energy & environment

MIT LABORATORY FOR ENERGY AND THE ENVIRONMENT JANUARY–JUNE 2004

A Multipronged Approach to Curbing Gasoline Use

The key to curbing America's ever-growing appetite for petroleum is not just fuel-efficient vehicles or high gasoline taxes or huge surcharges on gas-guzzling models. It is all of those measures and more, carefully combined into a set of self-reinforcing policies that affects everyone who makes, buys, or uses vehicles and their associated fuels.

This multidimensional approach to tackling the US petroleum consumption problem was outlined by Professor John B. Heywood and graduate student Anup P. Bandivadekar at a March 18 lunchtime seminar hosted by the Laboratory for Energy and the Environment (LFEE).

The United States consumes almost a quarter of the world's petroleum, and current projections suggest that by 2025 it will use 40% more petroleum than it does now (see the table below). About 70% of that petroleum will be imported, and almost three-quarters of it will be used for transportation.

Such tremendous growth in petroleum use has serious environmental implications, Professor Heywood noted. In addition, it sets the stage for possible petroleum system shocks that could disrupt the transportation system on which the US economy and lifestyle depend.

"We've had one or two such shocks, but they were isolated and our economy recovered. What happens if they come more frequently?" Professor Heywood said.

Developing better engine and vehicle technologies and fuels could cut petroleum use and make our transportation system more robust, he said. A recent comprehensive assessment by Professor Heywood, Dr. Malcolm A. Weiss, and

continued on page 4

Fuel Use by Light-Duty Vehicles

	2003	2025 (projected)
Total consumption	**20 million bbl/day**	**28 million bbl/day**
Imported	**55%**	**70%**
Consumed for total transportation	**69% (760 billion liters/yr)**	**73% (1200 billion liters/yr)**
Consumed by light-duty vehicles	**42% (500 billion liters/yr)**	**45% (750 billion liters/yr)**

If the United States is to reduce its rapidly increasing dependence on petroleum, it must focus on its transportation sector, in particular, on light-duty vehicles. In 2003, Americans owned some 230 million cars and light trucks, and close to 90% of all the kilometers they traveled were in those vehicles. As the table shows, without intervention, petroleum used for transportation is going to expand significantly. While most of the percentages in the table do not change dramatically from 2003 to 2025, the absolute quantities consumed jump by as much as 60%. (Sources: US Department of Energy, International Energy Agency.)

Assessing Electronics Recycling Firms

MIT researchers have developed new metrics for assessing the performance of firms that recycle scrapped electronic equipment, a rapidly growing waste stream and major source of toxic pollutants.

The metrics focus not just on how much of a firm's incoming waste is processed but also on the quality and reusability of the materials produced from it—a consideration critical to overall resource efficiency.

The work marks the beginning of a long-term MIT effort to develop analytical methods and tools that the electronics industry can use to identify and select materials, product designs, and process technologies that will improve the sustainability of materials use.

Almost a billion obsolete computers and other electronic devices are scrapped each year, and four out of five of them end up in basements or on sidewalks rather than in electronics recycling facilities. But the electronics recycling business is expected to grow quickly. The number of computers, TVs, VCRs, cell phones, and other electronic devices is escalating; regulations on handling large-scale electronics

continued on page 2

INSIDE:

> **Research Briefs** 5
> **News** 9
> **Reports from Meetings** 10
> **Education Update** 13
> **Publications and References** 15
> **New and Renewed Projects** 18

Assessing Electronics Recycling Firms

continued from page 1

waste streams are becoming more stringent; and public concern is growing about the "dumping" of electronics to countries not equipped to handle such toxic and hazardous materials.

As the need for electronics recycling grows, so does the need for effective measures of how well recycling firms do their job. For the past year, Randolph E. Kirchain, Jr., Frank Field III, Jennifer R. Atlee, and their colleagues in the Materials Systems Laboratory have been developing such measures. In their work, they draw on almost ten years' experience studying the mature, well-functioning recycling industry for another voluminous product stream: automobiles.

To assess the performance of electronics recycling firms, industry, regulators, and customers have focused mainly on the most easily measured indicator: the fraction of a firm's incoming waste stream that ends up as landfill. But minimizing landfill is not enough, according to the MIT researchers.

"Recycling companies will tell their customers, 'Don't worry; virtually none of your material is going to landfill.' While we recognize that that's important, we also know that not all end uses are equal," Professor Kirchain said. "For example, it's preferable to take a pound of recovered plastic and use it to make new components than to use it as roadbed filler."

The quality of the recovered material determines its potential uses. If the quality is sufficiently high, the material can be reused by manufacturers, reducing the need to extract and consume new, or "primary," materials.

To identify recycling firms and processes that achieve good materials recovery, the MIT researchers use a "proxy indicator" for quality, namely, price. "We hypothesize that the price that's received for those (recovered) materials is an indicator of the quality of the materials. A buyer will pay more for materials they can use in manufacturing components than for materials going into a roadbed," said Professor Kirchain.

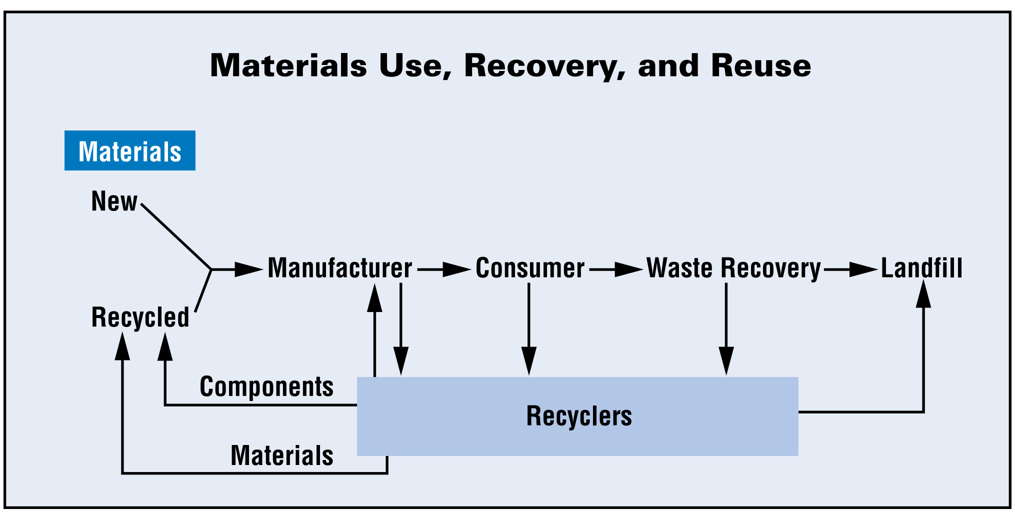
The researchers use two value-based metrics. The first—called value retention—measures how well the value of materials is maintained all the way from their first use to their recovery. (The diagram below shows pathways by which materials can be used, recovered, and reused.) The value-retention metric thus compares the value (or price) of the recovered materials generated by a recycler to the value of the primary materials consumed by the manufacturer of the original equipment (indicated by the market prices of those materials).

But that metric does not show the effectiveness of individual recyclers because recyclers do not start with primary materials. Indeed, the waste streams that firms receive can vary widely in content, value, and ease of recycling. (The design and composition of electronic units can profoundly affect the ease of recovering materials from them.)

The researchers therefore use a second metric—"value added"—to assess the performance of specific recyclers and the processing methods they use. That metric compares the value of the outgoing stream (again, the price of the recovered materials) to the value of the incoming stream (the price the recycler paid for the waste stream or was paid to take it away).

The table on page 3 shows the results of applying the traditional mass-recovery metric and the new, value-based metrics to three US recycling firms. Firms A, B, and C all take in a full range of "end-of-life" electronic products and materials. Most of it is information-technology related, but each firm has a distinct business focus. Firm A tries to maximize material that comes directly from manufacturers (for example, engineering scraps and imperfect products). Firm B receives fairly new equipment and has a high output of components rather than just materials. And Firm C takes in large amounts of telecommunications material.

To perform their analysis, the researchers estimated the compositions of the relevant material flows using models provided by the



recyclers themselves along with published data on the materials contained in different kinds of electronic equipment and scrap. They then assigned values to those flows based on price information from the recyclers as well as prices for primary materials published by the US Geological Survey and industry groups.

As shown in the table, all three firms recover most of the material they receive, sending only a few percent (by mass) to landfills. The traditional mass-recovery metric thus provides little information to distinguish among the three facilities.

In contrast, the value-based metrics suggest substantial differences among the three recyclers. The value-retention results suggest that Firms A and B do equally well at retaining the original value of the materials they process—and far better than Firm C does. The value-added results show that Firms A and B add significantly more value to their incoming flows than Firm C does. Indeed, Firm C adds very little value to its starting materials.

The value-based metrics thus provide guidance on which firms and processing methods are best able to generate high-quality recovered materials. Moreover, the metrics are easy to use. Accuracy will increase if recyclers carefully record the amounts and types of materials they receive in their incoming flows, but the rest of the needed information is already available.

The researchers stress that their materials-only analysis is just a baseline. In particular, it does not incorporate the effect of "device or component reuse." In some cases, recyclers produce intact components, whose value can be far higher than the value of the materials they contain. Not surprisingly, the researchers' initial efforts to include recovered components in their calculations yielded a substantial improvement in the performance of Firm B, which has a high output of components.

The researchers also note that other criteria could be used to assess the performance of recyclers. Examples include toxicity, emissions, energy use, and operating costs. In the long run, developing and using a variety of independent metrics could lead to significant improvements in resource efficiency.

Said Professor Kirchain, "We're interested in measures of performance that will lead to the best electronics-recycling practices. But if we really understand the recycling process, we may also be able to help manufacturers of original equipment make design and materials choices that will make recovering, recycling, and reusing materials easier, safer, and less expensive."

Assessing the Performance of Electronics Recycling Firms Using Three Metrics

	Firm A	Firm B	Firm C
Mass Recovery	97.0%	99.1%	98.8%
Value Retention	32%	33%	23%
Value Added	40%	34%	7%

Mass recovery = percent of incoming flow recovered (by mass)

Value retention = value of recovered materials/value of equipment manufacturer's primary materials

Value added = value of recovered materials/ value of recycling firm's incoming flow

MIT researchers have developed new metrics for assessing the performance of recycling firms based not only on the mass of materials' flows but also on their value, as indicated by their price. The data presented above suggest that the three recycling firms considered in the analysis do equally well at processing most of the material they receive. However, they show varying ability to produce recovered materials of high quality and value.

Randolph E. Kirchain, Jr., is an assistant professor in the Department of Materials Science and Engineering and the Engineering Systems Division. Frank Field III is a senior research associate in the Center for Technology, Policy, and Industrial Development. Jennifer R. Atlee is a master's degree candidate in MIT's Engineering Systems Division. *This research was supported by the Alliance for Global Sustainability and by MIT internal funding. Further information can be found in reference 4.*

A Multipronged Approach to Curbing Gasoline Use

continued from page 1

others at MIT concluded that even "evolutionary" improvements in "mainstream" gasoline and diesel technologies could yield a 35% reduction in fuel consumption in new vehicles in 20 years—and at moderate cost (see references 2 and 3 in the Publications and References section of this newsletter).

But better technology alone may not help. Indeed, over the past 20 years, vehicle efficiency increased by 30%, but any potential fuel savings disappeared because people bought bigger, heavier vehicles and drove them farther and faster.

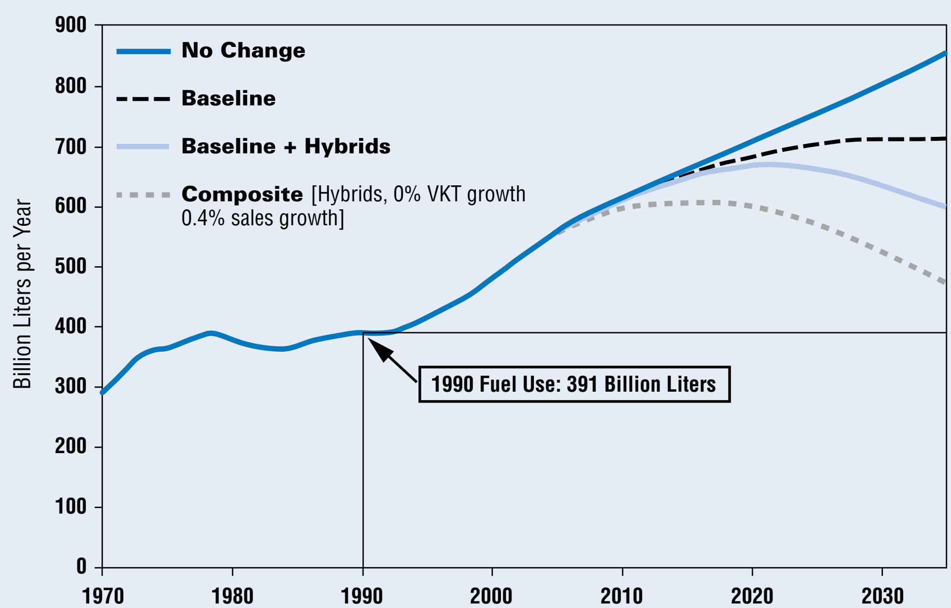
According to Mr. Bandivadekar, gains will come only when we tackle all aspects of the problem simultaneously. "A simple way to think about it is that petroleum use and greenhouse emissions depend on how fuel-efficient our vehicles are, how much we drive, and how carbon-intensive our fuel is. We need to target all those pieces of the puzzle," he said.

As an illustration, Mr. Bandivadekar and Professor Heywood looked at the impacts on fuel consumption of increasing fuel efficiency, of reducing vehicle-kilometers traveled, and then of making both of those changes simultaneously. Using a spreadsheet-based model and data from the automotive industry and other sources, they examined four possible scenarios. Those scenarios and the analytical results are presented in the figure on this page.

The curves in the figure show that tackling two pieces of Mr. Bandivadekar's puzzle—vehicle efficiency and distance traveled—can substantially reduce fuel use by 2035. But those results also demonstrate the difficulty of reducing transportation fuel use significantly in the near future. Climate-change targets are often defined in terms of 1990 levels of consumption. Even with all the changes assumed in the most-aggressive scenario, the estimated consumption in 2035 does not return to 1990 levels—and the researchers believe that the estimates they used in their analysis were optimistic.

What are the best ways to spur the needed changes? To answer that question, the researchers examined all the available policy options—economic incentives such as taxes and subsidies, regulatory actions such as emissions standards and fuel requirements, and public investment, for example, in alterna-

United States Petroleum Use



- **No change –** assumes that fuel consumption remains steady at 2008 levels. (Gains from any fuel-efficiency improvements are offset by losses due to higher performance or added vehicle weight or amenities.) Car sales grow at the same rate as population, and each car goes 0.5% farther each year.
- **Baseline –** adds the evolutionary improvements in technology identified in the comprehensive assessment (references 2 and 3). About half of the efficiency improvements translate into reductions in fuel consumption.
- **Baseline + hybrids –** assumes the previous scenario with the gradual addition of gasoline-electric hybrid vehicles into the fleet. By 2035, half of all the new vehicles sold are hybrids.
- **Composite –** adds to the mix a slowing in the growth of both vehicles sold and vehicle-kilometers traveled (VKT). In this scenario, car sales grow only half as fast as population grows, and the distance traveled by each car remains constant at 2008 levels.

tive-fuel development. For each option they asked a series of questions. How much will it cost? Who will have to pay? How will it affect oil consumption, greenhouse-gas emissions, traffic congestion, vehicle-miles traveled? Will it be politically acceptable? Are there major implementation barriers?

Not surprisingly, the answers varied dramatically from policy to policy—and that variation is key to the researchers' proposal. They believe that the key to success is combining a variety of measures so that they work together. For example, one proposal is a "feebate" system in which customers pay an extra fee to buy big gas-guzzlers but get a rebate if they buy small, fuel-efficient models (a measure that can be designed to be revenue-neutral). The feebate system combines well with stricter corporate average fuel economy (CAFE) standards. Auto manufacturers will be required to make smaller, more efficient cars—and that is what their buyers will want. Adding higher fuel taxes to the package will both discourage additional driving and add further incentive for customers to buy fuel-efficient models. Tax credits elsewhere can offset the added fuel costs so vehicle users will feel no extra financial burden.

As an example, Professor Heywood and Mr. Bandivadekar put together a package that combined stricter CAFE standards, feebates, a gasoline tax that increases by about 2¢ per liter per year, and a requirement for increased biomass-derived content in fuels. According to their best estimates, if we enact that package of policies now, petroleum use and carbon dioxide emissions will be 32% lower in 2035 than if we do nothing. The reduction in total distance traveled will be just 15%—not too much of a hardship for transportation users.

Professor Heywood and Mr. Bandivadekar are now gearing up to take their message to the business community and ultimately to Washington. They believe that an integrated policy package will have more chance of implementation than individual proposals have had. Lobbying groups are less likely to be able to defeat a policy package that spreads responsibility broadly.

"This approach will make people realize that it's not my problem or your problem or Detroit's problem—it's everybody's problem, and everybody will have to do something about it," said Mr. Bandivadekar.

The researchers' final warning: don't wait to take action. A few years' delay now will mean a significantly higher level of petroleum use in 20 or 30 years—and a significantly greater problem to be solved by hydrogen fuel cells or whatever technology we come up with for the long term.

"We need to find ways to change attitudes as well as technologies. It's not clear we'll win, but we'd better try," Professor Heywood said.

John B. Heywood is the Sun Jae Professor of Mechanical Engineering and director of the Sloan Automotive Laboratory. Anup P. Bandivadekar is a PhD candidate in MIT's Engineering Systems Division. Malcolm A. Weiss is a visiting engineer in the LFEE. This research was supported by the Alliance for Global Sustainability (AGS) and the MIT/AGS Consortium on Environmental Challenges. Further information can be found in reference 1. Information on the comprehensive assessment of vehicle and fuel technologies can be found in references 2 and 3.

Atmospheric soot changes regional weather, says MIT study

The fuel-efficient diesel vehicle is widely touted as a climate-friendly technology because of its low carbon dioxide emissions. But diesels also produce soot, which some experts believe is another potent contributor to the greenhouse effect. Is the diesel really a good choice for environmentally conscious automakers to pursue?

A recent MIT analysis concludes that the soot coming from diesels does not contribute to global warming in the same way that the greenhouse gases (GHGs) do. However, it is far from benign in terms of climate. According to the analysis—performed by Dr. Chien Wang of the MIT Joint Program on the Science and Policy of Global Change—soot accumulated in the atmosphere can dramatically influence regional climate, causing precipitation patterns to shift and snow depths to change.

Climate experts often compare GHGs' warming potential at the earth's surface by estimating the change they cause in long-wave radiation (radiated heat) at the top of the troposphere, some 8 to 14 km above ground, just above where airplanes fly. (The troposphere is the layer of the earth's atmosphere in which all weather occurs.) That approach is reasonable when comparing GHGs because they are generally well mixed in the atmosphere, and they all trap heat in a roughly similar manner.

But it does not work well for "black carbon," tiny particles of soot that are emitted when fossil fuels and biomass are burned. Much of the world's black carbon comes from

continued on page 6

continued from page 5

diesel engines; other major contributors are power plants and wood and agricultural-waste fires. Like other types of emitted particles, black-carbon particles do not mix evenly throughout the troposphere. They are short-lived and tend to concentrate within 2 kilometers above the earth's surface, typically downwind of major emissions sources. Black-carbon particles are especially tiny. While heavier particles settle back to earth, black-carbon particles can travel long distances, even from continent to continent. They also influence the formation of clouds and rainfall by serving as nuclei around which water vapor can condense.

To capture all those effects, Dr. Wang formulated a simulation of the atmospheric transport and removal of black carbon as well as its radiative properties. The simulation can track the fate of black carbon in the atmosphere and calculate its effects on cloud formation and rain and on the temperature gradient from the earth's surface up through the troposphere.

To put the black-carbon simulation into context, Dr. Wang inserted it into a three-dimensional climate model developed by the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. The NCAR model has high enough resolution to recognize the vertical distribution of black carbon and its transport by prevailing winds. Dr. Wang could thus investigate interactions between black-carbon aerosols and climate dynamics and physics, including particle transport.

In collaboration with Drs. Monika Mayer and John Reilly, Dr. Wang estimated emissions of black carbon from fossil fuel and biomass combustion around the world. With those estimates plus data on ocean temperatures and other relevant factors, he performed runs of the climate model, both with and without the effects of black carbon.

The simulations confirm that black-carbon particles absorb light and thus heat the atmosphere where they are heavily concentrated. But—unlike the transparent GHGs—they also block sunlight from reaching the ground, so the earth's surface cools. In the simulations, the two effects essentially balance each other out, so Dr. Wang concludes that black carbon has little net impact on the air temperature near the earth's surface. That result is in contrast to the warming that would be projected by the top-of-the-troposphere metric used for GHGs.

However, within 2 kilometers of the earth's surface, the layer of black carbon dramatically alters the temperature profile, the cloud cover, and convection above that layer that moves heat and moisture. The impact in the simulations is a significant change in regional precipitation rates and patterns. In particular, the black carbon causes high-precipitation regions of the tropics and subtropics to shift and snow depths in the middle and high latitudes of the Northern Hemisphere to change.

Those results confirm the importance of capturing interactions between aerosol-related processes and climate dynamics. Dr. Wang is now improving the simulation's characterization of black-carbon particles and their interactions with other types of aerosols, including the much-studied sulfate aerosols that appear to cool the troposphere. Black carbon and its impacts continue to be a major concern, particularly to automakers as they decide whether high-efficiency diesel vehicles are an answer to global climate change or part of the problem.

Chien Wang is a principal research scientist in the Department of Earth, Atmospheric, and Planetary Sciences. Monika Mayer was a research scientist in the Department of Earth, Atmospheric, and Planetary Sciences from 1999 to 2001. John Reilly is the associate director for research of the Joint Program on the Science and Policy of Global Change and a senior research scientist in the Laboratory for Energy and the Environment. *This research was supported by the industrial consortium of the Joint Program on the Science and Policy of Global Change, by the US Department of Energy, and by the US Environmental Protection Agency. Further information can be found in reference 5.*

The Clean Air Act: Measuring its effects on air pollution and infants

Using an unusual approach to analyze existing data, two economists have demonstrated that the 1970 Clean Air Act Amendments (CAAA) not only reduced air-pollution levels but also saved lives during the first year the regulations were in effect.

Measuring the benefits of air-pollution regulation is difficult. The general assumption is that regulations that reduce emissions will mean cleaner air and thus healthier people. Many studies have sought evidence of a correlation between pollution and health. Most often they have looked at health records in cities with differing pollution levels or at changes in health that have occurred during known episodes of high pollution. However, high-pollution and low-pollution cities tend to differ in other ways that can affect the health of their populations. And looking at changes over time is tricky because there is no "experimental control" showing what conditions would have been in the absence of a change in pollution.

Professor Michael Greenstone of MIT's Department of Economics and Professor Kenneth Y. Chay of the Department of Economics at the University of California, Berkeley, have found a "natural experiment" that has enabled them to distinguish the effects of the CAAA. The experiment is made possible by the structure of the CAAA itself, specifically, by its different treatment of different counties across the United States.

The researchers focused on the CAAA rules for "total suspended particulates" (TSPs), a pollutant that is carefully monitored by the Environmental Protection Agency (EPA) and known to affect health. The CAAA established a (somewhat arbitrary) limit for TSPs of 75 micrograms/cubic meter (an annual geometric mean concentration). Any county that exceeded that limit even slightly was deemed "nonattainment" and had to take dramatic steps to reduce emissions from all sources. A county with pollution even slightly below the limit was deemed "attainment" and not subject to those stringent requirements.

Here was the researchers' opportunity. There were a substantial number of counties with pollution concentrations within small ranges above and below the 75 micrograms/cubic meter threshold. In all of those counties—whether just above or just below the threshold—the mean values for other key determinants of infant mortality (for example, per capita income, prenatal care visits, and parents' level of education) were statistically identical. Thus, it seems reasonable to assume that the two sets of counties near the threshold were identical in all ways but one: the nonattainment counties were profoundly affected by the CAAA while the attainment counties were not. The attainment counties could therefore serve as the control group. Changes observed in the nonattainment counties but not in the attainment counties between 1971 and 1972—the first year that the regulations applied—could thus be attributed to the CAAA rules.

Working with EPA data, the researchers found that ambient TSP concentrations in attainment counties changed relatively little between 1971 and 1972. In contrast, in the nonattainment counties there was an abrupt decline, and the higher the starting pollution levels, the greater the drop. According to the analysis, the CAAA elicited a 9–12% reduction in ambient concentrations of TSPs during the first year of its implementation.

But the stated goal of the CAAA was to protect human health. Because the health of adults is influenced by numerous individual behaviors and cumulative effects, the researchers looked instead at babies. Using data from the National Center for Health Statistics, they examined mortality among infants up to one year of age (excluding deaths from accidents and homicides). As with the TSPs, the rate of infant mortality changed only slightly in the attainment counties between 1971 and 1972. But in the nonattainment counties, there was a 3–6% decline.

Based on their analysis, the researchers concluded that roughly 1,300 fewer infants died in 1972 than would have in the absence of the CAAA. Taken together, the data suggest that a 1% reduction in TSPs resulted in a 0.45% reduction in the infant mortality rate. Interestingly, most of the reduction was in deaths occurring within one month of birth, suggesting that fetal exposure is a possible pathway for TSPs to affect health. A series of analyses showed that the researchers' results are robust even when the impacts of a wide set of other causes of infant mortality are taken into account.

In a previous study, Professors Greenstone and Chay came to similar conclusions when they examined data from the 1981 to 1982 recession. During that period, changes in TSP concentrations differed sharply across regions of the country based on the geographic distribution of "dirty" industries. In that study, they found a decrease in infant mortality per unit decrease in ambient TSPs that was strikingly similar to the findings in the present study.

The researchers believe that continued research is needed on the benefits of cutting emissions. As economists, they see environmental regulation as a cost-benefit trade-off. Clearly, environmental regulation is expensive. Driving a car, running a power plant, and manufacturing goods all become increasingly expensive as stricter and stricter emissions limits are imposed. Quantifying the benefits of cleaner air is thus critical as society grapples with the question of what level of regulation is "best."

Michael Greenstone is the 3M Associate Professor of Environmental Economics at MIT. Kenneth Y. Chay is the Peevey-Vial Associate Professor of Economics at the University of California, Berkeley. This research, described by Professor Greenstone at a Laboratory for Energy and the Environment seminar on March 3, 2004, was supported by the National Science Foundation and the National Institutes of Health. Further information can be found in reference 6.

continued on page 8

Research Briefs

continued from page 7

Making gasoline engines run more like diesels

A team of MIT researchers has demonstrated an approach that could permit the gasoline-fueled spark-ignition engine (SIE) to come close to achieving the power, flexibility, and fuel efficiency of the diesel, all while maintaining its primary advantage: low emissions. The key is adding to the gasoline stream a bit of fast-burning gas that is rich in hydrogen or carbon monoxide—a mixture that can be prepared by a small, onboard fuel-conversion device developed and demonstrated at MIT.

The remarkable fuel efficiency and power of diesels are due in large part to their ability to run with a high compression ratio and lots of highly compressed air (more than needed to burn all the fuel). Operating SIEs under those conditions would bring similar gains. But it would also increase the likelihood of knock, the early spontaneous ignition of the air-fuel mixture inside the cylinder that causes a metallic, clanging noise and can potentially damage the engine. Knock is not a concern in diesels because spontaneous ignition due to compression (not a spark) actually starts the burning process. But in SIEs, temperatures and pressures inside the cylinder must be carefully limited to prevent knock—a serious constraint on achieving the operating conditions that make diesels so attractive.

In an effort to ease that constraint, a research team led by Professor John B. Heywood has been testing the effects of equipping an engine with a plasmatron fuel converter, a small device developed in the late 1990s by researchers in MIT's Plasma Science and Fusion Center. Used on a vehicle, the plasmatron converts some of the regular gasoline fuel into a hydrogen- and carbon-monoxide-rich gas. Mixing that gas with the remainder of the gasoline speeds up burning inside the engine. Tests led by Professor Heywood in the Sloan Automotive Laboratory confirmed that a plasmatron-equipped engine can run with a high air-to-fuel ratio, just as the diesel does. The result is dramatically reduced "engine-out" emissions (see *e-lab*, January–March 2002).

In a diesel, both high power and the efficient high-air-to-fuel ratio are achieved by compressing the injected air—a practice known as "boosting" with a turbocharger. (Using less fuel is not an option because power output would drop.) But boosting the plasmatron-equipped SIE might cause the engine to knock.

To find out, the researchers performed a series of experiments using a single-cylinder test engine. They measured its knock behavior using gasoline and then gasoline containing extra hydrogen and carbon monoxide, first separately and then combined in various proportions. They compared the knock behavior of the different mixtures with that of known reference fuels with different octane ratings, the standard measure of a fuel's knock resistance.

The impact of adding the gases was dramatic. When about 15% of the fuel energy was in hydrogen and carbon monoxide, the octane rating was about 10 points higher than that in tests with straight gasoline. (For reference, the octane rating of regular gasoline is about 87, that of premium about 95.) Moreover, the change was linear: the higher the fuel energy in the gas mixture, the greater the gain in octane. Such an improvement in knock resistance would permit not only boosting but also a significant increase in the compression ratio—a change that could produce an additional jump in engine efficiency of 5% or more. Thus, various operating conditions that benefit today's diesels would be possible in an SIE.

To understand their experimental results better, the researchers performed theoretical studies using chemical kinetic models and engine/vehicle simulations. They found that adding extra hydrogen and carbon monoxide slows down the chemical reactions that lead to spontaneous ignition, and the impact is not altered by variations in the air-to-fuel ratio or in the operating conditions or load on the vehicle. Their theoretical estimates of when knock will occur agree well with their experimental observations.

The researchers are now examining how to combine changes in air-to-fuel ratio, boosting, and compression ratio to get the best engine performance. Since using the plasmatron consumes energy, the most effective approach may be to operate it only when the engine is most likely to knock, for example, when the vehicle is going slowly up a hill or accelerating rapidly. If hydrogen becomes more plentiful, as some people predict, one could equip gasoline-fueled vehicles with an onboard tank of hydrogen just to deal with knock.

Professor John B. Heywood is the Sun Jae Professor of Mechanical Engineering and director of the Sloan Automotive Laboratory. *This research was supported by Ford Motor Company. Further information can be found in reference 7.*

News

New website ready to help building designers save energy

MIT researchers are now seeking architects and developers as well as non-experts to test a new, web-based building-design tool called the MIT Design Advisor. Using the tool, anyone planning a new building can readily see how much energy can be saved by orienting the building a certain way, by making it bigger or smaller or taller, or by selecting various types of windows and insulation. Unlike other building-design tools, the website requires only general information, so users can quickly and easily try out basic options before proceeding with a more detailed building design.

Many opportunities exist to make buildings more sustainable, according to Professor Leon R. Glicksman, director of MIT's Building Technology Program. Through that program, collaborators from the Departments of Architecture, Civil and Environmental Engineering, and Mechanical Engineering, and the Laboratory for Energy and the Environment have demonstrated promising energy-saving strategies and technologies. Options range from advanced window systems and high-performance thermal insulation to simple practices such as designing and orienting buildings to maximize natural ventilation, thereby reducing or even eliminating the need for air-conditioning.

Such technologies and approaches can cut energy consumption while providing better air quality and good comfort, often at little or no extra cost. So why are they not used more often, especially in the United States, where buildings consume more than a third of all the energy and half of the electricity used?

According to Professor Glicksman, one problem is that architects do not have adequate simulation tools to guide them. Sophisticated computer programs can predict the energy performance of a building, but figuring out how to use the programs can be a time-consuming challenge. In addition, they require detailed information from architectural drawings. By the time blueprints are available, many critical decisions affecting a building's energy use have already been made.

As an alternative, Professor Glicksman and a team of building-technology students developed the MIT Design Advisor website, an intuitive graphical tool that architects, developers, city planners, and others can use to explore their options in the initial phases of design. Suppose you are planning a new commercial building. Using Internet Explorer on a PC, open the Design Advisor (http://designadvisor.mit.edu). Select "setup," and you'll find an attractive page with a series of questions to answer and choices to make. Where will your building be located, and which way will it face? How many floors will it be, and what will the dimensions of the rooms be? What kind of insulation, window technology, and heating and ventilation equipment will you use? What lighting technology and levels do you want? (In case you need guidance, the US and European lighting standards for various occupant tasks are provided.)

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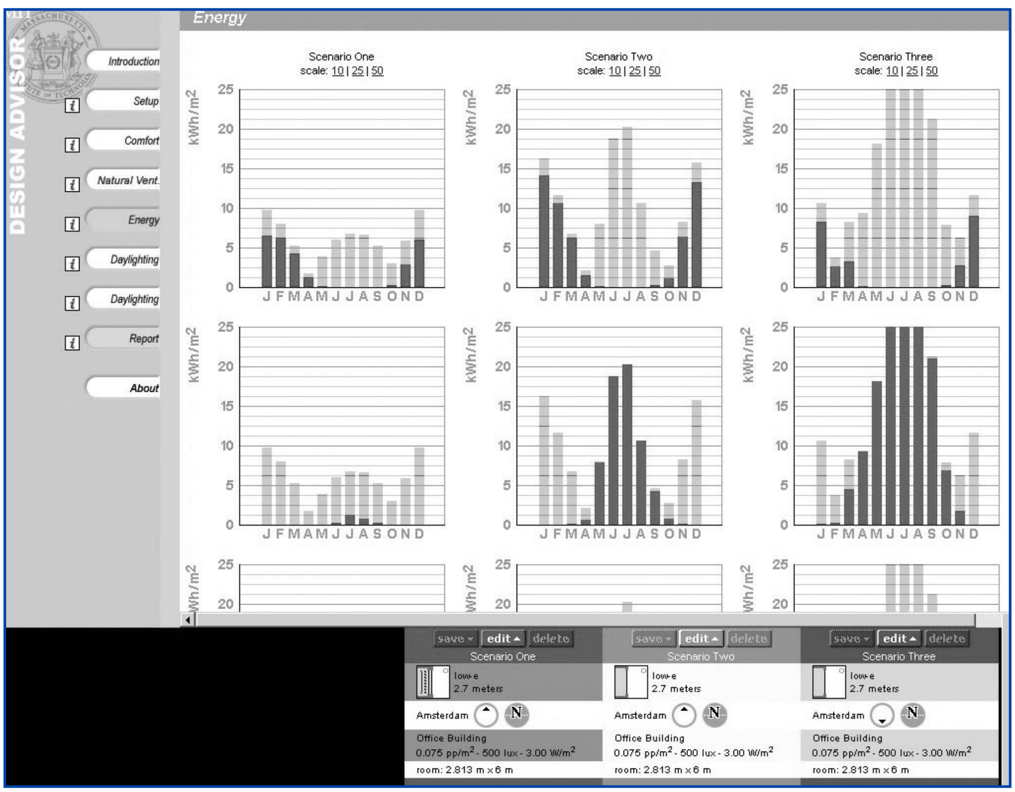


In this image, the MIT Design Advisor has calculated the impacts on energy consumption of using two types of windows in a proposed office building for Amsterdam. Scenario 1 (the left-hand column) assumes an advanced, low-energy window facing north; scenario 2 (the middle column), a conventional window facing north; and scenario 3 (the right-hand column), a conventional window facing south. In each case, the upper chart shows energy consumption for heating and the lower chart, energy consumption for cooling. At the bottom (mostly off-screen) is a row of charts showing energy consumption for lighting. The light gray bars on each chart show total energy consumption for heating, cooling, and lighting. Clearly, an advanced-technology window that faces north is the energy-efficient choice for this proposed building. (Screen shot courtesy of Matthew Lehar, PhD candidate, MIT Department of Mechanical Engineering and Building Technology Program.)

Reports from Meetings

AGS annual meeting focuses on research partnerships

The Alliance for Global Sustainability (AGS) held its annual meeting on March 22–24 at Chalmers University of Technology in Göteborg, Sweden. Among the 300 attendees were leaders of the four partner universities—Chalmers, MIT, the Swiss Federal Institute of Technology–Zürich (ETH), and the University of Tokyo (UT)—as well as researchers, industrial representatives, distinguished public policy makers, and many students involved in AGS-related research projects.

One highlight of the meeting was a forward-looking speech by Professor David H. Marks, director of the MIT Laboratory for Energy and the Environment and coordinator of the MIT/AGS. In his speech, he proposed an ambitious concept involving all four campuses in an integrated research program to investigate technologies and strategies for near- and mid-term energy alternatives.

Another highlight was a presentation by The Honorable Margot Wallstrom, the European Union Commissioner for the Environment. She thanked the AGS for providing experts to help her develop an action plan on environmental technologies that will support EU strategies for economic renewal and sustainable development.

Committed Leadership

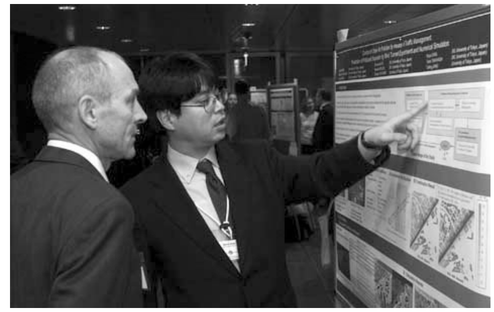
The commitment of the partner universities to the AGS was demonstrated by the presence of their top-level leaders at the meeting. Presidents Charles Vest (MIT), Jan-Eric Sundgren (Chalmers), and Olaf Kubler (ETH) all spoke and chaired plenary sessions. Vice President Hiroshi Komiyama represented UT, and MIT Chancellor Philip Clay was also present. Other universities were also

Speaking at the AGS meeting, EU Commissioner for the Environment Margot Wallstrom emphasizes the role that advanced research plays in the pursuit of sustainability.

represented by their leaders. Hans Weder, Rector of the University of Zürich, participated; and Kwesi Andam, Chancellor of the Kwame Nkrumah University of Science and Technology in Ghana, provided perspectives from the developing world.

An important feature of the meeting was the enthusiastic participation of the business community. Industrialists encouraged researchers to discover, innovate, and advise them on practicable strategies to achieve competitive and sustainable industrial processes. Business leaders chaired plenary sessions and joined in discussions at the meeting. Keynote speakers at the opening session included Lars G. Josefsson, CEO of Vattenfall AB, Sweden; Thomas Connelly, CTO of DuPont; and Hans-Olov Olsson, President and CEO of Volvo Car Corporation.

Leaders from non-governmental organizations (NGOs) provided their views on priorities for sustainable development. Oystein Dahle, Chairman of the Worldwatch Institute, also delivered a keynote address. Other commentary came from Mons Lonnroth of MISTRA, the Foundation for Strategic Environmental Research, which is based in Sweden and supports strategic environmental research with a long-term perspective.



During the poster session of the AGS annual meeting, Professor Ryozo Ooka (right) of the Institute of Industrial Science, University of Tokyo, discusses his research with Dr. Alfred Moser of the Department of Architecture, Swiss Federal Institute of Technology–Zürich.

Student Participation

The AGS meeting was enhanced by the participation of members of the World Student Community for Sustainable Development (WSC-SD). Their annual meeting, held March 17–21, focused on sustainable cities. Many of the students participate in AGS projects and contributed to plenary and workshop discussions. Students also produced an array of fascinating posters illustrating their wide-ranging sustainability research. The posters were presented in an evening session, and the best were recognized at the final plenary session.

Workshops

The heart of the meeting was seven workshops at which investigators and commentators discussed the past year's research into areas of special interest. Each workshop met for several hours each day, and participants presented findings at the final plenary session. In each workshop, "challengers" from industry, government, and other groups were invited to comment on how the research might eventually apply to the types of problems they face.

The first three workshops focused on results from AGS research partnerships established in 2003. Other workshops considered the potential for new partnerships and collaborations.

The **carbon capture and storage** workshop covered updates on efforts to identify and address nontechnical barriers to the capture and storage of carbon dioxide produced by fossil-fueled energy generation and to provide guidance to decision makers.

The **competitive advantage, regulation, and environment** workshop considered environmental performance as an aspect of competitive behavior, with a goal of proposing innovative business and regulatory strategies to reward firms that behave responsibly in environmental matters.

The **sustainable materials** workshop focused on methods to assess emerging material technologies from the social, economic, and environmental aspects of sustainability.

The **sustainability and urbanization** workshop assessed the value of consolidating and integrating the results of several past and current AGS projects in this area.

The **sustainable water management** workshop worked to identify key areas in which international collaboration among academic institutions, public policy makers, industry, and other stakeholders would help produce solutions to water-related development problems.

The **contaminated areas** workshop discussed research ideas for increased efficiency in the remediation of contaminated areas, including ways to reduce costs and to improve understanding of uncertainty and of local, regulatory, and technical problems.

The **learning for sustainable development** workshop focused on developing strategies to bring awareness of sustainability factors into higher education.

Next Year

Preparations are already under way for the 2005 annual meeting, which will be held at MIT. Meanwhile, investigators are working to develop their existing and proposed research partnerships and collaborations in directions honed by the lively interactions at the Göteborg meeting.

CEEPR workshop considers climate policy costs, emissions permits, OPEC, and more

On May 6 and 7, the Center for Energy and Environmental Policy Research (CEEPR) held its spring workshop in Cambridge, Massachusetts. About 65 people from academia, industry, and government attended, providing a wide range of perspectives that resulted in useful discussions and exchanges of information.

One focus was on modeling the costs of climate policy. Three groups presented analyses of the costs of the currently proposed McCain-Lieberman bill, which would cap carbon dioxide (CO_2) emissions for most industries at 2000 levels between 2010 and 2020. The groups' analytical models yielded surprisingly similar estimates of the cost per ton of carbon emitted that would result from implementing the bill. But their results differed widely on its impacts on macroeconomic factors such as welfare cost and consumption.

The researchers presented several explanations for the differing outcomes. For example, estimates of the macroeconomic costs of the bill vary considerably depending on whether a model permits a policy shock to cause unemployment of resources or just a reallocation of resources to different uses. Estimated costs also vary with different treatments of how policy measures in the bill interact with "pre-existing distortions" such as labor, capital, and energy taxes.

But the most significant differences were traced to assumptions about the future. For example, if an analysis assumes that the McCain-Lieberman bill remains in place indefinitely after 2020, estimated consumption drops significantly during 2010 to 2020. The reason? Consumers look ahead, see huge increases in costs in the future, and reduce consumption now so as to save money for (higher) future expenses. Thus, in such an analysis, the drop in consumption estimated for 2010 to 2020 is caused not by the proposed imposition of McCain-Lieberman bill during that period but by the expectation that the bill will remain in place after 2020. (As an aside, predicting the impact of a bill on consumers' expectations and resulting behavior is always tricky.) Overall, the workshop session demonstrated the challenges involved in interpreting such modeling studies and using them to support policy decisions.

Another session of the workshop considered the CO_2 trading system now being planned in Europe. Much heated debate is focusing on one feature: the initial allocation of permits to emit CO_2. Different European countries are proposing different rules for allocating their permits, and observers worry about possible impacts on firms' competitive positions. For example, will electricity generators that receive most or all of the permits they need be able to undersell competitors in other countries who get fewer permits?

An interesting comparison was made with the nitrogen oxides (NO_X) trading program already in effect in the Northeastern United States. At the start of that program, each state was allowed to allocate its own NO_X emissions permits, and the methods they used differed widely. Thus, the US experience can provide insights into what may happen with the CO_2 trading system in Europe. Investigations thus

continued on page 12

Reports from Meetings

continued from page 11

far suggest that despite the financial benefit, firms that received many permits continue to base their selling price on fuel costs and current market prices so as to maximize their profits. Additional findings will be presented in future workshops.

Another session of the workshop addressed the structure and behavior of the Organization of the Petroleum Exporting Countries (OPEC). Observers seeking to understand and predict OPEC's behavior have long argued about its actual structure. Is OPEC a true cartel, or is it really a group of cooperative or perhaps even competing friends? One view proposed at the workshop was that OPEC acts as a "bureaucratic cartel," that is, a cooperative enterprise that has difficulty pursuing the common good because of the high cost of forging consensus. Given that description, OPEC's behavior over the years becomes more explicable.

Further discussion considered whether the world has moved into a new era of OPEC pricing. OPEC prices typically vary within a given range, but since 2000 the prevailing range has been significantly higher than it was during the previous 15 years. OPEC claims that prices must be higher because of the depreciation of the dollar. However, the consensus at the workshop was that depreciation is an excuse rather than an explanation. OPEC nations do most of their buying and investing in US markets, so they are largely unaffected by the dollar's depreciation. Other possible explanations were considered, including the simple fact that demand is higher, due in part to the economic boom in China that has turned that country into a major oil importer. (The hypothesis that OPEC prices have reached a new plateau has now been confirmed. At a recent meeting, OPEC announced that it would move its pricing range from $22–28 per barrel up to $28–34.)

Other topics addressed at the CEEPR workshop were the regulatory restructuring of the electric power industry and possible impacts on generation efficiency, retail electricity competition in England and Norway, and methods of measuring the benefits of environmental policies. Keynote speakers were Professor Ian A. Waitz of MIT's Department of Aeronautics and Astronautics, who discussed the increasing role of aircraft emissions in local and global pollution problems, and Dr. Martin A. Zimmerman of Ford Motor Company, who described the challenge of dealing with issues that are politically interconnected, such as auto efficiency standards and climate change.

News

New website ready to help building designers save energy

continued from page 9

You save your combination of answers and choices as a "scenario." Behind the scenes, algorithms perform rapid, real-time calculations of various sustainability indices. Within seconds, colorful graphs and images display the month-by-month and annual energy requirements of your building for heating, cooling, and lighting. An image of a room shows how daylight will hit the walls, ceiling, and floor at various seasons, times of day, and with and without blinds, tilted at a selected angle. A graphical representation shows the comfort level at various locations within the room.

Not happy with the outcome? You can go back to the setup page, change one or more features, save the new combination as a second scenario, and get a new set of results displayed next to the first for easy comparison of gains and losses.

The Design Advisor does have limitations. For example, it cannot deal with furniture or with odd-shaped rooms, as more sophisticated simulation tools can. The researchers sacrificed such flexibility to get a simple program that is fast but detailed and accurate.

To demonstrate its capabilities, they analyzed a well-defined single room using both the Design Advisor and DOE-2, a simulation tool put out by the US Department of Energy. Describing the room for the Design Advisor involved a simple series of clicks. In contrast, defining it for DOE-2 required eight pages of single-spaced text prepared by an experienced user. Both simulation tools then calculated monthly heating and cooling requirements. The estimates generated by the Design Advisor were within 10% of those from DOE-2, and they were available within 20 seconds rather than 10 minutes—an important advantage for users who want to compare a series of options. The Design Advisor also simultaneously performed an integrated lighting analysis. Users of DOE-2 would have to use a different simulation tool to perform a separate analysis of lighting needs.

The Design Advisor offers several energy-saving design choices not available on conventional simulation tools. For example, window options include a "double skin façade" system made up of two or even three layers of glass with adjustable blinds and air circulation between the panes. A natural ventilation option uses only flows of fresh air from outdoors, while a "hybrid" option combines natural ventilation with just enough use of mechanical chillers to ensure comfort. Detailed background simulations calculate the impacts of each choice.

The researchers are now seeking suggestions and comments on the Design Advisor from architects and other users. Meanwhile, they are continuing to improve the tool. They are adding a Building Code Advisor that will present outputs in numerical form along with building-code requirements for selected cities. They are developing an "intelligent engine" that will guide users toward the most promising range of façade designs for a particular building and location. And they are developing a program that will enable the user to perform a life-cycle analysis to determine the money that will be saved over the long term by making more-expensive energy-efficient choices now.

Leon R. Glicksman is professor of building technology and mechanical engineering and director of MIT's Building Technology Program. This research is sponsored by the Cambridge-MIT Institute and by the Building Envelopes Consortium. Please send suggestions and comments on the MIT Design Advisor to Professor Glicksman at glicks@mit.edu. Information on the Building Technology Program is available at http://web.mit.edu/bt/www.

Education Update

MIT students develop plan to help reduce greenhouse gas emissions in Cambridge

MIT students have come up with a grassroots proposal that they think will help the City of Cambridge reduce greenhouse gas emissions. Their plan is simple: get elementary-school children to walk to school instead of being driven, a change in behavior that would both reduce auto emissions and give the children some exercise.

The plan is the product of a month-long seminar "Implementing the Cambridge Climate Protection Plan," offered by the Laboratory for Energy and the Environment and the City of Cambridge, collaborators during MIT's Independent Activities Period (IAP) in January. The aim of the seminar is for students to learn about climate change and then design community-level environmental initiatives, specifically, initiatives that will help the City of Cambridge meet the aggressive goals of its Climate Protection Plan, which calls for reducing greenhouse gas emissions to 20% below 1990 levels by 2010.

During the first three days of this year's seminar, students received a crash course on climate change, the City of Cambridge, and locally based climate initiatives. Lectures were presented by MIT instructors and City of Cambridge guest speakers. After considering a variety of issues, the students decided on their focus: they would develop a plan to reduce vehicle-kilometers traveled by encouraging public-school children to begin to walk to school.

The MIT students considered how they could foster this change in behavior using techniques of community-based social marketing such as grassroots communication and social incentives. They analyzed the benefits to individual children of walking to school and the barriers that keep them from doing so. Based on their analysis, they concluded that the main barriers to walking are parents' concerns about safety and children's concerns about conforming to their peer groups.

To overcome those barriers, the MIT students proposed a "walking school bus" for Cambridge children in grades 1 through 4. In a walking school bus program, an adult leader—or in this plan perhaps an eighth grader—picks children up at established "stops" and then walks the entire group to school. That approach addresses safety issues and makes walking to school a normal peer-group activity. Further benefits for the children are getting exercise and

continued on page 14

A walking school bus at the Menheniot County Primary School in Cornwall, England. Photo by Mary Neale, courtesy of the Cornwall County Council.

Education Update

continued from page 13

learning pedestrian-safety skills. By beginning to walk to school when they are young, children are likely to continue walking when they are older.

Through their work in this class, MIT students were exposed to the challenges of designing local initiatives and to some practical implications of climate change programs. For example, discussions of how to market the walking school bus program brought up an interesting point about climate policy: greenhouse gas reduction initiatives may not necessarily be marketed as greenhouse gas initiatives. Instead, participation in climate programs may be enhanced by finding other, more immediate and obvious benefits to the citizen, such as the health benefits of the walking program. However, such a marketing strategy will not help build public awareness of climate change. Local residents may continue to perceive climate change as a remote problem.

The MIT students concluded the seminar on January 29, 2004, by presenting their final proposal to an audience from the MIT and Cambridge communities. They outlined specific actions for implementing their plan; and they presented estimates of the human, financial, and management resources that would be required. The proposal as well as all materials from the seminar can be found at http://stellar.mit.edu/S/course/17/ia04/17.918/.

The IAP seminar was also offered in January of 2003, and two proposals resulted. One focused on persuading Cambridge residents to purchase fuel-efficient vehicles; the other encouraged them to purchase green power from their electric utility.

Massachusetts secretary of environmental affairs speaks at MIT

Ellen Roy Herzfelder, secretary of environmental affairs of the Commonwealth of Massachusetts, spoke to an MIT audience about a recently released plan for ocean management.

On April 20, Ellen Roy Herzfelder, secretary of environmental affairs of the Commonwealth of Massachusetts, described to an MIT audience a new, comprehensive strategy for managing our oceans that addresses both existing and evolving concerns and uses.

Her remarks, delivered at a special event hosted by the Laboratory for Energy and the Environment, focused on the report *Waves of Change*, which was released in March by the Massachusetts Office of Coastal Zone Management.

The report (available at http://www.mass.gov/czm/MOMI/finalrpts.htm) presents an extensive list of recommendations that work together as a systemic approach to ocean management. It is the culmination of a landmark collaboration among concerned people and groups with widely varying interests.

Secretary Herzfelder said, "I think the value of this report is that it is a consensus recommendation from the many stakeholders who represent the fishing industry, the shipping industry, the environmental community, energy business, and renewables. They all came together with the recognition that there are many things that we can do much better for the stewardship of our oceans."

Secretary Herzfelder noted the importance of the Atlantic Ocean to the people of Massachusetts. Massachusetts has often been defined by its relationship to the ocean; the historic whaling industry, small fishing villages, and coastal tourist towns come to mind. A third of the state's population lives in coastal communities.

Traditionally, Massachusetts state and local governments have had to address a variety of sometimes-conflicting ocean-related interests, for example, marine commerce, coastal development, habitat preservation, and recreation. Now those governments must also address new concerns such as off-shore wind farm development, ocean-based research, and the possibility of rising sea level due to climate change.

The set of recommendations in the new management plan is designed to be a cohesive response to all of those challenges. It recognizes the whole range of ocean uses, how they may interact, and how their management and impacts can be politically and economically distributed.

One of the more provocative ideas that Secretary Herzfelder mentioned was the use of zoning to manage ocean use—an approach now used for land management. This approach would raise many regulatory challenges, including the need to separate regulatory power between state and local governments.

Secretary Herzfelder also stressed the urgent need for research into natural ocean systems. To emphasize our current lack of knowledge, she said, “We know more about the surface of the moon than we know about the floor of the ocean.”

Secretary Herzfelder was appointed secretary of environmental affairs by Governor Mitt Romney in January 2003. Previously, she was a senior lecturer in entrepreneurship at the MIT Sloan School of Management. She is also co-founder of an energy company hailed for its environmentally friendly practices.

In her current position she oversees four state agencies and nine offices dealing with a variety of issues including water resources, energy, wetlands, parks and recreation, agriculture, coastal concerns, and general environmental policy and regulation. She oversees all of the state’s parks, which include 10% of the land in Massachusetts.

Secretary Herzfelder noted that among her highest priorities are infrastructure maintenance and “Lean & Green” initiatives to streamline regulatory processes.

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http://lfee.mit.edu

Center for Energy and Environmental Policy Research (CEEPR):
http://web.mit.edu/ceepr/www/

Joint Program on the Science and Policy of Global Change (Joint Program):
http://web.mit.edu/globalchange/www/

Center for Advanced Nuclear Energy Systems (CANES):
http://web.mit.edu/canes/

Inquiries can be sent by e-mail to thill@mit.edu for LFEE publications, bubluski@mit.edu for CEEPR publications, tzh@mit.edu for Joint Program publications, and canes@mit.edu for CANES publications. To obtain a copy of an MIT thesis, in paper or electronic format, go to http://libraries.mit.edu/docs/theses.html.

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continued on page 16

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NEW AND RENEWED PROJECTS, JANUARY–JUNE 2004

Topic	Donor or Sponsor	Investigators *(Department)*
GIFTS, CONTRIBUTIONS, AND MEMBERSHIPS		
Center for Energy and Environmental Policy Research (CEEPR) membership	Constellation Power Source; Electricidade de Portugal SA; Essent NV; Saudi Aramco Services; Southern Company	
Joint Program on the Science and Policy of Global Change membership	Alstom Power; DaimlerChrysler AG; Electricité de France; Ford Motor Co.; RWE/Rheinbraun; Statoil; TotalFinaElf	
Alliance for Global Sustainability (AGS)	AGS International Office	D. Marks *(Laboratory for Energy and the Environment)* J. Steinfeld *(Chemistry)*
EPA Summer Symposium: Air Quality Symposium on Air Toxics	Diesel Technology Forum Inc.; ExxonMobil Corporation; Marama; PSE&G Power LLC	D. Marks *(Laboratory for Energy and the Environment)*
NEW PROJECTS		
Impact of Diesel Vehicles on Climate	Ford Motor Co.	C. Wang *(Earth, Atmospheric, and Planetary Sciences)*
Tribological Phenomena for Advanced Diesel Engines	Adiabatics, Inc.	V. Wong *(Laboratory for Energy and the Environment)*
Investigation of Fundamental Thermal-Hydraulic Phenomena for Advanced Gas-Cooled Reactor Appliances	Bechtel BWXT Idaho	P. Hejzlar *(Nuclear Engineering)*

NEW AND RENEWED PROJECTS, JANUARY–JUNE 2004, CONTINUED

Topic	Donor or Sponsor	Investigators *(Department)*
RENEWED PROJECTS		
Gas Conversion Study–Phase 2	Shell International Exploration and Production, Inc.	J. Tester *(Chemical Engineering)*
Development of a Carbon Management Geophysical Information System (GIS) for the United States	US Department of Energy	H. Herzog *(Laboratory for Energy and the Environment)*
Energy Choices for Greenhouse Gas Constrained World Consortium	Alstom Power; Saudi Aramco	H. Herzog *(Laboratory for Energy and the Environment)*
Piston Ring Packing Analysis for High Performance Engines	Ferrari SpA	J. Heywood *(Mechanical Engineering)*
Engine and Fuels Research Consortium	Saudi Aramco; DaimlerChrysler AG	J. Heywood *(Mechanical Engineering)*
Oil and Lubrication Research Consortium	Dana Corp.	J. Heywood *(Mechanical Engineering)*

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