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The Role of Transportation in Driving Climate Disruption

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Supporting a new, low-carbon, location-efficient, productive, and high-growth economy for the twenty-first century will be key to maintaining U.S. leadership in an increasingly competitive global marketplace.

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Summary

The Earth's rapidly warming temperatures over the past several decades cannot be explained by natural processes alone. The science is conclusive: both man-made and natural factors contribute to climate change. Human activities—fossil-fuel combustion in transportation and other sectors, urbanization, and deforestation—are increasing the amount of heat-trapping gases in the atmosphere. These record levels of greenhouse gases are shifting the Earth's climate equilibrium.

Climate impacts differ by sector. On-road transportation has the greatest negative effect on climate, especially in the short term. This is primarily because of two factors unique to on-road transportation: (1) nearly exclusive use of petroleum fuels, the combustion of which results in high levels of the principal warming gases (carbon dioxide, ozone, and black carbon); and (2) minimal emissions of sulfates, aerosols, and organic carbon from on-road transportation sources to counterbalance warming with cooling effects. Scientists find that cutting on-road transportation climate and air-pollutant emissions would be unambiguously good for the climate (and public health) in the near term.

Transportation's role in climate change is especially problematic, given the dependence on oil that characterizes this sector today. There are too few immediate mobility and fuel options in the United States beyond oil-fueled cars and trucks.

U.S. and international policy makers have yet to tackle transportation-climate challenges. In its fourth assessment report, the Intergovernmental Panel on Climate Change (IPCC) found that the global transportation sector was responsible for the most rapid growth in direct greenhouse gas emissions, a 120 percent increase between 1970 and 2004. To further complicate matters, the IPCC projects that, without policy intervention, the rapidly growing global transportation sector has little motivation to change the way it operates, because consumer choices are trumping best practices.

Herein lies a fundamental mismatch between the climate problem and solutions: transportation is responsible for nearly one of every three tons of greenhouse gas emissions but represents less than one of every twelve tons of projected emission reductions. Clearly this sector is a major contributor to climate change; therefore, it should be the focus of new policies to mitigate warming. Government must lead this effort as the market alone cannot precipitate the transition away from cars and oil, which dominate this sector.

Policy makers need to remember four essential findings and recommendations when developing new strategies for ensuring that the United States maintains its leadership position in the global economy:

1. On-road transportation is an immediate high-priority target in the short term for reducing greenhouse gas emissions and mitigating climate change in the United States and around the globe.
2. The transportation sector is responsible for high levels of long-lived carbon dioxide (CO_2) and ozone precursor emissions that will warm the climate for generations to come.
3. The United States (and other nations) must transition quickly to near-zero greenhouse gas (GHG) emission cars and trucks, largely through low-carbon electrification for plug-in vehicles.
4. America's transportation culture must adapt to rely less on fossil fuels through technological innovation, rational pricing, and sound investments that expand low-carbon mobility choices and fundamentally shift travel behavior.

Background

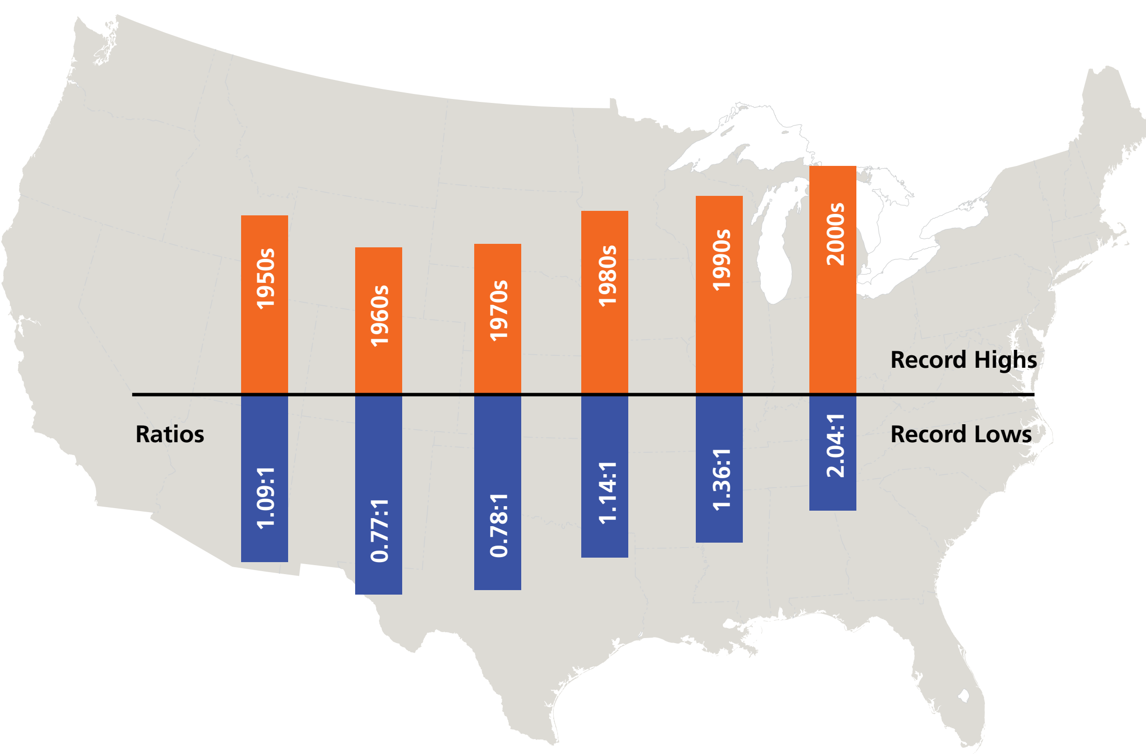
According to the National Oceanic and Atmospheric Administration and NASA, global surface temperatures have risen by 0.6°C since the middle of the twentieth century. The current decade has been the warmest worldwide on record, 0.2°C warmer than the 1990s.[1] According to the U.S. Environmental Protection Agency (EPA), the evidence of the Earth's warming is clear.[2]

The current decade has been the warmest worldwide on record.

The Earth's global average temperature is projected to rise from 1.7 to 3.9°C by 2100, and continue to warm in the twenty-second century.[3] Scientists are certain that human activities are changing the composition of the atmosphere, and that increasing the concentration of greenhouse gases will change the planet's climate. But they are still working to better understand the precise mechanisms of climate change, how much or at what rate temperature will increase, and to predict what the exact effects will be.

Still, scientists warn that the floods, fires, melting ice caps, and feverish heat witnessed in 2010 are signs of troubling climate change already under way.[4] As shown in Figure 1, about two new high temperature records were set for every low temperature record during the 2000s. And the ratio of record high

Figure 1. Ratio of U.S. Record High to Low Temperatures



Source: National Center for Atmospheric Research, November 12, 2009 http://www2.ucar.edu/news/record-high-temperatures-far-outpace-record-lows-across-us to record low temperatures has increased since the 1960s. Scientific evidence strongly suggests that man-made increases in greenhouse gases account for most of the Earth's warming over the past fifty years.

The National Research Council reports in *Climate Stabilization Targets: Emissions, Concentrations, and Impacts of Decades to Millennia* that a single long-lasting greenhouse gas, carbon dioxide, accounts for more than half of the current effect on the Earth's climate. Scientists are more concerned about the climate effects of anthropogenic (manmade) carbon dioxide emissions than any other greenhouse gas.[5] The atmospheric concentration of carbon dioxide is at its highest level in at least 800,000 years.[6]

Carbon dioxide flows into and out of the ocean and biosphere. Manmade CO_2 creates net changes in these natural flows, which accumulate over time; such extreme persistence is unique to CO_2 among major warming gases. Black carbon and greenhouse gases, such as methane, can also affect the climate, but these changes are short-lived and expected to have little effect on global warming over centuries or millennia.

Scientific evidence strongly suggests that manmade increases in greenhouse gases account for most of Earth's warming over the past fifty years.

But even if carbon dioxide emissions were to end today, scientists expect that changes to Earth's climate that stem from CO_2 will persist and be nearly irreversible for thousands of years. Scientists' best estimate is that for every 1,000 gigatonnes of anthropogenic carbon emissions (GtC), global average temperatures will increase 1.75°C.[7] Therefore, each additional ton of CO_2 released into the atmosphere forces warming.

The Science of Greenhouse Gas Emission Inventories[8]

High-quality and comparable information on national GHG emissions is crucial to designing and implementing international responses to climate change. In 1992, the United States and many other nations negotiated the United Nations Framework Convention on Climate Change (UNFCCC) to stabilize atmospheric concentrations of GHG emissions. Parties to the convention agreed, among other things, to periodically provide inventories detailing their manmade emissions and removal (by sinks) of GHGs. These inventories, and processes for their review, play an important role in ongoing negotiations for a post-2012 agreement on climate change.[9]

The EPA is responsible for developing and periodically updating, publishing, and making public "national inventories of anthropogenic [manmade] emissions by sources and removals by sinks of all greenhouse gases, using comparable methodologies. . . ."[10] Greenhouse gases and their Global Warming Potentials (in parentheses when known) are listed in Table 1.

Table 1. Catalogue of Greenhouse Gases and Their Global Warming Potential[1]

Naturally Occurring GHG	☑ Carbon dioxide, CO_2 (1) ☑ Methane, CH_4 (21)[2] ☑ Nitrous oxide, N_2O (310) ☒ Ozone, O_3 ☒ Water vapor
Industrially Produced (Synthetic Halocarbon) GHG	☑ Chlorofluorocarbons (CFCs)[3] ☑ Hydrochlorofluorocarbons (HCFCs) (3,400)[3] ☑ Bromofluorocarbons (halons)[3] ☑ Hydrofluorocarbons (HFCs) (8,000)[3] ☑ Perfluorocarbons (PFCs) (4,400)[3] ☑ Sulfur hexafluoride, SF_6 (23,900)
Air Pollutant Precursors with Indirect Influence on Formation or Destruction of GHGs[4]	☑ Carbon monoxide (CO) ☑ Oxides of nitrogen (NO_x) ☑ Non-methane volatile organic compounds (NMVOCs) ☑ Sulfur dioxide (SO_2) ☒ Particulate matter (PM) ☒ Aerosols[5]

Key: Checked box indicates UNFCCC inventories these GHGs; box with "X" indicates that these GHG are not currently inventoried.

Notes:
1. The Global Warming Potential (GWP) of a GHG is the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas, CO_2 (IPCC 2001). A 100-year time horizon is used.
2. The CH_4 GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor.
3. Estimates are provided, but these GWPs range from the hundreds to the tens of thousands for these compounds. For additional information on HFC and PFC warming potentials, see: http://www.epa.gov/ozone/geninfo/gwps.html.
4. The GWPs of these GHGs are not provided because there is no agreed-upon method to estimate the contribution of gases that are short-lived in the atmosphere, spatially variable, or have only indirect effects on radiative forcing (IPCC 1996).
5. Aerosols are suspended particles, which include PM, SO_2, black carbon, and organic carbon.

Sources: U.S. EPA, http://www.epa.gov/climatechange/emissions/downloads10/US-GHG-Inventory-2010_ExecutiveSummary.pdf; GHG Data from UNFCCC, http://unfccc.int/ghg_data/ghg_data_unfccc/items/4146.php.

Developing an inventory involves collecting data on activities across economic sectors, using numerous scientific methods. The convention's secretariat coordinates a review of inventories from the United States and other industrialized (Annex I) nations. The review team of international experts evaluates consistency with inventory guidelines, including technical methods developed by the IPCC.

Each year, emission source and sink estimates are recalculated and revised for all years in EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. Emission estimates generally are recalculated to incorporate new methodologies or, more commonly, to update recent historical data.[11] In its 2010 inventory update, the EPA reported total 2008 U.S. greenhouse gas emissions of 6,956.7

Table 2. U.S. Direct GHG Emissions by IPCC Sector and Uncertainty Estimates

IPCC Sector	2008 Direct Emissions (Tg CO_2 Eq.)	Emission Share %	Uncertainty of Inventory Estimate*** (%)
Energy	5,999.0	86%	-2 to +5%
Industrial Processes	334.5	5%	-24 to +43% (*CH_4-natural gas systems*)
Solvent and Other Product Use	4.4	<1%	n/a
Agriculture	427.5	6%	-22 to +53% (*Nitrous oxide from soil mgmt.*)
Land Use, Land-Use Change, Forestry (Emissions)*	32.2	<1%	-15 to +18%
Waste	159.1	2%	-39 to +33% (*CH_4-from landfill*)
Totals**	6,956.7	100%	-3 to +7%

Notes:
* Does not include net CO_2 flux from Land Use, Land-Use change, and Forestry (sinks) of 940.3 TgCO_2 Eq.,
** Total emissions include only sources, subtract land use sinks for a Net Emissions (sources and sinks) in 2008 of 6,016.4 TgCO_2 Eq.,
***GAO analysis of 3009 U.S. Inventory. Sources: U.S. EPA, http://www.epa.gov/climatechange/emissions/downloads10/US-GHG-Inventory-2010_ExecutiveSummary.pdf and GAO, "The Quality, Comparability, and Review of Emissions Inventories Vary Between Developed and Developing Nations, GAO-10-818, July 2010.

teragrams (Tg) carbon dioxide equivalent, the lion's share of which—86 percent—resulted from energy consumption, as reported in Table 2. U.S. GHG emissions rose by approximately 14 percent from 1990 to 2008.[12]

Scientists find that U.S. inventories overall are generally high-quality, yet some degree of uncertainty remains about emission estimates.[13] The U.S. inventory's overall uncertainty ranges from -3 percent to +7 percent.[14] However, inventory uncertainties vary among economic sectors, as noted in Table 2. Uncertainty is relatively low for estimates of carbon dioxide emissions from fossil-fuel combustion (the largest emission share) because the data on fuel use is generally accurate and the process well understood. Uncertainty is much higher in other IPCC sectors.[15] Even if all the uncertainties at the upper bound were factored into every sector, energy would still account for 82 percent of all U.S. direct GHG emissions.

The Science of Climate Change and Air Pollution[16]

The influence of air pollutant precursor emissions on warming is important, yet complex. Air pollutants—ozone-forming nitrogen oxides and hydrocarbons, carbon monoxide, particulate matter, and sulfur oxides—affect the global climate both directly and indirectly. Air pollution indirectly inhibits Earth's ability to emit radiation back into space. Some air pollutants react with other chemical compounds in the atmosphere to form compounds that are direct greenhouse gases.

Ozone formation (evidenced in urban areas as smog) also contributes to global warming. Nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOCs) react to form tropospheric (lower atmosphere) ozone. Air pollutants can alter the lifetimes of other greenhouse gases. Methane has a direct negative effect on climate, and an indirect role in exacerbating climate change by contributing to the formation of tropospheric ozone levels.

Carbon monoxide (CO) interacts with the hydroxyl radical—the major atmospheric sink for methane (CH_4) emissions—to form CO_2. That means that increased atmospheric concentrations of CO lead to higher carbon dioxide emissions.

Particulate matter, a broad category of air pollutants, affects the climate as well. Suspended particles, which are also considered aerosols, include black carbon, organic carbon, and sulfates; each has a different climate impact. Black carbon, which is sometimes referred to as elemental carbon or *soot*, differs from other aerosols because it absorbs incoming solar radiation, heats the atmosphere, and drives the evaporation of low-level clouds. Sulfates and organic carbon, on the other hand, cool the climate. High levels of sulfates and organic carbon mask the short-term effects of climate change. EPA's GHG inventory does not include aerosol and particulate emissions.

Each sector of the economy emits a unique portfolio of gases and aerosols that affect the climate in different ways and in different timeframes.

While regional air pollutants influence climate change, a warmer climate can also exacerbate air pollution. This effect occurs because heat accelerates many air-pollutant reactions.[17] Thus, an increase in global warming precipitates an increase in regional pollution, and vice versa.

Accurately inventorying air pollutants will continue to be important, especially as standards continue to tighten. In January 2010 the EPA proposed a rule to lower the primary National Ambient Air Quality Standard for ozone by as much as 20 percent.[18] It is expected that the EPA will finalize the new ozone rules by the end of 2010. Early in 2010, the EPA finalized a rule that tightened the NO_2 air-quality standard and established new requirements for an NO_2 monitoring network that concentrates measurement collection near major roadways.

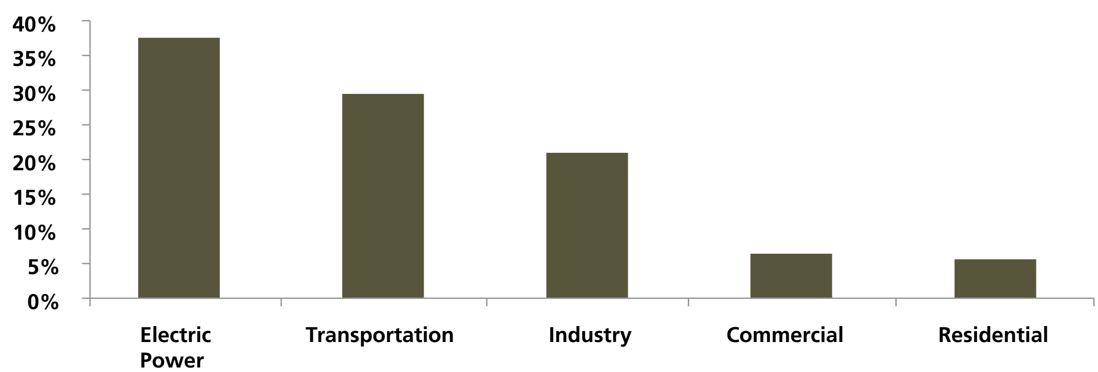
General Relationships Between U.S. Transportation and Climate[19]

Direct Greenhouse Gas Emissions From Transportation

Carbon dioxide, which has an atmospheric lifetime of at least one hundred years, dominates direct greenhouse gas emissions from transportation and other end-use sectors. Transportation edges out industry as the largest source of CO_2 emissions.

Emission inventories tally direct greenhouse gases and air pollution precursor emissions. Each sector's share of direct GHG emissions can be reported with or without electric power generation included. Electric power is an energy supplier to most of the economic sectors, except for transportation. When broken out, as in Figure 2, the electric power industry overall generates more direct carbon-equivalent climate gases than any economic sector. Transportation has the second-highest direct GHG emissions, followed by industry, commercial, and residential sectors. The agriculture sector is reported in GHG inventories but is not reported here given the large emission "sinks" that counteract emission sources.

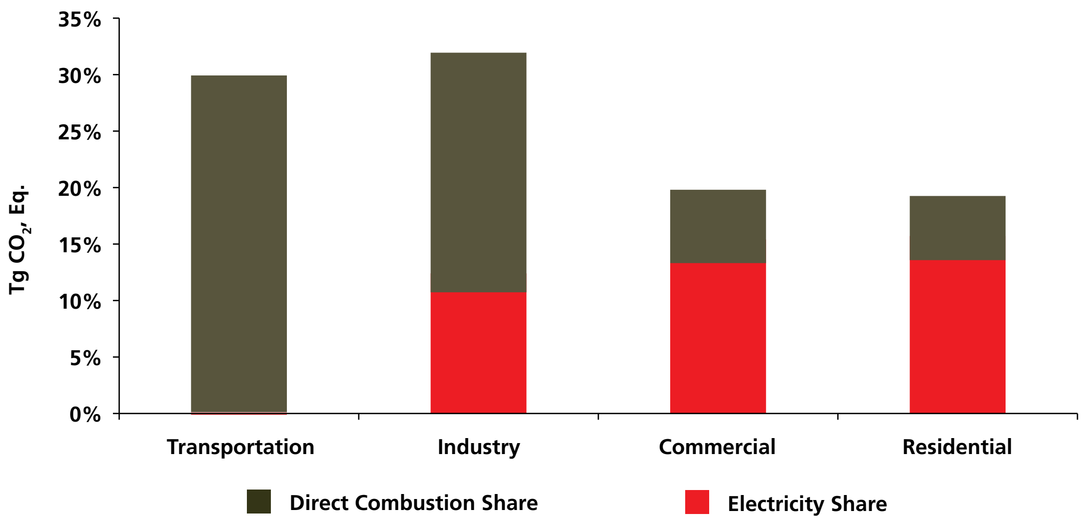
Figure 2. 2008 Share U.S. GHG Emissions by Sectors, Electric Power Generation Separated Out



Source: EPA, Trends in GHG Emissions, 2010, Table 2–12 http://www.epa.gov/climatechange/emissions/downloads10/US-GHG-Inventory-2010_Chapter2-Trends.pdf

Another way to evaluate direct climate gas emission inventories is to distribute electricity-related emissions based on actual use by each economic sector. Figure 3 illustrates the shift in direct GHG emissions when electricity consumption is not separated out. The transportation sector uses essentially no electricity, yet it still has nearly the same direct GHG emissions as industry (about 30 percent).

Figure 3. 2008 U.S. Greenhouse Gas Emissions by Economic Sector, with Electricity Emissions Distributed

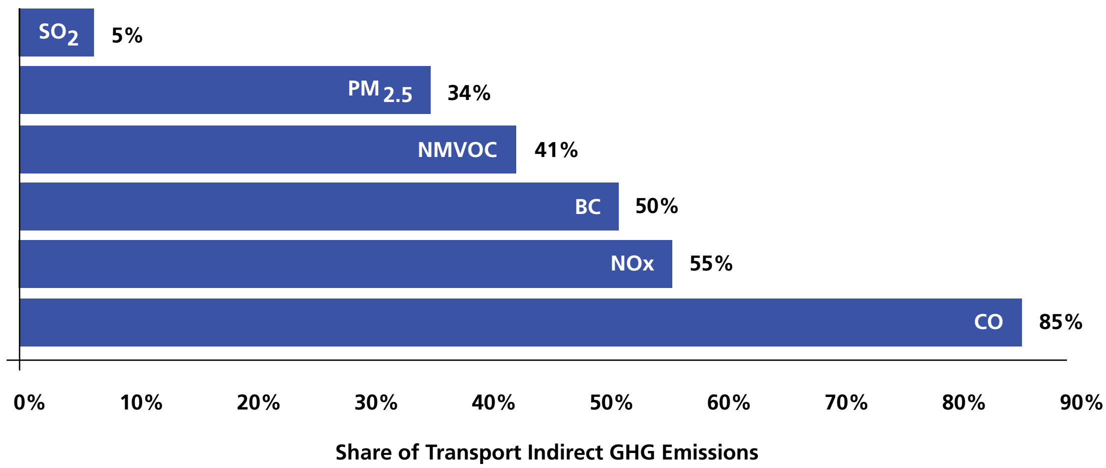


Source: EPA, Trends in GHG Emissions, 2010, Table 2-14

Air Pollutant Climate Precursor Emissions From Transportation

In addition to carbon dioxide and other direct GHG emissions mentioned above, the transportation sector accounts for a significant portion of air pollutant precursor emissions that affect the climate differently.[20] The transportation sector is responsible for the majority of air pollutant precursor emissions—a full 85 percent of carbon monoxide (CO), 50 percent of black carbon (BC), 34 percent of particulate matter of 2.5 microns ($PM_{2.5}$), 55 percent of nitrogen oxides (NO_x), and 41 percent of non-methane volatile organic compounds (NMVOC)—as shown in Figure 4. The utility sector, on the other hand, is responsible for 86 percent of total sulfur dioxide (SO_2) emissions.[21] In the United States, on-road transportation is not responsible for SO_2 emissions. These figures represent current emission levels from burning conventional oil as the primary fuel source.[22]

Figure 4. Share U.S. Air Pollutant Precursor Emissions Attributed to Transportation



Key: NO_x = nitrogen oxides, CO = carbon monoxide, NMVOC = non-methane volatile organic compounds (hydrocarbons), SO_2 = sulfur oxides, PM = particulate matter, BC = black carbon. Note: Transportation includes on-road and off-road "mobile fossil fuel combustion."

Source: EPA, Inventory of U.S. GHG Emissions and Sinks, April 2010, Table 2-17; Particulate/Black Carbon (PM/BC) data from EPA 2005 Mobile National Emissions Inventory, Version 2, December 2008

On-road transportation sources emit both NMVOC and NO_x in large amounts. These ozone precursors react to form ozone (smog). Carbon monoxide is produced when carbon-containing fuels fail to fully combust in cars and trucks, and nitrogen oxides (NO and NO_2) are created from the nitrogen in the air when burning fossil fuels.

Through the twenty-first century, on-road transportation is expected to be a leading climate-forcing activity worldwide.

Black carbon (BC) is another air pollutant precursor that acts as a climate agent. BC is rarely measured in its pure form. Instead, it is part of particulate matter, which constitutes a broad array of carbonaceous substances, sometimes referred to as *soot*. The incomplete combustion of fuel (from transportation and other sources) results in black carbon (and organic carbon), fine particles that are suspended in the atmosphere.[23] These particles are identified by their size: $PM_{2.5}$ and PM_{10}, or less than 2.5 µm (micrometers) and 10µm, respectively. Diesel fuel combustion, moving freight in heavy-duty trucks, is the major source of black carbon in the United States, but the EPA does not report black carbon (PM) emissions in its GHG Trends Reports. However, PM is inventoried for air-pollution modeling.[24]

General Relationships Between U.S. Transportation and Energy[25]

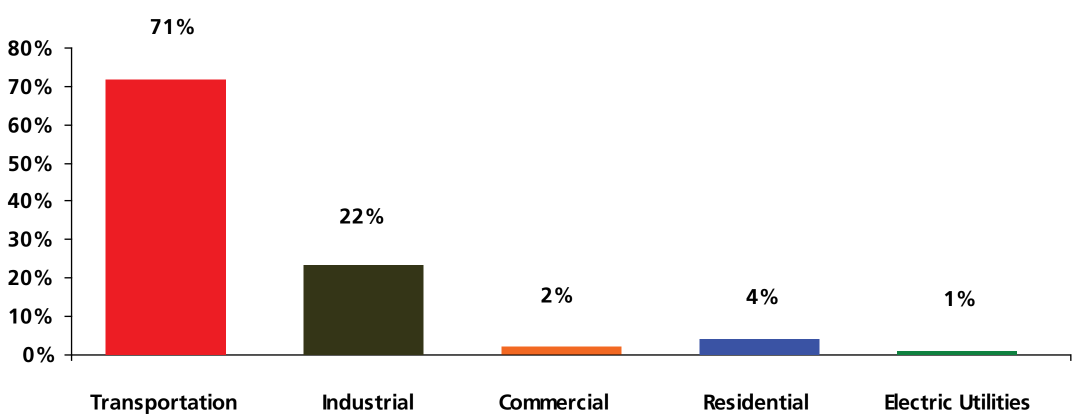
U.S. Transportation, Energy, and Oil Use

Energy consumption and climate change are inextricably linked; the energy sector in its entirety accounts for 86 percent of total direct GHG emissions. The energy requirements of each economic sector (transportation, industry, commercial, and residential) are responsible for the bulk of all man-made climate change gases. Transportation represents a significant portion of emissions in the IPCC energy sector.

In 2009, the transportation sector consumed 27 quads (quadrillion, or 10^{15} BTU) of direct energy, mostly in the form of refined liquid fuels, chiefly gasoline and diesel. Transportation's share of energy consumption is similar to its share of greenhouse gas emissions, at 32 percent. The linkages between energy use and climate gases are evident in all economic sectors.

Unlike other economic sectors, transportation runs nearly exclusively on petroleum, which fuels 94 percent of this sector's energy demands.[26] In 2009, U.S. mobility required nearly 13 million barrels per day (BPD) of oil. Transportation used three times more oil than did all other industries combined. And the transportation sector consumed over an order of magnitude more oil than the commercial, residential, or utility sectors, as shown in Figure 5.

Figure 5. U.S. Petroleum Consumption by End-Use Sector, 2009



Source: ORNL, *Transportation Energy Databook*, Edition 29, Table 1.13, 2010

Relationship Between Energy, Oil Use, and Carbon Emissions

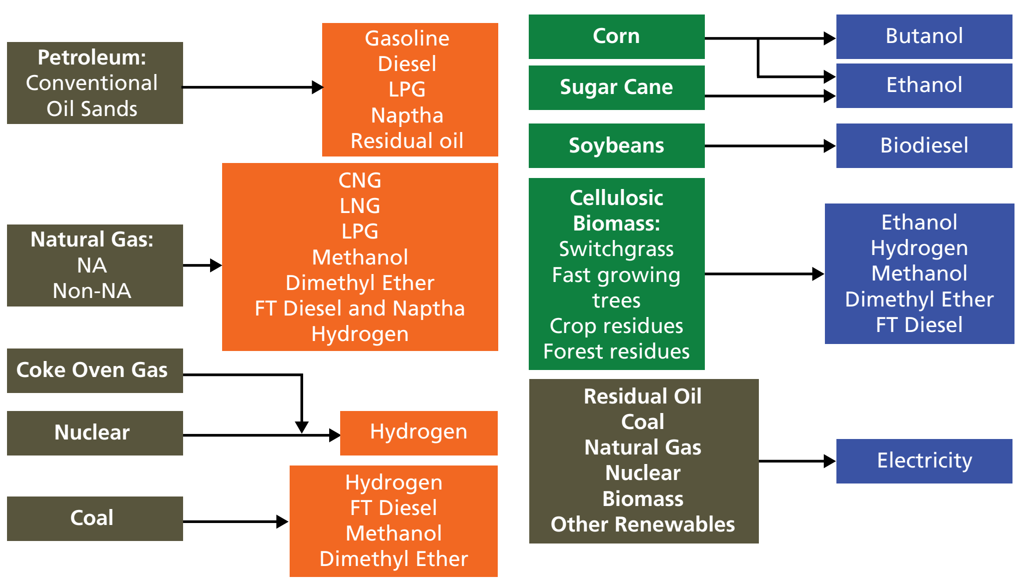
There is near parity between energy use and the principal greenhouse gas, carbon dioxide. Essentially all of the carbon contained in fossil fuels, which are hydrocarbons, is converted to CO_2 when burned. Solar, wind, hydroelectric, geothermal, wave, and nuclear energy contain no carbon and, therefore, have no direct effect on GHG inventories. Biofuels, on the other hand, contain carbon. Biofuels, a myriad of plant- and waste-based fuels, have a complex relationship to the climate. Their GHG emissions depend on their individual chemistries, how they combust, and even how their feedstocks are grown.

The amount of carbon released into the atmosphere is primarily determined by the fuel's carbon content.[27] Today, the on-road transportation system runs almost exclusively on gasoline and diesel fuels. An average gallon of gasoline contains 19.4 pounds of CO_2 per gallon (8.8 kg/gallon). Diesel, the fuel primarily used in heavy-duty trucks and off-road vehicles, has 22.2 pounds CO_2 per gallon (10.1 kg/gallon).[28]

Conventional gasoline and diesel fuels are beginning to be replaced by new oils such as unconventional crude oils, tar sands, shale, and coal-to-liquids. These fuels contain far more carbon than today's gasoline and diesel.

In the longer term, non-oil fuels might replace new oils. There are more than 100 fuel production pathways and over 70 vehicle and fuel system pairings, each with its own climate emission impact. General fuel production pathways are shown in Figure 6. Again, the carbonization of future fuels will vary,

Figure 6. Sampling of Transportation Fuel Production Pathways

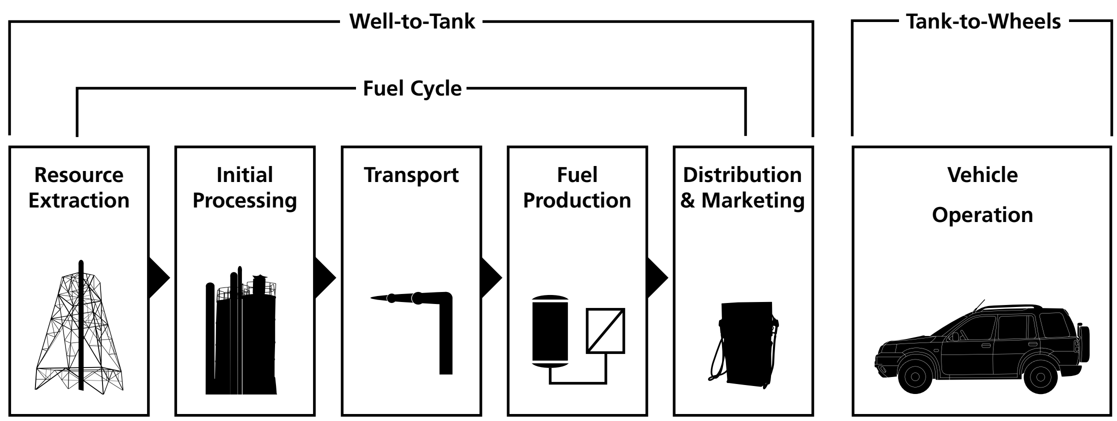


Source: M. Wang, Argonne National Laboratory, Well-to-Wheels Greenhouse Gas Emissions of Alternative Fuels, 2007, http://www.nga.org/Files/pdf/0712ALTERNATIVEFUELSWANG.PDF depending on the fuel source and production pathway chosen. Electricity generated by burning coal produces high carbon emissions, but electricity from many renewable and nuclear sources has zero emissions. A fuel-cycle analysis offers the best comparison of total emissions.

Overview of Fuel-Cycle Emissions From Various Forms of Transportation Energy

Fuel-cycle emissions consider all parts of the transportation energy process that could produce greenhouse gas emissions, as depicted in Figure 7. Also termed "well-to-wheel" emissions, fuel-cycle emissions start at the wellhead, where fuel is extracted, and end at the tailpipe, where emissions emerge after fuel is combusted in an engine.

Figure 7. Transportation Fuel Cycle

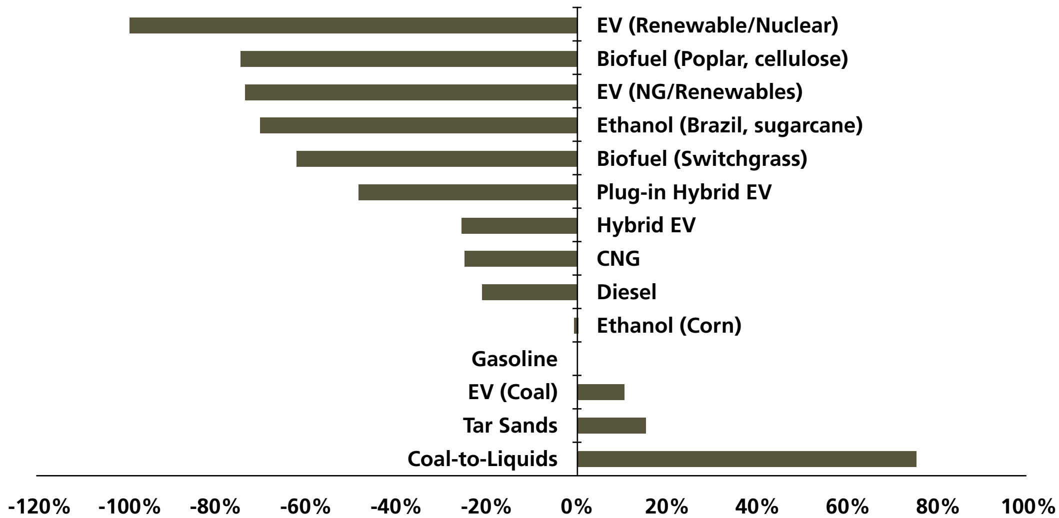


Source: M. Wang, et al., Argonne National Laboratory, "Well to Wheel Analysis of Advanced Fuel/Vehicle Systems, May 2005, http://www.transportation.anl.gov/pdfs/TA/339.pdf

The first part of the process, "well-to-tank," includes fuel extraction, initial fuel processing, intermediate fuel transport, finished fuel production and refining, and distribution and marketing. The second part of the fuel-cycle process, "tank-to-wheels," encompasses all emissions during vehicle operation and refueling.

Studies of fuel-cycle emissions from on-road transportation have found that emissions vary greatly depending on the fuel pathway, as depicted in Figure 8.[29] Low-carbon fuels and power production options can substantially reduce GHG emissions, depending on the specific fuel or power production technology and associated pathways. Electric vehicles refueled with renewable or nuclear fuels can result in near-zero emissions. Plug-in hybrid vehicles can reduce emissions about 45 percent, if powered by electricity generated with limited coal. CO_2

Figure 8. U.S. Estimates of Well-to-Wheel Greenhouse Gas Emissions, Relative to Conventional Gasoline



Source: CEC, Fuel Cycle GHG Emission Assessment, August 2007, http://www.energy.ca.gov/2007publications/CEC-600-2007-004/CEC-600-2007-004-REV.PDF

emissions are recycled through plant photosynthesis, so biofuels can provide large reductions (more than 60 percent compared with gasoline), depending on fuel source and processing intensity. Natural gas also reduces GHG emissions, although its potential reduction is much greater when used to generate power for electric vehicles (more than 70 percent) compared with burning compressed natural gas (CNG) directly in vehicles (less than 30 percent).

For heavy-duty vehicles, electric motors provide the most significant benefits (approximately 50 percent), followed by hydrogen fuel cells and CNG. Low-carbon biodiesel can yield a 10 percent to 20 percent carbon reduction.

Unconventional oils and coal fuels—tar sands, coal-to-liquids, and electric vehicles powered by coal-fired utilities—increase fuel-cycle GHG emissions by 75 percent or more.

Air pollutant emissions that contribute to climate change also vary depending on the alternative fuel and fuel cycle selected. Ethanol production and use can increase NO_x and particulate emissions, and natural gas-based hydrogen pathways can reduce criteria pollutant emissions. Heavy-duty vehicles with electric drive have lower particulate and NO_x emissions than do those powered by diesel. And renewable electricity used in electric vehicles and plug-in hybrids can reduce air pollutants that serve as indirect GHG emissions.

Scientists stress that changes in agricultural land use have a large-scale impact on the evaluation of biofuel pathways. Even employing sustainable agricultural practices to produce biofuels needs to investigate and account for actual fuel-cycle GHG emissions. The prevention of tropical deforestation associated with fuel production, for example, must be incorporated into efforts to promote low-carbon alternative fuel use. In that case, palm oil could be a low-carbon pathway, but only if grown sustainably, without deforestation.[30]

Differences in Climate Impacts Between Transportation and Other Sectors

Comparing Climate Effects From Transportation With Other Sectors

Each sector of the economy emits a unique portfolio of gases and aerosols that affect the climate in different ways and in different timeframes. Scientists have recently determined that transportation is a key in driving climate change. Research by NASA's Goddard Institute for Space Studies (Nadine Unger[31] and her colleagues[32]) suggests climate science needs to shift from looking at the impact of individual chemicals to economic sectors.[33]

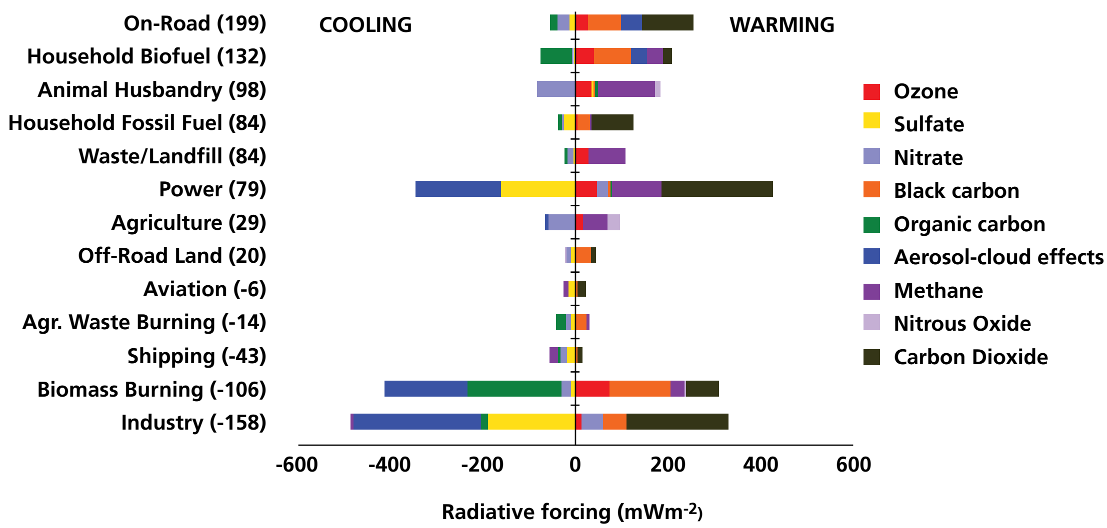
Until now, climate effects have been investigated by chemical species. A sector-by-sector approach is actually more revealing. Sector profiles differ greatly when one considers each sector's climate impacts of tropospheric ozone, fine aerosols, aerosol-cloud interactions, methane, and long-lived greenhouse gases.

In a seminal NASA paper, published by the *Proceedings of the National Academy of Sciences*, Unger and her colleagues described how they used a climate model to estimate the impact of thirteen sectors of the economy on the climate in 2020 and, more long term, in 2100. They based their calculations on real-world inventories of emissions collected by scientists around the world, and they assumed that in the future those emissions would stay relatively constant at their 2000 levels.

After one hundred years, the net temperature change because of global on-road transport is significantly higher than the change stemming from aviation, shipping, and rail.

Breaking the massive energy sector into its subsectors is the key because each produces a different, complex mixture of direct GHGs and air pollutant precursor emissions. Some cause longer-term warming; others cause shorter-term cooling, as shown in Figure 9.

Figure 9. Radiative Forcing Due to Perpetual 2000 Global Emissions, Grouped by Sector (in 2020)



Source: Unger, N., T. C. Bond, J. S. Wang, D. M. Koch, S. Menon, D. T. Shindell, and S. Bauer, 2010: Attribution of climate forcing to economic sectors, *Proc. Natl. Acad. Sci.*, 107, 3382–3387, doi:10.1073/pnas.0906548107

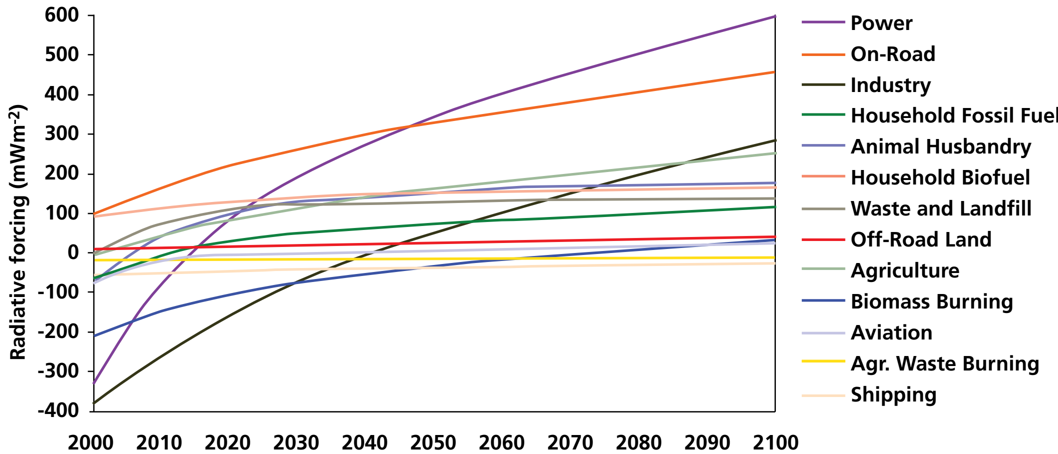
Framing warming by economic activity provides a better understanding of how human activities affect climate and over what timeframes. This approach can foster the development of smart climate policy that identifies new opportunities for controlling manmade warming.

Burning fossil fuels with high sulfur contents—particularly coal, high-sulfur diesel, and fuel oil—releases sulfates, which cause short-term cooling by blocking radiation from the sun and making clouds brighter and longer-lived.[34,35] At least in the short term, the cooling from sulfates outweighs the warming from carbon dioxide, so the net impact of heavy industries and coal-fired power production cools the climate. Still, carbon-dioxide emissions from coal-fired power generation are so massive that even their long-term warming effects greatly outweigh the short-term sulfate cooling effects on timescales relevant for climate change.[36]

Just because an activity causes cooling in the short term does not mean it is “good” for or harmless to the climate. Increasing emissions from coal-fired power generation is detrimental in the long term for the climate and air quality. For example, sulfate aerosols from power plants pose serious air-quality problems, including acid rain, and affect regional climate in other detrimental ways, such as changing the Earth’s water cycle.

As the number of coal-fired power plants increases in the United States and worldwide, the power sector will overtake transportation as the leading climate disruptor, as indicated in Figure 10. Therefore, cutting coal-fired power plant (and other industrial) emissions will be crucial in mitigating climate change in the longer term.[37]

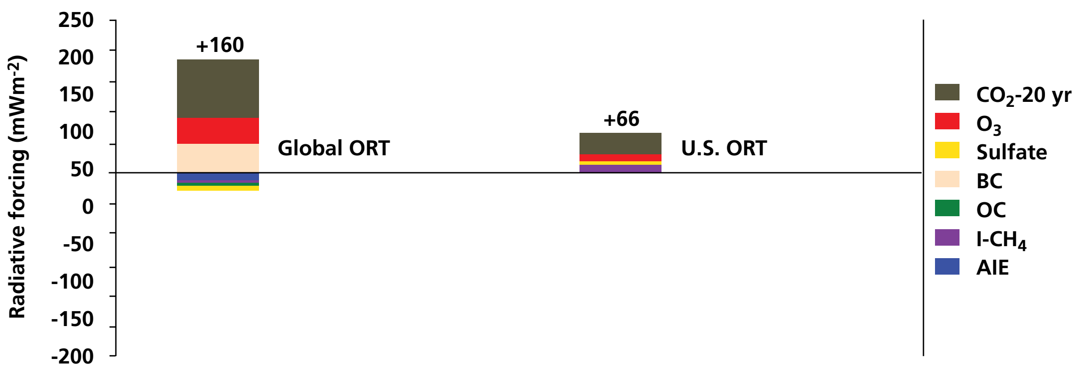
Figure 10. A Century of Total Radiative Forcing Due to Constant Year 2000 Emissions by Global Sector



Source: Unger, et al., *PNAS*, February 23, 2010, Figure 2

Through the twenty-first century, on-road transportation is expected to be a leading climate-forcing activity worldwide. Cars and trucks emit almost no sulfates (cooling agents) but are major emitters of carbon dioxide, black carbon, and ozone—all of which cause warming and are detrimental to human health. U.S. on-road transportation is responsible for 40 percent of global on-road climate warming ("radiative forcing" in climate terms). U.S. on-road transportation is projected to have a net radiative forcing of 66 mWm^{-2} on a twenty-year horizon, as shown in Figure 11.[38] U.S. on-road transportation represents nearly half (41 percent) of global radiative forcing in this sector over a twenty-year timeframe.

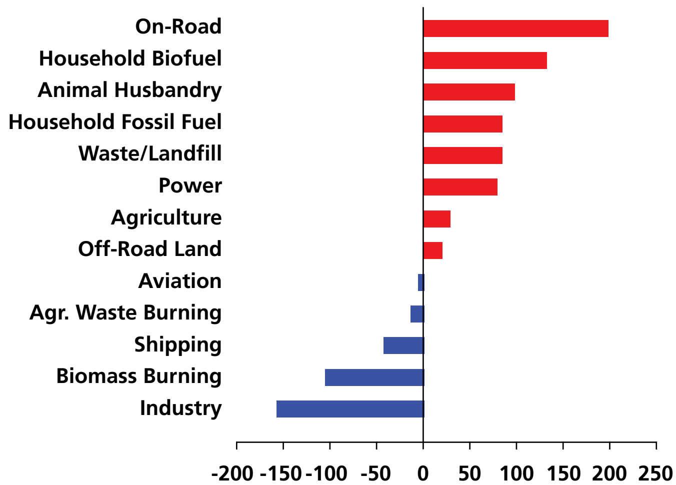
Figure 11. Radiative Forcing From Global and U.S. On-Road Transport, 20-Year Timeframe



Key: ORT = On-road transportation. Source: Nadine Unger, "Transportation Pollution and Global Warming," June 2009, http://www.giss.nasa.gov/research/briefs/unger_02

On-road transportation in the United States (and abroad) is a prime emission-reduction opportunity, at least through 2050. Electric power generation and industry are also high priorities, but they will be more problematic within longer timeframes. While Figure 12 ranks the climate actors in the short term, Figure 13 illustrates shifting climate-change drivers in the long term. On-road transportation is a principal target along the continuum from short to long term, as it is expected to be a top source of climate change throughout this century.

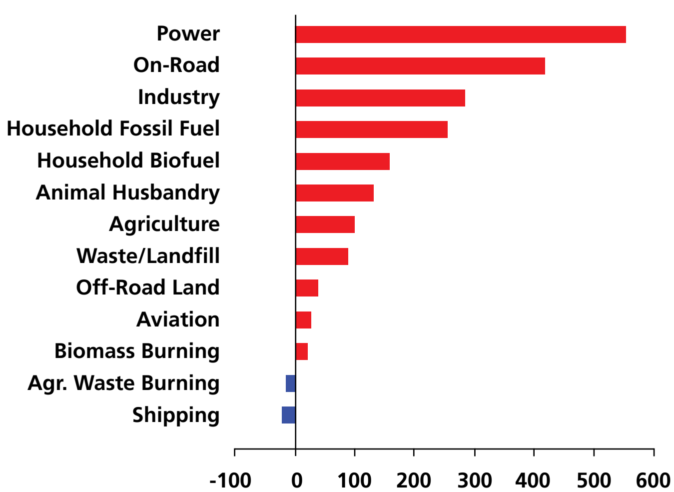
Figure 12. Climate Impacts by Global Sector, in 2020 (mW/m^{-2})



Source: http://www.giss.nasa.gov/research/news/20100218a

Notes: Refer to Figure 9 for the warming and cooling inputs to the net impacts depicted in this figure; short-term net cooling impacts result from industrial emissions (the production of metals, coke, cement, oil/gas, coal/mining, and a wide array of other stationary sources), biomass burning, and shipping because they have high particulate emissions that serve as a cooling agent.

Figure 13. Net Climate Impacts by Global Sector, in 2100 (mW/m^{-2})



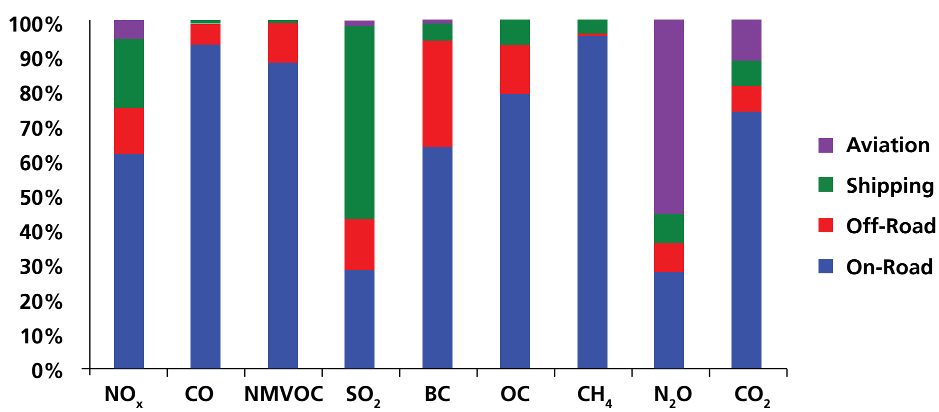
Source: Energy Bulletin, February 2010, www.energybulletin.net/node/51744

Sources of Climate Emissions and Energy Use Within the U.S. Transportation Sector

Climate Emissions From Transportation Sources

The inventory shares of GHG emission precursors from transportation sources are depicted in Figure 14. It is important to note that ozone is not included because it is not directly emitted; it is formed chemically in the atmosphere by other GHG precursors (principally NMVOC and NO_x) that are emitted directly. On-road transport is responsible for the vast majority (60–95 percent) of total transport GHG emissions, except in the case of SO_2 and N_2O emissions.

Figure 14. Share of Anthropogenic Emissions Inventory From Global Transportation Sources

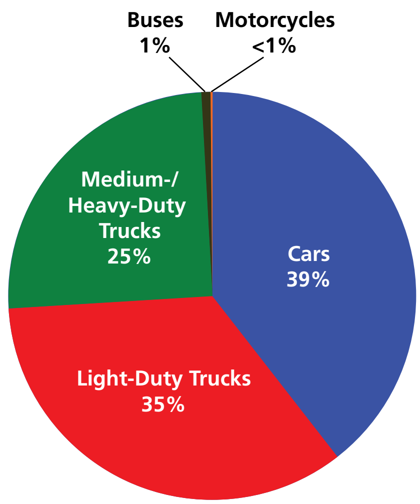


Key: NOx = nitrogen oxides, CO = carbon monoxide, NMVOC = non-methane volatile organic compounds, SO_2 = sulfur oxides, BC = black carbon, OC = organic carbon, CH_4 = methane, N_2O = nitrous oxide, CO_2 = carbon dioxide

Source: Unger et al., "Attribution of Climate Forcing to Economic Sectors," *PNAS*, February 23, 2010, vol. 107, no. 8, Table S1

On-road transportation includes cars; light-duty trucks (SUVs, pick-ups, and minivans); medium- and heavy-duty trucks; buses; and motorcycles. The U.S. inventory of on-road transportation direct emissions totaled 1,600 teragrams CO_2 equivalent in 2008.[39] Light-duty vehicles—cars, SUVs, pick-ups, and minivans—accounted for about three-quarters of GHG emissions, as shown in Figure 15.

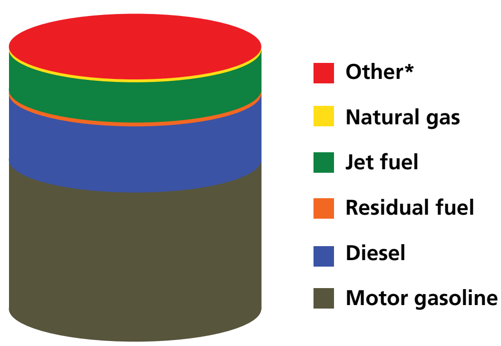
Figure 15. U.S. On-Road Transportation Share of Direct GHG Emissions



Source: US EPA, Trends in GHG Emissions, 2010, Table 2-15

The vast majority of these on-road GHG emissions resulted from burning fossil fuels in vehicle engines. On-road vehicles were responsible for about 84 percent of all transportation petroleum use in 2008.[40] Cars and light trucks again dominate oil use, making up more than 75 percent of all on-road vehicles. Motor gasoline is responsible for over one-half of U.S. carbon dioxide emissions from transportation sources. Shares for 2008 are shown in Figure 16.

Figure 16. Carbon Emissions from U.S. Energy Use in the Transportation Sector, 2008



* Other includes, LPG, lubricants, aviation gas, and electricity, which together account for less than 1 percent of transport carbon emissions.

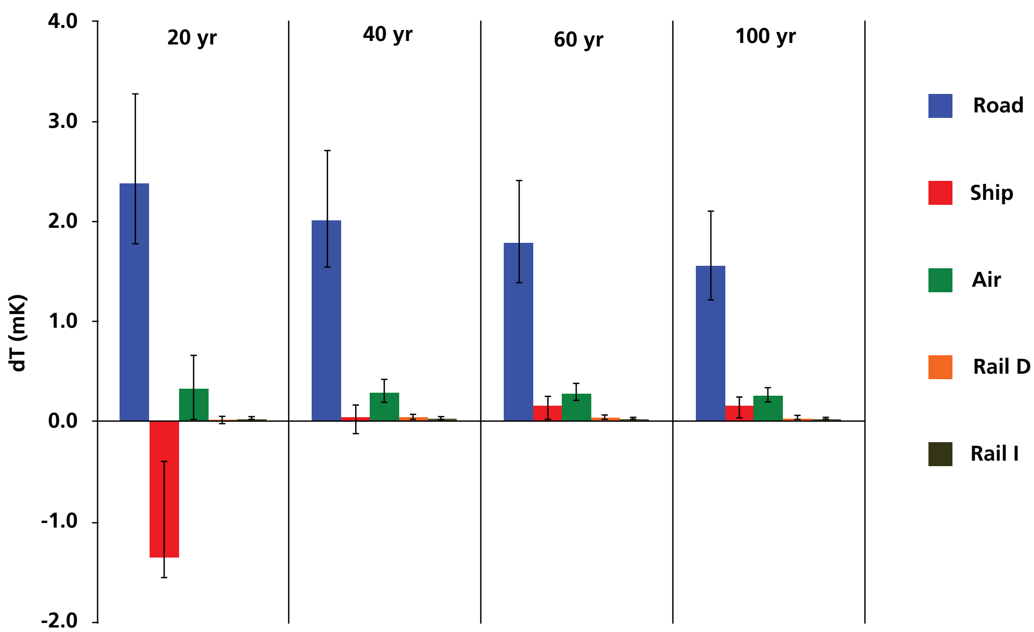
Source: ORNL, *Transportation Energy Databook*: Edition 29, Table 11.6

The differences in ratios in warming between transportation sources are approximately the same ratio as the ratio between the CO_2 emissions from these sectors. Thus, it is mainly CO_2 that controls the climate response on timescales beyond a decade or two.[41]

Climate Effects From Different Transportation Modes

The transportation subsectors—road, air, rail, and shipping—affect the climate on different timescales, because of a mix of short-lived and long-lived warming and cooling components. NASA's analysis, as well as research by the Center for International Climate and Environmental Research–Oslo (CICERO)[42], suggests that motor vehicles (cars, trucks, buses, and two-wheelers) are the greatest global contributors to near-term atmospheric warming, as indicated in Figure 17.[43]

Figure 17. Net Future Temperature Change for Global On-Road Transport over Different Timescales



Note: Net future temperature change (dT) measured in millikelvin (0.001 degrees K). Source: Bernsten and Fuglestvedt, *PNAS*, December 9, 2008, vol. 105, no. 49, p. 19157.

After one hundred years, the net temperature change because of global on-road transport is significantly higher than the change stemming from aviation, shipping, and rail.[44] Aviation and shipping have strong, but quite uncertain, short-lived effects—aviation fuels warming, and shipping fuels cooling—that create net cooling effects from these transportation activities during the first decades after the emissions are released.

Considerations in Managing Transportation-Driven Climate Disruption

Climate model outputs have recently been restructured, making it easier to identify emission sources, warming potentials, and temperature increases by economic sector and subsector. This dissembles the huge IPCC *energy sector*, an amalgamation of disparate activities with massive GHG emissions. These new scientific results make it easier to identify which human activities have the greatest impact on the climate over time.

Effects Over Different Timeframes

There is mounting evidence that different economic sectors affect climate change on different timeframes, and this realization could inform policy priorities.[45] On-road transportation is projected to have the greatest effect on climate through at least 2050. Electric power generation and industry are also high priorities, but they will become increasingly problematic over longer time frames.

Scientists and policy makers must treat air pollution and climate change as related challenges, not two distinct problems.

The significant enduring warming effect of U.S. on-road transportation makes it a prime target for early mitigation. Cars, with their more limited lifetimes (rarely exceeding twenty years), are more easily replaced in the short term. This facilitates rapid deployment of vehicle innovations that significantly reduce on-road GHG emissions. Power plants and industrial facilities (with lifetimes typically exceeding fifty years) are more feasibly replaced in the long term.

Significant effects of today's GHG emissions will likely be seen over the next century because a CO_2 molecule can exist in the atmosphere for one hundred years or more. As such, many chemicals involved in climate change will outlive current U.S. elected officials. Dealing with climate change effectively will require a lasting paradigm shift in public priorities on a national and international scale.

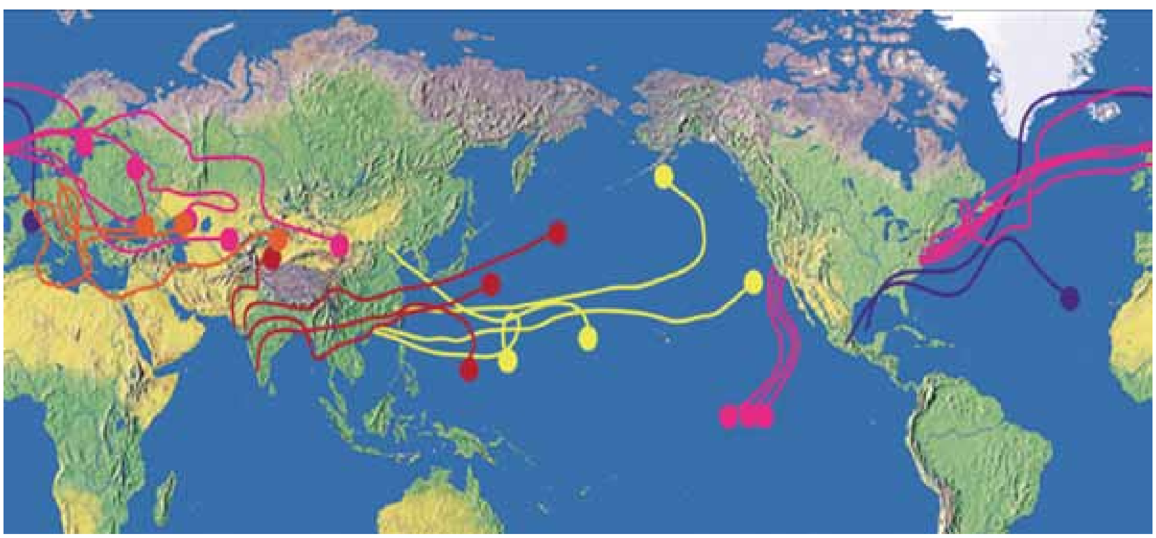
Managing Climate Change and Air Pollution

Scientists and policy makers must treat air pollution and climate change as related challenges, not two distinct problems. Tightening air-pollution mitigation standards will be a major factor in determining climate-warming trends of the coming decades. Research shows that carbon dioxide and ozone play the most significant role in near- and mid-term climate forcing.

Precisely tracking ozone formation is key. Understanding the intricate interactions between climate change in the upper atmosphere and air pollution in the lower atmosphere is crucial, requiring ongoing investigations in meteorology, physics, chemistry, and other sciences. A warmer climate also creates feedbacks that produce more photochemically generated ozone, escalating these related environmental concerns.

Although this paper is presented from a U.S. emission perspective, atmospheric transport means the world is interconnected. Figure 18 illustrates how air can travel from one region of the world to another in about a week. Trajectories indicate how air parcels travel thousands of kilometers from East Asia into North America; from North America across the Atlantic to Europe; from South Asia into East Asia; from Australia into the Antarctic; and onward. Although air pollution appears local in nature, it can have global ramifications.

Figure 18. Global Air Pollution Trajectories



Source: V. Ramanathan, Y. Feng, "Air pollution, greenhouse gases and climate change: Global and regional perspectives," *Atmospheric Environment 43* (2009), 37–50

Next Steps in Climate Research Relating to Policy Making

Reducing climate impacts from on-road transportation will require a shift to new low-carbon fuels. This transition must be accompanied by improved scientific evidence and data keeping on the climate characteristics of each fuel through its entire fuel cycle. Large uncertainties associated with the growing supply of transportation biofuels remain. It must be determined whether new fuels from crops, trees, and other biomass sources actually reduce GHG emissions in practice.

Improvements in battery technology and clean-power generation will lead to higher confidence estimates of the impact of various technological advances (including a larger plug-in hybrid fleet) on the on-road transportation and power-generation sectors. The simulations conducted by NASA scientists indicate that huge reductions in climate forcing from near zero-emission electrified transportation may be possible, making this technological shift an extremely worthwhile pursuit. The potential to improve the climate and alleviate local pollution justifies increasing investments in electric-vehicle battery research and development and clean power.[46]

Despite these promises, trends are headed in a higher-carbon direction. As conventional sources of oil are depleted, unconventional oils with even higher carbon contents will flow at increasing rates through the system to fill the gap. Tar sands from Canada, shale oil from the Rocky Mountain states, and liquefied U.S. coal will only *re-carbonize* our transportation system. The United States should investigate the climate and other environmental impacts of new oil fuels.

Reducing climate impacts from on-road transportation will require a shift to new low-carbon fuels.

Finally, above all, scientists warn that we must avoid mitigation measures that address one problem yet worsen another. This entails identifying unintended consequences of various vehicle and fuel options at the outset. Scientists are planning to partner with environmental economists to determine the damage costs (in terms of climate and air quality) from all sectors. These results can be used to develop alternative mitigation scenarios.

Policy-Making Considerations

Scientists have concluded that cutting on-road transportation emissions would be unambiguously good for the climate (and public health) in the near term.[47] On-road transportation is a key target sector to mitigate global climate change because this sector combines high carbon emissions and a composition of non-carbon emissions that act to enhance considerably the direct CO_2 warming impacts. These technical findings, while extremely valuable, do not consider economics, politics, or social factors. Mitigating on-road transportation climate emissions will not be easy, but this is necessary to reduce risks of climate change.

Moving from scientific knowledge to policy action will require a public policy–driven paradigm shift in the transportation sector. The market alone cannot accelerate change in this sector, which is dominated by autos and oil, and the institutions, land uses, and lifestyles to support them. Americans depend on their cars; in fact, 91 percent of all passenger-miles traveled, excluding air travel, are by car.[48] Petroleum is overwhelmingly the fuel of choice and is used by 94 percent of vehicles; there are few readily available substitutes.

Changing technology and behavior will be most successful if advocates adopt a wedge approach, promoting change at the margin over time. New low-carbon transportation options can be funded through revenues collected on the most over-used, least-efficient, and highest-carbon portions of the transportation system. Once viable travel options have been established, policies can be ratcheted up over time, encouraging wholesale shifts in sector supply and demand. Strategically pricing transportation carbon will be key in motivating a major paradigm shift.

Transitioning to a lower-carbon transportation system (through plug-in electric vehicles, for example) could result in a substantial benefit for the climate. A technology shift to zero-emission vehicles that results in a 50 percent reduction in on-road transportation emissions is projected to zero-out this source of climate warming.[49] These climate benefits from electrified on-road transportation are expected over both twenty-year and one hundred-year timeframes. Mitigating climate emissions in on-road transportation, however, will require that electric transportation support both climate and air-pollution goals.

Science can provide technical guidance for setting policy priorities. Recent scientific analyses, especially those by NASA and CICERO, point to on-road transportation as a win-win-win opportunity. Reducing on-road transportation emissions at home and abroad is good for the climate in the short term and long term, and it is good for our health.[50]

Conclusions

The Earth's rapidly warming temperatures over the past several decades are being driven by human activities. Fossil-fuel combustion in transportation, and in particular on-road vehicles, is a factor of growing concern. Today, 1 billion motor vehicles populate the world's roads, about one in three in the United States alone. Over the next decade or two, this figure is expected to double to 2 billion vehicles.

Supporting a new, low-carbon, location-efficient, productive, and high-growth economy for the twenty-first century will be key to maintaining U.S. leadership in an increasingly competitive global marketplace.

Recent research has determined that the individual climate emission profiles of different economic sectors make them behave differently from one another in terms of their climate impacts. Given their high emission levels of carbon dioxide, ozone-forming air pollutants, and black carbon, on-road transportation—principally cars and trucks—has the greatest net climate radiative forcing effect over a twenty-year timeframe. Unlike other economic sectors, cars and trucks have minimal emissions of sulfates, aerosols, and organic carbon with their short-term cooling effects. To exacerbate matters, cars and trucks continue to drive climate problems over a century and beyond, due to massive amounts of long-lived carbon dioxide emissions.

The climate problems attributed to on-road transportation are not going away. The market alone will not ameliorate them. A complementary set of policies will be necessary to simultaneously mitigate global warming, further reduce air pollution, and cut U.S. oil consumption. Transportation carbon must be priced to realize these potential gains. Rational pricing and wise investments can turn around the U.S. transportation system, bolstering U.S. economic productivity. Supporting a new, low-carbon, location-efficient, productive, and high-growth economy for the twenty-first century will be key to maintaining U.S. leadership in an increasingly competitive global marketplace. A clean, efficient, solvent transportation sector will be increasingly vital to the bottom line.

Notes

1 NOAA, "State of the Climate in 2009," Bulletin of the American Meteorological Society (BAMS), vol. 91, July 2010, http://www1.ncdc.noaa.gov/pub/data/cmb/bams-sotc/2009/bams-sotc-2009-chapter2-global-climate-lo-rez.pdf.

2 EPA, Climate Change Science Facts, http://www.epa.gov/climatechange/downloads/Climate_Change_Science_Facts.pdf.

3 EPA, ibid.

4 World Meteorological Organization, "Current Extreme Weather Events," August 11, 2010, http://www.wmo.int/pages/mediacentre/news/extremeweathersequence_en.html.

5 National Research Council (NRC), "Climate Stabilization Targets: Emissions, Concentrations, and Impacts Over Decades to Millennia," 2010, http://books.nap.edu/openbook.php?record_id=12877&page=1.

6 Ibid.

7 NRC, Ibid. Note: 1,000 GtC is equivalent to 3,666 gigatonnes of carbon dioxide. In order to convert mass units, 1 gigatonne (Gt) = 1 billion metric tons = 1,000 teragrams (Tg).

8 This section draws largely from GAO, "Climate Change: The Quality, Comparability, and Review of Emissions Inventories Vary Between Developed and Developing Nations," GAO-10-818, July 2010.

9 In December 2009, these negotiations resulted in the Copenhagen Accord, a nonbinding political agreement in which, among other things, certain nations announced various actions to reduce emissions and developing nations agreed to submit more frequent inventory reports.

10 This inventory adheres to both: 1) a comprehensive and detailed set of methodologies for estimated sources and sinks of anthropogenic greenhouse gases, and 2) a common and consistent mechanism that enables the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) to compare the relative contribution of different emission sources and greenhouse gases to climate change. The U.S. Department of State represents the United States in international negotiations to develop post-2012 agreements to address climate change, and participates in the assessment and review of whether the Convention is being effectively implemented, including the inventory review process. The State Department also officially submits the U.S. inventory to the Convention's Secretariat.

11 See EPA, http://www.epa.gov/climatechange/emissions/downloads10/US-GHG-Inventory-2010_ExecutiveSummary.pdf.

12 EPA, Ibid.

13 To ensure that the U.S. emissions inventory is comparable to those of other UNFCCC parties, the estimates are calculated using methodologies consistent with those recommended in the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC/UNEP/OECD/IEA 1997), the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000), and the IPCC Good Practice Guidance for Land Use, Land-Use Change, and Forestry (IPCC 2003). Additionally, the U.S. emission inventory has begun to incorporate new methodologies and data from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). For most source categories, the IPCC methodologies have been expanded, resulting in a more comprehensive and detailed estimate of emissions.

14 GAO, July 2010, Table 1, p. 15, op. cit., Note that other developed nations have comparable inventory uncertainty, cumulatively equating to 800 million metric tons of carbon dioxide equivalent, slightly more than Canada's total emissions in 2007.

15 To address concerns with the land-use inventory, the NRC recommended taking inventory of all land-based emissions and sinks for lands, not just man-made emissions on managed lands. See: NRC, "Verifying Greenhouse Gas Emissions: Methods to Support International Climate Agreements," National Academies Press, 2010.

16 This section draws largely from the UN document, "Air Pollution and Climate Change: Tackling Both Problems in Tandem," http://www.unece.org/press/pr2003/03env_p02e.htm.

17 See EPA, "Linkages Between Climate and Air Quality," August 30, 2010, www.epa.gov/AMD/Climate.

18 Ground-level ozone can trigger a variety of health problems including aggravated asthma, reduced lung capacity, and increased susceptibility to respiratory illnesses like pneumonia and bronchitis. Ozone also contributes to crop damage, ecosystem damage, and other effects. The EPA is projecting that a new primary ozone standard of 0.070 ppm would avoid 1,500 to 4,300 premature deaths annually in 2020, and the more stringent 0.060 ppm standard would avoid 4,000 to 12,000 premature deaths annually. Other benefits in 2020 would include preventing the following, annually: 880 to 2,200 cases of chronic bronchitis; 2,200 to 5,300 nonfatal heart attacks; 6,700 to 21,000 hospital and emergency room visits; 2,100 to 5,300 cases of acute bronchitis; 44,000 to 111,000 cases of upper and lower respiratory symptoms; 23,000 to 58,000 cases of aggravated asthma; 770,000 to 2.5 million days when people miss work or school; 2.6 million to 8.1 million days when people must restrict their activities.

19 The following data source was used extensively in this section: EPA, "Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2008," EPA-430-R-10-006, April 15, 2010, http://epa.gov/climatechange/emissions/usgginventory.html. Note that the total mass of GHG emissions is an indicator, but not a predictor, of climate impacts. Climate models take into account complex chemical reactions of direct emissions and air pollutant precursors to predict radiative forcing from emission inputs.

20 UNFCCC reporting requirements on indirect greenhouse gases to date include: CO, NO_x, NMVOCs, and SO_2 and are reviewed in http://unfccc.int/resource/docs/cop8/08.pdf. PM, BC, and aerosols are not yet reported per UNFCCC guidelines.

21 SO_2 is both an indirect GHG in its own right and also forms aerosols (fine particles) along with particulate matter. The transportation sector is not a significant producer of aerosols compared to industry and electric utilities burning coal. However, heavy-duty trucks (burning diesel), ships, and off-road transport equipment are the sector's main aerosol (SO_2 and PM) contributors.

22 The increased use of unconventional oil (shale and coal-to-liquids) is likely to increase direct GHG emissions and air pollution precursors, resulting in an even greater air pollution emission share from transportation sources.

23 Scientific studies link breathing PM to significant health problems, including aggravated asthma, difficult breathing, chronic bronchitis, myocardial infarction (heart attacks), and premature death. Diesel exhaust is likely a human carcinogen by inhalation and poses a non-cancerous respiratory hazard. PM is also the major source of haze that reduces visibility, and can cause erosion of structures such as monuments and statues. Particulate matter generated by fuel combustion (such as diesel engines) tends to be smaller on average than particulate matter caused by sources such as windblown dust.

24 In developing nations, burning organic fuels (animal waste, trees, grasses) contribute significant BC emissions.

25 For more energy and transportation information see Oak Ridge National Laboratory, *Transportation Energy Databook,* Edition 29, June 30, 2010, www.cta.ornl.gov/data/index.shtml.

26 ORNL, *Transportation Energy Databook*, Edition 29, Table 2.2, June 30, 2010. Note: the alcohol fuels (corn ethanol) blended into gasoline to make gasohol (10 percent ethanol or less) are counted under "renewables" and are not included in petroleum share.

27 There is a small portion of the fuel that is not oxidized into carbon dioxide when the fuel is burned. EPA has published information on carbon dioxide emissions from gasoline and diesel, taking the oxidation factor into account based on the carbon content used in EPA's fuel economy analysis.

28 EPA, "Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel," February 2009; Additional resources at www.epa.gov/OMS.

29 See TIAX report for the California Air Resources Board and California Energy Commission on the GREET model, 2007, http://www.arb.ca.gov/fuels/lcfs/greet.pdf.

30 For example, see Worldwatch Institute, 2009, http://www.worldwatch.org/node/6082.

31 Nadine Unger is now at Yale University directing the Climate Modeling Group (nadine.unger@yale.edu).

32 Center for Climate Systems Research at Columbia University, University of Illinois, Urbana-Champaign, Lawrence Berkeley National Laboratory, and Environmental Defense Fund.

33 This section is largely drawn from publications about Nadine Unger's findings: http://www.pnas.org/content/early/2010/02/02/0906548107.full.pdf+html and http://www.energybulletin.net/node/51744.

34 The indirect effect of sulfur-derived aerosols on radiative forcing can be considered in two parts: (1) the aerosols' tendency to decrease water droplet size and increase water droplet concentration in the atmosphere; (2) the tendency of the reduction in cloud droplet size to affect precipitation by increasing cloud lifetime and thickness. Although still highly uncertain, the radiative forcing estimates from both effects are believed to be negative. Since SO_2 is short-lived and unevenly distributed in the atmosphere, its radiative forcing impacts are highly uncertain. Unger notes that NASA's Glory mission will hopefully help reduce the uncertainties associated with aerosols.

35 In addition to acting as an indirect GHG, SO_2 is also a major contributor to the formation of regional haze, which can cause significant increases in acute and chronic respiratory disease. For this reason, SO_2 is a criteria pollutant under the Clean Air Act. Once SO_2 is emitted, it is chemically transformed in the atmosphere and returns to the earth as the primary source of acid rain. Electricity generation (using coal) is the largest anthropogenic source of SO_2 emissions in the United States, accounting for 80 percent. SO_2 emissions have decreased in recent years, primarily due to power generators switching from high-sulfur to low-sulfur coal and installing flue gas desulfurization equipment. While beneficial for air quality and acid rain mitigation, the removal of SO_2 aerosols has inadvertently been removing cooling agents from the climate, accelerating warming trends.

36 Nadine Unger, NASA blog, December 4, 2009, http://climate.nasa.gov/blogs/index.cfm?FuseAction=ShowBlug&NewsID=139.

37 NASA Earth Science News, February 18, 2010, http://www.nasa.gov/topics/earth/features/unger-qa.html.

38 Nadine Unger, "Transportation Pollution and Global Warming," June 2009, http://www.giss.nasa.gov/research/briefs/unger_02.

39 EPA, *Trends in GHG Emissions*, op. cit, Table 2–15.

40 ORNL, *Transportation Energy Databook*, Edition 29, June 2010, Table 1.16.

41 Bernsten, op. cit.

42 CICERO is the Center for International Climate and Environmental Research – Oslo, Norway.

43 Aviation has a very high climate-forcing contribution from short-lived contrails and cirrus clouds that strongly decrease with time. Still, aggregated on-road transport emissions are greater than air travel in the mid- to long-term. See: Jens Borken-Kleefeld, T. Berntsen, and J. Fuglestvedt, "Specific Climate Impacts of Passenger and Freight Transport," *Environmental Science & Technology*, vol. 44, no. 15, July 12, 2010, http://pubs.acs.org/doi/pdfplus/10.1021/es9039693.

44 Fuglestvedt, et al., "Climate Forcing from the Transport Sectors," January 15, 2008, Figure 2A.

45 In addition to NASA research previously cited, see: G. Myhre, et al., "Radiative forcing due to changes in ozone and methane caused by the transport sector," *Atmospheric Environment*, October 2010; Y. Balkanski, et al., "Direct radiative effect of aerosols emitted by transport: from road, shipping and aviation," *Atmospheric Chemistry and Physics*, May 17, 2010; J. Borken-Kleefeld, Berntsen, T., Fuglestvedt, J. "Specific Climate Impact of Passenger and Freight Transport," *Environmental Science & Technology*, 44 (15), 2010, 5700–5706.

46 Nadine Unger, "Transportation Pollution and Global Warming," June 2009, http://www.giss.nasa.gov/research/briefs/unger_02/; For full article see: N. Unger, D. T. Shindell, and J. S. Wang, "Climate Forcing by the On-Road Transportation and Power Generation Sectors," *Atmos. Environ.*, 43, 2009, 3077–3085. Note that the additional electricity needed to power EVs, at least in the short term, would likely be generated by coal, further reducing global warming through increased emissions of cooling sulfate particles. This is not a desirable long-term solution as the power sector emits huge quantities of CO_2 along with smog, particles, and other pollutants that are detrimental to public health.

47 NASA Earth Science News, February 18, 2010, http://www.nasa.gov/topics/earth/features/unger-qa.html.

48 When air PMT is included, autos still account for a whopping 81 percent of total U.S. PMT. Total 2008 travel equaled 5.5 billion PMT. See Bureau of Transportation Statistics, www.tbs.gov/publications/national_transportation_statistics/html/table_01_37.html, Table 1–37.

49 Nadine Unger, 2009, op. cit.

50 For hundreds of thousands of people, smog-polluted (and soot-filled) air means more breathing problems and aggravated asthma, trips to the emergency room, and hospital admissions, particularly to intensive care units. Moreover, studies have shown that ozone pollution at current U.S. levels contributes to early death. See: M. L. Bell, F. Dominici, and J. M. Samet, "A Meta-Analysis of Time-Series Studies of Ozone and Mortality with Comparison to the National Morbidity, Mortality, and Air Pollution Study," *Epidemiology* 2005; 16:436–445. J. I. Levy, S. M. Chermerynski, J. A. Sarnat, "Ozone Exposure and Mortality: An Empiric Bayes Metaregression Analysis," *Epidemiology* 2005; 16:458–468. K. Ito, S. F. De Leon, M. Lippmann, "Associations Between Ozone and Daily Mortality: Analysis and Meta-Analysis," *Epidemiology* 2005; 16:446–429. D. V. Bates, "Ambient Ozone and Mortality," *Epidemiology* 2005; 16:427–429.

Abbreviations

AIE	Aerosol Indirect Effect
BC	black carbon
BPD	barrels per day
BTU	British Thermal Units
CFC	chlorofluorocarbon
CH_4	methane or natural gas
CICERO	Center for Interational Climate and Environmental Research – Oslo
CNG	compressed natural gas
C	carbon
CO	carbon monoxide
CO_2	carbon dioxide
˚C	degree Celsius
EPA	Environmental Protection Agency
Eq.	equivalent
EV	electric vehicle
GHG	greenhouse gas
Gt	gigaton, or one billion metric tons
GtC	gigaton of carbon
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
Kg	kilograms
mWm^{-2}	megawatt per meter squared
N_2O	nitrous oxide
NASA	National Aeronautics and Space Administration
NMVOC	non-menthane volatile organic compounds

NO_2	nitrogen dioxide
NOAA	National Oceanic and Atmospheric Administration
NO_x	nitrogen oxides
O_3	ozone
OC	organic carbon
ORT	on-road transportation
PM	particulate matter
PPM	parts per million
RF	radiative forcing
SO_2	sulfur dioxide
SUV	sport utility vehicle
Tg	teragram
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organization

About the Author

DEBORAH GORDON is a nonresident senior associate in Carnegie's Energy and Climate Program, where her research focuses on climate, energy, and transportation issues in the United States and China.

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Gordon has served on National Academy of Sciences committees and the Transportation Research Board Energy Committee. Her recent book, *Two Billion Cars* (with Daniel Sperling), provides a fact-based case and roadmap for navigating the biggest global environmental challenge of this century—cars and oil (Oxford University Press, 2009).

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