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# The Other Climate Threat: Transportation

*A global travel surge is inevitable, but runaway growth of mobility-related CO<sub>2</sub> emissions is not*

By Andreas Schäfer, Henry D. Jacoby, John B. Heywood and Ian A. Waitz

After the Wright brothers invented the first powered airplane and Henry Ford manufactured the first affordable car, transportation innovation motored forward. Steady improvements in technology and reductions in cost enabled unprecedented gains in mobility. That, in turn, assisted extraordinary global economic growth. A century later, however, one early transportation practice persists. Oil-based fuels still power the world's transport fleets.

These fuels made sense for many decades for many reasons. Oil products, liquid at common temperatures and pressures, are easily handled and stored. They possess the highest energy content per volume of all practical fuels and per weight of all liquid fuels, imposing the smallest penalties for energy storage—a quality especially valuable for aircraft. And for many years, petroleum has been affordable and abundant. Some analysts argue it is likely to remain so for a long time to come.

Unfortunately, when burned, gasoline, diesel and jet fuel emit carbon dioxide, the most abundant human-made greenhouse gas. Thus, oil-based fuels are a prime player in climate change. Because of the enormous scale of our global transport systems, motorized trans-

portation already accounts for about 23 percent of energy-related carbon dioxide emissions, estimated at 31.5 billion metric tonnes worldwide in 2008. Passenger travel accounts for 60 percent of transportation's share of emissions. With coming global economic development, the relative importance of transportation CO<sub>2</sub> emissions will only increase. Imagine the additional impact of hundreds of millions of new commuters in China and India driving to work, and the residents of today's industrialized world increasingly relying on air travel. Then envision the rest of the world trying to catch up.

To prevent unrestrained growth in these emissions, transportation trends worldwide must be better understood. For that reason, we've assembled a unique data set describing the traffic volume of world regions since 1950 for each major transport mode. With this database, we studied the fundamental relationships that transformed the global transportation system in the past. Characterizing such forces and constraints has helped us understand the likely future course of transportation.

We have also analyzed the ways that industry and consumer choices may influence greenhouse gas emissions. Such insights give clues to which vehicle designs, aircraft technologies and alternative fuels can most effectively reduce those emissions. All this is needed to understand which public policy strategies should be pursued to achieve needed change. Because many greener technologies and fuels are more expensive than what's prevalent today, reducing transportation emissions is not a problem the marketplace can be expected to solve alone.

## Our Predictable Travel Habits

Central to our projections of future travel demand are two characteristics of aggregate human behavior. First,

regardless of income or geography, people on average spend a roughly constant amount of time on travel. At low income levels, for instance, residents in African villages spend slightly more than one hour per day traveling, mainly to obtain water and firewood, and to commute to and from agricultural work. Much wealthier residents in automobile-dependent societies such as Japan, Western Europe and the United States—where half of all trips are leisure-oriented—spend a similar amount of time en route.

A second characteristic is the connection between income and mobility: As per capita gross domestic product (GDP) grows, so does per capita passenger kilometers traveled (PKT). This pattern holds regardless of culture, political system or stage of economic development. Neither economic ups and downs nor changes in fuel price have fundamentally changed this relationship over long periods. To travel more within a stable time budget, people shift to faster modes of transport, to motor scooters and public transport in poorer places or to airplanes and high-speed trains in richer ones.

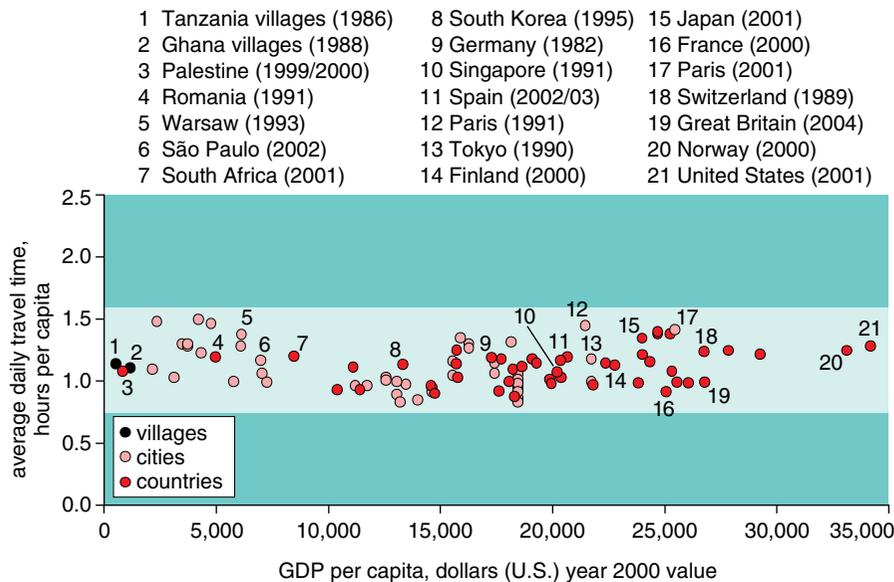
Indeed, there appear to be three distinct phases of motorized mobility development. Below an annual mobility level of 1,000 kilometers per person (fewer than 3 kilometers per day), low-speed public transportation accounts for nearly the entire traffic volume. These modes include urban public transport systems, commuter railways, intercity trains and intercity buses. At the next stage of development—a yearly travel demand of between 1,000 and 10,000 kilometers per capita (about 3 to 30 kilometers per day), the use of low-speed public transport modes declines to between 10 and 30 percent of total PKT and the use of light-duty vehicles rises. These vehicles consist primarily of auto-

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Figure 1. People around the world use whatever type of transportation they can afford to get where they want to go. As they grow richer, they pay more to travel farther faster. At bottom left, Cambodians on motorbikes, some doubled up on the same vehicle, sit stuck in a traffic jam in Phnom Penh. Above, vans, buses and pedestrians crowd a main thoroughfare in Khartoum, Sudan. To the right, traffic is even more intense in the southern Mexican city of Naucalpan. Below, near-gridlock strikes Hartsfield-Jackson Atlanta International Airport in the United States during a weekday evening. Below that, the train at left makes the trip between Alsace and Paris in two hours and 20 minutes. France inaugurated the new high-speed train line in 2007.



**Figure 2.** The amount of time people around the world spend traveling is startlingly consistent, no matter whether they live in African villages, Europe or the most affluent regions of Asia. People in the industrialized world spend a larger share of their traveling time for leisure activities—about half—but they travel similar amounts of time on average each day nonetheless.

mobiles, but include minivans, vans, pick-up trucks and sport utility vehicles. Finally, in the third stage of development, mobility levels of 10,000 kilometers per person and higher require a substantial share of air traffic or high-speed rail-based ground transportation. (We aggregate these as “high-speed transport,” although air travel is the largest single component now in use.) In North America, airline travel market share has grown at the expense of passenger cars over the past four decades. Nearly all passenger traffic is split between automobiles (81 percent) and aircraft (15 percent); rail and bus services are active mainly in niche, urban areas.

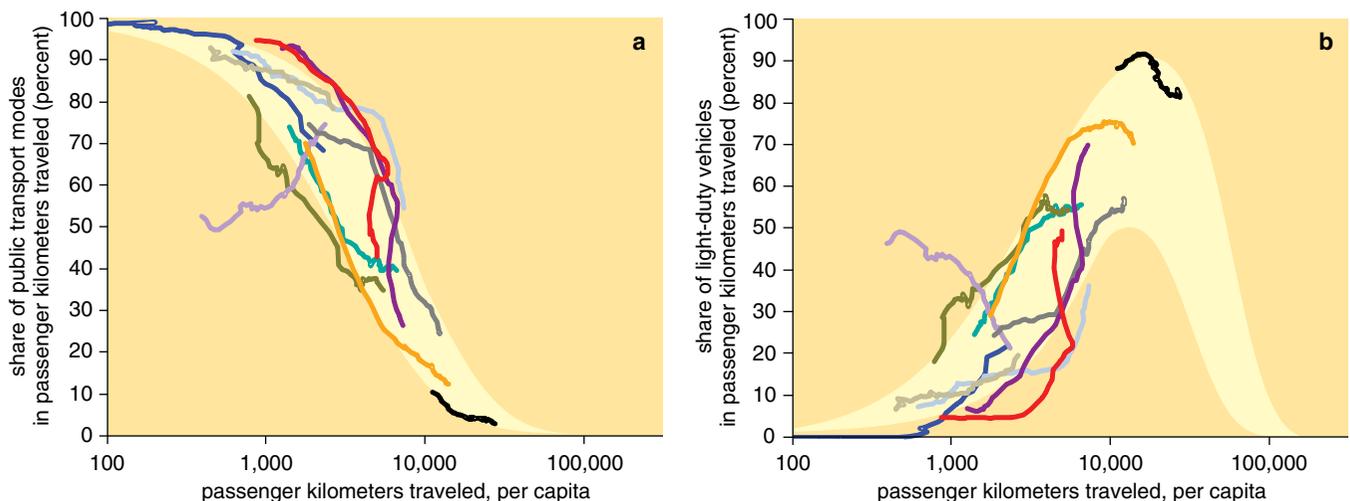
These two characteristics of aggregate human behavior may tell us something important about the future: If

average travel costs do not change dramatically, rising income will continue to push up travel demand. At the same time, the fixed travel-time budget will induce travelers to use faster transport modes. According to the United Nations’ “medium variant” projections, world population is expected to increase by 44 percent by 2050. During that same period, per capita world gross product (with nations aggregated by market exchange-rate equivalents) is projected to multiply by 2.2 to 2.6. Using simple statistical models, we project that gain could triple or quadruple world travel by midcentury. In the developing world, passenger mobility could increase to levels three to six times those in 2005. Over the same period, travel demand in the indus-

trialized world is projected to double or almost triple and retain the highest per-person mobility levels. Within that sector, North America would remain the region with the highest per-person mobility levels, rising from 27,400 kilometers per year in 2005 to 39,000 to 48,000 kilometers in 2050, depending on the rate of economic growth.

As is the case with mobility demand trends, the types of transportation people migrate to will likely remain consistent with historical patterns, in that people who grow more affluent will shift toward faster transport modes. If per-person travel time remains close to its current level of about 1.2 hours per day in 2050, high-speed transportation modes could claim about two-thirds of total PKT in the industrialized world. Automobile use would account for nearly the entire remaining traffic volume. In contrast, light-duty vehicle travel would grow most in developing regions, making up 40 to 50 percent of total PKT. Globally, automobiles could account for more than 40 percent, high-speed transport for almost 40 percent and low-speed public transport for about 20 percent of worldwide PKT.

Despite the increasing dependence on high-speed transportation modes, especially within the industrialized world, day-to-day travel would not be significantly different than it is today. Because of the comparatively low travel speed of automobiles, North Americans would still spend most of their travel time in cars, roughly 45 minutes per day. The remainder of their travel time budget would be spent in low-speed public transportation modes and increasingly high-speed transportation systems. In regions dependent on high-speed transportation, rapid

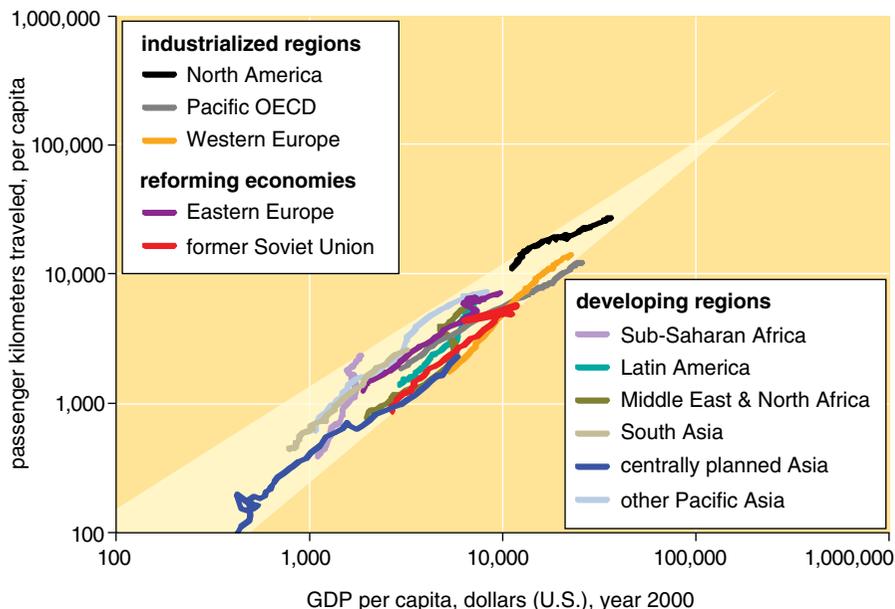


access to airplanes would become critical. Already, entrepreneurs are implementing business models to serve that demand. One model employs very light jets with four- to six-passenger capacity and low-traffic airfields to help travelers avoid long check-in times and congestion at primary airports.

### More Size and Comfort, More CO<sub>2</sub>

It isn't simply growth in travel demand that has expanded the amount of energy each passenger uses. Societal changes have played a role, as have consumer preferences. In the United States, for instance, energy use per passenger kilometer, which in 1950 was 2.0 megajoules, is now 2.2 megajoules. This has occurred even though automobile engines are much more fuel efficient now. Similar trends are observed in other industrialized countries. One prominent explanation is the decline in the number of people using the same car. The average number of people sharing a light-duty vehicle in the U.S. declined from 2.2 in 1969 to 1.6 in 2001, yielding a nearly 40 percent increase in energy use per PKT of light-duty vehicles. This trend has likely leveled off in industrialized countries, but it is only beginning in many parts of the developing world.

Another important contributor to the rising energy intensity of personal travel has been consumers' appetite for improved safety, comfort and engine power. Compared to Henry Ford's Model T, the average new light-duty vehicle sold in the United States in 2005 was three times as heavy and ten times as powerful. Still, fuel consumption has declined from about 15 to 10 liters per 100 kilometers over the same period. In fact, the decline in fuel use



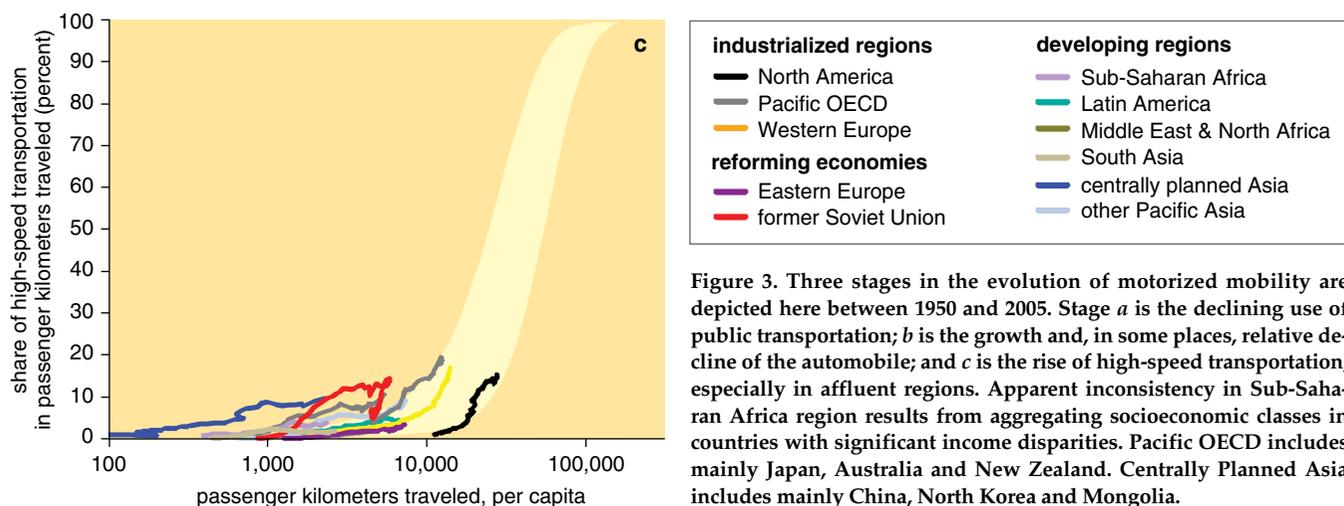
**Figure 4.** Per-capita passenger-kilometers traveled (PKT) is correlated with economic development, shown as growth in per capita gross domestic product. The 11 regional trajectories represent the years 1950 to 2005. The upper point of the shaded section is the theoretical highest mobility level, achieved when a population relies exclusively on the fastest mode of transport (aircraft) over the entire travel time budget (1.2 hours per person per day). Although development toward the endpoint seems possible through midcentury, the finite capacity of airspace will very likely limit that trend over the very long term. At some point, regional trajectories may level off. Pacific OECD includes mainly Japan, Australia and New Zealand. Centrally planned Asia includes mainly China, North Korea and Mongolia.

per kilometer and per ton of vehicle (a metric that corrects for the increases in vehicle weight associated with rising levels of safety and comfort) has been as much as 80 percent.

Airlines have always sought fuel efficiency, given that fuel expenditures are frequently the largest single fraction of their operating costs. In their attempt to remain profitable, airlines have also been able to increase the percentage of seats filled. Thus, energy use per passenger kilometer—after the transition from the propeller to the initially less energy-efficient jet engine—has de-

clined significantly for air transportation. Still, in air travel as well, trends toward comfort, convenience and speed have stood in the way of further energy use reductions. Expanding business and first-class sections in legacy carriers reduces passenger density, for example. The trend toward more frequent flights using very light jets also contributes, by increasing energy-intensive takeoffs and reducing economies of scale.

As was the case with the increase in travel generally, the main enabler of the move toward more comfort has been technology's success at lowering travel



**Figure 3.** Three stages in the evolution of motorized mobility are depicted here between 1950 and 2005. Stage *a* is the declining use of public transportation; *b* is the growth and, in some places, relative decline of the automobile; and *c* is the rise of high-speed transportation, especially in affluent regions. Apparent inconsistency in Sub-Saharan Africa region results from aggregating socioeconomic classes in countries with significant income disparities. Pacific OECD includes mainly Japan, Australia and New Zealand. Centrally Planned Asia includes mainly China, North Korea and Mongolia.

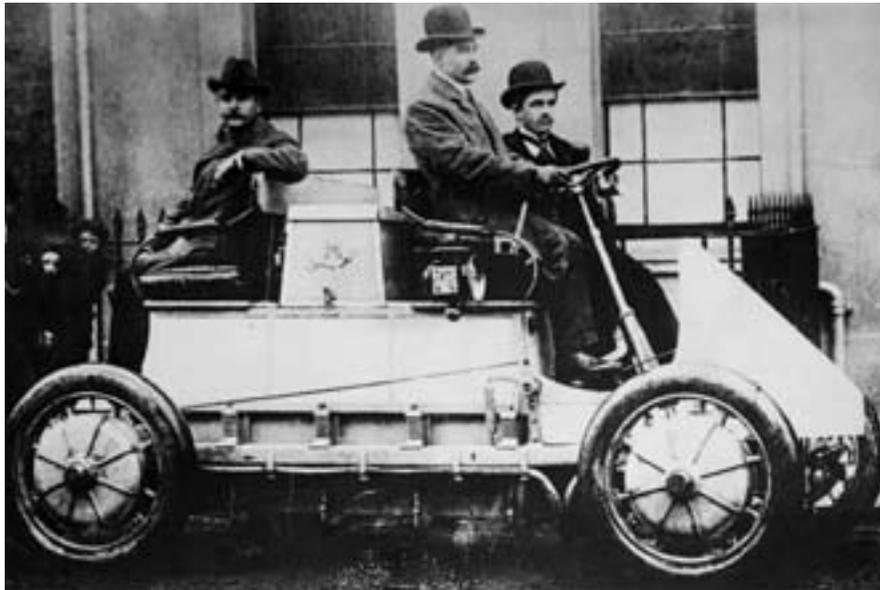


Figure 5. Although hybrid vehicles powered by battery and petroleum are only now gaining market share, efforts to combine an internal combustion engine and one or more electric motors date back more than a century. Above is the electric Voiturette System Lohner-Porsche, displayed at the 1900 Parisian World Exhibition. It was designed by Ferdinand Porsche, a pioneer of automobile engineering. Within a year, he added an internal combustion engine, creating the first hybrid. Image courtesy of Porsche Cars North America.

costs. Aggressive pricing policies and new business models, developed during battles for market share, also accelerated cost reductions. The combination of reduced costs and rising income made improved safety, comfort and speed increasingly more affordable. In 1967, the average U.S. household needed to work 21 weeks to afford a new car. Today, that period has shrunk to 17 weeks, despite the significant enhancement of vehicles.

Increases in energy use per PKT, of course, expand greenhouse gas emissions. If per-PKT energy use of air and road vehicles produced in 2005 re-

mained steady in the global transportation fleet in 2050—and oil products remained the primary fuel—energy use per PKT would increase by 12 to 25 percent globally. The energy cost per PKT would rise from roughly 1.4 megajoules per passenger kilometer to between 1.6 and 1.8 megajoules. The extent of this intensification depends on the rate of economic growth and its distribution across world regions. In this scenario, which we label “constant technology,” greenhouse gas emissions from transportation sources would triple to quintuple worldwide by midcentury.

## Technology and New Fuels Can Help

Fortunately, emerging technologies and alternative fuels could substantially reduce CO<sub>2</sub> emissions. But it’s important to be realistic about what can be accomplished. Sometimes, what looks like an obvious solution isn’t feasible without overcoming challenges that arise when implementing fuel-saving technology. For instance, one might assume that automobile engine efficiency could be improved significantly by increasing the amount of air per unit of fuel burned. But lean-burn engines would have an unwanted side effect. Three-way catalysts in today’s engines cannot reduce nitrogen oxide emissions in an oxygen-rich environment. In aircraft engines, higher combustion temperatures would increase engine efficiency but would also increase nitrogen oxide emissions.

Another key factor is time. Developing new road and air vehicles can take decades. An extreme example is the hybrid-electric vehicle, which was first designed by Ferdinand Porsche, more than 90 years before the marketing of modern hybrids. Even what are considered quick transitions in transportation aren’t always swift. It took 20 years between the first workable design of a gas turbine engine and the implementation of commercial jet service in 1952 with the de Havilland Comet, the world’s first jetliner. One reason is that developing new transportation technologies often requires huge investments, which carry significant risks.

Despite these difficulties, our analyses show significant potential for reducing fuel consumption of both road and

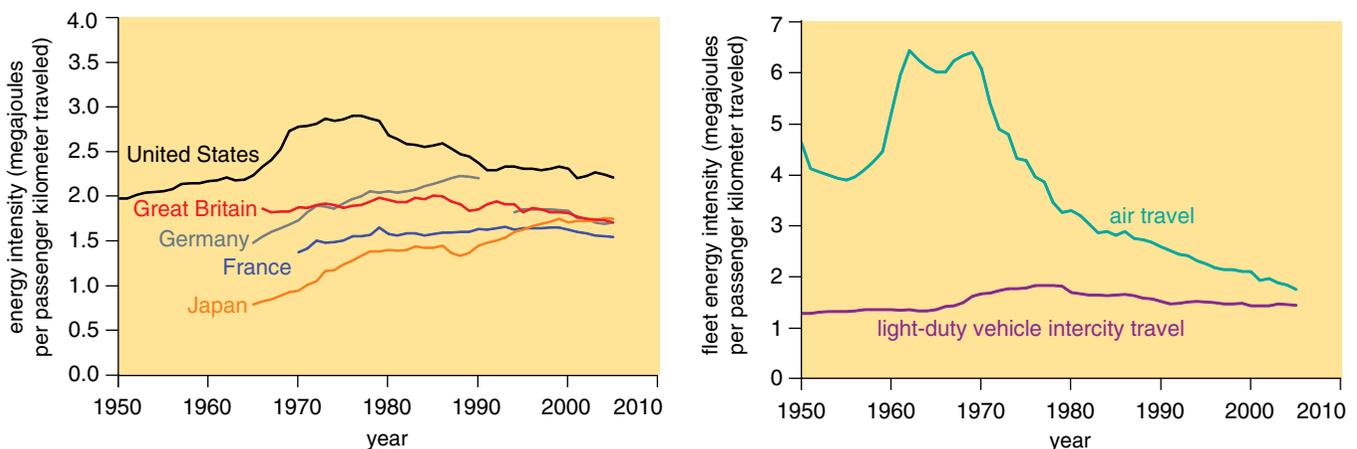
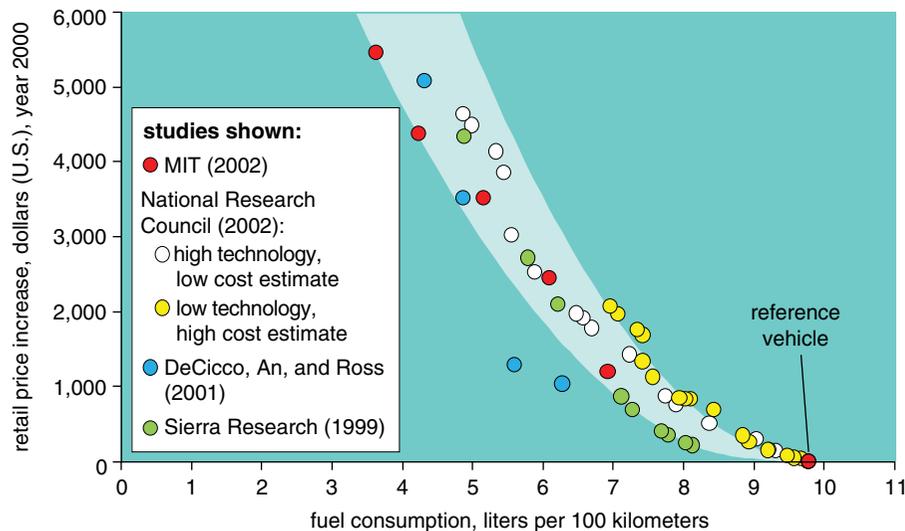


Figure 6. Despite continued improvements in technology, the amount of energy used per passenger kilometer travelled has not declined in much of the industrial world, as displayed at left. That’s due partly to consumers’ preferences for increased size, weight and power in new cars. The trendline in Germany drops after 1990, when West Germany and less affluent East Germany reunited. At right, the rate of decreasing energy use per passenger kilometer in aircraft outpaces that of automobiles in the United States, a development observed around the world.

air vehicles over the next 20 years. If consumer preferences for increasingly large and powerful automobiles alone could be moderated, we project there would be a roughly 30 percent reduction in fuel consumption in new cars by the mid 2020s, compared to new cars sold in the United States in the early 2000s. Such improvements would require vehicles with better-performing engines, a higher share of high-strength steel, more aluminum and plastics to reduce weight, tires with lower rolling resistance and body designs with lower aerodynamic drag. In addition, even more advanced and lighter hybrid-electric road vehicles could cut fuel consumption in half. (Note that a 50 percent reduction in fuel consumption corresponds to a doubling, or a 100 percent increase, in fuel efficiency.)

The expanded use of alternative fuels could also reduce greenhouse gas emissions. However, given oil products' excellent fuel qualities, finding satisfactory substitutes has been difficult. Achieving compatibility with the existing fuel infrastructure can be a significant barrier. The recent growth of corn-derived ethanol and biodiesel made from vegetable oils can be explained, in part, by their blending flexibility with oil products. But development of these products was spurred more by concerns over oil price volatility and energy security risks than concerns over greenhouse gas emissions. Nearly all biofuel blends deliver only a few percent reduction in greenhouse gas emissions over the course of the fuel's life cycle compared to petroleum fuels. Synthetic fuels derived from non-petroleum sources—whether coal, natural gas, or oil shale—can result in fuels with even higher life-cycle greenhouse gas emissions than petroleum, unless CO<sub>2</sub> released during their production is captured and sequestered.

Still, there is reason to be hopeful that the next generation of biofuels, expected to be derived from cellulose rather than from today's feedstocks, will emit substantially less CO<sub>2</sub> over their life cycle. They should also increase the fuel yield per hectare. Science hasn't yet produced a commercially viable means to break down cellulose into fermentable sugars, but progress is being made. A particularly promising future technology in road transportation is the electric vehicle with advanced batteries, perhaps in hybrid mode, with an internal combustion engine for long-distance driv-



**Figure 7. Reducing fuel consumption in new cars costs money and cost increases accelerate at higher fuel efficiencies. Above are the projected cost increases that four research studies predicted would occur when improving fuel efficiency in a so-called reference vehicle. That vehicle represents the average new automobile sold in the United States in 2000. It would sell for \$20,000 and consume about 9.8 liters of gasoline per 100 kilometers, or roughly 2.6 gallons per 62 miles.**

ing fueled by cellulosic ethanol. Efforts to develop synthetic oil products for surface and air transport also hold promise. In contrast, hydrogen is unlikely to gain significant market share before 2050. That is because of the lack of a hydrogen production, distribution, storage and fueling infrastructure, and the high cost of fuel-cell vehicles.

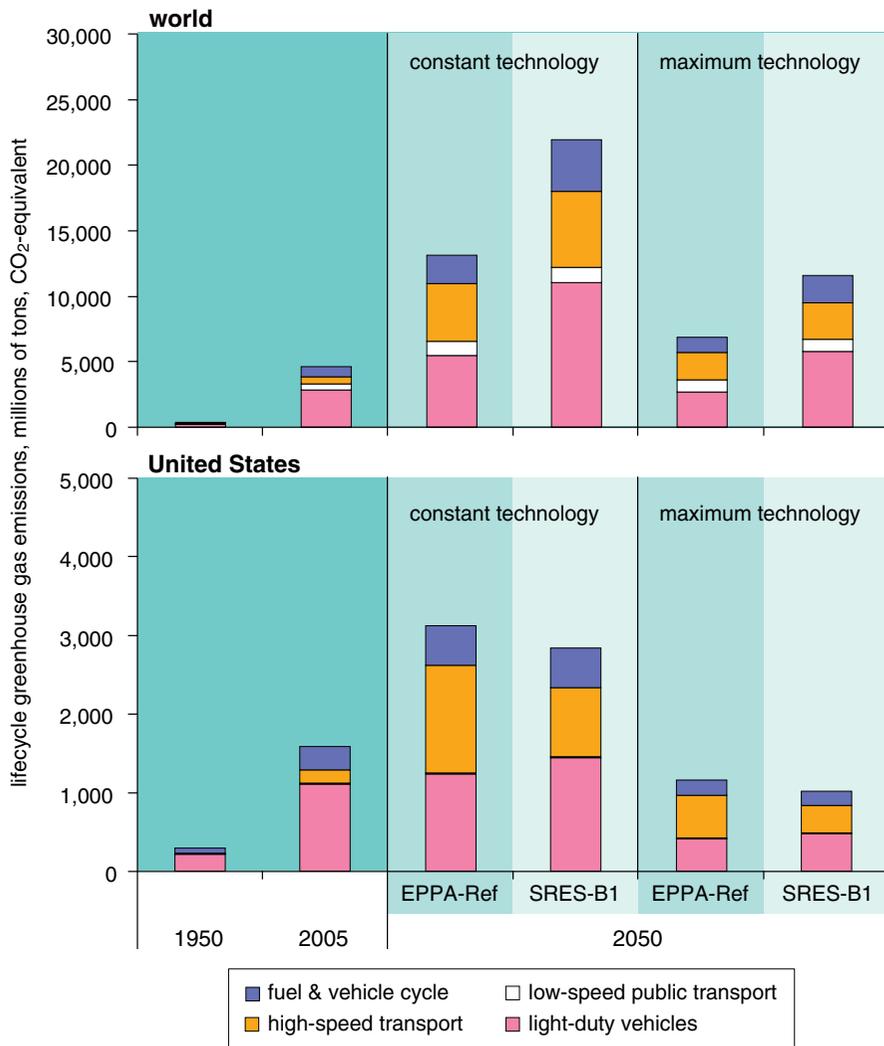
When we incorporate what we label "maximum technology" improvements into our world transportation projections, we predict that global average automobile energy use per PKT could decline substantially—by 35 percent by 2050 compared to 2005. That number represents a 50 percent reduction in the industrialized world and a 30 percent reduction in developing economies, where infrastructure and capital constraints will impede some change. We also predict a 40 percent reduction in energy use per PKT for aircraft relative to a constant technology scenario. If these reductions are complemented by second-generation biofuels, which we aggressively assume will provide 20 percent of world passenger travel energy by 2050, the level of life-cycle greenhouse gas emissions from world passenger travel could drop considerably by midcentury. This scenario would produce emission levels only 40 to 140 percent above the 2005 level—despite the huge expansion in transportation demand that is coming. In the industrialized world, including the United States, life-cycle greenhouse gas emissions from passenger travel in

2050 could fall below the 2005 level, due to lower growth in travel demand and quicker adoption of emerging technologies.

Costs will influence whether technological upgrades penetrate the world's vehicle fleets. New technologies can be expensive. The average car sold in the U.S. around the year 2000 consumed 9.8 liters of gasoline per 100 kilometers. We project that reducing vehicle energy use by 30 percent would increase the retail price of the car by \$1,500. Because further fuel consumption reductions will require still more sophisticated fuel-saving technology, cutting energy use in half would increase the price by \$5,000. Given that, the average \$20,000 cost of a new automobile in the U.S. could increase by 8 to 25 percent. With the luxury of relatively low fuel prices, U.S. consumers so far have shown more interest in vehicle comfort and power than fuel efficiency. These low fuel prices have also constrained research and development of liquid-fuel alternatives, such as second-generation biofuels. These are two reasons why introducing such technologies and fuels on a large scale will require public policy changes.

### Complicated Policy Choices

To expand the use of fuel-saving technologies and low-carbon fuels, governments have a range of policy instruments available. The ultimate objective is to induce consumers to change their vehicle preferences to favor low fuel consumption over size, comfort, en-



**Figure 8.** Depicted here are mobility-related greenhouse gas emissions in 1950 and 2005 worldwide, in the upper box, and in the United States, below. Projections for 2050 are based on two separate scenarios of economic growth. EPPA-Ref represents per capita GDP growth predicted by the MIT Emission Prediction and Policy Analysis model. The SRES-B1 scenario comes from the Intergovernmental Panel on Climate Change and predicts higher average GDP per capita growth. Increases in greenhouse gas emissions from transport sources are much higher in both scenarios when transportation technology does not change. But when aggressive steps are taken to lower fuel consumption, emissions fall.

gine power and other attributes. Ideally, new policies will induce the automobile and aircraft industries to implement fuel-saving technology at a faster pace and on a larger scale than they otherwise would. The potential payoffs can be significant, as indicated by the different emission levels in the “constant technology” and “maximum technology” scenarios described earlier. Either regulations or market-based measures, or both, could change consumer and industry choices. Historically, nearly all environmental legislation has been based on regulatory measures. That’s true, in part, because regulations tend to hide the extra costs for fuel-saving technologies, and thus

meet the least public resistance. However, because it takes several years for industry to design vehicles that meet new standards, and many more years for more fuel-efficient vehicles to be sold in sufficiently large numbers, several decades may pass before a regulation’s impact is felt. In addition, experience in the United States following passage of the Corporate Average Fuel Economy regulations suggests that as automobile drivers observe the reduced marginal costs of more fuel-efficient vehicles, they travel more. This so-called rebound effect could weaken energy use reductions.

More recently, governments have embraced market-based measures,

which use costs to influence consumer and industry behavior. This family of measures is more economically efficient than regulatory measures because it can impose the same penalty on all greenhouse gas emitters—whether they be vehicles, coal-fired power plants or other sources. Importantly, a surcharge in the transportation realm that raises fuel prices reduces energy use and emissions across an existing fleet, not just among new vehicles. Imposing equal marginal costs across CO<sub>2</sub> emission sources would be most easily accomplished with a national carbon tax or a cap-and-trade system. Over long periods of time, either price or regulatory approaches could achieve a target level of greenhouse gas emissions, although the rate at which each produces changes in the marketplace will differ. Complications regarding the likely impact of a market-based approach must be considered too, however. With income rising globally and the increasing reliance on the automobile and high-speed transport systems outlined above, an already small consumer response to fuel price increases and other market incentives will likely decline. The lack of alternatives to oil-based fuels does not help. As a result, any policy that imposes emissions penalties evenly across the economy will result in a lower percentage reduction in transport emissions compared to other sectors. This puts in question whether the transportation sector would carry an equitable share of the burden under an equal-cost approach. Because of this, governments must decide whether to treat passenger transport separately and impose different (and likely tougher) penalties compared to other economic sectors.

A related question is whether it would be wise to emphasize a single-policy approach in this sector—a price penalty for CO<sub>2</sub> emissions or a set of regulations, such as tailpipe emission standards, for example—or to apply a portfolio of measures. Neither a pure market-based nor a pure regulatory strategy is likely to succeed. One reason is that both types of policies are already in place. In the United States, they include fuel taxes, fuel economy and safety standards, research and development expenditures and subsidies for biofuels and hybrid-electric vehicles. Also, no single policy measure works equally well during all stages of a technology’s life cycle, from the

vehicle concept stage to its use on the road or in the air. Indeed, additional policy measures would be needed just to compensate for the undesired consequences of some interventions. For example, regulatory measures that aim to increase the fuel efficiency of new automobiles exclusively could produce a rebound effect unless they are accompanied by an increase in fuel tax.

These complexities could be addressed somewhat by an aggressive emission-reduction policy. An example would be a global carbon tax designed to stabilize the accumulated atmospheric concentration of greenhouse gas emissions to, say, 550 parts per million. Many observers consider that level unsafe, but it would be challenging to achieve nonetheless. Our analysis of the United States under such a scenario predicts that greenhouse gas emissions from passenger travel in 2050 would fall significantly, to about the 2005 level. That level would be considerably lower than what is expected with our "constant technology" scenario but well above that of our "maximum technology" scenario. At the same time, this approach's impact on the fuel efficiency of transportation technology and on reducing travel demand would be relatively small. That's because reaching that emission goal would not require extreme changes within transportation, such as expanded use of hybrid electric vehicles versus the traditional, mechanical drivetrain.

Alternatively, passenger travel could be treated as a special category, with its own targets for emission reductions. Arguments for this approach include the fact that controls are more politically acceptable on passenger travel than in other economic sectors—such as power generation. Also, it's argued that the combination of gains that would result could be more valuable than the extra costs imposed. The latter argument emerges when multiple policy concerns are pursued at once, such as reducing greenhouse gas emissions and reducing a country's dependence on foreign oil.

Whatever mitigation strategy governments adopt, advances in technology must also be encouraged by support of research and development. Points of focus should be improving propulsion and energy storage systems and reducing the driving resistance of road vehicles through further weight reduction and downsizing. It is also time to explore radical changes in aircraft de-

sign, such as the blended wing-body aircraft. Given the uncertainties regarding what will work, research and development investments should be distributed widely among promising options. Research on battery technology is critical, but competing technologies such as the production and storage of hydrogen should be supported as well. Because biomass-derived synthetic oil products can be readily used in automobiles and aircraft, research and development investments in these fuels could have an especially high payoff.

Changing vehicles and fuels—along with altering consumer and industry behavior in the transportation sector—can reduce emissions. But this will take time, possibly decades. That means efforts to reduce mobility-related emissions, as part of a broader effort to control all greenhouse gas emissions, must be a high priority now. Otherwise, we are confident, the past will repeat itself. Demand for motorized travel will grow apace with global population and incomes. And emissions will increase to levels where transport emissions alone could prevent the world from reaching the more ambitious targets for atmospheric greenhouse gas concentration limits. There will be no solution to the climate threat without changes in trans-

portation. And there will be no changes in transportation without coherent government policies requiring them.

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