 by Type of Fuel and Producer Association

	Manufacturers’ Association			All passenger cars
Fuel Type	ACEA	JAMA	KAMA	
Gasoline	-5.9	-7.3	-5.1	-5.8
Diesel	-10.8	-10.9	-20.7	-8.9
All fuels	-8.6	-6.6	-3.0	-7.5

SOURCE: European Commission (2001d).

Aviation Industry

Most aviation emission scenarios prior to September 11, 2001, take a figure of four to five percent for long-term growth of air transport and one to two percent for annual efficiency improvement (WEC, 1998, and IPCC, 1999). This indicates that based on "business-as-usual," CO_2 emissions from civil aviation will in the foreseeable future rise by two to four percent per annum.

The idea of a voluntary agreement between the EU and the aviation industry was abandoned when the Association of European Airlines (AEA) turned down a proposal from the European Commission suggesting that the target should be based on a four to five percent annual improvement. The AEA said that the projected 1.1 percent annual reduction of CO_2 emissions between 2000 and 2012 was itself "ambitious" and involved early aircraft replacements (ENDS Daily, 1.12.1999, and 7.1.2000).

The European Commission (2000d) says in its strategy on air transport and the environment that the European Community may introduce its own system of charges if no agreement can be achieved by the end of 2001 on a global system for aviation taxation. In September 2000, the European Parliament adopted a report in response to the Commission's communication calling for a kerosene tax on all flight departures from the EU (ENDS Daily, 7.9.2000).

Decoupling Transport Growth from Economic Growth

For years, environmental NGOs have advocated the need for decoupling transport growth from economic growth. It is not always clear whether the use of this term refers to relative decoupling (meaning transport would grow but at a slower rate than GDP) or a reduction in absolute terms. In its 1999 report to the Helsinki Summit, the European Transport Council agreed to the idea of decoupling; in adopting guidelines for the formation of a revised Common Transport Policy in July 2001, the European Commission announced that the Community should develop a program to gradually decouple transport growth and economic growth (T&E Bulletin, August/September 2001).

CRITICAL ANALYSIS OF THE EUROPEAN STRATEGY

The use of fossil fuels in the transport sector can diminish, in principle, by four types of action:

- Lowering demand for transport services;
- Shifting from high to low energy-consuming modes of transport;
- Improving efficiency in road vehicles, trains, vessels and aircraft; and
- Shifting to renewable sources of energy.

Each of these is discussed below.

Transport Activity

As mentioned in an earlier section of this paper, transport demand has for decades increased at or above the GDP growth rate. The driving forces differ somewhat between passenger and freight transport. Research indicates that personal travel on average takes place within a time budget that stays almost constant over time (Schafer and Victor, 1997; Michaelis et al., 1996). The average citizen spends 60-70 minutes per day on mobility, just as he or she did 50 years ago. Higher average speed is thus what makes the increase in passenger transport possible. With growing net income we spend more money buying speed. Freight transport is growing as a result of GDP growth, structural change, European economic integration, and reduced cost per tonne-kilometer, (the latter in particular in road transport).

Considering the driving forces behind transport growth, politicians in Europe must either make transport slower or more costly if they are serious about reducing demand and delinking transport growth from economic growth. The only Member State that hitherto has made convincing use of taxes for this purpose is the United Kingdom. The British diesel tax is now twice as high as that of most other member states. Switzerland, who is not a member of the EU, introduced distance (per kilometer) charges on heavy goods vehicles starting from January 1, 2001. The level of the charge will gradually increase until the social costs are fully covered. Germany, Austria, and the Netherlands have declared their intention to shift to distance charging but nothing is yet known about the charge levels.

Measures that increase the price of fuel will have only a small affect on overall demand for transport. The long-term adaptation to a higher gasoline or diesel price would be to reduce specific energy consumption rather than distance driven. For cars, the long-term fuel price elasticity for distance per vehicle is approximately -0.20. The fuel-price elasticity for specific fuel consumption is a great deal higher (-0.30 to -0.40) (Jansson and Wall, 1994; Michaelis, 1996b; Johansson and Schipper, 1997).

Factors other than prices can potentially affect demand for transport. This is the case with physical planning, including land-use regulation, affecting, for instance, the establishment of shopping centres or the location of major working cites. Video conferencing has a high potential to replace travel to short meetings, especially in cases where the participants know each other well. The cost-effectiveness of this measure is not affected much by fuel prices. What makes video-conferencing economically viable is mainly that it raises productivity and may reduce overall travel costs. The same is true for consolidated distribution as well as computer-based logistics and communications systems, including mobile communications, electronic maps, and GPS used for improved routing and management of fleets of distribution vehicles and taxis. The use of such systems has begun in some European markets. For delivery trucks efficiency improvements in the range of 10 to 20 percent have been reported (Holman, 1996). Taxi Stockholm has reduced empty driving (mileage without passengers) by around 12 percent following the introduction of a GPS-based system for fleet management (personal communication, Bertil Leismark, Taxi Stockholm).

The size and weight limits of trucks are essential factors for limiting the number of vehicle km per million tonne km in the context of modal competition. Higher limits also mean fewer accidents and exhaust emissions and less fuel per tonne kilometre. Currently the European Community enforces a weight limit of 45 tonnes. Sweden enjoys an exemption that permits the country to allow trucks of 60 tonnes. The fact that higher limits would give road haulage a competitive advantage over rail does not necessarily mean that overall energy consumption would increase. The amount of goods that would shift to road would presumably be a great deal less than the quantity that would transfer from smaller to larger trucks as a result of the reform. A recent Dutch study indicates that permitting a gross vehicle weight of 60 tonnes would cut CO_2 emissions from road freight by about 1 percent with negligible impact on intermodal freight transport. The so-called rebound effect (lower prices resulting in larger transport volumes) would be more significant. This effect is expected to cut the initial emissions reduction of two percent by half (Dings and Klimbie, 2000).

Modal Split

Many factors influence individuals' and companies' choice of transport mode. Price is important, but so are time, quality, flexibility, and reliability. Most firms have transport costs that amount to two to three percent of their turnover. This means that they, in many cases, value other factors higher than small differences in transport cost. This is particularly true for high value goods, which are generally transported by truck (or by air) even though it could have been cheaper for the customer to use ships, trains, or inland waterways (Schipper, Scholl and Price, 1997). The future competitive position of different modes may also be affected by continuing deregulation (rail in particular) and improved enforcement of working hours and load limits in road haulage. Hauliers may, on the other hand, gain more from computer-based logistics and communications systems. Transport brokers have just started to use the Internet for establishing a spot market for empty space on trucks. This is likely to improve the average load factor. Railway wagons are less flexible than trucks and can be expected to have difficulties making use of this opportunity.

Given these circumstances, the European Commission's prediction (mentioned above) that rail will significantly improve its market position over the next few years appears to be wishful thinking. The Community's wish to see a shift back to rail seems to be based partly on incorrect assumptions. The Green Paper on energy supply states that "an average lorry generates six times more CO_2 per tonne/km than a train" (p. 54) without understanding that this figure reflects high CO_2 emissions from local distribution where rail is generally not an option. AEA et al. (2000), consulted by DG Environment, cites a Dutch study (IPM&ET, 1996), according to which switching freight from road to combined road-rail could be expected to reduce CO_2 emissions from container transport by 50 percent (based on current European Commission weight and length limits for trucks). One should also keep in mind that the marginal electricity production takes place in coal-fired condensing powers stations with efficiencies around 40 percent and a higher content of carbon per unit of energy than diesel fuel.

The EU has started a process aimed at internalizing the social costs of transport (European Commission, 1998c; High Level Group, 1999), and environmentalists sometimes believe that making transport pay its true costs would result in a major shift back to rail. However, Swedish and Dutch studies show that internalizing the remaining externalities of all modes (concerning infrastructure, accidents, emissions, noise, and climate change) would not change modal split significantly (Kågeson, 1998; Dings et al., 1999). The percentage increase in current prices would not differ much between modes. The only clear "winner" is the gasoline car, which already pays all or most of its social marginal costs. The Swedish study also indicates that short sea shipping could gain a competitive edge over rail provided that it makes use of some comparatively inexpensive methods for reducing its high emissions of sulfur and nitrogen oxides (Kågeson, 1998).

Efficiency

As mentioned above, the EU made considerable efforts in the late 1990s to make the motor industry agree to undertake its "voluntary" commitment on CO_2 emissions from new cars. It is still an open issue whether the motor industry will achieve the target. The chances that the members of JAMA and KAMA will be able to honour their commitment look bleak.

The available measures for reducing the average specific CO_2 emission from new cars can broadly be divided into five different categories (down-sizing not included):

1. Shift from gasoline to diesel cars;
2. Shift from traditional gasoline engines to indirect injection;
3. Introduce new powertrain technologies, such as hybrid electric and fuel cell cars;
4. Shift to low or zero carbon fuels; and
5. Apply improvements that can be made regardless of powertrain—for example, reduce body weight, reduce air and rolling resistance, shift 42 volt electrical systems which will allow integrated starter-generator systems, variable valve-timing, and continuously variable transmission.

By analyzing current market trends, manufacturers' intentions and the opportunities for production and market entries, Kågeson (2000) concluded that continued "dieselization" could make diesel cars reach 35 percent of new sales in 2008 and that all new diesels would be of the common rail type. However, as shown in Table 5, ACEA's diesel share took a giant leap in the year 2000, reaching 37 percent. This clearly indicates that the diesel share for EU15 might be considerably above 35 percent in 2008. ACEA's share of the European market is dominant (85 percent of overall sales in 1999).

Kågeson (2000) assumed that 30 percent of new gasoline cars would be equipped with indirect injection engines in 2008. This may also turn out to be a conservative estimate. However, if the direct injection gasoline engine is to make a substantial contribution to the CO_2 target, the motor industry has to find a way to reduce its high emissions of nitrogen oxides. A de-NOx catalyst that can replace the current arrangement for NOx-reduction requires access to low-sulfur gasoline. ACEA has made the agreement with the EU conditional on a number of external factors that, according to the association, could impact its ability to honor its commitments. Among them is the availability of low sulfur gasoline in all European markets. Kågeson further assumed that electric hybrids would make up at best 5 percent of all new sales in 2008. This estimate could prove to be a too high as the contribution from hybrids (and fuel cell cars) to the CO_2 target depends not only on production capacity but also on price and market acceptance. The Toyota Prius currently sells in the price range €22,000 to 24,000, a figure that (although it may represent some subsidy by the manufacturers) is too high to be counter- balanced by the

TABLE 5 Trends in Diesel Share of Fleet Composition

Year	ACEA (%)	JAMA	KAMA	EU15
1995	24.0	9.5	1.6	22.2
1996	24.3	10.4	1.8	22.4
1997	24.3	11.2	2.4	22.3
1998	27.0	13.1	6.1	24.7
1999	31.0	14.9	7.4	28.4
2000	37.0	16.5	8.3	32.6
Share of total European sales in 1999 (%)	85.2	11.7	3.1	100.0

SOURCE: European Commission (2001d)

lower running cost. Kågeson did not expect that the introduction of low carbon fuels would contribute significantly to the CO_2 target.

Based on Kågeson's assumptions the four first categories of efficiency improvement listed above combined would contribute somewhat less than 50 percent of the reduction needed for achieving the target in 2008. This would leave more than half of the job to the fifth category, general efficiency improvements. Given the fact that the diesel share is currently growing considerably faster than anticipated, something on the order of 35 to 40 percent might in the end have to be achieved by general efficiency improvements. This would be feasible from a technological point of view. The real challenge, however, is to make customers give priority to fuel efficiency in a situation where the trend towards bigger and more powerful cars could be expected to continue. In some European markets there is now a trend towards increased sales of minivans and sport utility vehicles though market shares are generally still in the range of six to 10 percent.

The car manufacturing industry appears to be aware of this problem. A study by ACEA (no exact reference made at ACEA's website) concludes that nearly half of the total potential gains that are feasible by 2005 will be offset by regulations on safety, emissions, noise, and anticipated customer demands. Kågeson's conclusion is that the industry will need the help of market incentives and disincentives to be able to reach the 140g/km target (Kågeson, 2000).

Mandatory introduction and use of CO_2 labels on cars displayed for sale and information on fuel consumption in marketing cannot be expected to make much difference. The experience in Sweden and the UK, where such schemes have been in operation for around 20 years, is not promising. The power rating of new cars has increased faster in these countries than in any other Member State. Today Sweden has the heaviest, most fuel-consuming car fleet in Europe.

From the above it is evident that the success of the agreements with the European, Japanese, and Korean car industries is not yet guaranteed. It should also be underlined that these agreements were not even intended to meet the Community's 120 g/km target.

As mentioned above, the European Council's 1995 Community Strategy to reduce CO_2 emissions from passenger cars included economic incentives for low-consuming vehicles. However, the issue of policy instruments for reducing the specific carbon emissions from cars has been discussed for about a decade without resulting in legislation. The Commission was required under Directive 91/441 to put forward proposals for an instrument to control carbon dioxide emissions from cars, originally with a deadline of 1992. After having turned down numerous proposals, the Commission's Motor Vehicle Emissions Group (MVEG) finally agreed that a graduated sales tax based on CO_2 emissions would be preferable. A common tax, however, cannot be adopted and enforced unless unanimously approved by member states, which in this case proved impossible.

The UK's Department of Transport proposed a system of tradable credits (Fendick and Taylor, 1991) to MVEG in 1992. The idea was to provide each new car with official CO_2 emissions credits corresponding to the average permissible specific emission in that particular year. The average emission value would then be gradually tightened to reflect steps on the route to a long-term objective. For cars achieving a better fuel efficiency than required, manufacturers would be free to sell their surplus credits to those who did not meet the standard. To prevent manufacturers from withholding credits from sale to competitors, part of the credits would be reserved for an EU authority, which would auction them and return the revenue to the original owners.

Critics (e.g., Fergusson and Holman, 1992) feared that the British proposal might never make it due to market resistance and that the credits reserved for auction would not be enough to prevent a market failure. Kågeson (1992) responded by suggesting that all "free" credits should be banked automatically with the EU authority when the car was first registered. These credits would then be sold at weekly or monthly auctions, where all manufacturers and importers needing extra credits would have to compete. The revenue from the sales could be divided equally on all credits sold during a certain period in order to avoid short-term fluctuations in the revenue received by the companies who earned the credits. To prevent manufacturers from withholding credits bought at auction it would be sufficient to rule that such credits must be used within three (or four) months from the day of purchase or otherwise sold back to the authority.

In recent years focus has shifted towards a differentiated sales tax. Such a tax would have the advantage over annual vehicle taxes of providing a stronger incentive at the time of purchase (all else equal). A reason why some member states refrain from levying a sales or registration tax is that they want to avoid hampering the renewal of the car fleet. In a situation when new cars are expected to become much cleaner and less fuel-consuming it is essential not to use taxes that make it more expensive to buy a new vehicle. The conflict can be avoided if the tax is constructed as a fee on high-consuming models and a rebate on low-consuming models ("feebate" in American jargon). If well done, this means the system would not put any tax burden on the average new car.

IEA (2000b) takes an optimistic view when assuming that a purchase tax that rises by U.S.$ 250 for each litre per 100 km increase in rated fuel consumption would provide a price signal as strong as a fuel tax increase of U.S.$ 0.20-0.25 per litre. The United States currently employs a 10 percent tax credit for electric and fuel cell cars up to a U.S.$ 4,000 cap and the government proposes a new U.S.$ 1,000 tax credit for qualifying hybrid vehicles. Japan already provides a price incentive of about U.S.$ 3,500 per vehicle for hybrid-electric vehicles (IEA, 2000b).

To really influence choice there must presumably be a considerable differentiation of the fee and the rebate. It could be calculated as a certain fee on each gram of CO_2/km that exceeds a baseline value, which is lowered year after year until it reaches 140g/km in 2008. To do the job, the rate of the fee on emissions above the baseline would probably have to be in the order €100 to 200 per g CO_2/km. If the baseline is, say, 170g in 2003, a car emitting 180g would then be taxed €1,000 to 2,000. A real "gas guzzler" (emitting, say, 240g/km) would be charged between €7,000 and 14,000. A car emitting 140g/km, on the other hand, would earn a rebate of €3,000 to 6,000.

However, choosing a linear system of increasing taxation is not self-evident, the reason being that the price of cars does not increase linearly with fuel consumption. In essence this means that the rebate earned by a car that emits 160g (when the baseline is 170) is equivalent to a higher share of the purchase price than the fee paid by a vehicle that emits 180g. The net effect of this is that the tax becomes progressively less effective with increasing fuel consumption since it forms a smaller proportion of the total purchase price (DRI, 1995). To make the scheme effective, a non-linear scale of increase is needed.

At a workshop in 1998 (prior to the agreement with the automotive industry) the Commission presented a discussion paper containing different options for regulating vehicle fuel economy (European Commission, 1998d). The Commission's assessment presented fee-bates, economic incentives and tradable credits having the potential to significantly improve the cost effectiveness of regulation compared to binding limit values. A few weeks later the Commission presented a second discussion paper showing that the potential economic savings of tradable credits could be in the order of €300 to 800 million annually (European Commission, 1998b).

A system of tradable emissions credits is the only policy instrument that can guarantee the achievement of a certain target as it is based on a cap. It is neither exclusively regulatory nor truly fiscal in nature and could be regarded as an extension of a CAFE-style system.

Rebound Effect

The fact that most member states (the UK being the only exemption) tax diesel fuel far less than gasoline means that a further shift from gasoline to diesel engines will affect real consumption less than would have been the case under equal taxation. Having access to a cheaper fuel, owners of diesel cars tend to drive farther. An important conclusion, then, is that fossil road fuels should be taxed according to their content of carbon. This means taxing diesel fuel 13 percent above petrol as diesel contains more carbon per litre of fuel.

The rebound-effect from lower specific fuel consumption on total mileage and annual fuel demand needs also to be considered. To counter-balance this effect the tax on diesel and gasoline needs to be raised annually by around 20 percent of the rate of fuel efficiency improvement. When the specific fuel consumption declines by 1 percent, the fuel tax must be raised by 0.2 percent.

Negative Side-Effects of Diesel and Direct Injected Gasoline Engines

As mentioned in a previous section, the strategy of the motor industry is based on a major shift to diesel engines and direct injected gasoline engines is the single-most important part of the motor industry’s carbon abatement strategy. This strategy, however, has some negative side effects that may force the Community or individual member states to react. Both types of engine emit substantially more nitrogen oxides (NOx) and particles than conventional gasoline engines. The emission limits for diesel cars that come into force in 2005 will narrow the gap for particles. For gasoline cars there is no limit value as they have traditionally been known to emit much fewer particles than diesel cars. Direct injected gasoline cars, however, have been shown to give rise to nearly as many small particles as the cleanest diesel cars (Färnlund et al, 2001). A growing share of diesel and direct injected gasoline cars may make it difficult for some European cities to comply with the Community’s air quality standard for PM10.

Efficiency of Large Trucks

The specific energy efficiency of large trucks has improved by approximately 20 percent since 1970 (U.S. Department of Transportation, 2000). In a report for the European Commission, AEA Technology Environment et al. (2000) estimate the technological potential for reducing emissions from new trucks in 2010 to be around 9 percent. However, the European Union has shown no interest in making the motor industry agree to a commitment on the future fuel efficiency of heavy-duty vehicles.

Other Efficiency Issues

There has been limited interest in the Community for improving network efficiencies, for instance through optimized traffic speeds and reduced congestion. Congested traffic lowers vehicle efficiency. Fuel consumption may exceed that of driving at 50 km/h by four to five times (Henke, 1999). The European Commission has identified congestion pricing as an important element in a policy for sustainable transport, but no city or Member State has yet decided on the introduction of such a scheme.

There is, however, a growing interest among member states to improve the energy efficiency of vehicles in operation by training car, bus, and truck drivers to drive in an economic way. Training drivers in "EcoDriving" in Finland and Sweden has resulted in long-term fuel efficiency improvements in the range of five to 15 percent (Jochim Donner, MOTIVA, personal communication, and Trivector, 1999). A higher fuel price, however, would extend the profitability of such training to drivers with fewer hours behind the wheel. Under Swedish conditions the limit for profitability currently lies at approximately 13,000 km for drivers of diesel cars and 19,000 km for gasoline cars (the positive effect of reduced wear not included). Training drivers of buses and trucks always pays off as they drive very long annual distances in high-consuming vehicles (Kågeson, 2001).

Fuel consumption in road vehicles is highly related to speed. Cars are generally fuel optimized for speeds between 50 and 70 km/h. Running the car at constant speed at 120 km/h instead of 100 km/h increases fuel consumption by 15 to 20 percent (MTC, 1991). The European Commission (1998a) estimates the potential for reducing road fuel consumption by stricter speed limits and improved enforcement to 5 percent. Speed limiters are currently mandatory in heavy-duty vehicles. Extending them to light-duty vehicles and cars would increase the potential for reducing specific energy consumption in highway traffic.

Efficiency of Trains

Where the fuel efficiency of trains is concerned the EU has largely been inactive. Rail transport enjoys exemptions from fuel and electricity taxes which means it lacks a strong incentive to become more efficient.

Rail in EU15 increased its final energy consumption by 8.6 percent between 1985 and 1997 despite a rapid shift from diesel locomotives to electric trains and falling production figures for rail freight (passenger transport by rail rose by 8 percent). This is a surprisingly bad record that can only partly be explained by structural change.

Despite the disappointing historical record, the potential for energy efficiency improvements in the rail sector appears to be large. Several experts report potentials in the 20 to 25 percent range in 20 years time (AEA et al., 1998; Andersson, 1998; Michaelis et al., 1996). The energy efficiency of trains can be improved in many ways.

It can be questioned whether electrification of rail transport has really contributed to an improved overall energy efficiency. The marginal base load production of electricity is based on coal-fired condensing power in almost all of Europe. This means that the well-to-wheels efficiency for diesel trains and electric trains is about the same and that life cycle carbon emissions are higher from electric trains (due to higher carbon content of coal per unit of energy).

Some experts believe that fuel cells will become economically viable in trains before they become affordable in road applications (European Commission, 1999a; DeCicco, 2001). Diesel locomotives already use electric drive, powered by diesel generators, which means much of the electric drive costs are already part of the existing package (in contrast to road vehicles). A shift from diesel to fuel cells would raise the CO_2 efficiency of the propulsion system by around 25 percent and make further electrification of non-electrified railway lines not only unnecessary but also meaningless from an energy-efficiency point of view.

Fuel Choice

As yet a very limited amount of biofuels is used in European road transport. Bio-alcohol such as ethanol and methanol produced from agricultural products or wood residuals can—despite agricultural subsidies—only compete with fossil road fuels when they are exempted from tax.

What is often overlooked when assessing road fuels produced from biomass is the amount of primary energy consumed in the conversion. Life cycle analysis generally limits the comparison between traditional and new fuels to the amount of fossil CO_2 emitted from well to wheel. Biomass, however, is a scarce resource, which must be well utilised in order to contribute significantly to the abatement of greenhouse gases. The “World Energy Assessment” (UNDEP et al., 2000) has compiled existing data on net energy efficiency of conversion for the production of different road fuels from biomass. The results for conversion of lignocellulosic biomass are summarised in Table 6. Conversion of agricultural crops generally has lower conversion rates than those presented in the table. For instance, producing ethanol from sugar beet and sugar cane has net energy efficiency rates of only 50 and 44 percent respectively.

European biomass supplies will not suffice for heating, combined heat and power production, and production of biofuels for road transport. Based on an assessment of ten earlier studies, Hall and House (1995) calculated the long-term potential for Western Europe to fall into the 211–317 Mtoe per annum range. According to the European Biomass Association (1999), the heat market accounted for approximately 628 Mtoe percent of the primary energy demand in 1995. The current demand for low-temperature heat (382 Mtoe) alone is larger than the maximum future production of bioenergy.

TABLE 6 Net Energy Efficiency of Conversion of Lignocellulosic Biomass into Different Types of Road Fuel

Biofuel option	Ethanol	Hydrogen	Methanol	Bio-oil
Concept	Hydrolysis, fermentation and electricity production	Gasification	Gasification	Glash pyrolysis
Net energy efficiency short term, percent	—	55 to 65	50 to 60	70 (raw bio-oil)
Net energy efficiency long term, percent	60 to 70, incl. power and heat generation	60 to 70	60 to 70	—

SOURCE: UNDEP et al. (2000), based on a large number of primary sources.

From Table 6 it is evident that producing liquid road fuels from biomass is associated with a loss of primary energy in the range of 30 to 40 percent. This is ten times the loss of primary energy induced from producing wood chips or pellets from forest residuals. From an efficiency point of view it appears reasonable to produce liquid fuels from biomass only when the demand for wood chips and pellets has been satisfied. The most energy efficient way of using lignocellulosic biomass is for heating homes and in Combined Heat and Power (CHP) production.

Given that the production of liquid biofuels is currently around three times more expensive than conventional road fuels (European Commission, 1997b), it is by no means obvious that the EU and its member states should subsidize production of such fuels. Net energy efficiency is a great deal higher when the biomass is used for heating and CHP.

Aviation and Sea Transport

Fuels used in international aviation and maritime shipping are only to a small extent burnt in respectively the air space and territorial waters of the country where the fuel was purchased. The Parties to the UNFCCC therefore decided to exclude emissions from such fuels from the national emission inventories. Instead, IMO and ICAO were instructed to analyse ways to reduce carbon emissions from these fuels.

It would indeed be rather complicated to include marine bunker oils and fuels used in international aviation in a scheme for European CO_2 emissions trading. An inclusion would require the Kyoto Protocol to be amended accordingly and would also open a new discussion in the European Union over its internal burden sharing agreement. The Netherlands, for example, accounts for one third of all marine bunker oil sold in Europe and would probably demand the agreement to be renegotiated. Allocating emissions to Parties according to the nationality of the transporting company, the country where the vessel is registered or the country of the operator would be even more complicated. It is often difficult to determine the country of ownership of a vessel or who is the real owner or responsible for its operation (IMO, 2000).

To avoid such complications it appears wise to restrict CO_2 emissions from shipping and aviation by other means than national caps. In both cases the choice is primarily between CO_2 taxation and an environmental charge related to specific fuel consumption and distance. Where aviation is concerned one could also contemplate an international cap in combination with emissions trading. Use of efficiency standards is probably not a realistic option as it would rule out all types of high-speed craft unless numerous exemptions were granted (Kågeson, 2001b).

COST-EFFICIENCY?

From the above it is evident that the carbon abatement strategies of the EU and its member states are far from cost-efficient. A problem with the Community's current approach to road fuel taxation is the prevailing difference between the high rates applied on gasoline and those enforced on diesel and LPG. In addition fossil fuels used in industry and for power production are to a large extent exempt from energy taxation. From an efficiency point of view all emissions of carbon dioxide ought to be subject to the same charge or tax. The average taxation of emissions of CO_2 from fossil fuels in the EU is currently around €45 to 50 per tonne. The range is between €0 and 329 per tonne; taxation of road fuels represents the highest figures. It should be recalled, however, that fuel taxation in the case of road transport is used partly as a primitive method for internalising social costs other than CO_2.

Exempting fuels used by trains, ships, and aircraft implies a large loss of efficiency compared to a case where these modes would have to pay the same tax or have to buy CO_2 emission permits that match their consumption of fossil fuels.

However, the European Commission (2001c) suggests in a draft Directive on CO_2 emissions trading that interested member states should start trading within a system that includes all carbon intensive branches of industry. The sectors concerned account for close to 50 percent of the Community's current CO_2 emissions. This group could later be extended to other sectors of society, including households and the transport sector.

Some member states may go very far in undermining the cost-effectiveness of their climate change policies. The Swedish Parliament in 1998 decided in favor of a government proposal that CO_2 emissions from the transport sector in 2010 should not exceed those of 1990 (Government bill 1997/98:56). By enforcing this target, the government and parliament left cost-efficiency out of the account. The different state transport agencies and the Swedish Environmental Protection Agency concluded that meeting the sectoral target would in addition to the current energy tax require a CO_2 tax of 1:50 SEK/kg (160 Euro/tonne), which is far above the marginal cost of achieving the same target in most other sectors of society (SIKA, 1999). Sweden is not the only Member State that has adopted far-reaching and inefficient targets for the transport sector. Denmark, Finland and the Netherlands have also introduced similar targets.

The European Commission's services have analyzed the price of emissions allowance under different kinds of emissions trading based on the PRIMES model. They found that the price for complying with the Kyoto Protocol would be around €33 per tonne CO_2 in a case of EU-wide trading covering all sectors of society (European Commission, 2000b). Table 7 summarizes some of the results of a background paper. The "idealized" case represents a case where each Member State were to operate its own internal scheme for emissions trading covering all sectors of society. The "Cheese Slicer Case" refers to a situation where member states decide to enforce the same reduction target on all sectors of society. This would more than double the compliance cost compared to the "idealized reference case".

The Commission's calculations are based on the assumption that emissions trading supplements existing policies and measures, including current taxes on carbon and energy. This means that the case of internal emissions trading in EU15 does not represent the lowest possible abatement cost. Maintaining today's large differences in energy taxation would result in a relatively large loss of efficiency compared to a system where each tonne of CO_2 is taxed equally.

Aviation, shipping, and rail transport would be affected more than road transport by a common scheme for CO_2 emissions trading as they are generally not subject to energy taxation today.

Emissions trading would not encourage the introduction of biofuels in road transport. The incremental cost of producing ethanol or RME is much too high and cannot be expected to fall to the extent needed. Under emissions trading, bioenergy would be used predominantly for heating, in combined heat and power production, and for co-firing (up to 20 percent wood) with coal in condensing power plants. In the future, road fuels would also be produced from crude oil or natural gas. The latter would also be the base for hydrogen used in fuel cells (Kågeson, 1991b).

TABLE 7 Marginal Abatement Cost and Compliance Costs in EU15 for Reaching the Kyoto Target Under Different Scenarios

Scenario[a]	Marginal abatement cost € (1999)/tonne CO_2	Compliance costs Million € (1999)
Idealised reference case (based on domestic trading)	54.3	9,026
The "Cheese Slicer Case"	125.8	20,508
EU Emissions trading in all sectors	32.6	5,957

[a] See text for descriptions.

SOURCE: Capros and Mantzos (2000).

CONCLUSIONS

As shown in this paper, the European Union concentrates its efforts for reducing carbon emissions from the transport sector essentially to three areas of action: improving fuel efficiency in new cars, promoting rail transport and gradually shifting to alternative road fuels.

Reducing the average CO_2 emission from new cars to 140 g/km in the year 2008/2009 is a radical target. Current trends suggest that the automotive industry will achieve at least 75 percent of the required improvement. The cost-efficiency of this measure depends on how the target is achieved.

The outcome of the Community's efforts to "re-balance modal split" is much less obvious. In addition, some of the measures taken for this purpose are likely to be cost-inefficient as the European Commission has not recognised that the marginal production of electricity takes place in coal-fired condensing stations. This means that the impact on real CO_2 emissions from shifting from road to rail will be a great deal smaller than anticipated.

The proposed mandatory introduction of biofuels in road transport could also be put in question. The European Commission does not appear to be aware that even with the best technologies in sight the net energy efficiency of conversion of biomass would not exceed 70 percent. This is ten times the loss of primary energy induced from producing wood chips, pellets or briquettes. From an efficiency point of view it thus appears reasonable to produce liquid fuels from biomass only when the potential demand on biomass for heating purposes has been satisfied. In addition, producing liquid fuels from biomass is so expensive that the proposed measure cannot qualify on economic grounds.

If the European Union wants to limit carbon emissions from the transport sector in a cost-efficient way, it should thus re-think part of its strategy. More emphasis should be on making all emissions of carbon dioxide—including those from sea transport and aviation—subject to the same marginal incentive. Emissions trading or a tax regime where all fuels face the same CO_2 charge could achieve this. This would make stakeholders put more emphasis on fuel efficiency and driving behaviour—in all modes of transport—and less on modal split and alternative fuels.

NOTES

1. Fuels used in shipping not included.
2. A Green Paper is a background document on which member states and interested organisations are invited to comment.

3. Direct injection petrol engines [often referred to as Gasoline Direct Injection (GDI)] use modified chamber designs and direct fuel injection into the chamber to achieve a good combustion of a comparatively weak fuel/air mixture. Most experts believe that GDI will offer an improvement of around 10 percent during typical mixed cycle operation.
4. The text gives the arithmetic average; for a constant year on year reduction, the value would be 2.3% per year.

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An Analysis of the Effects of Car and Fuel Taxes on CO_2 Emissions in Japan and Germany

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This study presents the formulation of a model system to analyze the effects of car-related taxes for the cases of Japan and Germany. In particular, the model examines the changes in car fleet composition, the total CO_2 emissions, and the tax revenues due to different car and fuel taxation schemes. The model system is comprised of choice models designed to determine the effects of varying the weights of tax rates in the different stages of car ownership, the change in vehicle class and age mix, and road users' driving pattern, car class choice and behavior towards car disposal. The analysis conducted for the case of Japan highlight the effects of tax reform in 1989; A model sensitivity test is conducted by forecasting different taxation scenarios. Preliminary analyses for the case of Germany includes the impact of the drop in fuel prices in 1985 and the lower car tax introduced along with the ECE 15/04 standards in 1986. The comparison of the modeling parameters between the models for Japan and Germany, and the sensitivity analysis of model for Japan identify the general effects of car and fuel taxes. Based on these results, we propose the use of a *spiral* taxation scheme in order to optimize the combined effects of car-related taxes.

In the past decade, energy consumption and pollutant emissions from the transportation sector have been increased considerably, particularly in developed countries. In Japan for instance, fuel consumption and CO_2 emissions in the transportation sector increased by 16 percent from 1990 to 1995. With such a steady rate of increase, emission levels in the transportation sector are expected to increase by 40 percent of its 1990 level by the year 2010. The global threat posed by this trend has triggered countries to come up with emission reduction targets and strategies. Among other emission reduction schemes, fiscal measures have recently attracted a great deal of attention. This is indicated by the emergence of green taxes, environmental tax reforms and the so-called efforts directed towards the greening of the transport system.

Different fuel and car taxation schemes yield different economic and environmental impacts. In particular, each combination of tax weights yields different impacts on CO_2 generation, extent of car travel, degree of motorization and revenue collection. As European countries are currently going through tax reform based on economic and environmental considerations, it is important for transport planners and environmental specialists to be able to thoroughly examine the effects of these taxation changes. This study presents the formulation of a model system designed to analyze the effects of various car-related tax schemes. The models are comprised of aggregate choice models formulated for the case of Japan and Germany using car ownership and related data. Using the models, the study aims to analyze the impact of a change in car-related taxation policies. In particular, the study examines the effect of the 1989 Tax Reform in Japan, and the introduction of a new vehicle standard with a lower ownership tax rate in 1986 and the significant drop in fuel prices in 1985 for the case of Germany.

TRENDS IN CAR AND FUEL TAXATION

Car-related taxation is based on a sustainable environmental policy known as the user pays principle. Around the world, arguments are made to recover the costs incurred for transport facilities based on an axiom, "transport finances transport." For instance, industrialized countries have come to rely increasingly on fuel taxation as a means of financing roads and highways. The international trend most noted among the EU countries, is that fuel taxation is a suitable means of covering not only the total cost of roads and highways construction and administration, but also for offsetting railroad deficits. Taxation and fund allocation, systems, however vary from country to county. In the case of Germany, a statutory taxation of 0.15 DM/liter (U.S. cents 9/liter) is earmarked for the states' support of their regional rail traffic. Taxes can be used to influence the economic choices of individuals with respect to a certain commodity or service.

At present, tax schemes directly affecting the automotive industry are collected during car ownership stages of purchase, ownership and use of the car. Taxes levied at the purchase stage basically include the payment of sales tax or value added tax (VAT), while tax collections during the ownership include annual taxes and vehicle registration fees. Use tax is primarily comprised of fuel tax, among which are VAT, carbon tax, and other environmental taxes. The degree of taxation at these stages, however, varies among countries. As of 1998 for instance, VAT rate in Japan was the lowest at 5 percent while in Germany, France and the UK it was 16 percent, 20.6 percent and 17.5 percent respectively. In the United States, local government charges sales taxes and gasoline taxes at rates that vary among states and counties. Recently, a number of states in the United States have lowered or abolished car ownership taxes. This policy direction contrasts to continuing inspection regulation in Japan, which levies high car taxes for car users to continue the ownership of the vehicles. Trend in car taxation in EU member countries is that those with indigenous motor manufacturing industry have low car taxes.

The differences between countries include the type of taxes, tax rates, and vehicle classification. The applicable car classification systems used in the studied countries are presented in Table 1. The difference in taxation scheme is even more pronounced than in the price of fuel. A comparison of motor vehicle fuel prices among 160 countries shows that prices differ on a scale of one to 100 due to differences in fuel tax (Metschies, 1999). Difference in fuel prices together with a comparison of the total car-related tax rates per unit car are shown in Figure 1 and illustrate the different balance between categories of taxes being levied to car users in different developed countries.

MODEL STRUCTURE AND CONCEPTUAL FRAMEWORK

Car-related taxes can be classified based on the various stages of car ownership, namely: purchase, ownership, use, and disposal. During each of these stages there are a number of choices that the car users make. This includes matters such as what car to buy, how long to own it, how often to use it, and when to dispose and purchase a new car. Individual responses to these choices are dictated by one's socioeconomic background, and the perception of the cost of each choice against the perceived benefit. An aggregate of these responses, in combination with supplementary data, will determine (1) the composition of the vehicle fleet in terms of type and age; and (2) the average car usage pattern of each individual. These are two of the significant parameters that affect the total CO_2 load attributed to motor vehicles. The formulation of the model system as shown in Figure 2 was based on this concept.

The process of production, car maintenance, and disposal also contribute to CO_2 emissions. This is referred to as "life cycle embodied emissions" and can be measured by the concept of Life Cycle Assessment (LCA). The LCA is an environmental impact assessment tool and a component of International Standard Organization 14000 Series. Related research in the field of transport engineering (e.g. Sterner et al., 1992; Bunch et al., 1993; Gronau, 1994; Sperling et al., 1995; Koopman, 1995; Kurani et al., 1996) mainly evaluates the reduction of CO_2 during the car usage stage through simulations with respect to driving distance and fuel economy. However, very few researches (e.g. Delucchi, 1991, 1993 and 1997) incorporate CO_2 generation during production, maintenance, and disposal—the sum of life cycle embodied CO_2

TABLE 1 Car Classification Used in Modeling for Japan and Germany

Japan		Germany	
Classification	Engine Displacement	Classification	Engine Displacement
Class A	2,001 cc or bigger	Car a	2,001 cc or bigger
Class B	1,501 cc- 2,000 cc	Car b	1,400 cc to 2,000 cc
Class C	1,001 cc- 1,500 cc	Car c	1,400 cc or smaller
Class D	1,000 cc or smaller		

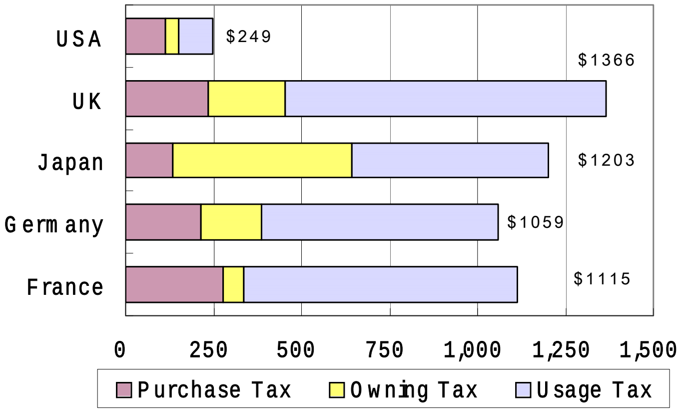


FIGURE 1 Comparison of car-related taxes in US$ per year. (Assuming gas engine, 13500 US$, 1500 cc, 1200 kg, 12000 km/yr, fuel consumption rate: 12 km/l, life time: 10 years)

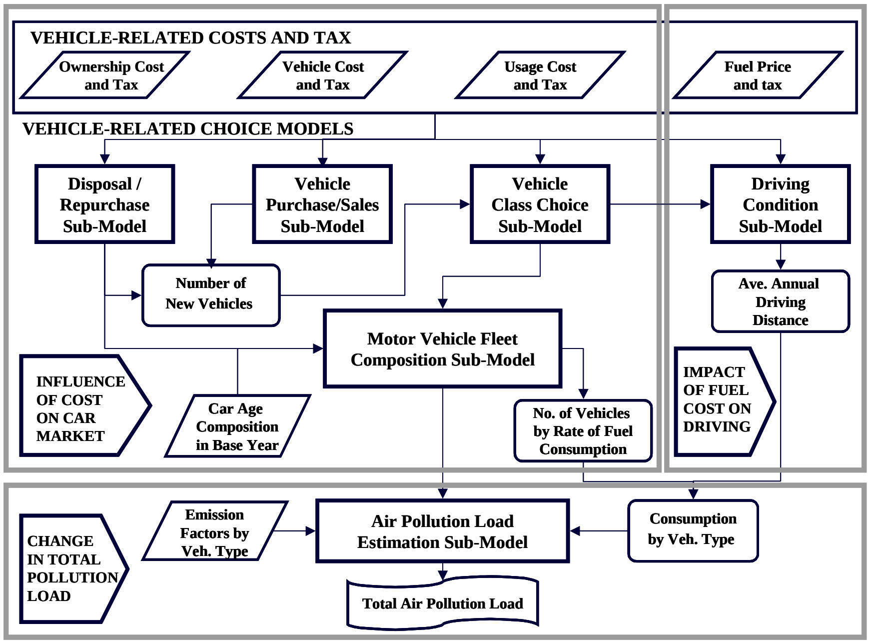


FIGURE 2 General structure of the model system

called the "Extended Life Cycle CO_2" (ELC-CO_2). DeLuchi et al. (1989) introduced this concept in measuring electric vehicle performance in 1989. In this study, ELC-CO_2 of car, along with the car fleet composition and revenue as influenced by car and fuel taxes, is estimated.

The model system is comprised of three main processes. (A) The first part is the examination of the influence of car ownership and related tax schemes on the motor vehicle market by tracing the change in motor vehicle composition over time considering the process of vehicle purchase, disposal, and car class choice during purchase. (B) Second, is the estimation of the influence of fuel tax schemes on the vehicle usage pattern like average driving distance as a function of fuel cost and other travel pattern parameters. (C) Third is the estimation of the total CO_2 load, considering all of the different stages of car ownership. The overall model system is designed to evaluate the effects of car-related taxation schemes on the composition of the motor vehicle fleet, total Life Cycle CO_2 emissions, and resulting taxation revenue.

THE MODEL SYSTEM IN DETAIL

The model system is comprised of six submodels: (1) disposal/repurchase choice; (2) vehicle purchase; (3) car class choice; (4) driving condition; (5) motor vehicle fleet composition; and (6) life-cycle CO_2 load estimation. The influence of car-tax schemes on car disposal, purchase, class choice, and driving pattern can be examined using the parameter estimates of the first four submodels. Results are then utilized to generate the fleet composition, which serves as a major input to the emission CO_2 load estimation. The submodels were estimated using car ownership and car market related data from 1970 to 1997 for Germany, and from 1980 to 1994 for Japan. This section briefly presents the submodel formulation, assumptions and results for each case. Further details of the model system and each submodel are presented in Hayashi et al, 2001.

Motor Vehicle Composition Submodel

The motor vehicle composition submodel is the core part of the model system. It is basically designed to generate the total number of vehicles, cross-classified by type and age, using a car cohort mathematical formulation as illustrated in Table 2. Morisugi and Ohno (1996) first developed the car cohort table to forecast the share of diesel-engined cars. Using the car cohort table, the total number of new vehicles for each year can be calculated based on the number of disposed vehicles, implying a repurchase, and the number of new vehicles purchased by new car owners, representing an increase in vehicle ownership. The annual survival rate equation is shown in a text box at the bottom of Table 2, where $C^k{}_{a,t}$ is the number of existing cars of age a and class k in year t. Survival rate over time of car class k and age a at any given time t ($S^k{}_{a,t}$), as used in the following section is defined as the ratio $C^k{}_{a,t} / C^k{}_{0,(t-a)}$.

Disposal/Repurchase Choice Submodel

The choice process whether to continue the use of one's current car or to repurchase a new car can be formulated as an aggregate binary logit model by car class as shown in Equation 1.

$$L = \exp(U_{cur})/[\exp(U_{cur}) + \exp(U_{new})] = 1/[1+\exp(U_{new}-U_{cur})] \qquad \textbf{(1)}$$

where

$U_{new}-U_{cur} = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + \ldots + a_nx_n$
U_{cur} = Utility gained by continuing to use the current vehicle
U_{new} = Utility gained by disposing the current vehicle and purchasing a new one

Input variables x_1 to x_n consists of cost and utility parameters compared between the two alternatives. The following are basic parameters used in the modeling exercises unless otherwise specified.

x_1 = difference in the purchase costs between the current and the new vehicle
x_2 = difference between owning cost of current vehicle and its remaining value
x_3 = difference in using the cost between the current and the new vehicle
x_4 = log sum of additional utility by purchasing a new vehicle; and
a_0 to a_n = parameter estimates

The purchase, ownership, and use components of cost, as employed in policy analysis, are shown in Table 3 for the case of Japan, and in Table 4, for the case of Germany. Each cost component includes tax and is normalized by per capita GDP for the case of Japan, and by individual annual income for the case of Germany. Similar cost parameters are used in the car-class choice model. In the absence of a calibrated car value depreciation model, the value of car is assumed to linearly diminish to reach 0 (zero) through its theoretical life span. The life span of 10-years based on car registration statistical data showing that scrapping rate is highest among 9-year-old and 11-year-old cars, is used for the case of Japan. Meanwhile, a life span between 10 and 15 years based on the gathered data is adopted for the case of Germany.

TABLE 2 Car Cohort Table by Age and Car Class

Year	0 (New)	1	2	3	…	Total
1997	$C^K_{0.97}$	$C^K_{1.97}$	$C^K_{2.97}$	$C^K_{3.97}$	…	$\sum_a C^K_{a.97}$
1998	$C^K_{0.98}$	$C^K_{1.98}$	$C^K_{2.98}$	$C^K_{3.98}$	…	$\sum_a C^K_{a.98}$
1999	$C^K_{0.99}$	$C^K_{1.99}$	$C^K_{2.99}$	$C^K_{3.99}$	…	$\sum_a C^K_{a.99}$
2000	$C^K_{0.00}$	$C^K_{1.00}$	$C^K_{2.00}$	$C^K_{3.00}$	…	$\sum_a C^K_{a.00}$
2001	$C^K_{0.01}$	$C^K_{1.01}$	$C^K_{2.01}$	$C^K_{3.01}$	…	$\sum_a C^K_{a.01}$
…	…	…	…	…	…	…

Annual Survival Rate: $S^K_{at} = C^K_{at} / C^K_{(a+1)(t+1)}$

TABLE 3 Estimated Disposal/Repurchase Choice Submodel[a] for Japan

	Class A	Class B	Class C	Class D
Constant	2.97	1.12	0.67	0.940
	(9.3)	(3.0)	(2.2)	(3.6)
Difference in Purchase Cost (x_1)[b]	-0.647	-1.16	-2.76	-5.54
	(-1.9)	(-1.2)	(-2.0)	(-3.5)
Owning cost- Car's current value	-2.93	-6.6	-10.9	12.8
(O-C_C)	(-17.2)	(-17.5)	(-20.0)	(-21.1)
Difference in Driving Cost (x_3)	10.6	-	-	14.2
	(0.8)			(0.4)
Log Sum Utility of New Car (x_4)	-0.453	-0.101	-0.047	-0.151
	(-3.9)	(-0.7)	(-0.5)	(-1.6)
Adj. R2-Value	0.78	0.70	0.74	0.79
No. of Observations	124	142	144	144

[a] The t-values are given in parenthesis.

[b] Difference in Purchase cost = ((new car price)-(price when purchased current car))/per capita income.

TABLE 4 Estimated Disposal/Repurchase Choice Submodel[a] for Germany

	Car c	Car b	Car a
Constant	0.77	0.57	1.22
	(3.3)	(1.8)	(5.2)
Diff. in Purchase Cost (x_1)[b]	-0.00031	-0.00015	-9.8E-5
	(-8.2)	(-4.0)	(6.6)
Value of Current Car-Owning Cost (C_C-O)	0.00032	0.00021	-7.38E-5
	(16.5)	(12.35)	(11.1)
Difference in Driving Cost (x_3)	-	-0.0063	-
		(5.5)	
Total diff. in using a new and current car (x_4)	0.00072	-	0.00418
	(3.2)		(5.9)
Adj. R2-Value	0.84	0.83	0.85
No. of Samples	268	270	270

[a] The t-values are given in parenthesis.

[b] Difference in Purchase cost = [(new car price)-(price when purchased current car)]/indiv. annual income.

Similar cost variables are used in the car class choice modeling. Disposal/Repurchase modeling as formulated in Equation 1 uses survival rate over time ($S^k{}_{a,t}$) as dependent variable with values ranging between zero and one. Estimated values close to zero signify disposal while those close to one signify continued usage of the current car. With the natural logarithmic transformation, negative coefficients for the parameter estimate indicate disposal while positive values indicate keeping the current car. Results of the modeling run indicate the difference between ownership cost and value of the current car is the most important factor in vehicle disposal. This result is consistent throughout the different class types in both Germany and Japan.

The t-values for the parameter for x_2 (the difference in ownership cost and value of current car) is the largest and it increases as the car-class gets smaller. This means that the owners of smaller cars are more sensitive to ownership cost. The high value of the constant for Class A means that this class has a peculiar attractiveness and that their owners' sensitivity to cost is low. The difference in driving cost is not significant. This means that fuel tax has less influence on disposal/repurchase choice.

Figure 3 compares the actual and the calculated data of survival rate over time in the case of car class C for Japan. This shows the model matches the actual data quite well over time. The rate of change between data points as calculated by the model is not as defined as the actual change. This can be attributed to the 2-year interval Japanese car inspection regulation. In the model the cost factors did not adopt the two-year inspection interval. The result of the model though, is good enough for the purpose of assessing CO_2 emissions overtime.

Purchase Submodel

In the absence a vehicle sales model, this study utilizes statistical trends in forecasting the number of new vehicles with respect to the number of disposed cars. For the case of Japan, an approximate annual growth rate of 35 percent of the total number of disposed cars is adopted in estimating new car registration. For the case of Germany, new vehicle registration is generated using the total car registration forecast, minus the previous year car total plus the calculated number of decommissioned vehicles generated using the Disposal/Repurchase model.

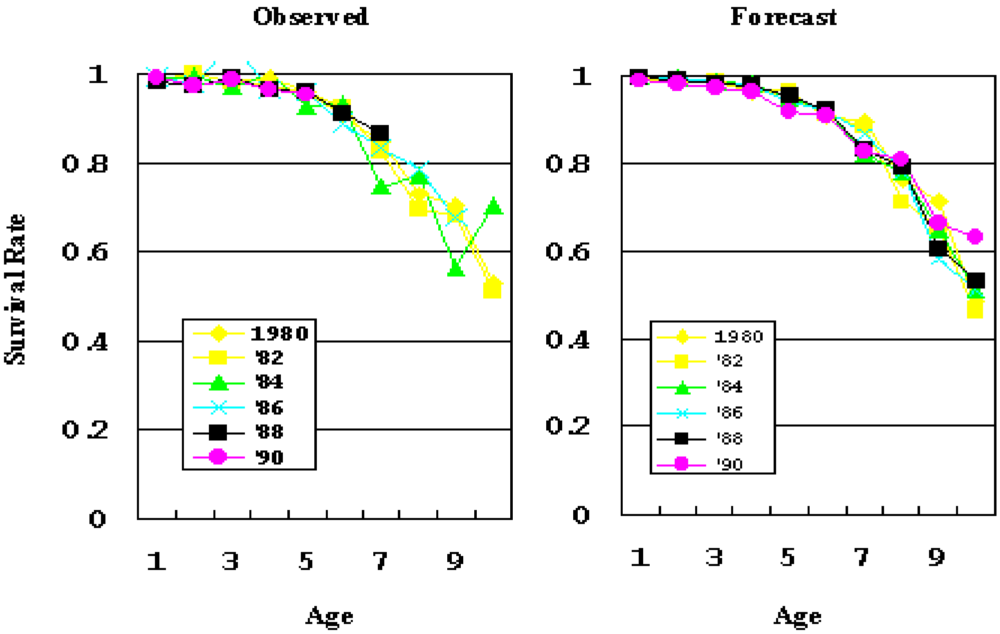


FIGURE 3 Comparison of the observed and forecasted values of survival rate over time.

Car-Class Choice Submodel

The aggregate multinomial logit modeling technique is used for the Car-Class Choice model as it is observed that people tend to choose a car-class which gives the highest utility. This approach is formulated as follows:

$$P_i = \exp(U_i)/\Sigma_{j=1,4}\exp(U_j) \qquad \textbf{(2)}$$

where the choice set is categorized into the number of alternatives: the four classes A, B, C and D for the case of Japan and Cars a, b, and c for the case of Germany; P_i = choice probability of class i; and U_i = utility of class i.

Equation (2) is rewritten as follows:

$$P_D/P_i = \exp(U_D - U_i) \qquad \textbf{(3)}$$

and,

$$\ln(P_D/P_i) = U_D - U_I = b_0 + b_1x_1 + b_2x_2 + b_3x_3 \qquad \textbf{(4)}$$

where b_0, b_1, b_2, b_3 are model parameter estimates; and x_1, x_2, x_3 are given by the same data as used in the disposal/ repurchase submodel (see Table 3).

The model parameter are estimated using the same data as used in the disposal/repurchase submodel. For the case of Japan, the data during the transition period from 1989 to 1992 was not included so as to generate a choice model representative of the before tax reform scenario. The resulting parameter estimates are presented in Table 5. The absolute value (namely, sensitivity) of each x_2 (difference in ownership cost) is six to 50 times more than that of x_1 (difference in purchase cost) while the x_3 (difference in usage cost) are statistically non-significant. The constant parameters are significant, indicating that the peculiar attractiveness of each car class dominates the preference of the consumers. Sensitivity to changes in cost of the class of small cars is higher than that of the class of large cars.

For the case of Germany, a similar model was also developed. As with the model for Japan, the model for Germany was estimated without the data period for the period that was affected by the changes in tax scheme. The model using data from 1970 to 1985 shows that differences between ownership costs and usage costs are the significant parameters influencing the choice between Car c and either Car b or Car a. This observation is consistent with the Japanese case, noting that the different signs of the coefficients are merely attributed to the differing definition in the parameter formulation. The difference in owning cost is more important in the choice between Car c and Car a. The parameter estimates for the German choice models are shown in Table 6.

A notable difference between the case of Japan and Germany is the peculiar preference for cars of Class A and D in the case of Japan (as indicated by high t-values in the constant) as opposed to the non-significant set of t-values for the equivalent parameter in the case of Germany. In Japan, a strong preference for big cars conflicts with the enticing preferential taxation and policy package in favor of the small cars. This creates a divide between those who are least sensitive and most sensitive to cost. On the other hand, in Germany car choice tends to be influenced by different combinations of tax weights. Another significant difference observed between Germany and Japan is that German road users are more sensitive to usage than their Japanese counterpart.

The curves generated by the model correspond fairly well to the observed fleet composition over the model period. Using the Car Class Choice model for Germany, Figure 4 shows the calculated car class mixes for the newly purchased cars plotted with the observed mix.

TABLE 5 Estimated Car Class Choice Submodel for Japan[a]

	Class A/B	Class A/C	Class A/D
Constant	1.38 (8.2)	2.42 (4.2)	27.9 (12.6)
Diff. in Purchase Cost (P_A-P_X)	-0.495 (-1.1)	-1.22 (-1.2)	-9.87 (-4.3)
Diff. in Owning Cost (O_A-O_X)	-24.5 (-12.7)	-17.9 (-2.9)	-59.2 (-3.7)
Diff. in Usage Cost (U_A-U_X)	-	-11.5 (-0.5)	-73.2(0.2)
Adj. R^2	0.99	0.96	0.96
No. of Observations	12	12	12

[a] The t-values are given in parenthesis.

TABLE 6 Estimated Class Choice Submodel for Germany [a]

	Car c/b	Car c/a
Constant	-0.95 (-2.5)	-0.62 (-1.4)
Diff. in Purchase Cost (P_n-P_1)	-1.06 (-4.9)	-0.16 (-2.3)
Diff. in Ownership Cost (O_n-O_1)	67.56 (5.2)	17.28 (3.4)
Diff. in Usage Cost (U_n-U_1)	12.76 (3.2)	6.33 (3.0)
Adj. R^2	0.786	0.8718
No. of Observations	16	16

[a] The t-values are given in parenthesis.

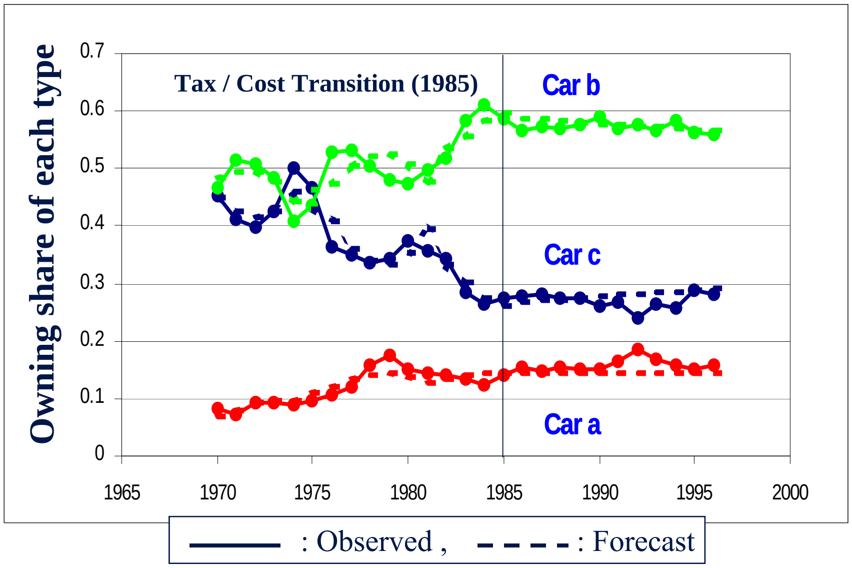


FIGURE 4 Results of the car class choice submodel for Germany in percent purchasing share.

Driving Condition Submodel

If fuel price increases, car users may reduce fuel costs by reducing their driving, given that they own a certain vehicle. In this study, this phenomenon is described simply as a change in driving distance where it is assumed that driving distance fluctuates with the price elasticity of gasoline. The price elasticity of gasoline in Japan was calculated to be -0.23, using the gasoline price and consumption data from 1981 to 1989, when gasoline prices experienced major fluctuations. With this value, the relationship between gasoline price P_t and driving distance D_t at any year t is expressed as follows in Equation 5.

$$D_{t+1} = [1+0.23(1-P_{t+1}/P_t)]D_t \tag{5}$$

A similar formulation relating vehicle-kilometer traveled and fuel cost was generated for Germany using regression analysis, as shown in Equation 6.

$$D_{t+1} = [1+0.0515(1-P_{t+1}/P_t)]D_t \tag{6}$$

The motor vehicle classification to be used in this study is based on a combination of the following parameters: type of vehicle, engine displacement, and type of fuel. Sub-categories for each parameter will be based on the prevailing vehicle classification system in each country. For Japan, the initial model simply considers cars classified by engine size as shown in Table 1. The average vehicle purchase price and fuel consumption rates will be calculated from the purchase price, engine size, and fuel consumption rate by vehicle type data derived from car registration record and other related statistics.

Carbon Dioxide Load Estimation Submodel

Total CO_2 emissions can be generated given the annual average travel distance and the fuel consumption by each car sub-group, e.g., age and a set of appropriate emission factors. As this study also considers the CO_2 generated upon car disposal, emission factors representing the approximate emissions attributed to scrapping of a car are adopted. The total estimated emissions are then the sum of emissions due to driving and disposal. The model for Japan calculates the total CO_2 using the Extended Life Cycle CO_2 (ELC-CO_2) estimation method, which combines the emissions from the car as derived using the Life Cycle Assessment method and the emissions generated from usage.

POLICY ANALYSIS

Analysis of the Effect of Changes in Taxation Policy

The application of the model system for both Japan and Germany aimed to quantitatively estimate the effects of tax policy changes on CO_2 emission in the different stages of car ownership. As the model system can forecast the number of existing cars by engine class and age, it makes it possible to examine the balance in taxation rates for reducing life cycle CO_2 emissions.

Effects of the Tax Reform in Japan

In Japan, car-related tax rates were changed in 1989 when a consumption tax was introduced. Before 1989, passenger cars were classified into big passenger cars (whose displacement is roughly over 2,000cc—class A) and small passenger cars. Tax rates for purchasing and owning big passenger cars were about twice as high as for small passenger cars. After the tax reform, the tax rates for purchasing and owning both classes became almost equal. As a result, purchases of big passenger cars increased dramatically.

The model system calibrated for Japan was applied to analyze the 1988 tax reform in order to test how the model estimates the (a) changes in car class share; (b) CO_2 emissions; and

(c) car-related tax revenue due to the tax reform. The result shows that, if the tax reform had not been executed, the shift from Class B to Class A (small to big passenger cars) cars would have not occurred, and that the ELC-CO_2 emissions from all passenger cars in 2010 could have been eight percent lower. Accordingly, the tax revenue would have been higher by 10 percent. The calculated results are presented in Figure 5.

Effects of the Tax Transition in Germany

The 1986 Taxation Transition in Germany was comprised of two components: the sudden decrease in fuel prices of about 25 percent in 1985 and the introduction of a new set of vehicle standards with reduced ownership tax through ECE 15/04. The decrease in fuel price was just prior to the introduction of unleaded gas fuel in the market. Meanwhile, the decrease in ownership tax made the tax rates applicable for cars under the ECE 15/04 standard about 30 percent lower than that of the ECE 15/03 tax rates. These changes in taxation have altered the trend in car class mix. The reduced tax rates have also resulted to an increase in the annual vehicle kilometers traveled breaking the decreasing trend from 1970 to 1985 (see Figure 6).

The model system calibrated for Germany was applied to evaluate CO_2 emissions, car class mix of newly purchased vehicles, disposal trends and the total revenue collected assuming that the taxation changes had not occurred. The "no tax reform" scenario for fuel price was assumed to be a linear increase between 1985 and 1992 with premium gas prices rising from 1.425 DM/l to 1.528 DM/l. This was used instead of the actual price, which fell abruptly to only 1.077 DM/l in 1986, decreased further over the next two years, then increasingly sharply to the 1992 price level. The ownership tax rates for ECE 15/03 were adopted for the tax reform

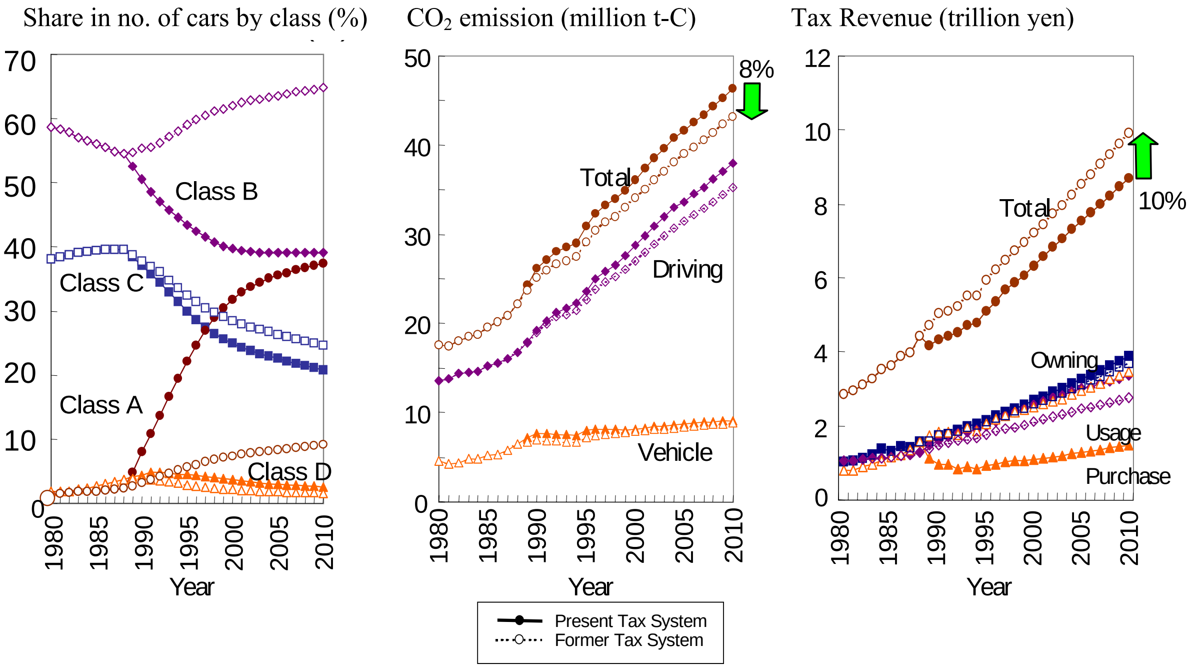


FIGURE 5 Forecast of current tax rate and case of a reset to pre-1989 tax reform rates for Japan.

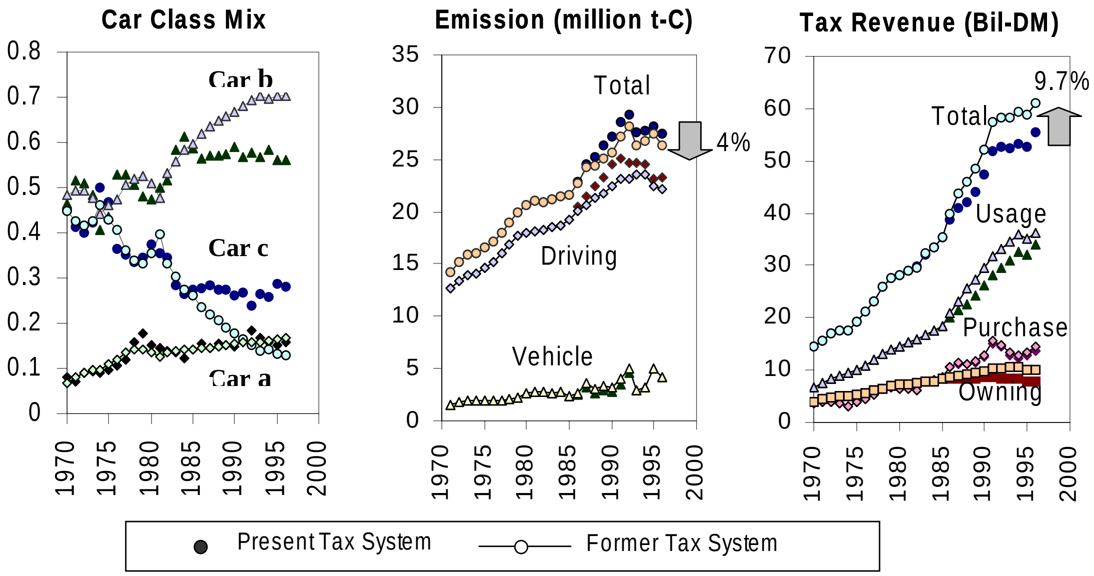


FIGURE 6 A comparative plot of with and without tax reform scenario for the case of Germany.

scenario. The general impact of both changes in fuel price and owning cost results in CO_2 emission that is higher by four percent and a revenue that is lower by 9.7 percent for the year 1996.

Sensitivity Analysis for the Model for Japan

The purpose of the sensitivity analysis was to compare the elasticity of an incremental increase in each tax category (purchase, ownership, and usage) to the changes in car-class share and CO_2 emission. A 10,000 yen (approx. U.S.$90) per car equivalent extra charge set to be linearly proportional to the engine displacement was used as an annual increment for the case of Japan. Using the model, the forecasted change in car-class share and in the ELC-CO_2 emission per car by engine class in 2010 due to the incremental increase in each tax category was generated and are presented in the following sections.

Purchase Tax

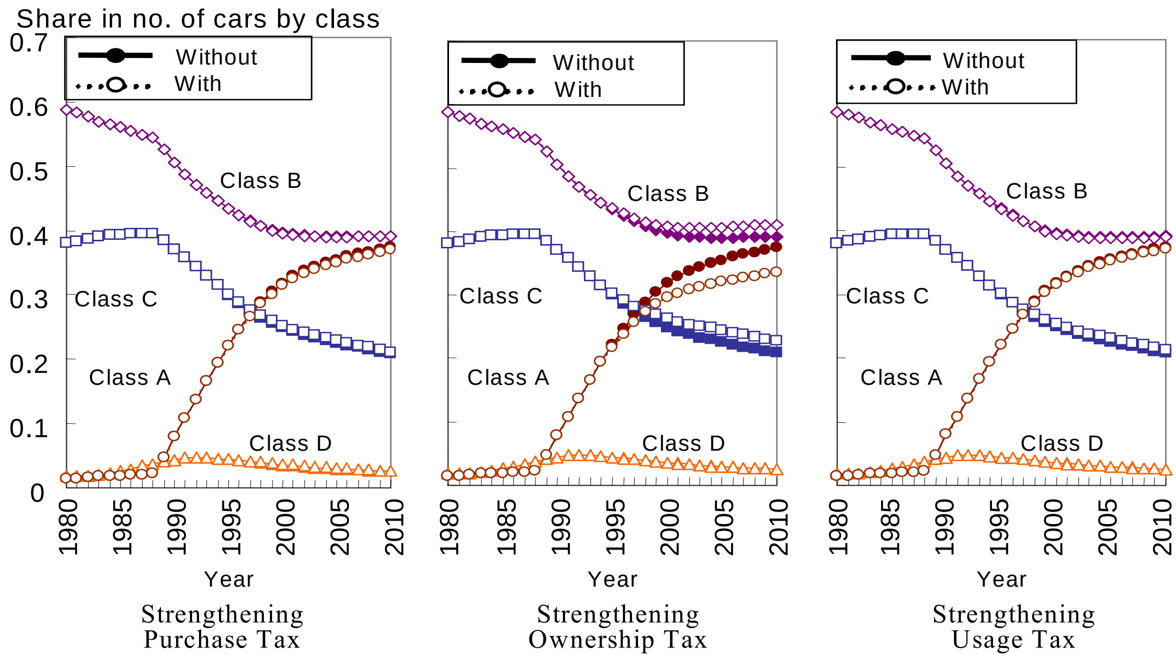
An additional charge of 10,000 yen/year in every class corresponds to an equivalent of 40 percent increase in purchase tax. The effect on car-class share (Figure 7*a*) is observed as only a slight increase in Class A. Emissions from car production is reduced by 0.2 percent in class A and by 1 percent in the other classes by the year 2010.

Ownership Tax

An additional charge of 10,000 yen/year in every class is equivalent to a 15.0 percent increase in ownership tax. The results show that the share of Class A decreased while the shares of classes B and C increased. This indicates that the incremental increase in ownership tax is more influential than that of the purchase tax. CO_2 emission from production increases because the lifetime of cars is shortened due to the lowering of the relative cost of purchasing against owning (see Figure 8). On the other hand, the total CO_2 emissions from driving all car-classes decrease in the long run because of the shift to lower class cars when repurchasing.

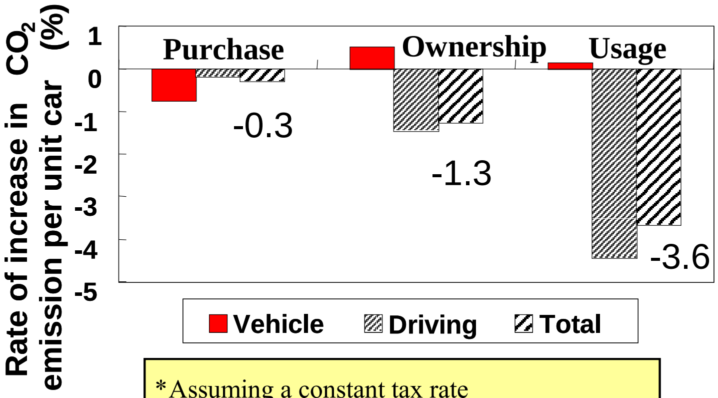
Usage Tax (Fuel Tax)

An additional charge of 10,000 yen/year in every class is equivalent to an average increase of 20.6 percent in usage tax. The study shows that the share of each car class changes a little as usage tax does not significantly affect purchase behavior as noted in the parameter estimates. On the other hand, the reduction rate in CO_2 emissions is at the highest, due to shorter travel distances and more efficient driving practices.



(a) (b) (c)

FIGURE 7 Effects of incremental increase per tax category in class mix of newly purchased cars.



*Assuming a constant tax rate
for purchase and ownership for all classes

FIGURE 8 Changes in CO_2 emissions by year 2010 due to an incremental Increase from 1995.

Comparison of the Effectiveness of Incremental Tax Burden on CO_2 Emission Reduction for Three Taxes

Usage tax can reduce CO_2 emissions most by a unit incremental burden equivalent to 10,000 yen/year per car. Most of the reduction comes from decreases in driving distance while only a small shift in car class share to smaller classes is observed. On the other hand, ownership tax changes result in a fairly large shift to smaller car class while purchase tax has a very small effect.

Preferential Taxation Policy

The minimal effect of an increase in ownership tax on the reduction of CO_2 emissions is due to the fact that each car class is allocated a tax increase that is linearly proportional to the engine displacement. However, if a tax rate is set in proportion to fuel efficiency or CO_2 emission rates, a larger effect is expected since the taxation scheme will be indirectly promoting the shift to lower emission cars. In this section, forecasting was conducted using different tax weight combinations for each engine type. This is referred to as a preferential taxation scheme where the tax is selectively applied so that a particular alternative will be more attractive than the other. The different scenarios are presented below:

- Policy 0: Keep the current tax rates
- Policy 1: Doubling ownership tax rate for only class A from 1995
- Policy 2: Doubling ownership tax rate for classes A and B from 1995
- Policy 3: Doubling ownership tax rate for all classes from 1995
- Policy 4: Preferential purchase and ownership tax, and usage tax increase from 1995

Policy 1: Doubling ownership tax rate only for class A from 1995

The share of class A will decrease reaching the level of that in1980 by the year 2003 when almost all cars will finish one cycle of disposal and will be repurchased. The decrease in Class A is mainly due to a shift to Class B and slightly to a shift to Class C. This will result in a six percent decrease of CO_2 emissions from driving as compared to that in Policy 0 (continuation of current tax rate). CO_2 from production, maintenance and disposal of vehicles will not have a significant change at -6 percent. Revenue will first increase due to the increased of tax rate but later will decrease due to the shift to smaller class cars for which ownership tax rates are lower, thus resulting in an eight percent decrease in tax revenues by 2010.

Policy 2: Doubling ownership tax rates for classes A and B

In the case of Policy 2, the share of classes A and B decreases while that of classes C and D increase to 80 percent of the class mix by 2010 (Figure 9*a*). In 2010, car emission is also forecasted to be 20 percent lower as compared to Policy 0. This can be attributed to a 25 percent decrease in driving CO_2 and a five percent decrease due to a reduced decommissioning rate (Figure 9*b*). The revenue is forecast to decrease by 13 percent by the year 2010 (Figure 9*c*).

Policy 3: Doubling ownership rate for all classes from 1995

In the case where the ownership tax rate is doubled for all classes, CO_2 emissions decrease by 10 percent and revenue increases by 30 percent. The decrease in CO_2 is less than Policy 2, implying that increasing ownership taxes only for higher classes is more effective than a uniform increase across all classes. This further shows Policy 2 to be a more efficient scheme as it attains significant CO_2 reduction at a lower overall increases in tax burden.

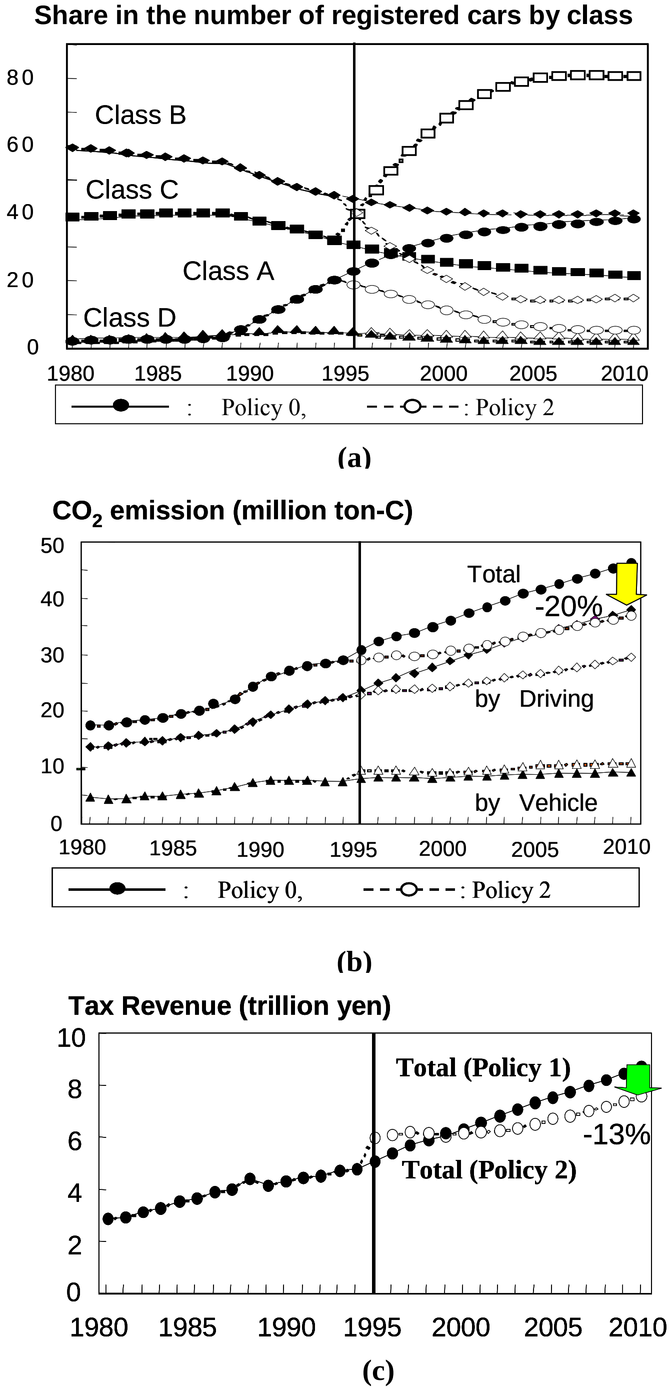
Policy 4: Preferential purchase and ownership tax, and usage tax increase from 1995

The combination of preferential purchase and ownership taxes and use tax increases in Policy 4 yields the highest CO_2 reduction (30 percent) and the highest revenue increase (75 percent). The preferential purchase and ownership taxes in this policy scenario utilized different tax rates for each car classes, as shown in Table 7, to make a small car more preferred to the bigger alternatives. The use tax on the other hand involves an annual increase of two percent in fuel taxes.

SUMMARY AND CONCLUSION

Model Development

A model system designed to evaluate the effect of car-related taxation schemes on the total Life Cycle CO_2 emissions and the total tax revenue was calibrated for the case of Japan and Germany. The system determines the effect of changing the weight of the tax components of the different stages of car ownership on changes in the car class mix, as well as the car users' driving patterns, car class purchasing choice, and disposal. The disposal/repurchase and the car class choice models were estimated using car ownership and car market related data from 1980 to 1994,



(a)

(b)

(c)

FIGURE 9 Effects of Policy 2.

capturing the 1989 tax reform, for the case of Japan, and from 1970 to 1996, covering the 1986 taxation transitions for the case of Germany. An aggregate binary logit model was utilized for the formulation of the choice models, whereas the driving condition submodel utilize linear functions of gasoline price elasticity. The formulated choice models generally yield a good correspondence between the expected and the observed values. Significant parameters in the models are likewise similar despite the overall difference between the general taxation policies of the two countries.

Recognizing the existence of similar and even more advanced models, the study primarily presents an integrated and comprehensive model system and does not necessarily promote the use of the adopted modeling techniques. The current model system is believed to be flexible enough to incorporate the use of more advanced existing models to come up with a system that can examine the effect of car tax policies to the car fleet mix, taxation revenue and CO_2 emissions.

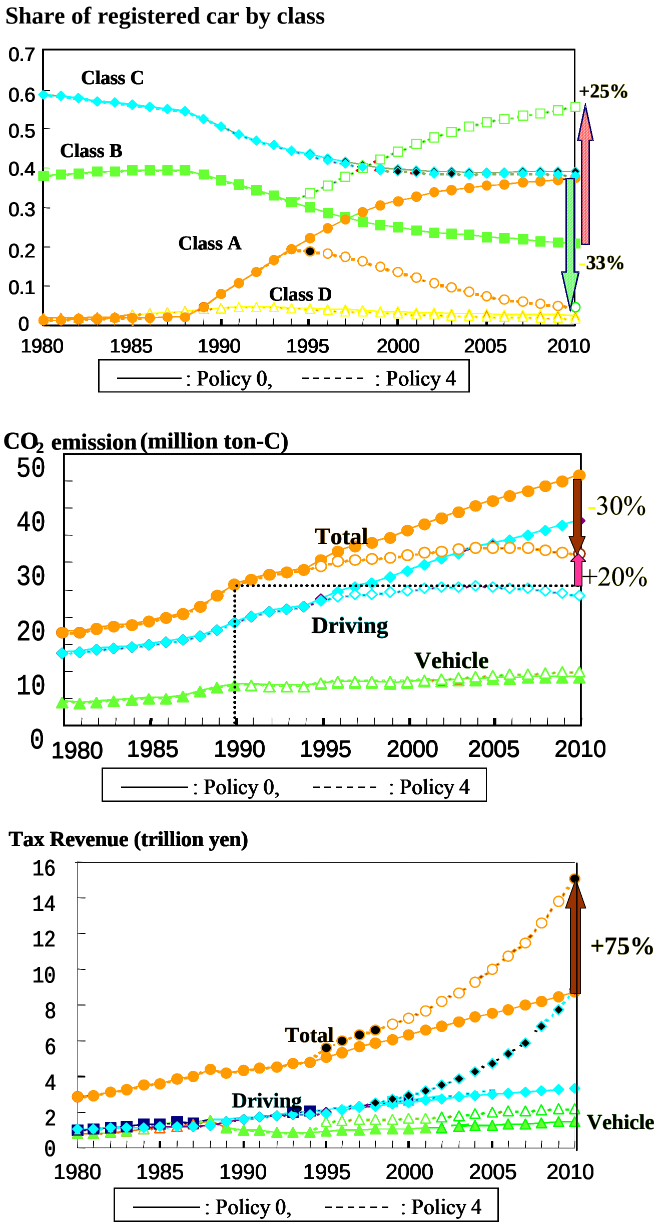


FIGURE 10 Effects of mixed policy (Policy 4).

TABLE 7 Tax Rate Factors for Mixed Policy (Policy 4)

Class / Stage	Class D	Class C	Class B	Class A
Purchase Tax	0.5	1.0	2.47	2.95
Ownership Tax	0.5	0.7	1.2	1.4
Fuel Tax	1.02			

General Effects of Car and Fuel Taxation Schemes

The resulting parameter estimates for the case of Japan and Germany define the general effects of "greening" car and fuel taxation in relation to CO_2 emissions. From the disposal/repurchase choice model, results show similarities among the parameters for both Germany and Japan. For instance, the most significant parameter for both countries is the difference between ownership tax and the cost of current car. These consistent results strengthen the findings that in order to influence the propensity to dispose a vehicle, a commensurate vehicle age-based owning taxation policy should be introduced. This can be rationalized by the impracticability of keeping an old car at a cost that is higher than its present value.

Meanwhile, car class choice results highlight the role of ownership taxes in influencing what type of car to choose. Further analyses points out that an increase in ownership tax will initially result to an increase in CO_2 due to vehicle disposal. A trend toward reduced CO_2 will be achieved later due to the shift to smaller cars. Notable difference between that of Germany and Japan is the peculiar preference for Class A (largest) and D (smallest) cars in Japan as compared to the more cost-driven Germans. Similarly, road users in Germany are more sensitive to use cost in their car class choice than are their counterparts in Japan. Sensitivity analysis for Japan further shows that most of the CO_2 reduction can be attributed to the car usage tax because of decreased driving. Ownership tax on the other hand significantly results to a shift to smaller cars while the purchase tax, along with ownership tax can significantly influence disposal and repurchase. Further analyses were conducted using several other tax weight combinations yielding the following general conclusions:

- CO_2 emission due to production and disposal of vehicles is proportional to the number of disposal/repurchase cases. The propensity to decommission and repurchase can be reduced by increasing the purchase tax and can be decreased by increasing the ownership tax. The change in CO_2 emission by production and disposal however is less significant than the change in CO_2 due to driving.
- The choice of disposal/repurchase and the choice of car class are not much influenced by use tax, but rather by purchase and ownership taxes. However, disposal and repurchase does not necessarily translate to significant CO_2 reductions.
- Reduction of emissions due to driving is significantly influenced by use cost. The vehicle stage is the dominant source of emissions among the stages of car ownership. An

increase in fuel tax can lead to considerable reduction of emissions due to reduction of travel and a shift to fuel-efficient cars triggered by the tendency to save fuel cost.

- Preferential taxation based on engine size and fuel economy, in combination with fuel taxation, will effectively reduce CO_2 emission and increase government revenue.

Shortcomings and Recommendations for Further Development

The current state of the models is far from perfect. The use of engine size classification and its average fuel consumption limits the model to the examination of engine size shift without considering the shift to fuel-economical engines within the same engine size category. The four-car classification system further limits the analysis of potential vehicle switching in response to changes in taxation. Another limitation is the failure to consider manufacturer's long-term response to car-related taxation policies in terms types of vehicles they offer. Likewise, the model does not consider possible developments in both engine and fuel technology. In the submodels, the driving condition submodel may require the incorporation of other transport planning parameters in addition to the fuel price elasticity. Established results of driving pattern studies for instance can be integrated in the model system. The estimation of emissions due to disposal translates all disposed vehicles to a single emission value. This may not be the case particularly in a global perspective since a significant number of "disposed" cars and engines are exported to other countries rather than scrapped.

The constraints, weaknesses, and limitations of the current model system can be generally attributed to data availability. The time series data requirement and the lack of adequate historical records capturing different cases of tax reform events further limited the model formulation and the conduct of performance testing. The availability of data, as well as the emergence of other related models that can be incorporated into the model system, are expected to further improve the accuracy and expand the applications of the model system. A thorough examination of the mechanism for scrapping disposed cars may likewise rectify the emission estimation due to disposal. A continuing study is being conducted to ultimately include other types of vehicles and vehicle classification, as well as the consideration of related economic and technological future scenarios in forecasting.

FINAL REMARKS

Summing up the initial findings, the general effects of purchase, ownership, and use taxes in relation to CO_2 generation, tax revenue collection and new car class mix were defined. These general findings as derived from the case of Germany and Japan are hoped to be of use in formulating appropriate tax schemes for particular objectives. The degree of impact of each tax scheme however needs to be further studied as this is expected to vary among countries. Given the appropriate taxation impacts, the effect of taxation schemes can be further optimized though preferential taxation promoting the use of both environment-friendly fuel and engines. A main output of the study is the formulation of a method to integrate the different submodels into a comprehensive taxation analysis tool. As simple as it is, the strengths of the current model system include the generation of the vehicle fleet composition matrix, which contains vehicle registration information by vehicle age and class type. The matrix can be easily updated and used to forecast repurchase and disposal trends. Another is the consideration of CO_2 emissions due to disposal by adopting the concept of an extended life cycle CO_2 assessment, thus covering all the stages of car ownership. The examination of the effect on car fleet mix likewise can yield useful information on the effect of car taxation to the car industry and vehicle traffic, while the estimation of revenue can be related to the potential to reduce emissions and to correct market externalities.

ACKNOWLEDGMENT

This paper is an initial output of a proposed collaborative study on this subject among developed countries. The authors are deeply indebted to Ing. Wolfgang Schade, of the Institute for Economic Policy Research (IWW), University of Karlsruhe, for his valuable contribution to this initial study.

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Research Agenda to Support
Transitions in Transportation Energy

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In this chapter we, the editors, present a research agenda to support transitions in transportation energy. This chapter draws upon efforts by many individuals participating in a number of activities. Three sources are particularly important: the chapters contained within this book; a chapter authored by Martin Lee-Gosselin (Université Laval) and Daniel Sperling, titled "Research Area 4: Emerging Technologies," in TRB's *Special Report 268: Surface Transportation Environmental Research: A Long-Term Strategy* (TRB, 2002b); and TRB's *Conference Proceedings 28: Environmental Research Needs [ERN] in Transportation Conference* (TRB, 2002a). The research recommendations from the ERN conference held in March 2001 are drawn from the Sustainability Committee chaired by Daniel Sperling and Kevin Heanue (USDOT), and the Energy and Alternative Fuel Committee chaired by David Rodgers (USDOE) and David Greene (Oak Ridge National Laboratory). Other source materials for this chapter include the NAS review of the Corporate Average Fuel Economy standard (NAS, 2002), the report from a U.S. Department of Energy sponsored meeting on transitions to hydrogen (USDOE, 2002), and a European Conference of Ministers of Transport report (2002) on urban travel.

This concluding chapter is the editors' synthesis and interpretation of many people's work, organized into five broad sets of research topics: 1) pathways to fuel and propulsion technologies; 2) user behavior, consumer choice, and demand; 3) behavior of private and public providers of vehicles, fuels, and infrastructure; 4) policy instruments related to evolving technologies; and 5) institutional arrangements for public sector involvement in research and development. Although we have drawn on a wide range of sources in developing this chapter, the commentary and suggestions that it contains are those of the editors, who have coauthored this chapter.

TOPIC ONE: ANALYZE TRANSITION PATHWAYS

The U.S. and other nations are seriously considering transitions away from petroleum fuels and internal combustion engines. With intensifying calls for more environmentally benign vehicles and fuels, and rapid innovation in propulsion technologies, major changes are about to happen. Better understanding is needed of the choices and pathways of change. An improved knowledge of these technologies and their impacts would inform both the policy and research and development (R&D) processes with respect to pollution, energy use, energy supply, and climate change. Government and the public need to be well informed to assure these factors are adequately considered in the development, evolution, and use of vehicles and fuels. The petroleum and automotive industries are among the largest in the world, are global in their operations, and conduct many tens of billions of dollars in research every year on product development and market research. The challenge for the public sector is largely to complement, leverage, and influence industrial R&D, not duplicate it. Some ideas about how to accomplish this are reserved for the fifth set of recommendations.

Research should address new transport and energy system designs that have the potential to dramatically improve energy consumption and other environmental attributes. These might include not only non-fossil based hydrogen, but also carbon sequestration, entirely new forms of hydrogen and electricity storage, and new energy-serving vehicle guideways. In the latter case, for instance, electricity could be supplied easily and cheaply to battery-powered vehicles along a guideway. The vehicles would have small (inexpensive) battery packs for short access and egress trips off the electrically powered guideway at either end of the line haul part of the trip. Other related system designs are possible, with the potential for large reductions in energy use and emissions.

It is widely believed that hydrogen will be the dominant energy carrier sometime in the future. The foremost question is when; Johnson et al. suggest in their chapter in this volume that the timeframe to start any transition from petroleum is the next few decades. The timeframe will dictate the answers to almost any other question about the transition. The current estimated world supply and demand for petroleum and the high expense and long period it will require to make a transition from petroleum-based fuel provides opportunity and peril. What do the people of the world want the “end of oil” to look like? An immediate aggressive transition to hydrogen (derived from non-petroleum sources) may lead to the collapse of oil demand and prices; as White and McNutt caution in their chapter, part of the cost may be large, abandoned investments in petroleum production, refining, and distribution networks that otherwise would still have useful lives. Wait too long, and the end of oil may be marked by high and variable oil prices, hoarding, and war.

Once a transition is begun in earnest, how will hydrogen be produced and distributed? How will it be used in vehicles? Farrell et al. and Brodrick et al. have suggested here two possibilities for initial applications; there are others, notably in light and medium-duty passenger vehicles. Is a direct-hydrogen fuel cell the desired “end-state” technology? If so, what is the desirability of introducing an interim hydrogen carrier different from “petroleum-like” liquids, such as methanol? How should emissions and energy rules be modified and when? What new standards and codes are needed for storage tanks, pipelines, and fuel handling, and how soon need they be finalized? Should investments for converting remote natural gas into liquids be encouraged? More generally, what transition strategies should be supported through basic R&D at national labs and universities, R&D tax incentives, and fuel quality and vehicle emission standards? The implications of any actions taken, or not, can influence billions of dollars in industrial investments, and can have far reaching impacts on the environmental impacts of the transportation system.

Even though medium and heavy-duty trucks are a principal source of air pollutants (about one-third of nitrogen oxides from vehicles are from medium and heavy-duty trucks) and greenhouse gases, they received far less scrutiny from regulators and policymakers until recently than light-duty vehicles. Emissions regulations and emission control technology on large diesel engines lag perhaps a decade behind those of light duty gasoline engines. As Brodrick et al. describe in this volume, data and knowledge about freight transport and its energy and environmental impacts are sparse. Research is needed on truck usage patterns (including idling); emissions and energy use characteristics; policy instruments to reduce energy use and emissions; development of infrastructure for new truck fuels; and vehicle and fuel tax policy.

Every fuel has a different set of safety and environmental attributes. More research is needed to understand and measure the full spectrum of those impacts. Research is needed regarding the costs and safety of new fuels infrastructure (e.g., where might hydrogen fuel stations be located and at what cost), on industry competitiveness issues associated with introducing new fuels, and strategies for sequestration of carbon from new fuels (for instance from natural gas converted into hydrogen). The recent reversal of California regulations concerning methyl tertiary butyl ether (MTBE), a chemical made from natural gas and added to gasoline to reduce air pollutant emissions, highlights the need for better scientific and policy research. MTBE has been banned in California because leakage from gasoline storage tanks has polluted ground water. This ban comes just a few years after oil refiners had been forced by regulators to invest billions of dollars in the production and distribution of MTBE. As the case of MTBE demonstrates, this research needs to cut across traditional boundaries, including those across and within public environmental agencies.

1.1 Analyzing the Sustainability of Various Alternative Fuels and Advanced Technology Vehicles in Selected Niche Vehicle Markets

Arguments have been presented in this volume for and against relying on niche markets to launch transitions. White and McNutt remind us there are powerful institutions and corporations with large vested interests in the current transportation energy system, and that pressures that seem to point to a transition away from those systems may well be met by increased investments to improve them. On the other hand, Williams, Farrell et al., Brodrick et al., and Elzen et al. provide examples of transitions based on substantial elements of the existing transportation energy system. In particular Farrell, Brodrick, and their co-authors provide examples of initial niche markets that allow for, in Elzen et al.'s terminology, "learning and embedding" in new socio-technological systems.

Early introduction of alternative fuel and advanced technology vehicles is often focused on specialized vehicle markets, rather than the mass market. These markets, such as airport shuttles, transit buses, and taxis, share common characteristics that may be more amenable to new fuel infrastructure or adoption of new technology. Farrell et al. provide the additional example of ships. Brodrick et al. provide the example of auxiliary power units (APUs) for heavy-duty trucks. However, little analysis has been done to determine if such niches are large enough, individually or collectively, to create sustainable supply and demand of specific alternative fuels and vehicles. For example, what portion of all transit buses in the U.S. must be powered by natural gas before engine and chassis manufacturers will be able to profitably manufacture and sell natural gas engines and buses? Little is also understood about the energy benefits of successful market applications taken alone, or whether such applications will lead to expanded use of alternative fuels and vehicles in the mass market. Furthermore the attributes of such markets attract more than one new fuel and vehicle technology, making it even more difficult to estimate the sustainability of each.

Proposed Research This research should address the numerous technology and market opportunities and barriers for the use of specialized vehicle markets as introductory markets and "launching pads" for alternative fuel and advanced technology vehicles. Research is required to accomplish the following:

- Identify and characterize vehicle market segments being considered as first applications for alternative fuels, advanced conventional fuels, and advanced vehicle technologies. These assessments should include the number and type vehicle sales; quantity of fuel consumed; costs; type and level of subsidy; suitability of vehicle and fuel characteristics to specialized markets. Further, as the examples in this volume highlight, assessments should examine light, medium, and heavy-duty applications.
- Assess manufacturer willingness to develop, manufacture, sell, and service various alternative fuels and advanced vehicle technologies to niche markets over an extended period of time. What factors change their willingness to sustain presence in a niche market?
- Assess fuel provider willingness to establish and maintain a fuel infrastructure and produce, distribute, and sell various fuels to these markets. What factors change the willingness to sustain presence in their market?
- Estimate the capacity of specialized markets to absorb one or more new fuels and vehicle technologies simultaneously on a sustainable basis. What factors change the fleets or consumers in these markets ability to create sustainable demand? How does competition within these markets affect this capacity?
- Distinguish between self-sustaining supply and demand, and various and presumably higher levels of supply and demand that could be sustainable due to government policy, correction of market failures, or consumer behavior.
- Assess the potential for various specialized markets to serve as launching pads for the broader use of alternative fuels and vehicle technologies. What are the factors that increase this potential? Are some fuels and technologies suitable only for these markets?
- Identify and estimate the energy and environmental impacts of sustainable specialty markets taken alone or collectively, and under various scenarios where niche markets serve as a critical launching pad for fuels and vehicles to enter the mass market.

1.2 Baseline Studies for Transition Pathways

It is important to understand the baseline for any transition—what are the current conditions from which any transition starts? In this volume, Elzen et al. highlight the importance of decisions made early in any process, but especially long-term and large-scale processes. As part of their contribution, Johnson et al. remind us that the baseline itself is dynamic, e.g., their baseline projections for petroleum energy consumption is one of increasing consumption over the next few decades. In a number of ways, we have only limited understanding of current conditions. The following proposals address such issues.

1.2.1 Benchmark Indicators

In the realm of transportation system performance, one of the greatest demands from both inside and outside the transportation planning community is for assessment of the sustainability of planned transportation and land use arrangements. There is a need for methods and tools that can be used to test alternative visions and public policies against the ability of a metropolitan area or community to maintain its systems over time. Research regarding the impacts of transportation policy and investments on environmental protection and enhancement, energy consumption, land consumption, economic health, and affordability must be translated into tools for use in transportation decision making. The need for this particular performance measurement is increased by the fact that the U.S. will have to accommodate the activities of tens of millions of additional residents in the coming years. Schipper's contribution to this volume includes vivid examples of metropolitan areas in the U.S. and around the world that continue to grow. These growing cities have a tremendous need for tools to assess the long-term sustainability of current and future practices.

Proposed Research Research is necessary to identify a range or menu of potential benchmarks that will allow transportation planners to evaluate progress towards new policy goals. The indicators should also enable comparison between cities. The research would accomplish the following:

- Review the current state of the practice in benchmarking techniques and approaches, both in the U.S. and abroad, particularly in relation to transportation and sustainability.
- Identify common measures (both existing and needed) and indicators of sustainability for use by all levels of government.
- Identify the data needs necessary to support the use of such indicators.
- Initiate a process by which selected urban areas and states would compare their development and use of benchmarks.

1.2.2 Reassess Modal Energy Intensities

The baseline evaluation of current conventional transportation energy systems is out-of-date. Energy intensities (energy use per unit of activity) are basic information for forecasting, policy analysis, planning, and monitoring progress toward national energy and environmental goals. Energy intensity values are essential for predicting the impacts of changes in the structure of passenger and freight transportation. In this volume, Brodrick et al. and Kågeson cite examples of analyses that require improved measures of energy intensities for freight modes. Because greenhouse gas emissions are closely linked to energy consumption, intensity numbers are a key factor in modeling the global warming impacts of different transportation activities. In general, only the most aggregate energy intensity values are readily available (e.g., energy use per total revenue passenger mile for air travel, energy use per vehicle mile for automobile travel, etc.). For some modes (e.g., truck freight) even the most basic estimates of energy use per ton-mile are not available. There is considerable value to having comprehensive, consistent, and objective measures of modal energy intensities with sufficient detail to be widely useful for the kinds of analyses mentioned above.

Proposed Research Comprehensive, consistent and objective measures of transportation energy intensity are required for all transportation modes, both passenger and freight, by mode and function, and at different spatial scales (e.g., national, regional, metropolitan). The level of detail should reflect analytical needs as well as the availability of reliable and accurate data. Detail is important to insure valid comparisons across modes and functions, and to improve the accuracy of derived estimates, such as greenhouse gas emissions.

- Review of U.S. and international literature to obtain modal energy intensity estimates for comparative purposes and to identify data sources and methods.

- Survey both the literature and relevant agencies to identify and evaluate the most important uses of energy intensity numbers.
- Based on the availability of data and the needs for energy intensity estimates, derive the modal, functional and spatial structure of the intensity estimates to be specified. Identify methods and data sources for developing the estimates.
- Use the best available data, together with engineering and transportation modeling methods to develop consistent, comprehensive estimates of energy intensities.

1.2.3 Information Required for Increasing the Energy Efficiency of Goods Movement

The lack of reliable data on the movement of goods hinders planning for an efficient and competitive freight infrastructure for the 21st century. Information is required for aggregate and disaggregate activities involved in intercity and urban goods movement, which includes the types of operations and their ownership. There is a need to develop a national, state and local information system for federal, state, and metropolitan planning organizations (MPO) planners to facilitate the introduction and evaluation of innovative major infrastructure improvements and investments that promote multimodal coordination to enhance the overall efficiency of goods movement

Heavy-duty trucks are very visible sources of urban congestion as a result of their imposing size, the lack of off street loading facilities in older urban areas, and the congestion events caused by truck accidents. Likewise, they are very visible sources of air pollution from their large diesel engines. Yet planners know little about their movements, specific use patterns, loads, etc. National data collection efforts such as the periodic Vehicle Inventory and Use Survey (VIUS) and the Commodity Flow Survey (CFS) provide useful data on national trends in goods movement and vehicle attributes. However, as described by Brodrick et al. in this volume little is known about specific truck operations behavior and therefore the opportunities for congestion relief, increased fuel efficiency in goods movement, and the reduction in damaging air emissions from heavy duty vehicles (HDVs). The availability of real-time traffic information technologies offers planners, shippers, and truck operators the opportunity to improve energy and operational efficiency. The growth in rail and multimodal operations may increase economic efficiency and performance while reducing energy use as well as GHG and conventional emissions.

Proposed Research The first step is to critically review available literature and data sources. Such a review would summarize what is known about HDV and other goods movement operations and how additional information could assist planners in developing improved plans. Based on this review an experimental approach could be taken toward developing uniform and ongoing data collection and analysis systems. The work plan for such an approach would specify the objectives of the data collection activities and provide a plan for the use of the information in improving goods movement fuel efficiency. Elements of such a work plan would include the following tasks:

- Design a freight activity database to provide the framework for describing activities of heavy-duty trucks and other modes. Data will include vehicle fleet characteristics such as number of vehicles, body types, goods carried, weights, areas of operation, engine types, energy efficiency technologies, operating behavior (starts, idle time, speed profile, fuel use, fuel efficiency, loads, trip length, etc.) and other data of interest for energy efficiency, air quality and highway capacity planning.

- Select two to three regions/states to develop a freight information database. The selection will be based on the availability of state and local freight information such as a multimodal management plan or an HDV emission information system. Selection will also consider the regional characteristics, types of goods moved, and other factors.
- Develop the regional/state freight information system for selected regions. The information incorporated will be from secondary sources and from surveys and HDV monitoring activities conducted to fill data gaps.
- Design surveys of truck, rail, water, and other goods movement operations in local areas to collect information needed to fill data gaps in the freight information system. Information collection activities may include surveys of shippers, shipping facilities, and carriers, as well as the instrumentation of vehicles to collect detailed operational data.
- Conduct surveys and instrument vehicles as needed to fill the information system for each region. Include the information in the system and finalize the data set. Provide and demonstrate the information in each selected region.
- Develop a web-based interactive tool comprising a freight information system for energy, environmental and transportation planning. The tool will identify sources of data and methods for developing local information to supplement what is known from other studies. The tool will provide a model database, including default values for most cells. Instructions for the use of information and the calculation of project benefits will also be developed.

1.3 Assessment of Pathways to Fuel Cell Vehicles

Fuel cell vehicles appear as a leading candidate technology in a transition away from conventional vehicles and fuels. An ever-growing interest in the promise of fuel cell vehicles has led to a variety of diverse efforts to accelerate their commercial introduction. Efforts from the private sector include eight major auto manufacturers (DaimlerChrysler, Ford, GM, Toyota, Honda, Nissan, Volkswagen, and Hyundai) collaborating with Federal, state, regional, and local government agencies under the auspices of the California Fuel Cell Partnership; and provision of fuel cell vehicles by Honda and Toyota in December 2002, and later by others, to a variety of entities for market testing. Efforts at the U.S. federal level include the Department of Energy’s long-standing effort on fuel cell development for light-duty vehicles; the announcement in January 2002 of DOE’s Freedom CAR program (with GM, Ford, and DaimlerChrysler) and in early 2003 of an even larger hydrogen fuel program; and the numerous fuel cell programs proposed by energy legislation in the 107th Congress. The sum of the current and planned investments from both the private sector and government in this technology is significant. To maximize the return on investment from these efforts, a comprehensive assessment of pathways to fuel cell vehicles is essential.

A key component of this research is to assess whether a solid case for public support for fuel cell vehicles and the needed fueling infrastructure can be made. The objective of this component is to develop a collective and unbiased understanding of the benefits associated with the successful commercialization of fuel cell vehicles in the mass market. The successful commercialization of fuel cell vehicles will most likely require significant public assistance. Public support will be critical in the near-term although near-term societal benefits will be few. The case for fuel cell vehicles appears to indicate long-term societal benefits—decreased utilization of fossil fuels and non-domestic fuel sources, improvements in urban air quality, reduced sources of ground water and open water contamination, a reduction in greenhouse gas emissions, and other societal benefits. Identifying and characterizing these benefits will be required to enhance public support for the near-term public investment needed.

Proposed Research This project effort would entail a comprehensive assessment of pathways to the successful mass-market commercialization of fuel cell vehicles in North America.

- Review previous related efforts from the California Fuel Cell Partnership (CaFCP), Argonne National Laboratory, and others.
- Examine the impact of the application of fuel cells for other markets including stationary, residential, portable and mobile power.
- Evaluate options for the early introduction of fuel cells into transportation applications—transit buses (Federal Transit Administration, CaFCP, European demonstration program), and other niche markets.
- Evaluate transition options, e.g., natural gas for gaseous fuels and hybrid electric vehicles for electric drive components.
- Evaluate the narrowing advantages of fuel cell vehicles against competing technologies, e.g., conventional gasoline and diesel, hybrid electric, and alternative fuels.
- Evaluate infrastructure requirements for on-board and off-board reformation.
- Assess benefits in terms of air quality/greenhouse gas emissions, energy security and global competitiveness.
- Describe prospective pathways with associated costs, benefits and potential barriers.
- Evaluate the case for public support of any particular pathway. This may be done by assessing the transitional and ultimate potential of each pathway to displace petroleum fuels, reduce emissions of criteria pollutants and greenhouse gases as well as releases of contaminants into terrestrial and aquatic systems, and facilitate or require formation of new lifestyles and development patterns.

1.4 Analyzing Pathways for the Transition to a Hydrogen Infrastructure

The Bush administration has announced a major initiative to develop and deploy hydrogen utilization technologies, and to produce and deliver hydrogen energy in an affordable, safe, and convenient manner: *A National Vision of America's Transition to a Hydrogen Economy—To 2030 and Beyond* (USDOE, 2002). Hydrogen has the potential to lessen dependence on foreign and domestic petroleum, reduce air and water pollution, and diminish greenhouse gas emissions. However, achieving this potential is no small task. Developing and deploying hydrogen vehicles is a formidable undertaking; coordinating infrastructure development with vehicle deployment is likely to be even more of a challenge.

Conventional highway fuels are distributed via what may be termed the "petroleum model." In this model, product terminals receive various grades of petroleum either directly from refineries or via tanker, pipeline, or truck and distribute it to local refueling facilities. Depending on the feedstock and conversion process, the hydrogen supply infrastructure could follow this model or one based on the natural gas delivery system (relying primarily on pipelines). Even further removed from the "petroleum model," hydrogen might be produced locally in every metropolitan area (at so-called "city-gate" plants) or even at individual fueling stations.

Additionally, hydrogen could be centrally converted to electricity. In addition to uncertainties regarding the infrastructure model itself, additional uncertainties revolve around the individual components of the supply infrastructure (e.g., any of the processes described by Williams in this volume), and the evolution of that infrastructure over time. Presumably, initial components of the infrastructure would include portions of the current hydrogen supply infrastructure (primarily captive production by petroleum refiners and ammonia, methanol, and merchant gas producers with distribution by pipeline, rail, and truck) and the existing petroleum, natural gas, and/or electricity supply systems. As volumes increase, the pathway could increasingly diverge from these components, eventually evolving into a dedicated hydrogen infrastructure.

Proposed Research The work would be divided into two distinct phases. In the first phase, components of one or more end-state hydrogen supply/distribution infrastructures would be identified. Options should include alternative hydrogen supply sources and production processes, technologies for sequestering or otherwise capturing carbon, as well as hydrogen distribution, off board storage, and refueling facilities. Potential barriers (e.g., perceived risk, codes and standards) should be identified and characterized. Williams and Farrell et al. provide specific examples in this volume; others should be explored too. Williams' research agenda specifically includes an examination of carbon sequestration—a proposal valid for many hydrocarbon-to-hydrogen production paths, not just the coal-to-hydrogen path. As one example, Farrell et al. propose that the early steps on a hydrogen pathway may occur in shipping rather than land transport—large hydrogen production facilities at ports would supply shipping and eventually land-based vehicles in the vicinity of the port.

In the second phase, potential transitions to those end-states would be described and compared. For the most promising alternatives identified in the first phase, one to three potential pathways for infrastructure development or evolution over time would be characterized. Rough cost estimates associated with infrastructure components would be developed and these pathway costs compared with initial estimates of end-state costs.

1.5 Strategies for Greenhouse Gas Reduction

Considerable effort is being devoted to understanding the relationship between GHG emissions and climate change, but relatively little to the relationship between transportation and GHG emissions, especially in the U.S. Europe and Japan are ahead in developing an understanding of the nature of the contributions of their transportation systems to the potential global warming phenomena, and of the potential strategies that are available or that could be developed to lessen greenhouse gas emissions. The work discussed in this volume by Elzen et al., Kågeson, and Hayashi et al. appear to be cases in point. Strategies may be grouped into those targeted at transportation technology, fuels, travel behavior, and land use. The strategies that are most effective are likely to be those that include a mix of policies and initiatives, as argued by Schipper in his chapter. The mix and specifics of the actions taken will vary considerably from one region to another, depending on local institutions, resources, economic activities, cultures, and expected impacts of global climate change (including the potential for local and regional air quality to be differentially affected). Given the broad and far-reaching possibilities for strategies to reduce greenhouse gas emissions, a two-phase program may be desirable: the first phase to provide an overall framework, and the second to analyze crosscutting strategies.

1.5.1 Overall Framework to Analyze Strategies for Greenhouse Gas Reduction

Proposed Research

- Document what is known about the contribution of different components of the transport sector to climate change, at as disaggregate a level as possible.
- Develop a framework to specify the amount of reduction in GHG emissions possible in different activities and with different initiatives. This framework would reflect what is known about demand elasticities, technological progress, and the linkage of GHG reduction strategies with other social goals (including pollution reduction, petroleum import reduction, public financing constraints, public health, and livability across a spectrum of land use types). This framework should identify opportunities for action at the local, state, federal, and international level.

Effective GHG reduction strategies are likely to be based on a mix of technology, behavioral, and institutional elements. Research is needed that considers synergies, interrelationships, and indirect impacts and benefits. The following four research projects are recommended.

1.5.2 Vehicle Technology and Fuels Strategies

Better understanding is needed of the choices and pathways of transition from conventional vehicles and fuels. Improved knowledge of alternative technologies and their impacts would inform the policy process with respect to pollution, energy use, energy choices, and climate change. Government and the public should seek to be well informed to assure that environmental and social factors are adequately considered in the development, evolution, and use of these products. The challenge is to complement and not duplicate industrial R&D.

Proposed Research Knowledge is needed to inform public strategies for diesel engines, hydrogen fuel, fuel cells, and a variety of other options. For instance, diesel fuels and engines have higher emissions of nitrogen oxides and particulate matter than gasoline combustion, but substantially lower greenhouse gas emissions and energy consumption. How large are these effects, and what are the countervailing effects on human and ecosystem health? Likewise, hydrogen and fuel cells are widely seen as the leading candidate for the dominant fuel and vehicle propulsion technology of the future, partly due to their potential superior environmental attributes. Better understanding is needed of the costs and benefits, the role of public policy in developing new fuel distribution systems, and the role of public policy in aiding the transition to environmentally beneficial fuels and vehicles.

Because of the especially broad crosscutting nature of a hydrogen path, it is recommended that special attention be given to hydrogen. Energy systems of the future will likely use hydrogen and electricity as the energy carriers, probably integrated into a single system. The implications for the transport sector—for fuel distribution, vehicle design and use, fuel and vehicle supplier industries, vehicle maintenance, and vehicle attributes—are large. Eventually, many expect that vehicles would be powered by fuel cells that operate on hydrogen, and likely capable of being integrated into stationary energy systems. In such a system, a long-term transition to hydrogen made from solar and other renewable sources would essentially eliminate emissions of air pollutants and greenhouse gases from the on-road operation of motor vehicles, and reduce international tensions that result from competition for limited petroleum supplies and the current international distribution of petroleum supply and demand.

The transition path to a hydrogen economy is unclear, however. Many different paths may be followed, with different economic, environmental, social, and political implications. Substantial research is already underway in the private sector—on developing better fuel cells for vehicles and electricity production, better hydrogen storage containers, and better hydrogen production processes. Ongoing public research is needed to guide public investments in R&D, support basic research (industry under-invests in these technologies and fuels since a large share of the benefits are market externalities), investigate environmental benefits and costs, inform policies addressing fuel and vehicle safety, air pollution, greenhouse gases, and energy dependence. Research is also needed to anticipate issues associated with the integration of mobile and stationary energy production (e.g., connecting fuel cell vehicles into the electricity grid) and development of hydrogen fuel distribution systems that might be linked with electricity supply systems.

1.5.3 Demand Management Strategies for Greenhouse Gas Reduction and Sustainability

Growth in vehicle miles of travel currently has exceeded growth in both number of households and population for several decades in the U.S. Most forecasts indicate this trend will continue in the absence of any new driving forces or historical dislocations that reduce travel demand. Demand management is one strategy that may reduce growth in vehicle travel and therefore greenhouse gas emissions (and related problems of congestion and air pollutant emissions). Demand management strategies promote the use of alternative modes or reduce the number or length of trips, thus reducing vehicle travel. Specific strategies include pricing strategies, transit, ridesharing, biking, and walking, telecommuting, teleconferencing, and teleshopping. Demand management strategies could be linked with new vehicle and fuel technologies, new intelligent transportation technologies, new mobility services, and land use management and planning. Travel alternatives and trip reduction strategies have been widely implemented, but few studies have explicitly assessed their impact on greenhouse gas emissions and other, broader sustainability goals. Some transport modes have not received as much attention as others. For instance, bicycling and walking are quiet, efficient, non-polluting, healthy, and economical. However, planning for bicycling and walking is often limited by a lack of data and funding. Further, because the use of these modes is fundamentally local, integration of bike and walk strategies into regional plans, programs, and budgets remains problematic. Further, pricing is a fundamental element of any technology strategy and is just beginning to be applied as an explicit demand management strategy. There are few detailed and comprehensive analyses of its impacts.

Proposed Research Four research steps are recommended:

- Inventory the demand management strategies that have been implemented, with particular attention to non-motorized modes and new transportation technologies. Document each strategy’s impacts, in particular its effects on emissions of greenhouse gases and other sustainability metrics.
- Prepare an inventory of the pricing strategies that have been proposed, including congestion pricing, toll pricing of road use, transforming motor vehicle pricing to more accurately reflect the distribution of fixed and variable costs, parking pricing, pay at the pump

insurance, fuel tax increases to include externality costs, emissions charges, carbon taxes, and other pricing strategies. Document social, economic, and environmental costs and benefits associated with each pricing strategy and implementation experience if any, paying particular attention to differences in context and their consequences.

- Prepare case studies of the implementation of major demand management programs at the state, regional, and local levels and document their effects on mobility, environmental quality, energy use, and other measures of sustainability. Investigate and document the incidence of these impacts by income, race/ethnicity, sex, and geographic area (e.g., central city, suburbs). Cases should include an explicit focus on modes and strategies that appear to offer the most promise for greenhouse gas reduction and improved sustainability, while addressing the distribution of who pays and who benefits.
- Investigate and document institutional, political, and other factors that appear to have fostered implementation of demand management strategies. Identify key planning practices and legal and regulatory frameworks, as well as the role of leadership, public education, public involvement, etc. in fostering the implementation of demand management strategies. Also investigate and document factors that have served as barriers to demand management. Recommend strategies for overcoming barriers, recognizing the variety of local circumstances extant in the U.S.

1.5.4 Integrated Transportation-Land Use-Environmental Strategies for Sustainability

Several states and metropolitan regions have implemented programs that combine land use, transportation, and environmental policies into integrated plans and programs. Examples include, the State of Oregon's state and regional planning requirements as implemented and refined over the past three decades, the State of Maryland's smart growth program implemented in 1997, and Atlanta's Georgia Regional Transportation Authority. European Union nations also are starting to implement similar integrated programs as documented by Kågeson in this volume and publications from the European Conference of Ministers of Transport, such as the report, *Implementing Sustainable Urban Travel Policies* (OECD, 2002).

Some programs have been in place for several years, potentially long enough that evaluations of their efficacy will capture long-term effects. The proposed research would document and evaluate these initiatives. The evaluation would be designed to help decision-makers and practitioners understand what land use policies, planning processes, and combinations of travel demand management, environmental policies and plans, capital investment, and technological innovation have been effective—as well as those that have not. It would also be forward looking in examining the planning efforts to incorporate innovations, including transportation innovations such as new types of vehicles and mobility services.

Proposed Research Identify and document integrated transportation, land use, environment, and technology plans and programs in the U.S. and other developed countries.
Identify and evaluate specific policies, regulations, agreements, and other tools included in the plans and programs. Describe plans and programs according to their implementation status as well as social, economic, and environmental performance. Identify specific land use, transportation, and environmental measures and combinations of measures that have proven effective in various implementation contexts, along with the processes through which they have

been implemented. Include measures that have been less successful, together with the apparent reasons for lower than anticipated performance.

1.5.5 ITS Technologies for Sustainability

Intelligent Transportation System (ITS) technologies offer potential opportunities for increasing transportation sustainability that have not been fully identified and evaluated. For example, state departments of transportation are testing the use of ITS to increase safety and improve traffic flow through better traveler information about road conditions and faster removal of disabled vehicles and other road obstacles. Transit operators are using ITS both to manage operations and provide better information to transit users. ITS applications are beginning to extend to provide environmental monitoring—for example, monitoring the transport of hazardous wastes. ITS applications also suggest ways to improve the economic efficiency of the transportation system, for example by using smart card applications for time of day pricing. Additional research could identify a wider range of potential applications of ITS for reducing environmental impact and increasing sustainability. This research could also identify long-term effects of ITS on urban systems and their performance.

Proposed Research This research would evaluate ITS technologies' social, economic, and environmental impacts and identify opportunities for using ITS technologies to improve overall sustainability. The research would identify both near and long-term applications and effects of ITS technologies. For example, ITS technologies could facilitate shared modes of transportation (such as "on-the-fly" car-pooling), permit variable pricing and manage subsidies and other transfer payments, manage parking and provide better information to drivers on its availability and location, coordinate information for multiple modes through automated "mobility management" systems, and improve pedestrian and bike safety. ITS technologies also could be applied to identify gross polluters, monitor and enforce speeds, and otherwise regulate transportation systems for safety and environmental performance. The research will identify new strategies for applying ITS technologies to improve sustainability.

1.6 Ecosystem Impacts

1.6.1 Integrated Planning Strategies and Assessment Methods

In the U.S., a 4-million-mile public road network currently carries 230 million vehicles. This road network was largely built prior to the first Earth Day in 1970, long before the increase in environmental knowledge represented by modern ecology. The TRB's (1997) *Report Toward a Sustainable Transportation Future* identifies ecosystem impacts as a key sustainability issue. Any pervasive transportation transition implies large new transportation infrastructure investments that will impact terrestrial and aquatic systems directly—through siting of hydrogen production and distribution facilities, expanded coal mining for hydrogen production, and crops for bio-fuels to mention some of the options considered by Farrell et al., Williams, and Kågeson in this volume—and indirectly through possible new patterns of settlement and lifestyle expression. Therefore it seems opportune to consider the relationship between transportation and landscape ecology as one step towards "stewardship economics" as discussed by Brown in his contribution to this volume.

Landscape ecology is a rapidly developing body of knowledge and research that represents a relatively new, highly useful, and far-reaching dimension for consideration in transportation planning and activity. Landscape ecology (including the related areas of conservation biology and watershed science) provides principles and models that directly address issues related to transportation networks such as habitat fragmentation; arrangements of green patches; wildlife corridors for foraging, dispersal, and migration; and groundwater and surface-water flow paths. Fragmentation of habitat and severing of migration routes by transportation infrastructure eliminates key adaptive strategies many species might make to large-scale habitat changes caused by global climate change.

Integrating transportation systems with these principles, processes, and models represents a key collaborative opportunity for engineers, ecologists, and planners. The results of such collaboration should have notable application in transportation planning, evaluation of transportation projects, and overall environmental stewardship. They also should establish an important approach for addressing sustainability issues.

Proposed Research The recommended research builds on foundations in transportation research in such areas as hydrology, sediment flow, roadside vegetation management, roadkills, traffic flows, and pollutant emissions—all factors that are critical to environmental sustainability. The research will develop a methodology to integrate transportation systems planning and ecosystems planning. At the planning and ecosystem level opportunities exist to approach problems on a broad basis where the greatest number of options for solution exist. For example, wildlife movements over large habitat areas can be studied to determine the most cost-effective ways of avoiding habitat fragmentation.

The research will identify ways transportation agencies can integrate ecosystem concerns into planning design, construction, and management. This integrated approach should identify opportunities to develop more ecosystem-friendly new projects, as well as identify appropriate maintenance and reconstruction policies and practices, including opportunities to mitigate situations where existing projects fragment habitat, impede migration, or impede fish spawning routes. Lastly, the project will identify ways to better integrate wildlife and plant resource considerations in the NEPA process. Ecosystem approaches should help develop more effective treatment of flora and fauna than the “project area limited species list” approach seen in many Environmental Impact Statements. Ecosystem consideration should facilitate the dialogue between transportation agency and resource agency staff and create opportunities to break away from “compliance” debates toward positive discussions on how to create win-win designs for transportation and wildlife.

1.6.2 Long-Term and Areawide Ecosystem Impacts of Transportation Systems

The majority of roads, railroads, ports, airports, and transportation support infrastructure were built prior to mainstream environmental analysis and assessment. The numbers of vehicles, boats, and miles traveled on these facilities continue to increase. One result is a variety of adverse impacts on the human and natural environments: air pollution, traffic noise, water pollution, congestion, neighborhood disruption, habitat fragmentation, invasive species, disposal and recycling concerns, and climate change. While impact assessment has traditionally been project related, there is growing understanding that cumulative, area-wide, indirect impacts, and their interactions are determinative of overall sustainability. Better methods for addressing cumulative impacts and area-wide impacts must be integrated into transportation planning and evaluation practices if we are to effectively increase the sustainability of the transportation system. Planning and design approaches are needed that would protect and enhance human and natural environments, as well as reestablish healthy conditions in areas that currently are adversely impacted by transportation, if we are to achieve a sustainable transportation system.

Proposed Research This project will identify best practices for addressing the cumulative and area wide impacts of transportation, including when possible the quantification of these impacts. The research also will examine and recommend ways to go beyond the current limited focus of individual transportation projects so that consideration is given to corridor, regional, and systems effects of transportation. The identified practices should allow project proponents to better understand and quantify the cumulative effects of their actions on sustainability. Planning and project development approaches will be recommended that emphasize environmental stewardship and incorporate environmental considerations into project design, rather than focus on simply mitigation. The results could also have utility applied in the NEPA environmental assessment process.

TOPIC TWO: ANALYZE USER RESPONSE TO, AND FUTURE DEMAND FOR, ENVIRONMENTALLY BENEFICIAL VEHICLES, FUELS, AND MOBILITY SERVICES

Public policy addresses the continuing tension between the desires of the individual and the interests of society. Relative to other countries, the U.S. has done more to facilitate the travel desires of its citizens—in particular it has made automobility affordable for a larger fraction of its population. Fuel prices are relatively low, vehicles are lightly taxed, and road capacity and quality have been rapidly expanded. In doing so, it has also nearly made automobility a requirement for full participation in social and civic life.

Given this clear role of government in shaping transportation and travel, to provide a better knowledge base for public policy, research is needed to understand the demand for, and use of, environmentally beneficial vehicles, fuels, and mobility services. Under what conditions, and with what incentives, would individuals and organizations embrace environmental products and services? What might be consumer responses to different packages of innovations? What would be the aggregate consequences for the environment of the ready availability of such products and services on a large scale? Do we even have suitable analytical tools to ask and answer these questions?

2.1 Demand for and Use of New Environmentally Beneficial Vehicles and Fuels

With the proliferation of light-duty vehicles (overall in the U.S., there are now more than one light-duty vehicle per licensed driver) and the introduction of new fuels and propulsion technologies, the opportunity arises to efficiently match specialized vehicles to applications. However, U.S. vehicle users are familiar with only a narrow range of vehicle types and attributes. The U.S. population of private automobiles and light trucks has few small vehicles and almost all vehicles operating on gasoline and diesel fuel. Against these facts, little is known about the demand for novel characteristics of new energy and vehicle propulsion systems. Notably home recharging and refueling, the driving “feel” of electric motor propulsion, the perceived safety aspects of new fuels, the use of smaller vehicles in various settings, or attractions of new auxiliary services made possible by on-board high-power electrical systems are all relatively unexplored.

A number of other questions also arise. Are private companies following or leading the market? Under what conditions might consumers shift buying patterns towards “green” vehicles, and if those products are not already being offered to them, how else would industry know that consumers wanted them? Does the development of new technologies, even without mass commercialization, lead to a restructuring of demand patterns? How might more environmentally benign vehicle technologies be introduced to the marketplace? How might the market be segmented differently if they are introduced? What is the role for social marketing? What additional research is needed to understand the demand for “new” attributes unfamiliar to consumers, especially those that are associated with lower environmental impacts?

2.2 Demand for and Use of New Integrated Packages of Communication and Vehicle Technologies

Many of the above research priorities for vehicles and fuels also apply to new modes of transport and new mobility services that are being created, including smart car sharing, smart paratransit, and dynamic ridesharing. They also apply to information services that permit the spatial and temporal reorganization of activities, notably work and shopping. Under what conditions will individuals and organizations pay for and use new mobility and information service packages? To what extent will purely electronic services complement and/or replace physical movement? People are already using telecommunications spontaneously to become more mobile and more flexible. In the work domain, this seems to have influenced travel behavior more than organized telecommuting: but will the penetration of flexible work become more substantial when it is coupled with smart car-sharing and other innovations?

Patterns of travel and access to activities, goods, and services could be transformed in ways that lead to radically different life and work styles. Integrated information-communication-transportation systems are unlikely to simply substitute into current patterns of demand for transport. There is uncertainty as to whether successful business models for such systems correspond with the systems that produce environmental and social benefits. This uncertainty is compounded if we allow that these systems will change demand for transport.

A particular case of interest is the role of integrated transportation and information services in meeting the mobility needs of the growing elderly segment of the population. What will be the effect on total travel of these technologies, and what will be the environmental and energy impacts? Again, would environmental benefits be greater if governments actively promoted these transformations?

2.3 New Methods for Estimating Demand and Simulating Adoption Paths

In addition to research on the demand for environmentally beneficial vehicles, fuels, and mobility services, research is needed on the *methods* of estimating the penetration of these technologies and alternative paths for their adoption. Conventional models and other methods of projecting private vehicle and travel demand are likely to be less and less helpful to answering these complex questions about emerging technologies, either individually or in integrated systems.

The challenge is to estimate a sufficiently broad set of interacting outcomes in a future that may, in some respects, be unfamiliar. Most survey methods that address stated preferences for particular attributes of new products and services do not provide stable results except for questions that are very limited in scope and frame. Research is needed to improve the design of simulations of consumer responses, such as those used in some pre-market surveys of new types of vehicle, or for exploring responses to unusual circumstances such as fuel shortages. The focus of these methods is more on understanding decision processes than on forecasting outcomes. Understanding demand for technologically advanced packages of mobility, access, and information services also requires new urban modeling tools that take the interactions with land-use into account.

2.4 Understanding Consumer Behavior and Increasing Awareness of Link Between Fuel Consumption and Global Warming

Surveys of the general public in the U.S. indicate that many believe global warming is a concern that needs to be addressed. However, there has been little action in the U.S. in support of this expressed concern. Unlike criteria air pollutants, where public support has led to tough emission standards, there is less public demand to do anything about greenhouse gases. This may be partly due to the fact that people do not understand what can be done. For example, they do not understand the link between fuel efficiency and emissions of greenhouse gases. Further, until recently many of the largest energy companies and automobile makers were allied with others to contest the very notion of global climate change. Faced with an unmotivated electorate and orchestrated industrial opposition, Congress has done little to improve vehicle efficiency since passing the CAFE standards in 1975, promote non-carbon based fuels, or develop zero or near-zero carbon emission energy cycles.

Vehicle purchasers generally rate fuel economy very low on their priority list for selecting a vehicle. It is also very difficult to market improved fuel efficiency to consumers, in part because vehicle purchasers appear to severely discount the value of the fuel savings. While public research on the value consumers place on fuel savings does not exist, sources with access to proprietary data indicate that the average consumer only values about the first three years, or 50,000 miles, of fuel savings.

Proposed Research The first goal of this project is to study and understand consumer behavior with respect to transport and energy. This includes whether and how they get information on fuel consumption, what do they do with it, how it influences their purchase decisions, how much they value fuel cost savings, why they appear not to value fuel savings for the full useful life of a vehicle. The project should provide information that would help researchers and policy makers to assess consumer’s value of fuel savings. It should also include an assessment of how concerns for global climate change and energy security might affect consumer decisions about fuel economy and fuel choice.

The second goal is to assess ways to increase public awareness of the link between fuel consumption and global warming. Different strategies should be assessed, including, but not limited to, consumer education campaigns, advertising, social marketing, and outreach to schoolteachers and administrators. Similar cases, such as the increasing public concern with criteria air pollutants, should be evaluated and assessed for relevant lessons.

A wide variety of theories of decision-making, attitude-behavior correspondence, and cultural influence are available from various disciplines of social science. Even high-involvement decisions—which some insist invoke more detailed decision-making processes that might approach economic rationality—are made by some people on the basis of past experience, personal recommendation, memories formed early in life, a compulsion to conform to culturally-constructed norms, and a variety of other reasons that diverge from economic rationality.

It seems an early step in understanding consumer behavior is to test the hypotheses that the general public does not understand the macro-statistics on energy use, emissions of criteria pollutants and GHGs, health impacts, other impacts of climate change, and the cost of the continued near sole reliance of transportation on oil. If such hypotheses are substantiated, then one research stream would explore under what conditions people would make these connections, and how will such connections would affect their response to new vehicle, fuel, and information technologies.

A short, and by no means complete, list of hypotheses to be addressed would include those listed below.

- The general public does not consider fuel efficiency to be an environmental attribute.
- There may be no corresponding underlying consumer behavior or belief behind statistics on payback periods for investments in automotive fuel economy.
- Attitudes toward fuel efficiency are poor predictors of observed efficiency of purchased vehicles. Family life-stage, income, cohort effects, local and regional land use and transportation, the perceived existence of a standard set of products throughout (American and other) cultures, and several other variables may explain as much or more about vehicle purchase choices than attitudes and subjective norms related to automobiles and automotive efficiency.

2.5 Potential Travel Responses to Alternative Highway Pricing and Financing Systems and the Impact on Fuel Consumption and Greenhouse Gas Emissions

An extensive body of recent research shows that the current pattern of highway travel imposes large costs such as congestion and vehicle emissions that are not borne by motorists who impose them. It also demonstrates that many of the costs of highway travel that are borne by individual users, such as those for vehicle ownership, some types of parking, and insurance, are paid in (more or less) fixed increments even though they may arise as a function of individual trips or vehicle mileage. There remains some need to examine which specific categories of “external” and fixed costs associated with motor vehicle usage actually vary incrementally with the number of trips taken or miles traveled. These costs could thus logically be imposed on a per-trip or per-mile basis. Such charges for highway travel could significantly revise travel decisions by highway users to select other modes, times and frequencies. Precisely how these pricing and financing changes would affect travel decisions is another research topic.

Advances in microelectronic technology currently permit the deployment of non-intrusive, low administrative cost mechanisms for assessing these costs to specific vehicles and travelers who impose them. This situation affords the opportunity for a comprehensive overhaul of the current structure of highway transportation pricing and financing, including a move away from the current reliance on mechanisms such as motor fuel taxes, vehicle registration fees, and property taxation to finance road system construction, maintenance, and administration. This project would evaluate the potential magnitude of behavioral responses to new forms of pricing and the likely levels of such charges, including changes in the volume and patterns of trip-making and the energy efficiency of motor vehicles, and assess the implications of these changes for energy consumption and greenhouse gas emissions in urban transportation.

Proposed Research Research in this area would include the following:

- Identify external costs of highway transportation that are sensitive to changes in the level of vehicle travel and select the best available estimates of their magnitude and reasonable range from the available literature.
- Identify traveler-paid costs that vary with distance traveled but are commonly paid in fixed increments because of institutional arrangements, custom, or other reasons, and estimate their per-mile values.
- Identify the structure and level of taxes currently used to finance transportation infrastructure investments, highway maintenance, and road system administration, including motor fuel, taxes, vehicle registration fees, local property taxes, etc.
- Identify alternative pricing structures for (a) each component of costs now covered by motor fuel or other transportation-related taxes; (b) each motorist-borne cost component now paid in fixed increments; and (c) each empirically significant external cost element associated with highway travel. One of the alternatives should represent an attempt to maximize the social welfare of the highway transport system by economically efficient pricing.
- Use available behavioral theories and empirical evidence to develop a consistent analytic framework for predicting potential behavioral changes in response to the replacement of existing fuel and other transportation taxes and fees with alternative charge structures based on "internalizing" external costs of highway travel and converting fixed vehicle and driving-related expenses to a per-mile or other variable basis. Behavioral changes of interest should include household vehicle ownership levels and vehicle type choices, household-level or fleet-wide average vehicle utilization and total VMT, vehicle and fleet fuel economy, trip characteristics (frequency, timing, length, etc.), density of development, motor fuel consumption, and emissions of criteria pollutants and greenhouse gases.
- Assess the willingness of the public to accept new pricing systems and technologies, (vehicle based and non-vehicle based), and the perceived privacy issues. This public acceptance should be further evaluated within the context of improved information about not only new technological options, but also improved information, education, outreach, and marketing campaigns to enlist the public in the process of technology development, transition strategy identification and advancement, and campaigns to support public policy goals such as public health, reduced risk of global climate change, improved ability of the economy and transportation systems to respond to threats to fundamental energy systems, and to reduce such threats.

2.6 Traveler Attitudes and Behavior Toward Sustainable Transportation

With the proliferation of light-duty vehicles, the availability of low-cost wireless and information technologies, and the introduction of new fuels and propulsion technologies, the opportunities arise to better serve travelers. Implemented as suites or systems of technologies, these may meet travelers' desires at lower cost, higher quality service, and possibly lower environmental impact.

With the advent of new technologies and a growing awareness of the health and livability cost associated with high dependence on automotive travel, it is time to better understand traveler behavior. However, little information currently exists about the public's willingness to accept likely attributes of suites or integrated systems of these new transportation and communication technologies. Research is needed on traveler attitudes and behavior in the context of the broader set of transportation choices becoming available to consumers. Research also is needed on ways to provide the public with information about travel choices, and to educate them about the consequences of their choices.

Proposed Research The proposed research will investigate traveler attitudes and behavior in order to better understand the conditions and circumstances under which travelers would make more sustainable transportation choices, i.e., choose to walk or bike, use car sharing and other mobility services, e.g., dynamic ride sharing, buy and use environmentally beneficial vehicles and fuels, e.g., fuel cell vehicles, small battery electric vehicles, and reduce travel, e.g., through more efficient activity patterns, telecommunications substitutes, etc. The research also will examine ways in which new transportation technologies could be introduced to the marketplace, including the identification of possible new market segments for innovative transportation options. Roles for and effects of marketing and public education, especially with regard to new vehicle and fuel attributes and transport services unfamiliar to consumers, will be examined. Finally, the possibility that new transportation choices could lead to significantly different activity patterns and work styles will be considered in assessing the implications for travel, vehicle choice, energy use, and the environment.

TOPIC THREE: ANALYZE PRODUCER RESPONSE TO ENVIRONMENTALLY BENEFICIAL VEHICLES, FUELS, AND MOBILITY SERVICES

Producers of automobiles have been called on for several decades to reduce emissions of criteria pollutants. With the exception of the removal of lead from gasoline in the 1970s in the U.S., the fuels industry has only more recently been called on to reformulate fuels to assist. As regards fuel economy, vehicle manufacturers have borne more of the responsibility than fuels producers. Historically, both industry groups have resisted direction given to them by government. Yet within these industry groups, individual corporations have responded differently from each other. For example, different vehicle manufacturers responded differently to CAFE—their responses at any point in time being somewhat predictable from the line up of vehicles they manufacture at that point in time.

Changes to cars and trucks over the past few decades demonstrate technological "progress" is a matter of socially defined goals. Whether the source of the goals is "the market" or public policy, the direction of technological development is not solely a matter of technological imperative. Many of the same technologies that were used to increase power, performance, and size of LDVs in the 1980s and 1990s could have been used to improve fuel efficiency. The same situation faces us now. Hybrid electric drive trains can be used to boost either efficiency or performance (or both). The choice is not inherent to the technology.

Promises by the automobile manufacturers of future technological deployments are not necessarily equivalent to promises or requirements to meet emission, efficiency, or fuel type goals. The question then arises, under what conditions would these be equivalent? As policy, resource, and market pressures for change begin to apply to petroleum consumption, will the automobile and petroleum companies invest to improve and extend the life of these "conventional" systems as suggested by White and McNutt in this volume? Or will they be on the vanguard of the transition? If past history provides lessons, we may not be able to treat either the vehicle or fuel industry as a monolith; individual companies are already exhibiting distinct strategies.

The public sector produces much of the transport infrastructure for automobility; it finances, builds, and maintains most of the roadway infrastructure. Additionally, the public sector directs much of the system level transportation and land use planning.[1] Questions about the public sector's role include how it can address transportation related environmental goals through its role as infrastructure provider, and the effects on government of the advent of new vehicle and fuels technology. The classic example of the latter is the impact on gasoline tax revenues of implementing alternative fuels, especially if an exemption from such taxes is part of any incentive scheme. In this volume Hayashi et al. discuss their modeling framework for examining the related effects of changes in the vehicle fleet over time, revenues from several tax instruments, and effects on sustainability metrics such as carbon dioxide emissions.

3.1 Alternatives to CAFE

A longer discussion of CAFE and alternatives to it can be found under Topic Four (see 4.5). There it is treated as part of an assessment of policy frameworks; it is repeated here to emphasize the importance of understanding vehicle producers' responses to alternatives.

3.2 Investments in and Marketing of New Technologies

Under what conditions will vehicle and fuel producers market technologies in a manner consistent with the long-term benefits of an overall transition away from petroleum? Are these conditions different from those that drive shorter-term marketing strategies and profit motives? More broadly, how do the variety of new evolving vehicle and fuel configurations compete both with each other and with improving petroleum-fueled ICEs for market share and attainment of social and environmental goals?

As with fuel economy, this topic is addressed more broadly elsewhere, but is included here to emphasize the need to understand the producer decision to pursue, for instance, fuel cell vehicles, as opposed to other competing technologies – both conventional and advanced. Why would producers pursue one or another socio-technological pathway?

A related question is the approach to niche marketing. Which producers of vehicles and fuels are likely to be interested in niche markets, and which niche markets?

Proposed Research

- Assess manufacturer willingness to develop, manufacture, sell, and service various alternative fuels and advanced vehicle technologies to a niche market over an extended period of time. What factors change the willingness to sustain presence in the niche market? As illustrated by the examples of Farrell et al. and Brodrick et al. in this volume, this evaluation of manufacturers should not be limited to light duty vehicles.
- Assess fuel provider willingness to establish and maintain a fuel infrastructure and produce, distribute, and sell various fuels to these markets. What factors change the willingness to sustain presence in their market?

3.3 Implications of Climate Changes on Infrastructure: Transport and Potential Adaptations to Climate Changes

Much of our transportation infrastructure—roadway infrastructure in particular—is provided by the public sector. A growing body of research documents the possible effects of climate changes on the U.S. and the world. A National Assessment conducted by the U.S. Global Change Research Program (2000), *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*, discusses a range of potential impacts. These include changes in temperature, shifts in precipitation rates, increasing frequency and severity of storm events, and melting permafrost. The national assessment process has so far included 17 regional assessments that examine the potential effects of climate changes on various regions of the country, as well as five sectoral assessments. While changes in climate, water levels, storm activity, and other effects will each have important implications for transportation infrastructure and operations, little research has yet been conducted to explore these effects, which vary by location. There are numerous studies that could be conducted to examine potential impacts on transportation, as well as numerous possible adaptation strategies to avoid or minimize these effects.

Proposed Research The proposed research would examine the potential effects of climate changes on transportation networks, drawing from the scenarios developed by the U.S. Global Change Research Program's National Assessment, the IPCC, and other scientific research. The research would be conducted as a series of case studies. Each case study would focus on a different region of the United States and/or the effects on a particular mode or service component of the nation's transportation system, e.g. flooding of critical highway and transit facilities, potentially reduced aviation safety and reliability, pavement durability, and marine freight. The studies would include a review of the potential climate changes, and the probability of these changes, based on available science. The impact of these potential climate changes on the transportation element will be assessed. The case studies might include:

- An analysis of the implications of the climate changes on the transportation elements in the region/mode under discussion, including an analysis of the associated risks and costs.
- A discussion of potential adaptation strategies that could be considered by transportation agencies and regional planners.
- An examination of how potential adaptation strategies could be accomplished in a manner consistent with other environmental goals.

3.4 Assessing the Limits of Biofuel Supply for Transportation

Biofuels are gaining attention for reasons that include mandates for oxygen content in gasoline, domestic energy security, compatibility with existing vehicles and fuels, favorable emission characteristics, and low net greenhouse gas production. However, there may be practical limits to the contribution that biofuels can make to fuel supplies. In this volume Kågeson concludes that the potential for bio-fuels in Europe is limited and that it has other more economical applications than in transportation. The case for the U.S. should be examined to assess possible limits. These include limits on the amount of biomass resources available, competition with other uses of biomass, competition for arable land to produce biomass resources, production cost, limitations on blend percentage, e.g., vapor pressure limitations for ethanol in gasoline, cold-flow performance for some types of biodiesel, limitations on production incentives, and availability of vehicles that can use the fuel, e.g., flexible fuel vehicles that can use E85. Options for increasing biofuel quantities include expanding the resource base that can be used, developing advanced production technologies, e.g., cellulosic ethanol production, and imports from foreign countries. Global climate change may affect future biofuels production due to shifts in arable land. In addition, little is know about the stability of biomass feedstock production.

Proposed Research The contribution that biofuels can make to the transportation fuel market should be estimated.

- Estimate the maximum practical production potential for ethanol and biodiesel and other potential biofuels, taking into account the existing resource bases for each, the economics of competing uses, and a range of incentives.
- Estimate the long-term potential (more than 20 years from now) for biofuels production and use, including consideration of additional resources, advanced technology production processes, consideration of the impact global climate change will have on the resource base, and the potential for imports from foreign countries.
- Perform a sensitivity analysis on the factors affecting biofuels production. Technical limitations on the use of biofuels in vehicles should be taken into account when estimating the total amount that could be used as fuel, including an assessment of whether production incentives can lead to future production that is self-sufficient.

TOPIC FOUR: DEVELOP POLICY INSTRUMENTS TO ENCOURAGE ENVIRONMENTALLY BENEFICIAL VEHICLES, FUELS, AND MOBILITY SERVICES

Public policy is to a large extent premised on historical circumstances—social, political, environmental, economic, and technological. The advent of new system-transforming technologies means that many of the central premises of existing policies and policy instruments may no longer be relevant or appropriate. Policies that explicitly reject those conditions, e.g., “technology forcing” policies and regulations, are often offered as either famous examples of government creating a vision of the future or infamous examples of government’s “inability to pick winners.”

Today’s environment, energy, and transportation policies and policy instruments may need to be overhauled. Emissions and fuel economy standards are premised on the use of internal combustion engines and petroleum fuels. Roadway construction and operation standards and traffic rules are premised on all vehicles using all roads. Road financing is premised on vehicles consuming petroleum fuels roughly in proportion to their use. Rules limiting jitney services are premised on the ubiquity and effectiveness of conventional bus and rail services. All of these fundamental understandings and conditions may become anachronistic with the introduction of new fuels and propulsion technologies, and the widespread availability of inexpensive wireless communication. New understandings of environmental threats—largely with respect to climate change and particulate matter—require even further overhaul of policy instruments. New policy research is needed that would maximize health, environmental, and social justice benefits, with explicit attention to opportunities and problems created by new technologies.

4.1 Reform of Policy Instruments to Reduce Energy and Environmental Impacts of Transportation Technologies

Today’s policy instruments may need to be overhauled to deal with the shift away from petroleum fuels and internal combustion engines, the increasing emphasis on particulate matter in vehicle exhaust and climate change threats, and the desirability of making greater use of market instruments. Given these, what type of policy structure might be used to reduce greenhouse gas emissions from transportation? Might it replace or be appended to the existing air quality regulatory structure? How might emissions trading be employed to reduce greenhouse gases? What is the role of voluntary instruments? How might policy instruments be crafted to integrate behavioral and technological strategies? What are the potential advantages and problems associated with introducing passive vehicle monitoring, such as on-board diagnostics linked to a pollution pricing system? How can instruments be devised that allow for tradeoffs between different goals (such as diesel’s lower greenhouse gas emissions but higher particulate emissions)? How should fuel taxes in the U.S. evolve given that they are now calculated on a volumetric basis, and provide most of the funding for roads? As vehicles become more energy efficient and use different fuels, with different units of measurement, differing energy characteristics, and differing greenhouse gas emissions (from vehicle and upstream), the current fuel tax system becomes not only inadequate but grossly distorted. Underlying this empirical research is a need for fundamental social science research on political processes and public knowledge, beliefs, attitudes, and desires.

4.2 An Equitable Regulatory Environment for Emerging Transportation Systems

Minimal research has been devoted to analyzing the policy implications of new transportation system configurations. The more specialized nature of future fuels and vehicles, coupled with the potential to reduce the transaction costs for intermodal travel (with low-cost information and communication technologies), creates the opportunity to link vehicles to applications in a more efficient, and socially and environmentally desirable manner. Instead of buying and using conventional-sized personal vehicles for all trips, travelers could choose alternative options, including: shared lease concepts (e.g. for an "everyday vehicle" in exclusive use plus an allotment of time on vehicles with larger carrying capacity or other attributes such as 4-wheel drive); shared-use vehicles; smart paratransit services that promptly pick one up at home or elsewhere; and small neighborhood electric vehicles. All of these concepts require policy research on regulatory structures that would maximize health, environmental, and social justice benefits, with due regard to the opportunities and problems created by enabling technologies such as electronic toll collection, integrated smart cards for parking, shared-use vehicles and transit, and vehicle positioning. Research is needed with respect to standards and codes, insurance requirements and taxi and jitney regulation. Research is also needed on the best ways to address safety concerns, such as the operating limits of neighborhood vehicles.

In this book, Schipper argues that much of this research and policy making needs to be conducted within integrated experiments conducted by regional and metropolitan governments empowered by policy making at state and national levels. While local jurisdictions may be more sensitive to local needs and variation, they may require a larger policy context to maintain "governance sustainability." While his policy prescriptions are few, Schipper argues that the primary obstacle to progress on all components of the ASIF identity he uses is political will. Political will is required to allow rapid progress in the development and deployment of technologies that can address the IF components—energy intensity and fuel types. Political will is required to affect the AS components—total travel activity by transport modes. The ASIF identity may be as useful a tool for organizing political action as research and development. This brings us to perhaps the central research question posed by Schipper: "How well do the components of ASIF need to be known and monitored for success with technologies and policies?"

4.3 Environmental Life-Cycle Policy Approaches

Over time, efforts to reduce environmental degradation have shifted toward prevention through better product design and more efficient use of resources. Future efforts are likely to go a step further: toward the use of materials and resources that are regenerative, rather than depletive, and that are fully biodegradable or fully re-usable. In this volume Brown offers a new *stewardship economics* as a framework to organize research, knowledge bases, policy, and decision-making with such goals in mind. Research is needed to determine what role government can play in encouraging new and existing companies to design and produce transport technologies that are more sustainable environmentally. A knowledge base needs to be developed to better understand opportunities, costs, and benefits. Possibilities range from the use of more recyclable and less toxic materials to technologies that leave a smaller environmental footprint. A strategy needs to be developed to determine what types of products and companies merit support, the nature of the support, and the economic and environmental benefits of those investments.

4.4 Develop and Analyze the Costs and Benefits of Transportation Strategies to Improve Energy Security

Recent terrorist attacks in the U.S. and turmoil in the Middle East have renewed attention to energy security issues, as a component of national security. Energy security objectives have been offered as one motivation for a variety of initiatives that pursue new transportation technologies, systems or fuels. Energy security concerns stem partly from the supply side, notably the exercise of market power by a few major oil-exporting countries. Another aspect of the supply problem is that many major oil supplies are in politically unstable parts of the world, and there is a risk of oil market shocks from revolutions, wars, embargoes, and accidents. Transportation fuel supply, largely based on oil, is unstable. There have been 18 significant oil supply disruptions in last 50 years. Not all these supply shocks led to major price spikes, but some did lead to large and sustained price increases.

In the face of this unstable supply, the other part of the problem is that demand for fuel is inflexible, especially in the short run and especially in the transportation sector. Therefore, supply disruptions can be and have been costly to the economy. There is a need to assess the merits of transportation strategies which promote greater energy security, by reducing oil use or by increasing the flexibility of the transportation sector to respond to short run shocks in supply or price.

This research will focus on the prospects for enhancing energy security with a variety of transportation initiatives. It will include the expected costs and benefits of measures, which reduce oil demand over the longer term and measures, which increase the flexibility of fuel demand or transportation services demand to adjust to sudden energy emergencies in the short-run. Issues to be addressed include the benefits and costs of reducing long-run petroleum use through conservation, e.g., greater fuel efficiency, or substitution of alternatives for petroleum fuels. In considering the displacement of oil use with alternative fuels, the study will compare strategies based on the use of alternative fuel vehicles with strategies that blend alternative fuels with conventional fuels. Attention will be paid to the effect of fuel diversification on supply risk, which depends in part on the extent to which the supply and price of alternative fuels is linked to that of petroleum fuels.

Examples of measures to promote greater short-run flexibility include the following: establishing a vehicle fleet which relies on a greater diversity of transportation fuels; expanding the use or deployment of dual-fueled and flexibly-fueled vehicles; and creating the capacity for modal shifts or shifts in trip patterns during energy emergencies. A better understanding is needed of the relative cost-effectiveness of these measures in reducing the risks and costs of fuel supply shocks. An important contribution of this research will be to establish a consistent analytical framework for comparing the relative energy-security merits of this diverse set of strategies. These strategies are both short-run and long-run, and create options and capabilities to quickly shift transportation energy patterns. Some consideration will be paid to possible local energy security benefits in specific transportation regions as well as national energy security benefits.

4.5 Analysis of Alternatives to CAFE for Increasing Fuel Economy

The CAFE standards passed by Congress in 1975 attempted to address societal concerns about fuel availability and price. New concerns about global climate change and security have arisen since then. While the CAFE standards have been successful in improving vehicle fuel efficiency, there have also been some unintended consequences, such as possible impacts on safety and differential impacts on manufacturers. The recent report, *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards* (National Research Council/Transportation Research Board, 2002) evaluated the impact of the CAFE structure. The final report recommends the evaluation of possible alternatives to the current CAFE structure, including tradable credits, feebates, higher fuel taxes, standards based on vehicle attributes (for example, vehicle weight, size, or payload), and combinations of these.

Proposed Research The purpose of this research would be to follow up on the NRC Committee work on CAFE and provide analyses of alternatives to CAFE. An evaluation of alternative CAFE structures would also be performed. This should include, but not be limited to the following:

- Fuel economy based systems, where each manufacturer gets a fleet-average fuel economy target, including modification to the existing CAFE structure.
- Attribute-based standards, such as weight, size, and class.
- Market-based system, such as continuously variable manufacturer incentives (feebates).

- Tradable credits should be evaluated for their impact with the first two items in this list.

The goal is to provide comprehensive analyses that could be used to explain each alternative; that is, how the concept works and the impact on cost, manufacturer flexibility, fuel consumption reduction, safety, and inequities between manufacturers. To help illustrate the various impacts, the analyses should include likely manufacturer response. The analysis of each option should include the economic efficiency of the system, equity (or fairness), and potential for gaming (loopholes).

4.6 What Is the Responsibility of the Surface Transport Sector for Sustainability?

While much is known about the impacts of surface transportation on criteria pollutants and some is know about its impacts on greenhouse gas emissions and climate changes, much less is known about its impact on other indices of sustainability. The idea of sustainability is increasingly coming to be understood as a collective process for considered decision-making and action and not simply a particular end-state or outcome. There is growing consensus that sustainability must include economic betterment and social equity, not just a narrow technical focus on greenhouse gases or other aspects of the natural and human environment.

Transportation professionals are being asked to implement projects and programs that are responsive to issues and policies outside their normal realm and which may serve multiple policy objectives under the banner of sustainability. Research is needed to help transportation officials and policy-makers better understand the connection between the surface transportation system and public policy goals that extend beyond motorist safety, air quality, traffic flow, and environmental protection.

Proposed Research As a first step towards developing this better understanding and thus redefining and improving “transportation” policy, research is necessary to document examples of sustainable development initiatives that incorporate transportation projects and programs, both in the U.S. and internationally. This review would provide a broad overview of the ways in which transportation is being used as a tool to achieve more sustainable communities and should focus on identifying:

- Measures and indices of sustainability that incorporate transportation.
- Transportation projects and programs that have been adopted in response to policies aimed at achieving sustainable development.

As a second step, best practices in the U.S. should be presented as case studies. The case studies would identify common elements among successes, pitfalls to avoid, and detailed evaluations. Example case studies include the following:

- Maryland Smart Growth: The state of Maryland implemented a comprehensive smart growth program in 1997. It is designed to ensure that state resources were focused in planned growth areas. It is seen as a model program in the United States, but its effectiveness has not been evaluated.

- New York Quality Communities Program: The state of New York has developed a Quality Communities initiative to encourage infill development and urban renewal within its cities and towns. While comprehensive in scope, the program has not been evaluated for its environmental or preservation benefits.

4.7 Reform of Policy Instruments to Encourage Sustainability and Climate-Friendly Policies

Current public policies and the instruments to implement them reflect past and current environmental, social, political, economic, and technological experience and circumstances. New challenges such as global warming and newly revisited challenges such as national security, as well as the advent of new system-transforming technologies, may require changes to today's policy instruments intended to reduce GHG emissions and petroleum consumption.

Proposed Research Projects in this area would identify needs and opportunities for policy reform and identify policy instruments that may be used to help government agencies and actors manage and take full advantage of changing technologies, as well as respond effectively to possible new environmental challenges such as global warming. The study will address such questions as the following:

- How and at what levels of government might emissions trading be employed to reduce greenhouse gases?
- What is the role of voluntary programs for emissions reductions?
- What are the implications for public policy of moving toward a vehicle fleet that operate on non-petroleum fuels?
- What policy instruments can be devised that allow for tradeoffs between different goals (such as diesel's lower greenhouse gas emissions but higher particulate emissions)?
- What are the regulatory issues associated with potential new patterns of vehicle ownership and use due to the integration of transport and information technologies in systems such as carsharing?
- Will new forms of "smart" paratransit require a rethinking of regulations on transit, taxis, and other forms of transportation?
- What policies and programs are needed for pricing and other demand management strategies to be applied most effectively?

4.8 Institutional Arrangements and Planning Processes for Sustainability

Decision-making institutions must be capable of meeting the challenges posed by global climate change and sustainability issues. This requires capacity building at both the policy and technical levels of transportation agencies, planning organizations, and state and local governments. It also requires exploration of the barriers to effective coordination between transportation decisions and land development. Research is needed to identify the institutional arrangements and policy structures that have the capacity, authority, and public support needed to effectively carry out sustainable transportation planning and project development. The recommended research would address institutional arrangements and finance.

4.8.1 Institutional Arrangements and Planning Processes for Sustainable Transportation

This research would identify institutional arrangements and planning processes that effectively support integrated, performance-based planning and decision-making. Specific topics to be addressed include organizational arrangements and assignments of responsibility, methods and processes for 1) better integrating transportation, land use and environmental planning and programming, considering both capital and non-capital strategies for mobility improvement; 2) communicating the results of sophisticated technical analyses to decision makers and the public; 3) incorporating citizen needs, preferences, and viewpoints into the decision-making process; 4) better coordinating land use and environmental decision making across disparate agencies and programs; and 5) dispute resolution. The research will focus as much or more on institutions as on techniques. The research will examine the contribution of institutional barriers to the current lack of integration of planning functions, and suggest structural changes that can eliminate the most significant barriers.

4.8.2 Transportation Finance

Transportation decision-making is strongly influenced by the sources and amounts of funding available for various activities and by the mandates and limitations imposed on the use of funds. The implementation of sustainable transportation strategies may alter existing petroleum-based revenue streams and also could provide new revenue sources. This project will evaluate how various transportation strategies being proposed for greenhouse gas emissions and petroleum-based fuels consumption reduction and sustainable development are likely to affect transportation revenue streams. For example, petroleum-based taxes will decline as electric-drive and other alternative fueled vehicles penetrate the market; strategies that dampen travel growth and increase vehicle fuel-efficiency may reduce per capita revenues based on fuel consumption. Pricing strategies, on the other hand, would generate new revenues, and how the revenues are directed will have implications for mobility as well as for environmental and economic performance. The project also will identify alternate strategies for providing adequate funding for a sustainable transportation future. For each strategy, efficiency, equity, and political acceptability will be evaluated.

TOPIC FIVE: DESIGN AN INDEPENDENT INSTITUTIONAL CONTEXT FOR RESEARCH AND DEVELOPMENT

Technology development is principally an industrial activity. But transport technologies have large environmental externalities and large societal impacts, and many transport activities are owned, managed, and/or regulated by government. The public sector plays an important role in encouraging the development of technologies that are more environmentally and socially beneficial. Industry R&D resources, especially in the automotive, energy, and information technology sectors, are far larger than the corresponding resources of government. The challenge is to devise a cohesive public sector R&D strategy that leverages and stimulates industrial investments in environmentally beneficial technologies, and provides a knowledge base for designing and implementing efficient and effective public policy toward transportation technologies. A stable and independent institutional arrangement is needed to oversee public

R&D investments related to transport-related technologies, and to assure the continuity and expansion of the knowledge base.

The goals of an independent institutional capability in research and development would be:

- Define and articulate an appropriate and effective role for public R&D in accelerating the development and commercialization of environmentally-beneficial technologies (given the fact that government resources are much less than that of private investment on transportation technologies); and
- Create the scientific basis for effective and wise government policymaking, investments, and regulation with respect to implementing transportation technologies to attain the desired end state of environmental stewardship.

5.1 The Role of Cities in the Transition

Schipper argues in this volume that cities must lead. They are the appropriate geopolitical unit to effect change on a large enough scale to make a difference and a small enough scale to allow genuine experimentation and civic participation. He further argues that higher level (state, national, and international) governments must support cities; among the many reasons is that only larger governmental units insure minimal migration or export of one cities problem to another. (In the U.S., the Ozone Transport Commission is one example of multi-state body formed to address just such a problem.) The goal for government is to acquire the ability to evaluate transportation systems along a broad range of impacts including environmental and social effects. Further, the explicit attention to the role of government underscores the necessary interplay between technological and behavioral approaches. Arguing for a combined technological-behavioral approach, Schipper also recognizes that the private sector (the usual provider of technology) must be a collaborator too. He argues: “Technologies gain strength in the battle against pollution and congestion as other systems that reinforce them are also strengthened….Policies and management strategies must be in tune with technological innovation….”

In effect, Schipper argues for increased analytic capability at the level of city and regional government, combined with a collaborative approach between multiple levels of government and private industry. Such collaborations would implement, test, and promote the positive outcomes of experiments with integrated transportation and land use systems intended to diminish the deleterious effects of mobility.

5.2 Vehicle and Fuels Research and Development

Considerable government funds are invested in cutting-edge research to develop cleaner burning and more efficient vehicles and fuels (as well as to increase the global competitiveness of domestic companies). In recent years in the U.S., much of this R&D has been bundled under the label of the “Partnership for a New Generation of Vehicles,” and now “FreedomCAR.” Much is also spent by the military and through various other programs. Historically, little of this research is directed through the Department of Transportation (DOT), even though DOT administers fuel economy standards. Better vehicle and fuels R&D strategies and more effective R&D programs are needed. Questions to consider are: What strategies and what R&D activities would be most effective? What relative priorities should be given to GHG emissions, particulates and other pollutants, acid deposition, safety, basic science research, and the role of OEMs?

5.3 Improving the Effectiveness of Public Research and Development and Public-Private Research and Development Partnerships

Challenges and problems increasingly cut across many institutional jurisdictions, across political and national borders, and across disciplines. Many transportation and energy companies are increasingly mounting joint R&D ventures, within and across industries. In this context, what is the most appropriate and effective role for public R&D?

Public-private research partnerships for transport technologies launched in the 1990s and early 2000s include FreedomCAR, the Partnership for a New Generation of Vehicles (PNGV), U.S. Advanced Battery Consortium, Intelligent Vehicle Initiative, Future Truck Initiative, and the California Fuel Cell Partnership. While PNGV is often cited as a model, and a series of National Research Council (NRC) reports have evaluated the progress of PNGV, no evaluation has been made of the overall benefits of PNGV, nor of its effectiveness and efficiency in meeting the goal of developing affordable advanced technology.

From the public sector perspective, a better understanding is needed of the opportunities and challenges provided by partnerships between federal agencies, and even more so between federal agencies, universities, state and local governments, small companies, other countries, energy companies, and automaker OEMs. Intra-industry and inter-industry partnerships, which are becoming more common (for instance, between automakers and major suppliers to develop new technologies, and between automakers and oil companies to develop new fuels), should also be understood. Such research is thus about evaluating the *processes* of partnership. It should throw light on the types of companies and partnerships that are most likely to bring environmentally beneficial products to market, and help identify the best methods for leveraging public R&D funds.

5.4 Forecasting and Analysis Tools to Support State and Local Global Climate Change Analysis

Transportation agencies in the U.S. have not had the opportunity to study their current and planned transportation systems, including vehicles and fuels, to examine the degree to which they contribute to climate change. Although the issue is on the minds of many officials, few modeling tools have been made available for climate change analysis. A modeling structure does exist for transportation planning and air quality analysis. It is widely used and supports planning for highway and transit systems and for air quality conformity analysis. Models also are widely used for traffic operations analyses. These models could be enhanced to produce estimates of greenhouse gas emissions.

Proposed Research This project will review the most commonly used models and identify those that could be enhanced in a cost-effective manner to produce information about greenhouse gas emissions pertinent to transportation and land use planning and project programming. The core transportation models would not be entirely rewritten, but additional routines might be added, or alternatively post-processors could be provided to calculate GHG emissions from the vehicles moving on the transportation systems. The models also will be reviewed and recommendations will be made on other modifications to the software to more broadly include benchmarks and sustainability measures (to be addressed in a separate effort.) These models can then be made available to states and MPOs to undertake studies to help understand global climate change consequences of existing transportation systems and proposed changes to them.

5.5 Sustainability Analysis Pilot Program for State and Local Governments

Greenhouse gas emissions and other sustainability issues are of concern to federal, state, and local governments. Policy debates increasingly involve the questions about what they are doing about the possibility of global warming. Although the federal government has been involved in global warming discussions for many years, very few opportunities have existed for state and local transportation officials to evaluate their infrastructure and the vehicles on them to consider the sustainability implications of current policies and practices and the potential implications of project and program proposals. There is an urgent need for state and local officials to better understand the sustainability of their systems if they are to be informed participants in the discussions/debates that will lead to the development of national policies. It would be costly if all state and local governments were to undertake such analysis, especially since at the present time there are no well-established approaches for such studies. A pilot program can serve to develop methods and procedures and to establish the feasibility and desirability of sustainability analysis.

Proposed Research Selected states and MPOs should be supported to undertake pilot sustainability research projects to permit them to understand the degree to which their current and proposed transportation systems are sustainable under criteria—especially those measures developed by research conducted in response to the baseline and benchmark studies discussed under items number 2 and 4 above. Computer software will be provided to allow the selected recipients to undertake a greenhouse gas emissions analysis of their existing systems. The projects will then look at the various policies or policy packages that will be necessary to allow them to meet their sustainability criteria. Based on these case studies, plans should be made to extend the process to other states, MPOs, and other local transportation bodies.

5.6 Freight Transportation and Sustainability

Sustainability consists of economic, environmental, social, and governance components. Economic stability and growth is partially dependent on the movement of freight. Since 1970, truck travel has more than tripled in the U.S. and heavy combination trucks have nearly quadrupled. There is a need for a national, state, and local information system developed for state and MPO planners to facilitate the introduction and evaluation of innovative major infrastructure improvements and investments to promote intermodal coordination and to enhance the efficiency of goods movement. The result should be an increase in economic efficiency and performance and reduced energy use and emissions of greenhouse gases and criteria pollutants.

Proposed Research To achieve an understanding of freight movement, research is needed to identify the sustainability characteristics of freight transport. Furthermore, there is a need for a local, state, and national information system developed to facilitate the introduction and evaluation of innovative infrastructure improvements and investments to promote intermodal coordination and to enhance the efficiency of freight movement leading to sustainability.

Sustainable alternatives will need to consider energy efficiency that will likely require novel and innovative research initiatives for freight systems and major infrastructure investments (i.e., MAGLEV) by government and the transport industry.

CONCLUSION

The current transportation and energy systems of the world are made up of enormous investments with formidable inertia. They include the largest corporations in the world and vast interconnecting public institutions; they are the net result of entrenched interests, historical conditions, values, and behaviors. The final result is not an optimal arrangement, as it is subject to evolving understandings, realities, and preferences.

The challenge is to conjure a collective vision of a transportation and energy system that is efficient, equitable, and environmentally benign. More difficult still is crafting a strategy to get there. New approaches are needed to deliver transportation and energy services that simultaneously promote economic growth, add to the health of communities and individuals, are safe, use energy efficiently, and enhance the natural environment. The greenhouse gas emissions, air pollution, and petroleum dependence of current systems already impose high costs on economic security and growth, and human and environmental health. Growth—in population, vehicles, and travel—adds to the challenges. Innovative responses are needed.

Change is accelerating, not slowing. Renewed effort is needed to forge an investment and policy agenda that will focus research, realign practice, redirect investments, and position institutions to become more informed and engaged players in the critical transportation and energy transitions of the new millennium.

NOTE

1. Intermediate producers of services—freight companies, delivery services, and even households—may also be considered to be producers. However, we address research recommendations to them under other topics.

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