Transportation in a Climate-Constrained World

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Introduction: From Local Impacts to Global Change

Consider this traffic situation: the roads are highly congested and clogged with broken-down vehicles. Exhaust emissions are a thousand times higher than those of the average vehicle today and leave air quality miserable. Traffic-related fatalities claim one of every two hundred residents each year. The streets are dangerous, noise levels are intolerable, and a noxious smell hangs over all. Beyond the packed streets, the increasing demand for transportation fuel is about to threaten other basic needs of daily life.

A bleak forecast by the sixteenth-century seer Nostradamus? In fact, the passage describes the societal impact of the horse-drawn urban transportation system of the second half of the nineteenth century.

The magnitude of this impact becomes even more impressive when seen in a specific location. In Victorian London, an 1850 traffic count recorded a thousand horse-drawn vehicles per hour passing over London Bridge in the course of a day. Given total horse droppings of about five tons per horse per year, new markets developed to take care of this "exhaust" problem. The function of one new job, crossing sweeping, was to create a passage through the often liquid, ankle-deep manure so that London pedestrians could cross from one side of the street to the other.[1] At the time, it was forecast that within a few decades, current rates of traffic growth would bury London under six feet of horse manure.

Clearly, the urban transportation system of the nineteenth century had reached its limits. Further increases in horse traffic would have been constrained not only by the already extreme levels of congestion, emissions, and noise, but also by the limited amount of land available for growing horse fuel at reasonable cost. According to one estimate, the demand for hay in the United States had already taken up about one-third of the

cropland at that time.[2] (As we will see later in this book, this land constraint reappears in today's drive for *modern* biofuels.)

Given these limiting conditions, it was just a question of time as to when a revolution in transportation technology would emerge. Although the first horse*less* carriages were widely regarded with skepticism, their advantages soon became obvious. The early automobiles released hundreds of times lower tailpipe emissions, occupied less than one-half of the road space, and liberated huge cropland areas to feed a growing population. The rest is history.

The Rise of the Automobile

Analysts identify two phases of motor vehicle adoption in the United States. From about 1900 to the early 1920s, the automobile was expensive; it was mainly wealthier horse owners who switched to the motor vehicle.[3] During that period the U.S. automobile fleet increased at almost 40 percent per year. Such rapid growth, sustained over such a long period, has remained unmatched in the subsequent history of transportation. The next phase of motor vehicle adoption allowed a growing portion of the middle class to own an automobile, a development made possible by lasting economic growth, a sharp decline in vehicle purchase costs (mainly because of the advent of mass production), and the introduction of vehicle-financing plans.

During the 1930s the automobile became the single most important mode of transport in the United States, two decades before the construction of the interstate highway system.[4] Given long-term growth in vehicle ownership at rates of about 2 percent per year during the second phase of vehicle adoption, mass motorization—when on average every U.S. household owned one automobile—was achieved by 1952. In combination with generous government housing programs, rising car ownership enabled an increasing portion of the middle class to realize the American dream of affordable housing in a safe suburban environment. In light of increasing car dependency and decreasing urban population densities, the gradual decline of public transportation was unavoidable. In the 1980s, a Chicago transit official declared that mass transit was "no longer relevant to the American way of life."[5]

Although the onset of motorization was earliest in the United States, it has become a global phenomenon. In Western Europe the rapid increase in the number of vehicles per person started only after the Second World

War. Since then, Western Europe has maintained a roughly constant delay of about thirty years behind U.S. motorization levels. This delayed growth resulted in part from lower average household income, but also in part from a different industry approach to marketing. U.S. manufacturers aimed their products at the mass market early on and soon were able to exploit economies of scale. In contrast, European manufacturers initially targeted their products toward the wealthy upper class, necessarily incurring higher costs and reduced sales.

In both the United States and Western Europe (along with other industrialized countries), the vehicle market has essentially become a replacement market, where new vehicles mainly substitute old or outdated ones. In contrast, today's largest growth market is in the developing economies. Given the currently small size of their vehicle fleets, auto ownership is growing at about 30 percent per year, a rate nearly as high as that in the U.S. market a century ago. Since about 80 percent of the world population lives in the developing countries, the largest wave of motorization is yet to come.

Figure 1.1 shows the century-long growth of the world motor vehicle fleet in the United States, other industrialized countries, and the rest

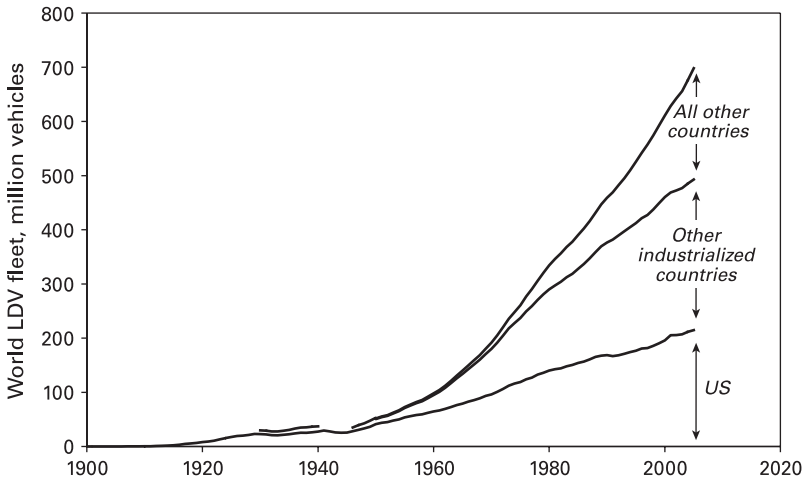

Figure 1.1
Historical growth of the world light-duty vehicle fleet, 1900–2005. Sources: U.S. Department of Transportation, various years. *Highway Statistics*. U.S. Federal Highway Administration, Washington, DC. Motor Vehicle Manufacturers Association, 1996. *World Motor Vehicle Data*, Detroit, MI. Authors' database.

of the world. The motor vehicle fleet includes automobiles and other light-duty vehicles (LDVs; vans, minivans, pickup trucks, and sport-utility vehicles) that are predominantly used for passenger travel.[6] In 2005, the world LDV fleet comprised 700 million vehicles, up from essentially zero in 1900. Over the past five decades alone, the vehicle fleet grew by 5 percent per year, corresponding to a doubling of its size every fifteen years. Should that rate continue to hold into the future, the global fleet of LDVs would increase to about 2 billion in 2030.

The growing motor vehicle fleet has transformed national economies by enabling the integration of distant labor, product, and consumer markets. In addition, the vehicle industry itself has become a pillar of the economy. A 2003 report by the University of Michigan and the Center for Automotive Research concludes that the automobile industry alone provides one out of ten jobs in the United States, either directly or indirectly.[7] Rising automobile ownership has also contributed to a higher quality of life. Compared with a person living in the nineteenth century, a representative of the automobile age has greatly improved access to education and health care, much greater freedom of choice in where to live and work, and where, when, and how to travel. These invaluable opportunities have lead to the perception of the automobile as an icon of personal freedom.

These benefits have not come without challenges, however. Although the transition from the horse to the automobile has provided significant environmental and societal benefits on a transport-system level, many of these improvements have been outpaced by growth in transport demand and associated side effects. At the same time, the original challenge that innovations in transportation technology were expected to resolve has spread. Take traffic congestion as an example, a phenomenon originally observed in city centers. Although automobiles occupy only less than one-half the road space of horse carriages, the enormous growth in automobile ownership has led to congestion levels as severe as in the horse age but at a larger geographic scale. Traffic congestion today typically covers entire metropolitan areas.

A similar increase in geographic scale of transport-related impacts has been observed for urban air pollution, even though significant technical improvements have been achieved. In the horse age, the immediate impact of solid and liquid emissions was confined to urban areas, mainly owing to the limited range of the flies that transmitted infectious dis-

eases. In the automobile age, gaseous vehicle pollutants are transported over hundreds of kilometers and have effects at distant locations. Already during the early 1950s, automobile emissions were shown to contribute to the photochemical smog in large areas of the Los Angeles basin. That mixture of reactive pollutants was soon found in other U.S. cities and abroad.

In response to concerns about deteriorating urban and regional air quality, regulatory measures were adopted. In 1966 California introduced the first tailpipe emission standards for hydrocarbons and carbon monoxide, and shortly thereafter federal legislation regulated so-called criteria pollutants (carbon monoxide, lead, nitrogen dioxide, sulfur dioxide, particulate matter, and ground-level ozone) that affect human health. This and subsequent U.S. legislation led to the development and adoption of the catalytic converter and cleaner transportation fuels, which decoupled the criteria emissions from gasoline use. Between 1970, when the federal clean air legislation was passed, and 2002, U.S. automobile and light truck emissions of carbon monoxide, nitrogen oxides, and unburned hydrocarbons declined by 60 to 70 percent even while gasoline use increased by 60 percent and vehicle kilometers traveled multiplied by a factor of 2.5.[8] Governments from many other countries have followed suit, and similar reductions in criteria emissions are being achieved worldwide. Examples of other vehicle-level improvements that have been outpaced by the strong growth in road traffic, and whose impacts have increased in geographic scale, include noise and traffic accidents.[9]

And how did the vehicle industry respond to traffic congestion? While automobile manufacturers cannot mitigate traffic congestion itself, the industry has started offering onboard satellite-guided navigation devices, which in combination with traffic updates allow drivers to avoid the most congested areas. Vehicle manufacturers also offer more advanced entertainment systems and onboard work opportunities to mitigate the *impact* of traffic congestion on car occupants.

The Growing Competition from Air Travel

Although automobiles began to dominate U.S. travel in the 1930s, for several decades long-distance trips continued to be made predominantly via rail. Among rail options, the streamliners, lightweight diesel-electric

trains, offered high-speed intercity connections.[10] Yet, after the Second World War, government investments in interstate highways and airports contributed to the demise of this first-generation high-speed train.

The strong increase in commercial air travel after the Second World War was also enabled by technological innovations like the introduction of the jet engine in the early 1950s, allowing a significant increase in aircraft capacity and speed. By the mid-1950s aircraft had already displaced buses and intercity railways to become the second most important mode of U.S. intercity travel. Since about 1960 the strong growth in air travel has captured market share from automobiles as well. By 2005 commercial aircraft accounted for about half of all passenger kilometers traveled (PKT) on long-distance trips, here defined as travel at trip distances greater than 100 kilometers (62 miles).[11] Aircraft ultimately dominate travel markets at distances greater than 1,000 kilometers; that is, distances that would require automobile drivers to spend at least one night in a hotel. Over the past five decades, the demand for air travel in the United States has grown by nearly 9 percent per year, compared with about 2 percent per year for the LDV fleet.

Similar growth trends can be observed in other parts of the industrialized world, even in countries with an extensive high-speed rail network. In Western Europe also, aircraft provided half of all long-distance PKT in 2005, up from 2 percent in 1950. (Despite the dense network, high-speed rail accounted for only 3 percent of the 2005 total PKT in long-distance travel.) In Japan, the country with the longest continuous history of high-speed rail, air travel supplied one-third of total long-distance PKT, with Shinkansen trains accounting for an additional one-sixth. While the air travel share currently is lower than in rich countries, even stronger growth in air travel is seen in the rapidly developing Asian economies, where rising income, poor-quality surface transport, and large travel distances are contributing to the trend.

Figure 1.2 shows the historical growth in U.S. and world passenger air traffic. Although the era of commercial air travel began after the Second World War, PKT started to grow strongly only in the 1960s, when a critical number of large jet aircraft entered the U.S. fleet. In 2005, U.S. aircraft provided about 1,250 billion passenger kilometers (pkm), an average of 4,200 kilometers (2,610 miles) per person. Total U.S. air traffic volume roughly compares to that of all other industrialized countries, and to that of the remaining countries. All together, in 2005, the commercial world aircraft fleet provided about 4,000 billion pkm, up from

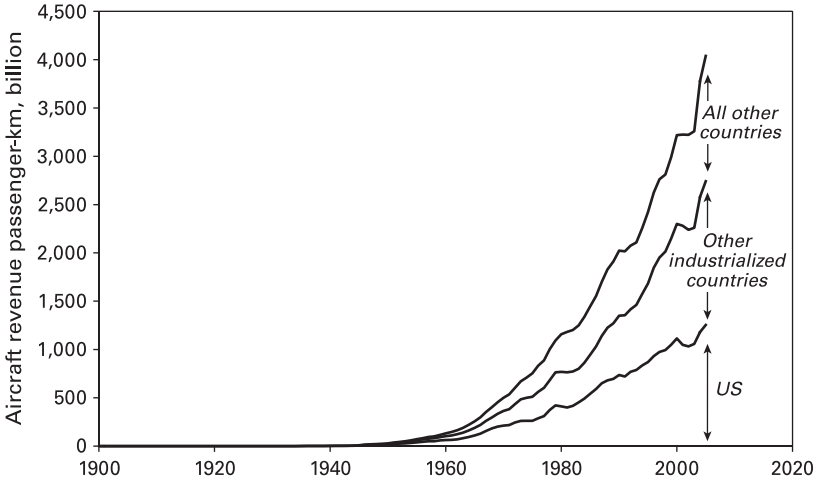

Figure 1.2
Historical growth of world commercial passenger aviation, 1900–2005. Sources: U.S. Census Bureau, 1975. *Historical Statistics of the United States, Colonial Times to 1970*, U.S. Department of Commerce, Washington, DC. Air Transport Association of America, 1950–2007. *Economic Report* (formerly *Air Transport Facts and Figures*), U.S. Department of Commerce, Washington, DC.

virtually zero in 1950, and corresponding to an average growth in excess of 9 percent per year.

In 2005, more than 60 percent of the 4,000 billion pkm supplied by aircraft occurred in international traffic. Not counting the large North American market, in which 70 percent of all aircraft-related PKT occurred in domestic travel, international air traffic accounted for nearly 80 percent of all world aviation-related PKT in 2005.[12] While the defeat of the immediate "distance barrier" has made the automobile an icon of personal freedom, overcoming national and continental boundaries has turned air travel into a symbol of globalization. The very existence of many industries and services has become reliant on the fast and efficient movement of people and goods over long distances.

As with the automobile, strong growth in air travel demand has forced the aircraft industry to try to mitigate its vehicles' environmental and societal impacts. Unfortunately, even impressive improvements at the vehicle level have been outpaced by growth in travel demand, so impacts have increased in geographic scale. Take surface air quality, for example. In 1973, the U.S. Environmental Protection Agency regulated emissions

of smoke, unburned hydrocarbons, carbon monoxide, and nitrogen oxides for several classes of subsonic aircraft engines. Due to the focus on surface air quality, such regulations apply to landing–take off cycles, which extend to an altitude of 915 meters (3,000 feet); emissions above that threshold have remained unregulated to date.[13] Over time, the emission standards have become increasingly stringent, and significant reductions have been achieved per aircraft operation. Yet, in contrast to automobiles, where the catalytic converter and cleaner transportation fuels have decoupled local air pollutant emissions from fuel use, the growing demand for air travel has caused most of these emissions to increase. Between 1970 and 2002, the number of departures at U.S. airports from scheduled passenger and freight aircraft increased by 80 percent. Over the same period, emissions increased by a low of 33 percent (sulfur dioxide) to a high of 200 percent (large particulates); carbon monoxide and nitrogen oxide emissions increased by about 60 percent. Only emissions of unburned hydrocarbons declined, by about 60 percent.[14] In addition, the geographic scale of aviation-related air pollutants has increased. Aircraft emissions are increasingly being understood to contribute to regional environmental impacts, even when aircraft operate at cruise altitude.[15]

Another impact that has grown in geographic scale is air traffic congestion. Absent any capacity increase or changes in operational strategies, air traffic congestion would have already become a binding constraint for a significant further rise in air travel. However, the increase in traffic congestion at primary airports has induced the airline industry to adopt new business models aimed at greater use of secondary and tertiary airports. As a result, airport operations have been dispersed to multiple points in many metropolitan areas. Most prominent are the budget airlines, which—as a result of increasing traffic congestion at primary airports along with prospects of cost savings at secondary airports—started a network of airline services parallel to that of the large commercial carriers as early as the 1970s.[16] More recently, very light jets (VLJs) equipped with precision satellite navigation have begun to open up a third, largely parallel network of airline operations, with the prospect of operating routinely among the several thousand U.S. airfields that do not have control towers or radar. If successful, these comparatively affordable single-pilot aircraft, which seat between three and six passengers, would further spread aircraft operations (and air pollution) over a regional scale. The geographic scale of other impacts has been

less pronounced. Significant progress has been achieved in aviation safety, but these improvements have also been offset by the strong growth in traffic.[17] And aircraft noise has been reduced, even on an absolute scale.[18]

Although some of the environmental and societal concerns could not be resolved completely yet, continuous improvements in aircraft technology and fuels are likely to result in further reductions in pollutant emissions and noise on a per aircraft and per operation basis. However, most projections suggest that, at least over the next ten to thirty years, these reductions will not be sufficient to compensate for the expected increase in air travel.[19] Fortunately, in the longer run, concepts for future aircraft designs and cleaner fuels could diminish these air travel impacts.

Oil Dependence and Climate Change

While the reduction of many environmental and societal impacts on a vehicle and operation basis have been offset by the strong growth in traffic, there is a growing sense that all can eventually be controlled, at least over the long term. Two concerns, however, remain unresolved. Both are related to the dependence of our transportation system on petroleum products: gasoline, diesel, and jet fuel account for 97 percent of all transportation fuels in the United States and 94 percent on a global average.[20]

One concern is oil dependence. Over the past century, the U.S. demand for petroleum products has grown strongly. However, domestic oil production could not keep pace with that development. After the Second World War, oil imports began to exceed exports, and the share of imported oil has risen ever since, from 36 percent in 1975 to 65 percent in 2005.[21] Since the great bulk of the world's oil reserves is located in politically less stable regions, the rising dependence on oil imports raises national security concerns. The vulnerability of the global fuel supply systems was made clear by the oil supply disruptions during the 1973 Middle East War and the 1979 Iranian Revolution, and oil and gas security remain important concerns of the foreign and military policies of importing regions, importantly including the U.S.

In an effort to mitigate oil dependence, the U.S. Congress enacted the world's first fuel economy regulations. Introduced in 1978 with the intention of doubling the fuel economy of new motor vehicles within a decade, the regulations forced vehicle manufacturers to design products that met increasingly stringent fuel-efficiency targets. In addition to

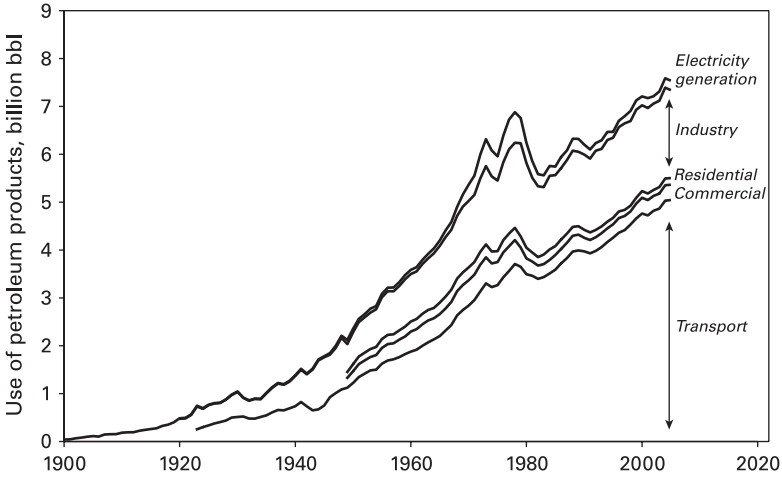

Figure 1.3
Use of petroleum product by sector in the United States, 1900–2005. Sources: U.S. Census Bureau, 1975. *Historical Statistics of the United States, Colonial Times to 1970*, U.S. Department of Commerce, Washington, DC. U.S. Energy Information Administration, 2007. *Annual Energy Review 2006*, U.S. Department of Energy, Washington, DC.

government responses, the expectation of further oil price spikes led to market and other economic adjustments; the amount of oil used in electricity generation, industry, and the residential sector declined in favor of less price-volatile fuels. Because of the stronger responsiveness of non-transportation sectors, transportation accounted for an even larger share of oil consumption after this period of market disruption.

The century-long growth in the consumption of petroleum products and their use across sectors in the United States is reflected in figure 1.3. Between the early 1920s and 2005, consumption of petroleum products rose more than tenfold. During this same period, passenger and freight transport increased their share of oil use from less than half to two-thirds. As a result, U.S. transport-sector oil use increased more than twentyfold. Given the likely continuation of the strong increase in the world motor vehicle fleet (figure 1.1) and of air travel (figure 1.2), the demand for petroleum products, especially for transportation fuels, is likely to continue to grow also on a global scale.

The strong dependence of transport systems on oil products and the projected growth in consumption not only raises energy security con-

cerns. Burning a liter of gasoline, diesel, or jet fuel in an automobile or aircraft engine releases nearly 2.5 kilograms (around 5.5 lbs) of carbon dioxide (CO_2), a major greenhouse gas (GHG), into the atmosphere. Already, the atmospheric concentration of CO_2 has increased from a preindustrial level of 280 parts per million by volume (ppmv) in 1800 to about 380 ppmv in 2005. Given the projected increase in human activity, concentration levels will continue to rise, changing the radiative balance of Earth and affecting the global climate. The projected implications of the anthropogenic (human-influenced) greenhouse effect are significant. An increase in the mean Earth temperature leads to the thermal expansion of oceans, the melting of the ice shelves, and thus to a sea level rise. An increase in the mean Earth temperature also induces an increase in extreme weather events, such as heat and cold waves, droughts, heavy rains, and tropical storms. Some of these ecosystem alterations form the basis for secondary impacts, including the spread of tropical diseases outside their current latitude band, mass migration of people most affected by climate change, and economic losses.

Due to its abundance, CO_2 is the most important contributor to the anthropogenic greenhouse effect. Other GHG emissions, however, can have a stronger warming effect. Among those are methane emissions from agricultural practices, animal farming, landfills, energy-related activities, and other sources. Over a span of one hundred years, methane has a 21 times stronger climate impact than the same mass of CO_2. A still stronger climate impact of 310 times that of a mass unit of CO_2 results from nitrous oxide (N_2O) emissions if measured over the same time horizon.[22] N_2O emissions result from soil cultivation, nitrogen fertilizer use, and animal waste. As we will discuss in more detail, some strategies that aim at reducing CO_2 emissions can result in an increase in these stronger GHG emissions and thus reduce the potential of GHG emission reduction as given by CO_2 alone.

Two other important components of the greenhouse effect are water vapor and clouds. Along with CO_2, water vapor is the other major product of fossil fuel combustion, but water emissions at Earth's surface have no climate effect. If released at cruise altitude by commercial aircraft, however, water vapor emissions can be more significant. The precise climate impact of aircraft water emissions, especially the extent to which they result in persistent contrails, depends on several factors, including the prevailing ambient atmospheric conditions and the amount and types of particles formed in the engine exhaust.

While line-shaped contrails contribute to global warming, they can evolve into larger regions of cirrus clouds, which also tend to warm Earth, although the amount of the warming is subject to great uncertainty. A similar complication is the climate impact of aircraft nitrogen oxide (NO_x) emissions, because they cause changes in the concentration of other greenhouse gases. These changes partly offset each other, and their impacts are regional and thus not strictly additive. Overall, however, the combined global warming impacts of the various consequences of commercial aircraft are estimated to be larger than the impacts of the CO_2 emissions alone.[23] (However, because of the formation of troposphere ozone, automobiles also contribute to climate change to a larger extent than suggested by their CO_2 emissions alone.)

The Intergovernmental Panel on Climate Change (IPCC) summarizes the results of computer models that simulate the dynamics of the biosphere, ocean, and atmosphere. The IPCC concludes that an increase in the atmospheric CO_2–equivalent concentration to 550 ppmv—roughly twice the preindustrial level—would result in a global average temperature increase of about 3°C above the preindustrial equilibrium. The associated global average sea level rise would correspond to 0.6–1.9 meters (2.0–6.2 feet). Limiting the effects to such levels, however, would be very ambitious, because global CO_2 emissions would need to peak before 2030. A later peak in CO_2 emissions would correspondingly result in a larger atmospheric concentration, a stronger temperature increase, and a higher sea level rise.[24]

GHG emissions differ from urban air pollutants in two important ways. Because the atmospheric lifetime of CO_2 is on the order of one hundred years, changes in the composition of the atmosphere are long lasting. Thus, while the impact of urban air pollutants have been limited to a regional level, the long lifetime of CO_2 and other long-lived greenhouse gases means that their impacts expand to global scale. In addition, unlike urban air pollution, there is no practical end-of-pipe technology that could be used to reduce CO_2 emissions from transport systems. Since CO_2 is formed by the oxidation of carbon atoms in the transport fuel, all reduction options must aim at burning less (nonrenewable) carbon-containing fuel. Because of oil dependence and the huge scale of the transportation system today, changing automobile and aircraft technologies and their supporting fuel systems is an enormous task that may require instituting the largest technological transformation since the transition from the horse to the automobile itself.

Table 1.1 indicates GHG emissions by type, country, and source in 2005, ranked according to per capita emission levels. Not counting the CO_2 emissions from land-use change, global GHG emissions amounted to nearly 40 billion tons of CO_2 equivalent. As can be seen, their distribution across countries is inhomogeneous. Nearly one-fifth of the world GHG emissions were emitted by the United States, with more than 7 billion tons of CO_2 equivalent, which include emissions of CO_2, methane, N_2O, and various industrial gases. A close second is China, which in 2007 overtook the United States as the leading emitter of GHGes, albeit with a much larger population. In general, CO_2 accounts for the large majority of total GHG emissions, and nearly all CO_2 emissions (aside from those related to forest destruction) result from activities involving fossil fuels (the "energy-related" CO_2 emissions in table 1.1). In the United States, passenger travel accounts for 22 percent of all energy-related CO_2 emissions and for 18 percent of total national GHG emissions. This emission level is especially significant when comparing to the total GHG emissions from other countries. The CO_2 emissions from U.S. *total* (passenger and freight) *transportation* of 1,920 million tons are larger than the *total national* GHG emissions from each of the other countries with the exception of China and Russia. U.S. *passenger* travel CO_2 emissions alone are larger than the *total national* GHG emissions of Germany and are about twice the national GHG emissions from the United Kingdom or France.

Global passenger travel currently releases a comparatively small share of total GHG emissions. In 2005, world passenger travel accounted for roughly 14 percent of the global energy-related CO_2 emissions. Yet, the relative importance of passenger travel CO_2 emissions is likely to increase in the future mainly because of structural changes in the world economy. Early in the economic development process, agriculture is usually the dominant production sector. With economic growth, agriculture is bypassed first by industry and then by services. Within services, total transport use (industrial and personal) takes an ever-increasing economic role. Since each of these sectors consumes energy to produce goods or services, we observe a similar sector shift for energy use and CO_2 emissions. Indeed, the historical data in figure 1.4 show these shifts in CO_2 emissions, from the residential sector (for heating, cooling, and running appliances), to the industry sector, and finally to the service sector, with transportation being by far the single largest energy consumer of the service sector.[25]

Table 1.1
Greenhouse gas emissions (in million tons of CO_2 equivalent) for selected countries and the world by source in 2005

	GHG emissions		CO_2 emissions					
	Total	Per capita		Energy-related				
					Transportation-related			
						Passenger travel		
	Mt[a] CO_2-eq[b]	tCO_2-eq	$MtCO_2$	$MtCO_2$	$MtCO_2$	$MtCO_2$	% $EnCO_2$[c]	% $TrpCO_2$[d]
Australia	534	26.3	393	384	91	60	16	66
United States	7,300	24.6	6,140	6,090	1,920	1,340	22	70
Russia	2,170	15.0	1,780	1,740	165	86	5	52
Germany	1,020	12.4	894	873	184	132	15	72
United Kingdom	696	11.6	596	558	171	106	19	62
Japan	1,380	10.8	1,320	1,290	281	170	13	61
France	576	9.5	434	417	154	85	20	55
China	6,940	5.3	5,300	5,170	335	135	3	40
India	1,900	1.7	1,270	1,250	110	47	4	43
World	38,400	5.9	28,200	27,900	6,370	3,890	14	61

Sources: GHG and CO_2 emissions were mainly derived from UN Framework Convention on Climate Change (UNFCCC), *Gas Inventory Data—Detailed Data by Party*; http://unfccc.int/ghg_data/ghg_data_unfccc/ghg_profiles/items/3954.php. These figures were complemented with CO_2 emission data from international air traffic, which are not included in the UNFCCC data. The basis for estimates of CO_2 emissions from international air traffic is International Energy Agency, 2007. *Energy Balances of OECD and Non-OECD Countries*, IEA/OECD, Paris. The IEA *Energy Balances* were also the basis for estimating missing CO_2 emissions data for China, India, and the world. Source for land-to-atmosphere CO_2 fluxes: Denman, K.L, G. Brasseur, A. Chidthaisong, P. Ciais, P.M. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, El. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P.L. da Silva Dias, S.C. Wofsy, X. Zhang, 2007. Couplings Between Changes in the Climate System and Biogeochemistry, IPCC Fourth Assessment Report, Working Group I Report, *Climate Change 2007—The Physical Science Basis*, Cambridge University Press, Cambridge, UK.

[a] Mt = million metric tons.

[b] CO_2-eq emissions include CO_2 emissions and those of other greenhouse gases, converted to CO_2 emissions on the basis of a 100-year global warming potential. Data exclude land-to-atmosphere CO_2 fluxes of 1,800–9,900 $MtCO_2$.

[c] Percent energy use-related CO_2 emissions.

[d] Percent transportation-related CO_2 emissions.

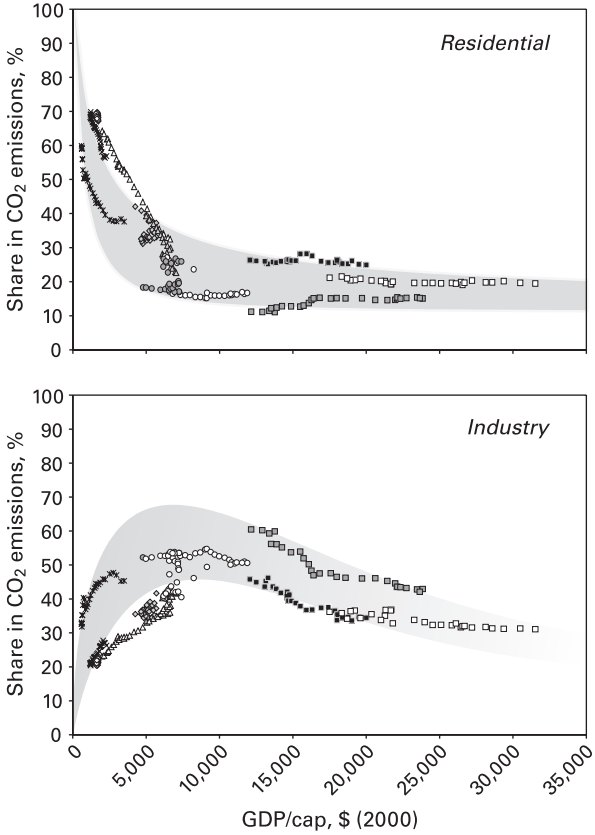

Figure 1.4
Structural change in CO_2 emissions for eleven world regions, 1971–1998. Source: Schäfer, A., 2005. Structural Change in Energy Use, *Energy Policy*, 33(4): 429–437.

While the structural shifts shown in figure 1.4 lead to a continuous increase in transportation's share of energy use and CO_2 emissions, the rising relative importance of passenger travel is also caused by its faster growth in comparison to freight transport. At early stages of industrialization, most transportation energy is used in freight transport, which is vital for setting up the basic urban and industrial infrastructure. Passenger movements are conducted largely by non-motorized transport modes and by motorized two-wheelers, buses, and railways. With subsequent growth, first in LDV motorization and later in air travel, the share of

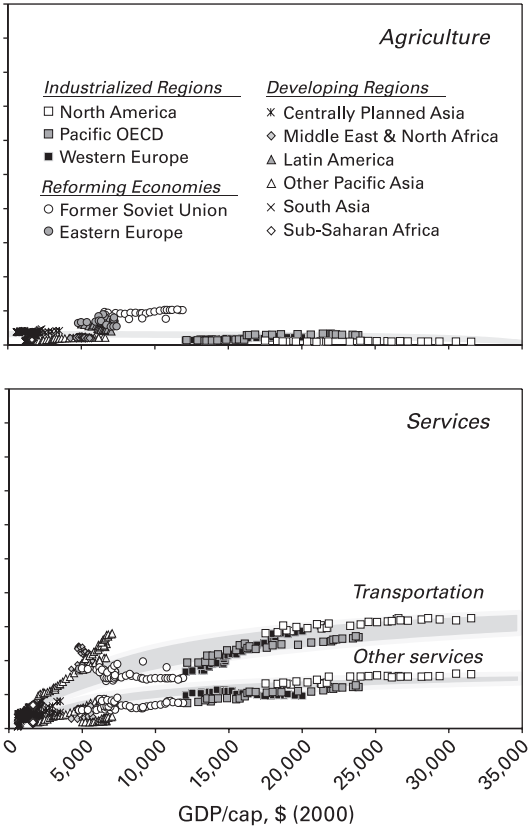

Figure 1.4
(continued)

passenger transport energy use and CO_2 emissions rises strongly, saturating at a roughly 70 percent share of total transport CO_2 emissions, as can be seen from the right column in table 1.1. The combination of these trends, the structural shift toward services and the rising relative importance of passenger travel, argue that passenger travel GHG emissions are likely to continue their growth relative to other sectors.

Why This Book?

Governments have reacted to the threat of climate change in various ways. In the United States, efforts to mitigate GHG emissions have been

voluntary to date and have focused on research and technology development rather than controls or price measures applied directly on the emissions. In contrast, the European Union (EU) is imposing policies to meet low-emission targets it accepted with its ratification of the Kyoto Protocol, importantly including a union-wide emissions trading scheme (ETS). This scheme anticipates the inclusion of aviation but excludes surface transport. In surface transport, freight is excluded from any policy mechanism, but a voluntary approach has been tried for automobile transport, with vehicle manufacturers agreeing to achieve increasingly stringent CO_2 tailpipe emission targets for their vehicles over time. However, because the first target has not been met, the EU Commission has adopted a mandatory industry-wide CO_2 tailpipe-emission limit.

The lack of coherent strategy results in part from policy makers receiving mixed signals about their efforts to reduce emissions from this sector. Independent researchers often point to an untapped potential for reducing GHG emissions. Some believe that by "doing it right," a vast improvement in automobile and aircraft fuel efficiency is technologically feasible and economically affordable.[26] In contrast, automobile manufacturers point to the many technological difficulties that need to be overcome before low-GHG-emission vehicles can be produced at reasonable cost. They argue that if their products are forced to meet stringent GHG-emission targets, the rise in consumer costs will lead to reduced sales and factory layoffs.

The intensity of this debate over the potential trade-offs between reduced GHG emissions (and oil dependence) and cost is overshadowed by an apparently insatiable human demand for more travel, at higher speeds, and in greater comfort. To help inform this discussion, and the crucial public policy decisions that are at issue, we attempt to do three things in this book: first, assess the opportunities for transportation technologies and fuels to achieve GHG-emission reductions; second, evaluate the potential limitations on those possibilities; and finally, review the structural challenges that face the implementation of promising technological advances—and the policy approaches that would be required to overcome them.

Since the growth in travel demand has undermined many improvements that were achieved on a vehicle level in the past, we conduct this analysis in the context of a projected plausible future demand for passenger mobility. Together, the projected change on a vehicle level and the anticipated change in travel demand will determine the change in abso-

lute levels. Such projection leads to the first decision to be made. Whenever looking into the future, an immediate issue that arises is the study's time horizon. On the one hand, our interest in observing the long-term effects of policies put into place over the next decades requires a possibly long time horizon. On the other hand, our ability to assess the technology development fades the further we look into the future. Thus, the time horizon is a compromise. We chose the year 2050, since we believe that some of the promising technologies now under development will take about twenty years to enter the market—a period over which we still feel confident to project these new technologies' main characteristics. It would then take another twenty years to displace much of the then-prevailing fleet of air and ground vehicles.

Outline of the Book

The amount of GHG emissions from passenger travel depends on various factors, including how much travel is undertaken, the type and use of transport modes and technologies, and the transport fuel used. These determinants, and the structure of the chapters to follow, can be summarized using the algebraic statement shown on the right-hand side of equation 1.1, which describes the overall identity of passenger travel greenhouse gas emissions (GGE). Among all the influences on this sector's energy (E) use, growth in travel demand—PKT, passenger kilometers traveled—is the most obvious. The relationship is direct: a doubling in global PKT causes a proportional rise in energy use, all other factors being equal. Since understanding travel growth is crucial to making an assessment of the urgency and scale of GHG mitigation—remember the compensation of many improvements on a vehicle level in the past—in chapter 2 we discuss the past and possible future trends in world-regional and global travel demand.

$$GGE = \frac{GGE}{E} \cdot \frac{E}{PKT} \cdot PKT \tag{1.1}$$

For a given transport mode, energy use is also determined by the technology characteristics of the transport system, that is, the amount of energy use per PKT and how efficiently it is used. "Use efficiency" is determined by the average occupancy rate, the driving cycle of a given vehicle, and other factors. These determinants of energy intensity are analyzed in chapter 3. The product of PKT (projected in chapter 2) and

E/PKT (examined in chapter 3) describes passenger travel energy use. In chapter 3, we also project future levels of passenger travel energy use and GHG emissions in a constant technology scenario.

Chapters 4 to 6 describe the technology and fuel opportunities for reducing (the projected) GHG emissions. Chapter 4 discusses the technology opportunities for reducing the energy intensity (E/PKT) of LDVs, and chapter 5 describes those for reducing the energy intensity of passenger aircraft. Translating energy demand into GHG emissions requires knowledge of the type of transportation fuel in use, characterized by the amount of GHG emissions released per unit of energy consumed (GGE/E). As we will discuss in more detail in chapter 6, each type of transportation fuel and the underlying production process results in a specific value of GGE/E and thus a distinct global warming impact.

In these three chapters, we identify a range of technology and fuel options that could greatly reduce GHG emissions per unit of travel activity. The question of why these technologies have not yet been introduced (on a large scale) is addressed in chapter 7, in which we discuss policies that could help bring low-GHG technologies and fuels into the market and influence total levels of use, PKT. Chapter 8 summarizes our view of future prospects and the challenges facing policy makers.

Limitations of This Study

This book examines the opportunities and limitations of current and future technologies and fuels for mitigating GHG emissions from passenger travel. It also discusses the policies that may be used to speed these technologies into the market and to influence total travel. Such a broad scope necessarily imposes some limitations.

One limitation is national scope. Although we describe the evolution of GHG emissions from passenger travel with respect to the entire world, most of our technology analysis focuses on the United States. This choice has a practical justification: the air and ground vehicle data at the required degree of detail is more easily available for the U.S. transport system than for any other one in the world. However, we do not see this "geographic technology focus" as a drawback. The U.S. is the largest national market in the world and will likely remain so over the next few decades. Its sheer size is overwhelming. As we show in table 1.1, CO_2 emissions from U.S. passenger travel alone are greater than the total GHG emissions of nearly any other country. In addition, as we will

argue, motor vehicle technology is similar across the industrialized world and increasingly to that used in developing countries. The similarity applies to aircraft technologies to an even larger extent and is also true of measures to influence total vehicle use, particularly through changes in fuel price.

Another limitation is modal. Although our demand projections include all major modes of motorized travel, our technology assessment focuses on the two major modes, automobiles and aircraft. These two modes already dominate passenger travel in virtually all industrialized countries, and trends we identify in chapter 2 will likely lead to their dominance in the developing world as well.

Finally, this book neither provides revolutionary proposals nor formulates groundbreaking recommendations. Rather, it explores practical means by which lower GHG-emission technologies and fuels could evolve over time. The scale of the problem precludes any revolution in our view: it inherently requires an evolutionary change process (though several of the steps may appear revolutionary to some). Overall, we will explore and discuss changes that have the potential for significant real-world impact within the next few decades. With this focus, we give scant attention to options that would fundamentally transform the transport system. For example, some combination of land-use controls, massive investment in urban public transit, and rapid intercity surface systems could be used to mitigate GHG emissions. However, such policies could affect emissions only on a time horizon beyond the one considered here. Changes in technologies and in fuel price will be the key ingredients of a policy package that can effectively reduce the rate of GHG-emission growth over the next thirty to fifty years.