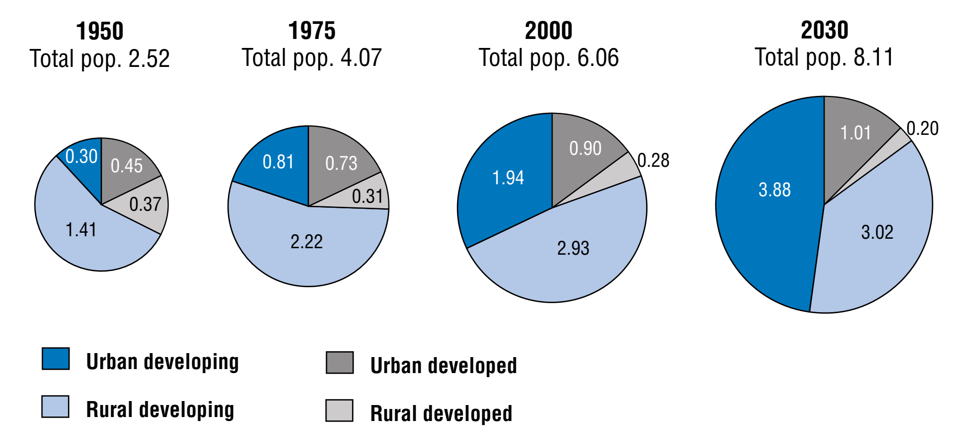
e-lab
RESEARCH REPORTS
MIT LABORATORY FOR ENERGY AND THE ENVIRONMENT
JANUARY–MARCH 2002

Worldwide Mobility: A Status Report and Challenges to Sustainability

MIT researchers and their collaborators have completed a comprehensive assessment of the state of worldwide mobility at the end of the 20th century, and the results are sobering. Demand is escalating for the transport of both people and freight by all modes—cars, trucks, airplanes, railroads—and the increase in travel is overwhelming any environmental gains from using more efficient, cleaner vehicles. Rapid urbanization and suburbanization are causing demand for passenger cars to soar and are undermining the effectiveness of public transport systems—a burden especially for the poor and the elderly, for whom cars are not an option. Highway construction cannot keep up with increasing traffic, especially in the developing world where megacities are characterized by gridlocked old-model cars, traffic accidents and injuries, and health-compromising air pollution. Nearly all transportation modes—land, water, sky—depend on petroleum-based fuels; and as petroleum use skyrockets, so do greenhouse gas (GHG) emissions. If current trends continue, GHG emissions in developing countries will exceed those in developed countries by 2015. Based on those and other findings, the MIT researchers have identified "grand challenges" for special attention, among them adapting the personal motor vehicle by making it safer, cleaner, and more efficient; reducing carbon emissions, perhaps by phasing out carbon-based fuels; strengthening public transport; tackling congestion; and reinventing the process of mobility-related infrastructure development, including the combined use of that infrastructure for personal transportation and freight. The first—and perhaps biggest—challenge is to create the institutional capability and political will needed to tackle such complex, long-term issues. The six-month study was a joint effort of the Laboratory for Energy and the Environment and the Engineering Systems Division and

Mobility and Patterns of Human Settlement

(billions of people)



In addition to supporting social and economic well-being, mobility systems have a profound impact on patterns of human settlement. The figure above shows world population in 1950, 1975, and 2000 and projections for 2030. The growth rate is remarkable, but even more remarkable is the increase in urban dwellers—a trend made possible by the improved mobility of both people and goods. The urban population has gone from 0.75 billion in 1950 to 2.84 billion in 2000; and growth is expected to continue, mainly in the developing world. Indeed, by 2030 almost half the world's population is expected to live in developing-world cities. Already, a defining characteristic of the developing world is its "megacities" of more than 10 million people. Meanwhile, cities are sprawling into suburbs, making public transport systems less effective and the personal vehicle more essential. Thus, the settlement patterns made possible by improved mobility are now driving the nature of demand for mobility—in a direction that raises serious sustainability questions. (Source: United Nations. World Urbanization Prospects: The 1999 Revision. *New York: UN Department of Economic and Social Affairs, Population Division, 2001.)*

IN THIS ISSUE:

involved MIT researchers from 10 departments, laboratories, and centers. Also participating were collaborators from Charles River Associates and from 11 leading fuel and auto companies on whose behalf the World Business Council on Sustainable Mobility commissioned the study. The study now moves into its next phase, which calls for devising strategies aimed at making mobility sustainable over the coming decades.

The 20th century saw an extraordinary expansion in mobility. Greater numbers of cars, trains, and airplanes carried people faster and farther, giving them ever-widening access to job opportunities, social interactions, and a variety of services. Trucks and railways hauled more and more food, manufactured goods, and raw materials over long and longer distances. But expanded mobility also had negative side effects including increases in congestion, urban pollution, GHG emissions, and accidents and injuries. Moreover, the benefits of increased mobility were not reaped equitably. Indeed, certain groups—in particular, the poor and the elderly—are often finding themselves less mobile rather than more.

As we enter the 21st century, people's appetite for mobility remains insatiable. Will the mobility we need now and expect to need in the future be available? And will the economic, environmental, and social costs associated with that mobility be tolerable?

To help answer those questions, MIT and a host of collaborators undertook a six-month, million-dollar examination of the current state of mobility and potential challenges to its sustainability. The study, "Mobility 2001," released in October 2001, presents the most systematic, broad, and comprehensive analysis of mobility to date. It considers both passenger and freight mobility and all modes of transport. It looks at mobility's impact on economic development, environmental quality, and social welfare. And it considers both developed and developing countries.

Perhaps the most unusual feature of the study is its sponsors. The study was commissioned by the World Business Council for Sustainable Development (WBCSD) on behalf of 11 of its member firms, all of them leading fuel companies and automotive manufacturers (see list on page 8). They are among the largest firms in the transportation business today: the auto companies together produce fully two-thirds of the world's vehicles. Thus, they are well placed to influence the evolution of mobility.

In 2000, the firms agreed that they wanted to understand how companies like theirs could help ensure that mobility is sustainable in the future. In response, the WBCSD initiated a three-year project to develop a vision of sustainable global mobility in 2030 and to identify possible pathways and strategies to get there. Because mobility involves our largest infrastructures—transportation systems and cities—measures to produce change by 2030 must be undertaken almost immediately. Moreover, they must be based on a deep understanding of the problem, its history, and its diversity across the developed and developing world.

Mobility 2001—the first phase of the three-year project—provides that understanding and presents a snapshot of the worldwide state of mobility at the end of the 20th century. Assessing the current state of mobility and its impacts in a holistic way, and in just six months, required an extensive team of investigators. At MIT, the study was a joint effort of the Laboratory for Energy and the Environment and the Engineering Systems Division. Researchers from 10 departments, laboratories, and centers collaborated, drawing on expertise gained in other ongoing MIT studies that consider mobility and global warming, transportation networks, transportation technology for 2020, and mobility demand forecasts for 2050. Other collaborators included representatives from Charles River Associates and from the sponsoring fuel and automotive companies. Critical information and a broader perspective were gathered in "stakeholder" meetings with environmentalists, government representatives, researchers, students, and consumer groups around the world.

To perform a systematic assessment, the researchers first needed to define "sustainable mobility" and identify measures of it. According to the WBCSD, sustainable mobility is "the ability to meet the needs of society to move freely, gain access, communicate, trade, and establish relationships without sacrificing other essential human values today or in the future." Thus, for mobility to be sustainable, it must improve accessibility (defined by the US Department of Transportation as the ease by which desired social and economic activities can be reached from a given place) while simultaneously avoiding disruptions in societal, environmental, and economic well-being that more than offset the benefits of the accessibility improvements.

The researchers therefore judged the state of mobility by looking at both sides of the equation. They examined measures that society would like to see increased (access to means of mobility, equity in that access, mobility infrastructure, inexpensive freight transportation) as well as measures that society would like to see reduced or controlled (congestion, various kinds of emissions, noise, accidents, energy use, and others).

The results of their analyses are summarized in the two tables at the right. The top table presents results for the developed world, the bottom for the developing world. The color-coded column indicates whether a given measure is at an acceptable or unacceptable level and the far-right column whether it is getting better or worse.

A glance at the tables shows (not surprisingly) that the developed world is faring far better than the developing world is. The developing world has many measures estimated at an "unacceptable and/or dangerous level"—and most measures (including some of the already-unacceptable ones) are getting worse. Even in the developed world, only two measures are at acceptable levels; and as many measures are getting worse as are getting better.

Some measures are of concern in both the developed and the developing world. One such measure is the overwhelming dependence of transportation on nonrenewable energy, in particular, petroleum. According to the International Energy Agency, fuel derived from petroleum now accounts for more than 96% of all the energy used in transportation. Transportation is responsible for about half the world's total consumption of petroleum; and as mobility increases, the fraction is growing. Use of that petroleum leads inexorably to GHG emissions and—in many regions of the world—to other emissions harmful to health. Given the high energy density of

Sustainability Scorecards

Developed World

Measures to be increased	Level	Direction
Access to means of personal mobility	light blue	+
Equity in access	blue	–
Appropriate mobility infrastructure	blue	–
Inexpensive freight transportation	light blue	+
Measures to be reduced		
Congestion	blue	–
"Conventional" emissions	blue	+
Greenhouse gas emissions	black	–
Transportation noise	blue	+
Other environmental impacts	blue	–
Disruption of communities	blue	–
Transportation-related accidents	blue	+
Transportation's demand for nonrenewable energy	black	=
Transportation-related solid waste	blue	+

Developing World

Measures to be increased	Level	Direction
Access to means of personal mobility	black	+
Equity in access	black	?
Appropriate mobility infrastructure	black	–
Inexpensive freight transportation	blue	+
Measures to be reduced		
Congestion	black	–
"Conventional" emissions	black	–
Greenhouse gas emissions	blue	–
Transportation noise	black	–
Other environmental impacts	blue	–
Disruption of communities	blue	–
Transportation-related accidents	black	–
Transportation's demand for nonrenewable energy	black	=
Transportation-related solid waste	blue	?

Key:
- (black) the particular measure is at an unacceptable and/or dangerous level
- (blue) the level is of concern and needs improvement
- (light blue) the level is acceptable or shows signs of becoming so
- \+ indicates that the situation appears to be moving in the desired direction
- – suggests that the situation appears to be deteriorating
- = no clear direction is apparent
- ? available information is not enough to make a judgment

petroleum-derived fuels, the researchers conclude that the transition to non-carbon-based fuels may be more difficult and take more time than others have forecast.

Also of worldwide concern is the inadequacy of the mobility infrastructure. Surging worldwide demand for mobility is putting extreme stress on current transportation facilities. Construction of new highways, railways, and airports is made difficult by factors ranging from lack of financing to siting problems due to community resistance. Even when it is possible, infrastructure expansion is often quickly overwhelmed by increases in demand for transportation.

Another pervasive problem is the negative impacts of mobility on land and water. Building and using roads, bridges, railroads, and airports sever the landscape and produce runoff, degrading local and regional ecosystems, damaging natural habitats, and reducing biodiversity. Those impacts are occurring at an increasing rate and over an expanding area and may be more damaging in the long term than is generally recognized.

Other measures—congestion, safety, emissions, and so on—vary enough from mode to mode and region to region to warrant a closer look. The following sections focus on conditions in four areas: personal mobility in the developed world, personal mobility in the developing world, intercity personal travel (air and rail), and freight transport.

Personal Mobility in Urbanized Developed Countries

Almost all large cities in the developed world depend overwhelmingly on personally owned light-duty vehicles for motorized personal mobility. In cities of the United States, for example, the private vehicle accounts for about 95% of passenger-kilometers traveled. The number of vehicles per capita and the annual per-capita use of those vehicles continue to grow.

However, some people are becoming less mobile, largely because of dramatic changes in patterns of human settlement. Increasing mobility has made possible a rapid increase in urbanization (see the figure on page 1). At the same time, it has permitted the urban areas to expand outward. As a result, the population densities of most metropolitan areas are declining. Those trends not only increase the need for private automobiles but also undercut the competitiveness of traditional mass transport. The reduced availability of public transport disadvantages two groups: the poor (who may lose access to job opportunities) and the elderly (a population expected to increase in much of the developed world during the next two decades).

Road construction has not kept pace with travel growth, and the inevitable result is congestion. By virtually any measure, congestion is getting worse in most urban areas in the developed world. In some areas it is no longer confined to traditional peak commuting periods but extends through much of the day.

Despite the congestion, accident rates have fallen in almost all developed countries; and people involved in accidents fare better because of structural improvements in vehicles and use of seat belts, airbags, and so on. But the aging of developed-world populations may result in an increase in auto accidents and deaths. The requirements of elderly drivers, passengers, and pedestrians need special attention.

Propulsion systems and vehicles have improved dramatically in recent decades, and advances are expected to continue. However, essentially all developed-world vehicles still use petroleum-based fuels; and together they are now responsible for the majority of worldwide GHG emissions from transportation. GHG emissions are increasing in virtually all developed countries, though the rate of increase has slowed in some countries. Improvements in energy efficiency are more than offset by increases in the number of vehicles and their use and by changes in the vehicle mix. Achieving major and durable reductions in GHG emissions will probably require an eventual shift away from carbon-based fuels.

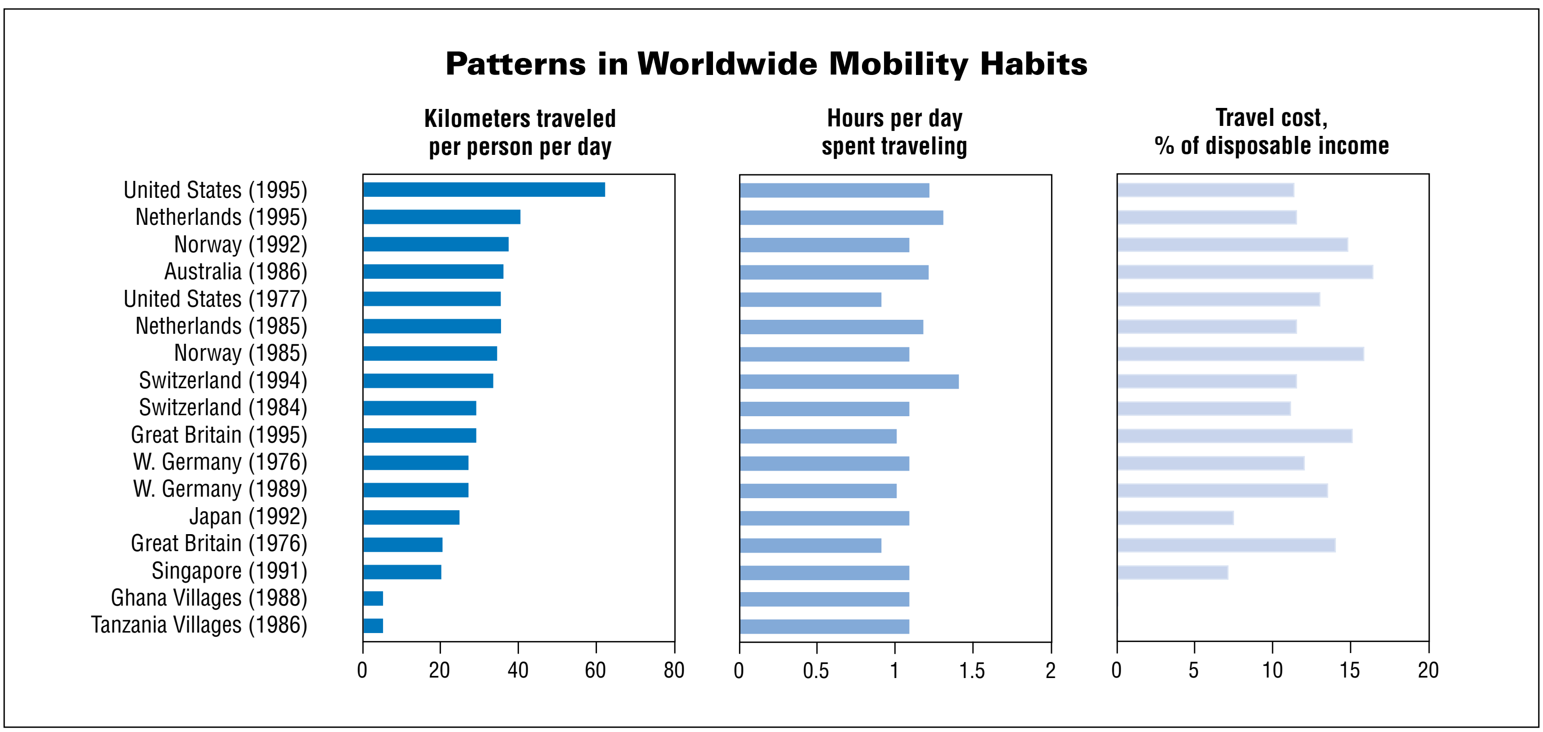
Vehicle emissions also account for much of the air pollution that plagues many cities and poses local and regional health problems. The good news is that levels of "conventional" emissions—sulfur oxides (SO_x), nitrogen oxides (NO_x), particulates, and lead—have stabilized and are declining in many developed countries, despite increased vehicle use. Stricter emissions standards and better technology have reduced emissions per vehicle-kilometer.

Automobiles and light trucks are major users of materials such as steel, iron, aluminum, glass, and plastics. The extent to which those materials are reused varies significantly by region. In the United States, for example, more than 95% of ferrous materials in all scrapped motor vehicles is reprocessed, with at least 75% of the vehicle mass extracted for reuse. In other countries, many vehicles are not scrapped but instead are shipped abroad—for example, from Europe to North Africa and Eastern Europe, and from Japan to Southeast Asia—leading to exportation of the eventual disposal problem.

Personal Mobility in the Urbanized Developing World

In the developing world, most citizens have generally poor levels of mobility; and in many cases conditions are deteriorating even where they had been improving in the past. The central problem is that cities are growing at an astonishing rate, and mobility infrastructures and technologies cannot keep up. The number of vehicles—from bicycles to motorized two-wheelers to cars, trucks, and buses—is growing even more rapidly than the populations are. Incomes, though low, are generally rising, causing the vehicle fleet to expand at a phenomenal rate. (Historical data are consistent the world over: when incomes rise, people buy cars.) In 1996, there were on average about 30 vehicles per thousand people in the developing world (in contrast to 400 or more in the developed world). But in some regions of the developing world vehicle ownership is now growing by as much as 25% per year.

As in the developed world, many cities in the developing world are spreading out; and public transport systems are becoming inadequate. This trend has particularly serious implications in the developing world, where most people cannot afford to buy a car so must rely on public transport. Therefore, while those with growing incomes are buying vehicles and



As background for their study of sustainable mobility, MIT researchers gathered historical information on the distances people travel and the time and money they devote to travel. The results of their analyses showed surprising—and important—regularities in the patterns of movement of people worldwide. The distance people travel has increased during the last 50 years and is greater in richer countries. But the time devoted to transportation is roughly constant. And regardless of their situation, people tend to spend about same fraction of their incomes on personal travel. Thus, as people's incomes grow, they spend more money on travel and substitute faster means of travel for slower ones. Since "faster" relates to total trip time (including access time, frequency of service, and so on), the private car comes out far ahead of public transport, for example. As incomes grow in the developing world, the implications for future mobility are considerable. (Based on A. Schafer, "Regularities in Travel Demand: An International Perspective." Journal of Transportation and Statistics, *no. 3, pp. 1–31, 2000.)*

gaining better access to jobs and other amenities, the poor and less wealthy are gradually losing their primary means of motorized mobility.

Most developing countries have not had the time or money to build new infrastructure, and the lack of highway infrastructure is acute. Even maintenance activities are difficult due to lack of finances. The escalating numbers of vehicles are therefore causing gridlock conditions in many cities. Many trips are still made on foot, and the intermingling of pedestrian traffic with self-propelled and motorized vehicular traffic generates both massive congestion and high accident rates. Indeed, traffic-related deaths and injuries are a serious public health issue in many developing-world cities. The poor are especially affected, and the accident rate is expected to rise due to increasing congestion coupled with poor driving habits and inadequate traffic controls. Seat belts are present in most vehicles but not widely used, and many cars are based on old designs and are less crashworthy than are those in developed countries.

In the developing world, emissions of conventional pollutants are escalating rather than declining. In many countries, vehicles have no emissions controls; those that do are often poorly maintained; fuels tend to be poor in quality; and gasoline still contains lead. In many developing-world cities, ambient levels of pollutants such as ozone, SO_x, NO_x, particulates, and even lead exceed—often by several times—their levels in developed-world cities. Total GHG emissions are lower than in the developed world simply because there are fewer vehicles. However, if the rapid growth in vehicle ownership continues, carbon emissions in the developing world will surpass those in the developed world by about 2015. Demand for petroleum to fuel those vehicles is also a concern. The developing world's share of global transport energy is expected to rise from a third at the start of the 1990s to 44% by 2015.

Intercity Passenger Travel

In the developed world, the principal modes of intercity travel are the private automobile, rail (increasingly, high-speed rail), and commercial aircraft. In the developing world, intercity travel occurs less frequently and mostly by bus, by conventional rail, and, to a small but rapidly growing extent, by air.

Air

Air transportation has been growing extremely rapidly and is generally forecast to continue to do so for the next several decades. In the developed world, air travel is struggling with its own success. Many airports already exceed capacity; air-traffic control systems are heavily overloaded; and delays are increasing. Increasing the capacity of the air transport system is likely to be difficult due to public opposition to airport expansion and construction. In the developing world, growth in air travel is viewed favorably by many governments and their populations, so siting airports seems to be less of a problem.

Airports continue to be a major source of noise and traffic congestion. Technological improvements and retrofits have greatly reduced the noise produced by aircraft as they land and depart, especially in the developed world; but the number of aircraft operations has been growing rapidly enough to offset much of the benefit. The tens of millions of passengers arriving in cars and buses cause airports to be major centers of traffic congestion.

Air transport's contribution to air pollution is surprisingly large and growing. Airports are major local sources of emissions of conventional pollutants, which come from idling aircraft engines; from freight, fuel, and maintenance vehicles; and from vehicles that carry travelers to and from airports. But more important and less appreciated is the significance of air travel's GHG emissions. Air transportation is now responsible for 8–12% of transport-related carbon dioxide (CO_2) emissions. And those emissions make an unexpectedly large contribution to global warming. According to the Intergovernmental Panel on Climate Change (IPCC), the impact on global climate of GHGs emitted high in the atmosphere is about double the impact of GHGs emitted at the earth's surface.

Technological improvements have increased the energy efficiency of airplanes, but the gains have been offset by the growth of air travel and the increasing use of smaller aircraft. Fuel use for air travel is growing substantially faster than is fuel use for road transport, a trend that is expected to continue. Air transport now accounts for about 11% of total transportation energy consumption. By 2015, that level is projected to rise to 13%. Shifting to non-carbon-based fuels is more difficult for air transportation than it is for motor vehicles, primarily due to energy density and storage requirement issues.

Rail

Rail passenger traffic is important in numerous countries, including Japan, China, India, the European Union, and Russia. Many systems in the developing world are poorly maintained and have antiquated rolling stock. In the developed world, some countries are upgrading their rail systems to enable them to compete not so much with road vehicles but with airlines. Interest in high-speed rail is growing in the United States, but whether such systems will be built remains to be seen. Given the troubles facing air transportation, rail's competitiveness may grow substantially in the coming decades.

Railroad stations are usually located in city centers, and they often cause significant traffic congestion and noise in their area (unless they are integrated with subway systems). Where dedicated passenger rail routes cannot be built, passenger trains must share the track with freight trains. In some places, coordinating freight, passenger rail, and commuter rail is a growing problem.

Energy use and emissions per passenger-kilometer are lower for rail travel than for other transport modes (assuming reasonably full trains). However, railroads are not environmentally benign. Unless they are powered by electricity from hydro or nuclear plants, they generate emissions of NO_X, SO_X, particulates, and some level of GHG emissions.

The economic sustainability of rail passenger systems remains a major concern. Rail passenger systems around the world typically run substantial deficits, representing a drain on the budgets of the governments that support them.

Freight Mobility

Freight systems are moving larger and larger quantities of goods, both domestically and internationally, as global trade increases. Freight transportation is relatively energy efficient, yet it uses fully 43% of all transportation energy.

Trucks have always been the principal motorized means of distributing freight locally. In the past, the developed world moved most freight from city to city by railway. But during the past 50 years, intercity freight has shifted increasingly to trucks—a higher-emission, less energy-efficient form of transport. In the developing world, trucks haul most of the growing volumes of freight from the hinterlands to cities and ports.

The vast numbers of freight-carrying trucks are responsible for about 30% of all transportation-related CO_2 emissions; and that share is projected to grow modestly, reaching 33% by 2020. Compared to gasoline engines, the heavy-duty diesel engines that power most large trucks are more efficient but have higher emissions of NO_X, SO_X, and particulates. Improved technologies and fuels are reducing diesel emissions in developed countries, but the gains are modest because of the slow turnover in truck fleets and the rapid growth in freight movements by truck.

Competition is growing between freight and passenger systems for access to existing highways and railways. In some areas, large numbers of trucks on the road restrict the use of highways by passenger vehicles; and dense truck traffic on high-speed motorways creates safety concerns. Trucks can also contribute to infrastructure degradation. If roads are not built to handle high-axle loads, truck traffic can literally pound roads and bridges to pieces. In developing countries, where road infrastructure is often poorly constructed and maintained, high volumes of truck traffic can be especially damaging. Trucks are also major sources of urban congestion and noise (often resulting from poor vehicle maintenance).

In some areas, freight is transported using inland waterways. This mode is extremely energy efficient, but diesel exhaust from towboats and from self-propelled barges can be significant. The biggest challenge here is associated with the construction and maintenance of the required infrastructure. The damming of waterways, building of locks and canals, and dredging of channels to accommodate barge traffic are especially controversial because of the impact of those activities on water pollution and river ecosystems.

The Grand Challenges

The previous sections present just some of the findings from the Mobility 2001 study. The full set of analyses and observations is even more extensive and broad—and perhaps too overwhelming to be useful in identifying strategies that will lead to achievement of the WBCSD goal: sustainable mobility by 2030. The researchers therefore extracted from their findings the following set of seven "grand challenges" that, if successfully addressed, would go a long way toward ensuring that mobility is sustainable.

- Ensure that transport systems continue to serve essential human needs, enhance the quality of life, and support economic development.

• Adapt vehicles to evolving requirements on air-pollutant emissions, vehicle load-carrying capacity, amount of fuel use, and ownership structure.

• Reinvent public transport to provide mobility to those who do not have access to cars and a reasonable alternative for those who do.

• Reinvent the process of planning, developing, and managing mobility infrastructure.

• Drastically reduce CO_2 emissions, which may require transitioning away from carbon-based fuels.

• Resolve the competition for use of infrastructure between personal and freight transportation.

• Tackle congestion by developing a portfolio of mobility options for people and freight.

Technological change can play a major role in addressing most of those challenges. But there is another overarching challenge that transcends any one mode or region: to create the institutional capability and political will needed to tackle such complex, long-term issues. In general, political institutions determine which transportation modes and fuels get favored through subsidies, regulations, and protection from competition. Political and social institutions influence whether transportation infrastructure can be built, where it can be built, how long it takes, and what it costs. Economic institutions can either take the lead in encouraging change or drag their feet and make change more difficult and expensive. Assuming the institutional capabilities that exist today, both developed and developing countries will find it nearly impossible to reach a consensus about what needs to done to make mobility sustainable and then to design, implement, and monitor the necessary plans for change. Thus, institutional capability rather than technological capability may well determine the pace and direction of change in mobility systems.

While the task of achieving sustainable mobility appears daunting, it is not impossible. Mobility 2001 noted a number of promising opportunities and trends. For example, new technologies are successfully reducing conventional emissions from vehicles in the developed world—and could do so in the developing world. Promising technological advances can increase the fuel efficiency of vehicles, decreasing GHG emissions per kilometer traveled; and vehicles powered by non-carbon fuels are beginning to appear. Congestion can be eased by using intelligent transportation systems that provide drivers with better information and by imposing congestion charges that reflect the real-time cost of using roadways. Incentives to get freight off trucks and back on railways could significantly decrease overall energy use and GHG emissions —without involving the millions of individual drivers of passenger cars. And improved telecommunications may make movement of people and certain goods less necessary. Evaluating those and other options will be part of the next phase of the WBCSD project: "Mobility 2030."

MIT leaders of the Mobility 2001 project were David H. Marks, Morton '42 and Claire Goulder Family Professor of Engineering Systems and Civil and Environmental Engineering and director of the Laboratory for Energy and the Environment; John B. Heywood, Sun Jae Professor of Mechanical Engineering and director of the Sloan Automotive Laboratory; and Daniel Roos, Japan Steel Industry Professor of Engineering, Associate Dean for Engineering Systems, and director of the Engineering Systems Division. Project director was George Eads of Charles River Associates. The study was commissioned by the World Business Council on Sustainable Development on behalf of Daimler-Chrysler, Volkswagen, Ford, General Motors, Renault, Honda, Toyota, Shell, Norsk-Hydro, Michelin, and British Petroleum. The report Mobility 2001 *can be accessed via the Laboratory for Energy and the Environment's home page at <http://lfee.mit.edu/> (see reference 1).*

Using a Plasmatron to Cut Engine Emissions and Boost Efficiency

Recent laboratory tests confirm that a small device called a plasmatron may enable today's gasoline and diesel engines to meet increasingly strict emissions standards without major redesign or novel fuels. The plasmatron fuel converter, developed in the late 1990s by researchers in MIT's Plasma Science and Fusion Center, quickly changes liquid fuels—even canola oil—into hydrogen-rich gas. Researchers in the Sloan Automotive Laboratory and the Laboratory for Energy and the Environment have simulated the effects of using the plasmatron on a conventional gasoline engine to convert a small fraction of the liquid gasoline stream into hydrogen-rich gas. In their experiments, they used a standard spark-ignition engine and bottled gas replicating the gas that would form inside the plasmatron. Mixing the bottled gas with the main stream of liquid gasoline and lots of air reduced the engine's tendency to form nitrogen oxides (NO_x), a major contributor to smog. Under optimal conditions, "engine-out" NO_x dropped by 90%—about the same reduction as is achieved by the catalytic converters in today's vehicle exhaust systems. Use of a higher compression ratio and other changes could make the plasmatron-equipped engine almost as efficient as a diesel. In other studies, the researchers are using the hydrogen-rich gas to clean and thus regenerate devices being developed to capture NO_x from diesel exhaust. Cleaning up diesel exhaust poses special challenges but is critical if the highly efficient diesel is to meet future emissions limits.

Ever-tightening regulations on vehicular emissions are creating serious problems for today's engine designers. Gasoline spark-ignition engines must soon be substantially more fuel-efficient with lower emissions of NO_x. Diesel engines are already fuel-efficient; but getting them to meet new, more stringent limits on NO_x and particulate emissions will be difficult. Progress could be made on all fronts if some of the gasoline or diesel fuel could be effectively converted to hydrogen-rich gas. Special devices that can robustly convert those types of fuels are available for industrial applications such as metal processing, but they are as big as a car engine and can consume large amounts of electricity.

In the late 1990s, Daniel R. Cohn, Leslie Bromberg, Alexander Rabinovich, and others in the Plasma Science and Fusion Center (PSFC) produced a small version of that type of device. About the size of a wine bottle, the plasmatron fuel converter accomplishes the same task as its bigger cousin but uses far less power. A mixture of fuel and air is injected into the plasmatron, where an electric discharge converts it into a plasma, a collection of electrically charged atoms and electrons. The plasma accelerates chemical reactions that generate a hydrogen-rich gas (a mixture of hydrogen and carbon monoxide as well as molecular nitrogen from the air). In demonstrations, the research team used the plasmatron to convert gasoline, diesel fuel, and even canola oil into hydrogen-rich gas. The invention won the Discover Magazine Award for Technological Innovation in Transportation in a 1999 competition that included the Toyota Prius hybrid.

During the past couple of years, the PSFC researchers have been teaming up with John B. Heywood, Rudolph M. Smaling, Edward J. Tully, and Jennifer A. Topinka of the Sloan Automotive Laboratory and the Laboratory for Energy and the Environment to figure out exactly what the plasmatron can do as an "onboard fuel refinery." Much of their work has focused on using the hydrogen-rich gas from an onboard plasmatron to make possible a long-sought change in gasoline engine operation: running with extra air.

In today's gasoline engines, fuel and air are mixed in proportions such that when burning is complete, the fuel and the air are both completely used up. But operating with excess air would have advantages. With extra oxygen around, fuel can be used more efficiently (improving fuel economy) and the temperature of the burned gases would remain lower (reducing the formation of NO_x). However, when today's engines operate under such "fuel-lean" conditions, burning is too slow to be practical, and hydrocarbon emissions are too high for the standard catalytic converter to handle.

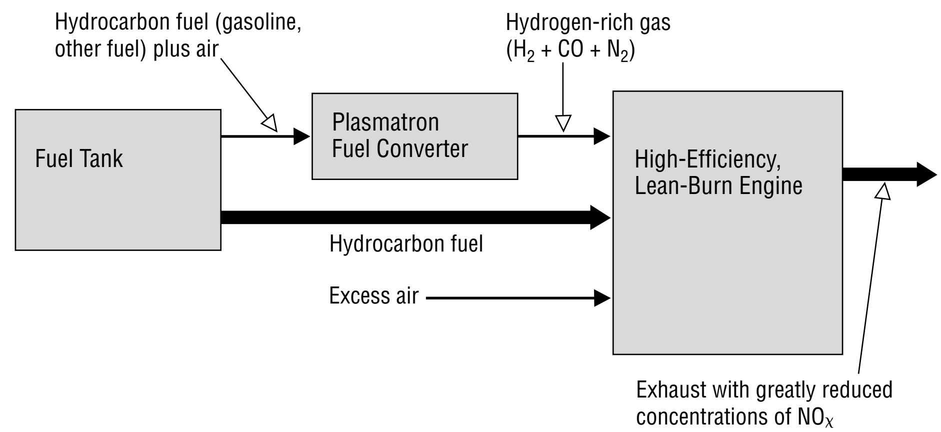
Installing a plasmatron fuel converter can alleviate both of those problems. The diagram on page 10 shows the researchers' concept. A small fraction of the gasoline (for example, 20%) or other hydrocarbon fuel passes from the fuel tank, mixes with air, and enters the onboard plasmatron. Hydrogen-rich gas formed inside the plasmatron mixes with the remaining liquid gasoline entering the engine. Hydrogen burns so quickly that even the small amount of extra hydrogen from the plasmatron significantly speeds up burning inside the engine. When excess air is added to the engine, the burning rate decreases but remains within acceptable bounds. Thus, the plasmatron may be the key to a practical fuel-lean engine—with no need for advanced engine designs or novel fuels.

The researchers have now performed tests simulating the use of the plasmatron fuel converter linked to a four-cylinder car engine. In one series of experiments, they varied the concentrations of hydrogen-rich gas and excess air injected into the engine and measured exhaust emissions. In their best runs, the amount of NO_x in the engine exhaust dropped below 10% of the amount typically generated by a gasoline engine —about the same reduction as now achieved by running exhaust gases through a catalytic converter. About 20% of the energy in the fuel running through the plasmatron is lost (about 4% of the total fuel), but that loss can be more than offset by the gain in energy-conversion efficiency from having extra air present.

Other findings are equally encouraging. In the experiments, the plasmatron ran reliably for long periods of time under realistic conditions without any signs of deterioration. In commercial use, the device should require minimal maintenance. If the electrode does need to be replaced a few times during a car's lifetime, changing it should be as easy and inexpensive as changing a spark plug. And use of the plasmatron fuel converter looks economically attractive, assuming (as early results indicate) that it cleans up exhaust at least as well as a catalytic converter does.

Theoretical studies suggest additional changes to the plasmatron-equipped engine that will substantially increase fuel efficiency without affecting emissions. For example, to minimize energy losses, the researchers are minimizing the amount of gasoline they divert to the plasmatron while maintaining fast-enough burning. They propose optimizing the turbocharging process, compressing the air so as to achieve a sufficiently high air-to-fuel ratio without reducing the amount of fuel. (Injecting less fuel would reduce the engine's maximum power output.) And they are working out ways to increase the compression ratio. In a conventional engine, the compression ratio must be kept relatively low to prevent "knock," the early spontaneous ignition of the fuel-air mixture. With hydrogen-rich gas and excess air present, the researchers will be able to raise the compression ratio—a change that will significantly increase fuel efficiency. With all those changes made, the researchers predict that the efficiency of the plasmatron-equipped engine could approach that of a diesel engine.

Use of the Plasmatron on an Engine Burning Hydrocarbon Fuel



The plasmatron fuel converter, a device the size of a wine bottle, is attached between the fuel tank and the engine. Part of the hydrocarbon fuel plus added air passes through the plasmatron and is converted to hydrogen-rich gas. Mixing that gas with the remainder of the fuel speeds up burning inside the engine, making possible other changes that together significantly increase fuel efficiency and decrease emissions of nitrogen oxides.

Based on the promising results to date, Sloan Automotive Laboratory researchers will continue to define the combustion, emissions, and efficiency characteristics possible in a lean-burning engine equipped with a plasmatron; and the PSFC team will focus on making the plasmatron even more compact and efficient. The plasmatron will then be integrated into a conventional engine, with minimal changes to existing hardware.

The MIT researchers are also working to develop computer simulations that can quantify the effects of specific changes on efficiency and emissions. The goal is to perform detailed cost-benefit analyses for specific regions of the world. Regulatory requirements and fuel costs vary considerably from country to country. For example, the United States has stricter emissions standards but far cheaper fuel than Europe has. Developing countries may have quite different priorities and circumstances. The value of saving fuel, reducing emissions, or changing the exhaust catalyst will therefore differ from place to place. A good computer simulation will enable designers to tailor an engine concept that best meets the needs of specific countries.

The researchers are considering several other applications for the plasmatron. For example, the plasmatron may help efforts to clean up diesel engines. Many researchers are working to develop catalyst "traps" that remove NO_x from diesel exhaust. (Catalytic converters now used on gasoline engines do not work on diesels because of differences in the chemical composition of the exhaust gases.) A major stumbling block is how to remove the captured NO_x to regenerate the trap for continued use. Hydrogen-rich gas from a plasmatron could quickly accomplish that cleanup process. Such gas could likewise be used to regenerate aftertreatment devices that capture particulates from diesels. Cleaning up both NO_x and particulate emissions is imperative if the fuel-efficient, powerful, and reliable diesel is to remain a viable transportation option for the future.

Daniel R. Cohn is a senior research scientist and head of the Plasma Technology Division of the PSFC. Leslie Bromberg is a PSFC principal research engineer and Alexander Rabinovich a PSFC research engineer. John B. Heywood is the Sun Jae Professor of Mechanical Engineering and director of the Sloan Automotive Laboratory. Rudolph M. Smaling is a graduate student in the System Design and Management Program of the Engineering Systems Division. Edward Tully and Jennifer Topinka are graduate students in the Department of Mechanical Engineering. *This research has been supported by the US Department of Energy.* *Further information can be found in reference 2.*

News Items

On Friday, May 3, MIT will hold **"Sustainable Mobility: Global Challenges for the 21st Century,"** a symposium on transportation issues in developed and developing countries. The symposium will highlight the report *Mobility 2001*, which is described in the article on page 1. The symposium will explicitly target each of the seven grand challenges identified in *Mobility 2001*, offering a public platform for discussion of its findings. The event will help set the stage for the next phase of the project, which will focus on sustainable mobility in the year 2030 and the challenge of ensuring sufficient mobility to support economic growth while balancing environmental, energy, and resource requirements. For further information, go to <http://esd.mit.edu/tpp/symposium.htm> on the Web or send e-mail to <tppsymp@mit.edu>.

The **annual meeting** of the **Alliance for Global Sustainability** (AGS) was held on March 21–23 in San José, Costa Rica. The meeting, "Building the Future: Leadership, Technology, Global Citizenship," was led by the four members of the AGS—MIT, the Swiss Federal Institute of Technology (ETH-Zürich), the University of Tokyo, and Chalmers University of Technology (Sweden)—and was hosted by the Instituto CentroAmericano de Administracion de Empresas. At the meeting, scholars collaborated to examine the AGS research and education portfolio and to consider ways in which the academic community—in collaboration with industry, government, and civil society—can help generate a clear and focused research agenda for the future. Topics of discussion included challenges to sustainable development (water, food, energy, transportation, buildings, climate change, other environmental issues, problems of megacities); the role of technology in sustainable development; preparation of the next generation of leaders; and opportunities for collaborative action by industry, governments, and academia. Keynote addresses were given by Professor Jeffrey D. Sachs, Director of the Center for International Development, Harvard University, and by Dr. Eduardo Lizano, President, Central Bank of Costa Rica. The guest dinner speaker was former president of Costa Rica and Nobel laureate Oscar Arias. The 400 attendees included the presidents of the AGS member institutions, world-class scholars, and thought leaders from business, industry, governments, and civil society from both developed and developing countries. A more complete report on the meeting will appear in the next issue of the Laboratory for Energy and the Environment (LFEE) newsletter *Initiatives in Energy and the Environment* and can be found on the Web at <www.globalsustainability.org>.

A new book series, **"Science and Technology: Tools for Sustainable Development,"** has been launched by **Kluwer Academic Publishers** in cooperation with the **AGS.** The series editor is Dr. Joanne M. Kauffman of the LFEE. The aim of the series is to provide timely accounts by authoritative scholars of the results of cutting-edge research into emerging barriers to sustainable development and of methodologies and tools to help governments and civil society overcome them. The work presented draws mainly on research being carried out by the AGS. The level of presentation is for graduate students in natural, social, and engineering sciences as well as policy and decision makers around the world in government, industry, and civil society. The first two books in the series are described in the following news items. For information on the new series, go to <http://www.wkap.nl/prod/s/AGSB>.

Future Cities: Dynamics and Sustainability, edited by Professor Fred Moavenzadeh (MIT), Professor Keisuke Hanaki (University of Tokyo), and Professor Peter Baccini (Swiss Federal Institute of Technology—Zürich), provides new ideas for managing the megacities of our future. Conventional wisdom suggests that cities are sinks of energy, vast drains of natural resources, and obstacles to sustainable development. But the authors in this book claim that, properly managed, cities can be transformative arenas in which raw materials may be rationally and economically developed to support people decently and whole regions in a sustainable manner. The editors' goal is to shape a new way of thinking about megacities—one that promotes their function in modern societies as engines of the ideas, technologies, and loci of political will needed to build a new regime of global sustainability. For book ordering information, go to <http://www.wkap.nl/prod/b/1-4020-0540-7>.

In ***Air Quality in the Mexico Megacity: An Integrated Assessment,*** edited by Dr. Luisa T. Molina of the Department of Earth, Atmospheric, and Planetary Sciences and Institute Professor Mario J. Molina, experts in atmospheric sciences, human health, economics, and social and political sciences contribute to an integrated assessment of the complex elements needed to structure air-quality policy in the 21st century. The analysis is developed through a case study of the Mexico City metropolitan area. The international team of collaborating researchers is coordinated through MIT's Integrated Program on Urban, Regional, and Global Air Pollution, which is led by the editors. The book concludes with an extensive list of policy recommendations, emphasizing the value of integrated assessment and a long-term perspective. Although intended to guide policy makers in the Mexico megacity, the case study presented in the book demonstrates ways for leaders of other megacities to work toward the comprehensive knowledge needed to build robust policy. For book ordering information, go to <http://www.wkap.nl/prod/b/1-4020-0452-4>.

Dr. Petter L. Skantze (PhD 2001 in electrical engineering) and Dr. Marija D. Ilić of the Department of Electrical Engineering and Computer Science have published a new book entitled ***Valuation, Hedging and Speculation in Competitive Electricity Markets: A Fundamental Approach.*** The 232-page book examines the fundamentals of trading in electricity markets and indicates how it differs from trading in other commodities. The goal is to provide both the engineering and the finance communities with the necessary tools to meet the industry challenges. Emphasis is on valuation, hedging, and operational decisions made by market players. The work is based on Dr. Skantze's doctoral research, which was performed under the auspices of LFEE's Competitive Power Systems Group, led by Dr. Ilić. (See *e-lab*, January–March 2001, on the Web at <http://lfee.mit.edu/publications/report/archives>.) Information on ordering the book from Kluwer Academic Publishers is available at <http://www.wkap.nl/prod/b/0-7923-7528-9>.

Publications and References

The following publications covering Laboratory for Energy and the Environment (LFEE) and related research became available during the past period or are cited as references in this issue. Center for Advanced Nuclear Energy Systems (CANES) reports are available from Michael Messina, MIT Department of Nuclear Engineering, Room 24-215, Cambridge, MA 02139-4307 (tel.: 617-253-7407). MIT theses may be ordered from the Libraries Document Services, MIT, Room 14-0551, Cambridge, MA 02139-4307. Other publications may be ordered from LFEE Publications, MIT, Room E40-473, Cambridge, MA 02139-4307, only if a price is assigned and only if prepaid by check payable to "MIT Laboratory for Energy and the Environment." Prices are postpaid surface mail. For air delivery, add 15% to US, Canada and Mexico, and 30% elsewhere. A list of publications is available on request.

Publications marked by an asterisk (*) can be found or are forthcoming on-line via the following addresses:

Laboratory for Energy and the Environment:

http://lfee.mit.edu

Center for Energy and Environmental Policy Research:

http://web.mit.edu/ceepr/www/

Joint Program on the Science and Policy of Global Change:

http://web.mit.edu/globalchange/www/

Instructions for ordering paper copies of the reports and working papers are also available at the above-listed sites or by telephoning 617-258-0307 for LFEE publications, 617-253-3551 for Center publications, and 617-253-7492 for Joint Program publications.

Reports and Working Papers

Babiker, M., H. Jacoby, J. Reilly, and D. Reiner. *The Evolution of a Climate Regime: Kyoto to Marrakech.* Joint Program on the Science and Policy of Global Change Report No. 82. 17 pages. February 2002.*

Ellerman, A. *Analysis of the Bush Proposal to Reduce the SO_2 Cap.* Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 2002-002WP. 16 pages. February 2002.*

Ellerman, A. *Considerations for Designing a Tradable Permit System to Control SO_2 Emissions in China.* Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 2001-009WP. 33 pages. October 2001.*

Jacoby, H., and A. Ellerman. *The "Safety Valve" and Climate Policy.* Joint Program on the Science and Policy of Global Change Report No. 83. 11 pages. February 2002.*

Montero, J.-P. *Trading Quasi-Emission Permits.* Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 2002-001WP. 40 pages. January 2002.*

NEW AND RENEWED PROJECTS, JANUARY–MARCH 2002

Topic	Donor or Sponsor	Investigators *(Department)*
GIFTS AND CONTRIBUTIONS		
Center for Energy and Environmental Policy Research (CEEPR) membership	Alstrom Power AG; Bewag; Electric Power Development Co., Ltd.; ExxonMobil Foundation; Mannheimer Versorgungs-und-Verkehrsgesellschaft MBH; Pennsylvania Power & Light Inc.; Shell; Southern Company Services, Inc.; Tennessee Valley Authority; Tractebel SA	
Joint Program on the Science and Policy of Global Change membership	ABB; ChevronTexaco; Electric Power Development Co., Ltd.; Mirant (new member); Statoil; TotalFinaElf	
US Environmental Protection Agency Symposium: Exporting and Importing Air Pollution, Regional and Global Transport	American Chemistry Council; California Air Resources Board; Chevron; ExxonMobil; Health Effects Institute; MARAMA; NACEC; New England States for Coordinated Air Use Management (NESCAUM); Pennsylvania Power & Light; PG&E National Energy Group; Toyota; US Department of Transportation; US Environmental Protection Agency; Volpe Research Center	
NEW PROJECTS		
MIT Alliance for Global Sustainability (AGS)	Alliance for Global Sustainability	
Sustainable Buildings in Developing Countries		L. Glicksman *(Architecture and Mechanical Engineering)*
Designing, Implementing, and Measuring Sustainable Urban Development		R. Gakenheimer *(Urban Studies and Planning)*
Breakthroughs in the System of Sustainable Technologies, Actions, and Institutions: Understanding and Experimenting the Dynamics of Green Innovation		L. Susskind D. Laws *(Urban Studies and Planning)*
AGS Future Cities–Guangzhou: A Partnership for Sustainable Urban and Regional Development in the Pearl River Delta		F. Moavenzadeh *(Center for Technology, Policy, and Urban Development)*

Sokolov, A., C. Forest, and P. Stone. *A Comparison of the Behavior of AOGCMs in Transient Climate Change Experiments.* Joint Program on the Science and Policy of Global Change Report No. 81. 14 pages. December 2001.*

Symposium Summary: Exporting and Importing Air Pollution, Regional and Global Transport. Laboratory for Energy and the Environment Report No. MIT LFEE 2002-001RP. 16 pages. February 2002. Available on the Web at <http://lfee.mit.edu/publications/PDF/LFEE_2002-001_RP.pdf>.

Wang, C. *A Modeling Study on the Climate Impacts of Black Carbon Aerosols.* Joint Program on the Science and Policy of Global Change Report No. 84. 23 pages. March 2002.*

Other Publications

Bromberg, L., D. Cohn, A. Rabinovich, and J. Heywood. "Emissions reductions using hydrogen from plasmatron fuel converters." *International Journal of Hydrogen Energy*, v. 26, pp. 1115–1121, 2001. **(Ref. 2)**

Bugnion, V. "Reducing the uncertainty in the contribution of Greenland to sea-level rise in the 20th and 21st centuries." *Annals of Glaciology*, v. 31, pp. 121–125, 2000.

Cavender-Bares, K., D. Karl, and S. Chisholm. "Nutrient gradients in the western North Atlantic Ocean: Relationship to microbial community structure and comparison to patterns in the Pacific Ocean." *Deep-Sea Research*, v. I, no. 48, pp. 2373–2395, 2001.

NEW AND RENEWED PROJECTS, CONTINUED

Topic	Donor or Sponsor	Investigators *(Department)*
MIT AGS, continued	AGS	
Delivering Research Results to the Educational Process: An Investigation of Approaches and Methodologies		J. Steinfeld *(Chemistry)*
SESAMS—Romania		S. Connors *(Laboratory for Energy and the Environment)*
Yellow Dust: Interactive Model Approaches		K. Polenske *(Urban Studies and Planning)*
Mitigation of Groundwater-Derived Arsenic Hazards and Sustainable Water Supply System in Asian Countries		H. Hemond C. Harvey *(Civil and Environmental Engineering)*
Implications for Greenhouse Gas Emissions of Technological Learning in the Transport Sector		H. Jacoby *(Sloan School of Management)* A. Schafer *(Center for Technology, Policy, and Urban Development)*
Platinum Group Elements from Automobile Emission to Global Distribution		H. Hemond G. Rivizza *(Civil and Environmental Engineering)*
Origin and Potential Control of Air Pollution in the Kathmandu Valley, Nepal		R. Prinn *(Earth, Atmospheric, and Planetary Sciences)*
Isolated Rural Distribution Networks with a Large Penetration of Renewable Sources		M. Ilić *(Electrical Engineering and Computer Science)*
Development and Sustainable Environment in the Greater Mekong Subregion		H. Hemond *(Civil and Environmental Engineering)*
Development of Urban Air Monitoring Network in China Based on Differential Optical Absorption Spectroscopy ("China Sky")		J. Steinfeld *(Chemistry)*
Corporate Strategy, Regulation, and Global Competition		K. Oye *(Political Science)* J. Foster M. Roman *(Center for International Studies)*

Chisholm, S., P. Falkowski, and J. Cullen. "Discrediting ocean fertilization." *Science*, v. 294, pp. 309–310, October 2001.

Forest, C., M. Allen, A. Sokolov, and P. Stone. "Constraining climate model properties using optimal fingerprint detection methods." *Climate Dynamics*, v. 18, pp. 277–295, 2001.

Forest, C., P. Stone, A. Sokolov, M. Allen, and M. Webster. "Quantifying uncertainties in climate system properties using recent climate observations." *Science*, v. 295, pp. 113–117, January 2002.

Gavrilas, M., P. Hejzlar, N. Todreas, and Y. Shatilla. *Safety Features of Operating Light Water Reactors of Western Design.* Available only from CANES through their Web site: <http://web.mit.edu/canes/publications/lwr_book.html>.

Moavenzadeh, F., K. Hanaki, and P. Baccini, eds. *Future Cities: Dynamics and Sustainability.* Volume 1 in Alliance for Global Sustainability Series. Dordrecht, The Netherlands: Kluwer Academic Publishers, 2002.

Molina, L., and M. Molina, eds. *Air Quality in the Mexico Megacity: An Integrated Assessment.* Volume 2 in Alliance for Global Sustainability Series. Dordrecht, The Netherlands: Kluwer Academic Publishers, 2002.

Schmidt, D., V. Wong, W. Green, M. Weiss, and J. Heywood. "Review and assessment of fuel effects and research needs in clean diesel technology." In *Proceedings of the ASME Internal Combustion Engine Division*, 2001 Spring Technical Conference, ICE-Volume 36-1, April 29–May 2, 2001, Philadelphia, Pennsylvania. 15 pages. $10.00

NEW AND RENEWED PROJECTS, CONTINUED

Topic	Donor or Sponsor	Investigators *(Department)*
The Sentient Vehicle: Mobility and the Environment	Cambridge-MIT Institute	J. Heywood *(Mechanical Engineering)* I. Chabini M. Ben-Akiva *(Civil and Environmental Engineering)*
Analysis for Design of the Piston Ring System for a Spray Bore Engine	General Motors Corp.	V. Wong *(Laboratory for Energy and the Environment)*
Plasmatron Fuel Converters—Auto Lab	US Department of Energy—Oakland	J. Heywood *(Mechanical Engineering)*
Plasmatron Project	ArvinMeritor, Inc.	J. Heywood *(Mechanical Engineering)*
National Assessment of Emissions Reduction of PV Power Systems	US Environmental Protection Agency	S. Connors *(Laboratory for Energy and the Environment)*
Alternative for the Transition to Sustainable Electric Services in Northern Europe	Ford Motor Co.	S. Connors *(Laboratory for Energy and the Environment)*
RENEWED PROJECTS		
Strategic MIT-INEEL Nuclear Research Collaboration	Bechtel BWXT Idaho, LLC	M. Kazimi *(Nuclear Engineering)*
Advanced Nuclear Fuel Cycles for Enhanced Proliferation Resistance		M. Kazimi K. Czerwinski *(Nuclear Engineering)*
Advanced Fuel Project		K. Czerwinski *(Nuclear Engineering)*
Pebble Bed Reactor		A. Kadak *(Nuclear Engineering)*
Bismuth Reactor		N. Todreas *(Nuclear Engineering)*
Investigation of an Innovative Gas-Cooled Fast Reactor (new project)		M. Driscoll *(Nuclear Engineering)*

Schwer, D., J. Tolsma, W. Green, and P. Barton. "On upgrading the numerics in combustion chemistry codes." *Combustion and Flame*, v. 128, pp. 270–291, 2002.

Skantze, P., and M. Ilić. *Valuation, Hedging and Speculation in Competitive Electricity Markets: A Fundamental Approach.* Dordrecht, The Netherlands: Kluwer Academic Publishers, 2002.

Taylor, J., F. Pacheco, J. Steinfeld, and J. Tester. "Multiscale reaction pathway analysis of methyl *tert*-butyl ether hydrolysis under hydrothermal conditions." *Industrial & Engineering Chemistry Research*, v. 41, no. 1, pp. 1–8, 2002.

Tester, J., R. Danheiser, R. Weinstein, A. Renslo, J. Taylor, and J. Steinfeld. "Supercritical fluids as solvent replacements in chemical synthesis." Chapter 22 in *Green Chemical Syntheses and Processes*, ACS Symposium Series 767, P. Anastas, L. Heine, and T. Williamson, eds. Washington, DC: American Chemical Society, 2000.

Tolsma, J., and P. Barton. "Hidden discontinuities and parametric sensitivity calculations." *SIAM Journal of Scientific Computing*, v. 23, no. 6, pp. 1862–1875, 2002.

World Business Council for Sustainable Development (WBCSD). *Mobility 2001: World Mobility at the End of the Twentieth Century and its Sustainability.* Prepared for the Sustainable Mobility Working Group of the WBCSD by the Massachusetts Institute of Technology and Charles River Associates Inc. 188 pages. 2001.* **(Ref. 1)**

York, G., B. Junker, J. Stubbe, and A. Sinskey. "Accumulation of the PhaP phasin of Ralstonia eutropha is dependent on production of polyhydroxybutyrate in cells." *Journal of Bacteriology*, v. 183, no. 14, pp. 4217–4226, July 2001.

York, G., B. Junker, J. Stubbe, and A. Sinskey. "The Ralstonia eutropha PhaR protein couples synthesis of the PhaP phasin to the presence of polyhydroxybutyrate in cells and promotes polyhydroxybutyrate production." *Journal of Bacteriology*, v. 184, no. 1, pp. 59–66, January 2002.

laboratory for energy and the **environment**

Nancy W. Stauffer, editor

Karen K. Luxton, associate editor

ISSN 0739-4233

Nonprofit Organization
US Postage
PAID
Cambridge, Massachusetts
Permit Number 54016

Massachusetts Institute of Technology
Room E40-467
Cambridge MA 02139-4307

Return Service Requested