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Testimony for the Hearing on Black Carbon and Arctic
House Committee on Oversight and Government Reform
United States House of Representatives
The Honorable Henry A. Waxman, Chair
October 18, 2007

By Mark Z. Jacobson

I would like to thank the Honorable Chairman and committee for inviting me to testify today. I will speak on the role of black carbon in global climate change, the U.S. contribution to black carbon's global climate effect, and methods of reducing black carbon emissions.

Summary

Soot particles containing black carbon, from fossil-fuel and biofuel burning sources, have a strong probability of being the second-leading cause of global warming after carbon dioxide and ahead of methane[1,2]. Because of the short lifetime of soot relative to greenhouse gases, control of soot emissions, particularly from fossil-fuel sources, is very likely to be the fastest method of slowing global warming for a specific period[1]. Because soot particles are generally small, and small aerosol particles are the leading cause of air pollution mortality, controlling soot emissions will not only slow global warming but also improve human health. The United States' soot contribution to global warming may exceed each its methane and nitrous oxide contributions to global warming. Despite soot regulations to date based on health grounds, the United States has significant room to reduce soot emissions further, thereby improving the length and quality of life and reducing the impacts of global warming.

Definitions

Soot is an amorphous-shaped particle emitted into the air during fossil-fuel combustion, biofuel combustion, and biomass burning. Soot particles contain black carbon, organic carbon, and smaller amounts of sulfur and other chemicals. Soot from diesel combustion usually appear black because it contain a high fraction of black carbon, which absorbs all colors of visible light, preventing such light from reaching our eyes. Soot from biofuel burning is brownish because it contains a higher ratio of organic carbon to black carbon than diesel soot, and organic carbon absorbs short light wavelengths preferentially, appearing brown.

Soot particles heat the air by converting sunlight into infrared (heat) radiation and emitting that heat radiation to the air around them. This differs from greenhouse gases, which do not absorb much sunlight; instead, they absorb the Earth's heat radiation and reemit it to the air.

Soot particles that fall to snow and sea ice surfaces, either on their own or within ice crystals or snow flakes, darken those surfaces, contributing to the melting of snow and ice and the warming of air above both[3,2,4].

When soot particles age in the atmosphere, they become coated by relatively transparent or translucent chemicals, increasing their size and the probability that sunlight will hit and be absorbed by the particle. As such, aged, coated soot particles heat the air more than do new, uncoated soot particles. The enhanced heating by soot upon its coating has been demonstrated from physical principles and in the laboratory[5-10].

Whereas new soot particles from fossil fuel sources in particular are oily so do not allow clouds to grow on them easily, coated soot particles attract water and allow clouds to grow on them. The growth of a cloud drop on a coated soot particle eventually causes the soot particle to reflect light significantly, reducing sunlight significantly, cooling the ground and air. However, cloud drops containing soot still warm the air more than do cloud drops without soot[11-13]. Determining the overall effect of soot on climate requires accounting for these and other effects. Such calculations suggest a strong net global warming by fossil-fuel plus biofuel soot (Table 1, Figure 1).

Table 1 shows the direct radiative forcing of anthropogenic (fossil-fuel, biofuel, and biomass burning) greenhouse gases, as provided by the Intergovernmental Panel for Climate Change[14], and black carbon from all anthropogenic sources, as provided from several studies. Based on these results, black carbon may be the second-leading case of global warming after carbon dioxide and ahead of methane in terms of its direct radiative forcing.

Table 1. Top-of-the-atmosphere global direct radiative forcing by anthropogenic gases and particulate black carbon.

	Global direct radiative forcing (W/m^2)	Percent of total
Carbon dioxide	+1.66	48
Methane	+0.48	14
Nitrous oxide	+0.16	4.6
Halocarbons	+0.34	9.7
CFCs*	+0.268	
HCFCs*	+0.039	
HFCs+PFCs+SF$_6$	+0.017	
Ozone (tropospheric and stratospheric)*	+0.30	8.6
Total gases	+2.94	84
Anthropogenic black carbon*	+0.55	16
Total gases + black carbon	3.49	100

*Non-Kyoto chemicals. Greenhouse gas direct forcings are from IPCC[14]. The anthropogenic black carbon direct forcing is from Ref. 15 and compares with 0.54 W/m^2 from Ref. 8, 0.50 W/m^2 from Ref. 16, 0.53 W/m^2 from Ref. 17, and 0.5-0.8 W/m^2 from Ref. 18.

Because biomass-burning particles (which differ from biofuel particles), when emitted, are less oily and contain a much lower black carbon fraction than do fossil fuel soot particles, biomass-burning particles tend to cool climate on a global scale, but may cause regional warming[19]. Biomass-burning gas warming, though, from permanent deforestation, exceeds the global cooling due to biomass burning aerosol particles[19].

Because of the net cooling due to biomass-burning particles, the discussion that follows will be concerned with fossil-fuel and biofuel burning soot. Of the two, fossil-fuel soot warms

more per unit mass than does biofuel soot because of the greater fraction of black carbon and greater oiliness of fossil-fuel soot relative to biofuel soot.

Figure 1 shows the relative contributions to global warming, as determined by recent computer model simulations, by greenhouse gases, fossil-fuel plus biofuel soot, the urban heat island effect, and cooling aerosol particles. Cooling aerosol particles include particles containing sulfate, nitrate, chloride, ammonium, potassium, certain organic carbon, and water, primarily. The sources of these particles differ, for the most part, than sources of fossil-fuel and biofuel soot. The figure shows that about half of actual global warming to date is being masked by cooling particles, suggesting that, as such particles are removed by the clean up of air pollution, a significant amount of global warming will be unmasked. Nevertheless, the removal of such particles is desirable to improve human health. The figure also shows that fossil-fuel plus biofuel soot may contribute to about 16% of gross global warming (warming due to all greenhouse gases plus soot plus the heat island effect), but its control in isolation could reduce 40% of net global warming.

Figure 1. Primary contributions to observed global warming 1750 to today from global model calculations. The fossil-fuel plus biofuel soot estimate is from Ref. 2. and accounts for the effect of soot on snow albedo.
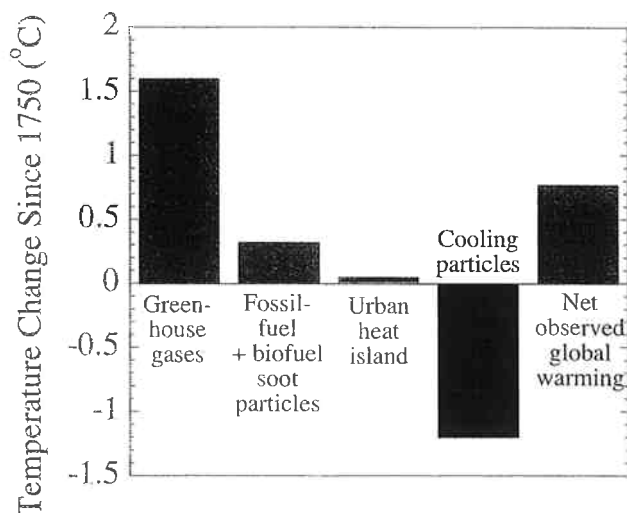

Soot particles also differ from greenhouse gases in that soot particles have relatively short lifetimes in the atmosphere of around one to four weeks. Greenhouse gases have long lifetimes (e.g., 30-43 years for carbon dioxide[20,21] and 8-12 years for methane). The lifetime of a chemical is the time required for the chemical's concentration to decay to about 37% its original value.

Because of their short lifetimes, soot particles containing black carbon have strong warming effects regionally, near where they are emitted[7,22-24], although many soot particles travel globally.

Because of soot's short lifetime and its strong climate impact, the reduction in its emissions can result in rapid climate benefits. This point is illustrated in Figure 2, which shows the modeled reduction in global near-surface air temperatures resulting from the elimination of all anthropogenic methane, carbon dioxide, and fossil-fuel plus biofuel soot emissions, separately. The figure shows that controlling all soot would reduce temperatures faster than

controlling all carbon dioxide for a period on the order of 10 years, but controlling carbon dioxide, has a larger overall climate benefit than controlling soot over a 100-year period. Controlling soot also slows warming faster than controlling methane.

Figure 2. Comparison of time-dependent change in globally-averaged near-surface temperature due to eliminating global anthropogenic emissions of each CO_2, CH_4, and fossil-fuel plus biofuel soot. From Ref. 2. For CO_2, two possible lifetimes are shown. The actual lifetime of CO_2 is closer to 30 years than 50 years[20,21].
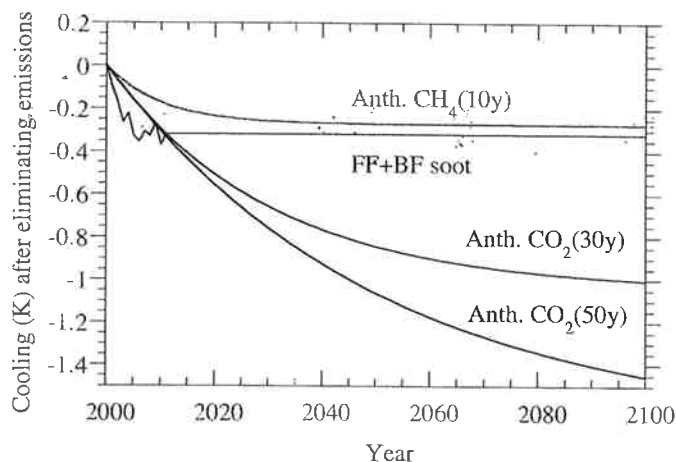
As mentioned earlier, fossil-fuel soot is a stronger warmer than biofuel soot. Table 2 summarizes the 20- and 100-year global warming potentials of fossil-fuel soot and, separately, the black carbon in fossil-fuel soot. These numbers mimic the results in Figure 2, which apply to fossil-fuel plus biofuel soot, that controlling a unit emissions of soot continuously will have a greater impact over the short term than controlling a unit emissions of carbon dioxide.

Table 2. 20- and 100-year global warming potentials (GWPs) for fossil-fuel soot and black carbon within fossil-fuel soot.

X	20-year GWP	100-year GWP
FF soot	2530	840-1280
BC in FF soot	4470	1500-2240

The global warming potential is defined here as the change in temperature per unit emissions of X relative to the change in temperature per unit emissions of CO_2. Multiply the GWPs in the table by 12/44 to obtain the GWP relative to CO_2-C. BC= black carbon. FF soot=56% black carbon + 43% primary organic carbon + 1% sulfate.

U.S. and World Emissions of Soot

Whereas the U.S. emits about 21% of globally-emitted anthropogenic carbon dioxide, it emits about 6.1% of the globally-emitted fossil-fuel plus biofuel soot (Table 3).

Table 3. U.S. contributions to world non-aircraft, non-shipping fossil-fuel (FF) and biofuel (BF) black carbon (BC) and primary organic carbon (POC) emissions in particles ≤2.5 μm in diameter ($PM_{2.5}$) and particles ≤10 μm in diameter (PM_{10}).

	U.S. (Gg-C/yr)	World (Gg-C/yr)	U.S. Percent of World Total
$PM_{2.5}$			
FF BC+POC	347.2	5400	6.4
BF BC+POC	477.7	8124	5.9
Total	824.9	13,524	6.1
PM_{10}			

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FF BC+POC	457.5	7165	6.4
BF BC+POC	4668	11,392	4.1
Total	1125	18,556	6.1
Carbon dioxide	1,660,000	7,900,000	21

$PM_{2.5}$ data are from Ref. 25. PM_{10}:$PM_{2.5}$ ratios are from the 2002 U.S. National Emission Inventory (Ref. 26). The U.S. $PM_{2.5}$ FF BC+POC emission rate from Ref. 25 of 347 Gg/yr compares with 526.8 Gg/yr from the U.S. National Emission Inventory (Table 5), thus is conservative. Most of the differences are due to higher organic carbon in the U.S National Emission Inventory.

Nevertheless, the warming due to the U.S. soot exceeds the warming due to either U.S. methane or nitrous oxide (Table 4). As such, fossil-fuel plus biofuel soot may be the second-leading source of U.S. global warming emissions.

Table 4. Percent warming of component relative to carbon dioxide

	Worldwide	U.S.
FF+BF soot	32	9.3
Methane	29	8.8
Nitrous oxide	9.6	7.7

Derived from Table 1 and Figure 2.

The main sources of U.S. fossil-fuel soot are nonroad vehicles, followed by onroad mobile vehicles, stack emissions, and fugitive sources, respectively (Table 5). Fossil fuels include diesel fuel, heavy fuel oil, aviation fuel, liquefied petroleum gas, gasoline, kerosene, coke briquettes, hard coal, brown coal, peat, coking coal, and fuel waste.

About half of U.S black carbon in particles smaller than 2.5 μm in diameter ($PM_{2.5}$) is from fossil-fuel sources (Table 5). The rest is from areas sources: agricultural fires, structural fires, slash/prescribed burning forest wildfires, unpaved road dust, paved road dust, and construction dust, according to the 2002 U.S. National Emission Inventory[26].

Table 5. United States black carbon (BC) and primary organic carbon (POC) emissions (Gg/yr) in particles ≤2.5 μm in diameter ($PM_{2.5}$) and particles ≤10 μm in diameter (PM_{10}), from the 2002 U.S. National Emission Inventory (Ref. 26). Total fossil-fuel is the sum from all sources except area sources.

	Stack	Fugitive	Area	Nonroad Mobile	Onroad Mobile	Total	Total Fossil-fuel
$PM_{2.5}$							
BC	28.1	3.6	221	123.3	74.1	449.9	229.2
POC	135.2	28.8	1637	87.2	46.4	1935	297.6
Total	163.3	32.4	1858	210.5	120.5	2384.9	526.8
PM_{10}							
BC	41.3	5.8	422.1	145.4	90.6	705.2	283.1
POC	173.3	40.1	3914	101.5	70.2	4299	385.1
Total	214.6	45.9	4336.1	246.9	160.8	5004.2	668.2

By 2030, global fossil-fuel black carbon emissions are expected to increase (Table 6), according to two future emission scenarios that follow the Special Report on Emission Scenarios (SRES) A1B and B1 emission trajectories[27]. These scenarios account region-specific, chemical-specific, and emission-sector-specific changes in future emissions. Although emissions in the United States and much of Europe are expected to decline, emissions in the rest of the world are expected to increase to a greater extent, causing a net increase in black carbon emissions.

Table 6. World fine-particle global emission rates (Tg-C/yr) of black carbon (BC) and primary organic carbon (POC) in soot today and in 2030 under the A1B and B1 IPCC emission scenarios,. Sulfate emissions are described in the footnote. From Ref. 27.

	(a) Aircraft	(b) Shipping	(c) All other Fossil Fuel	(d) Total Fossil Fuel (a+b+c)	(e) Biofuel	(f) Biomass burning	(g) Total (d+e+f)
Today							
BC	0.0062	0.147	3.029	3.182	1.634	1.728	6.544
POC	0.0062	0.047	2.371	2.424	6.490	14.89	23.80
A1B scenario							
BC 2030	0.0062	0.155	5.616	5.777	0.808	1.728	8.313
POC 2030	0.0062	0.050	3.911	3.967	3.290	14.89	22.15
B1 scenario							
BC 2030	0.0062	0.135	3.273	3.414	0.668	1.728	5.810
POC 2030	0.0062	0.044	2.268	2.318	2.725	14.89	19.93

Fine BC and POC emissions from aircraft were obtained by applying emission factors of 0.038 g-BC/kg-fuel (Ref. 28) to fuel-use data from Ref. 29 and Ref. 30 and assuming a POC:BC emission ratio of 1:1. Those from shipping were estimated by dividing the gridded, monthly sulfur shipping emission rate from Ref. 31, which totaled 4.24 Tg-S/yr, by 29.5 g-S/kg-fuel (Ref. 32, Table 1, for 1999 data) and multiplying the result by 1.02 g-BC-C/kg-fuel for shipping (Ref. 25). That for POC was obtained in the same manner, but by multiplying the result by 0.33 g-POC-C/kg-fuel (Ref. 25). Fine BC and POC for all other fossil-fuel sources globally were obtained from Ref 25 after subtracting out shipping emissions. The totals from Ref. 25 before subtracting out such emissions were 3.040 Tg-BC-C/yr and 2.408 Tg-POC-C/yr. Fine biofuel-burning BC and POC emissions were obtained from Ref. 25. The POM:POC emission ratio is about 1.6:1 for fossil fuels and 2:1 for biofuel and biomass burning, where POM is Primary Organic Matter and equals POC plus non-carbon functional groups. The emission rate of S(VI) from fossil fuels was 1% that of BC+POM+S(VI).

Proposals to Reduce Soot Emissions

Proposed methods of controlling fossil-fuel soot have included improving engines, changing fuels, adding particle traps, and changing vehicle technologies. Recent particulate matter emission regulations in the U.S. have begun to address reducing onroad and nonroad vehicle particulate matter emissions, but more can still be done.

A concern that is often raised with respect to controlling soot emissions, such as with a particle trap, is whether such controls will reduce emissions of particles that cool climate or only those that warm climate. First, the control of all particles is beneficial from a health perspective, regardless of whether the particles cause cooling or warming. Second, almost all particles emitted from diesel vehicles are types that warm climate rather than cool climate. Particles that cool climate generally originate from different sources than but have some overlap those that warm climate. For example, most sulfate particles, which cool climate, originate from sulfur dioxide from coal-fired power plants. In the U.S., such plants emit some, but not a lot of fossil-fuel soot (Table 5).

Although controlling soot emissions from existing diesel engines is beneficial for reducing particle emissions, the addition of a trap decreases the mileage, thus increases the carbon dioxide emissions from such vehicles by 3.5-8.5%[33-35].

Alternatively, the conversion of gasoline vehicles to diesel vehicles, even with a particle trap, may increase particle emissions and is unlikely to reduce global warming, as discussed in detail below

Comparison of diesel versus gasoline

It is generally thought that diesel vehicles obtain better gas mileage and emit less carbon dioxide than equivalent-class gasoline vehicles and, therefore, using more diesel vehicles will address the climate problem. However, this concept ignores the larger emissions of fossil-fuel soot from diesel than gasoline vehicles and the resulting climate effects. It also ignores the fact that the addition of control devices to diesel vehicles to reduce their soot and nitrogen oxide emissions, required to meet California and EPA Tier 2 Permanent Bin emission standards and to address the climate problem of soot, reduces the gas mileage of the diesel vehicles. Finally, it does not consider that, in the United States, the lowest-carbon-emitting vehicles in 2006 were gasoline and gasoline-electric hybrid vehicles, not diesel vehicles (Table 7). The addition of particle traps to the best diesels sold in 2006 in the U.S. would reduce the standing of the diesels further. Also, the addition of a particle trap to diesel increases the NO_2:NO ratio in diesel exhaust increases, exacerbating photochemical smog[36]. Finally, even with a particle trap, diesel vehicles still emit more particles than do gasoline vehicles.

Table 7. Highest-mileage passenger vehicles in the U.S. in 2006, ranked by their CO_2 emissions (with and without a particle trap in the case of diesel).

Vehicle	Energy source	Avg. mpg	CO_2 (g-C/km)	CO_2 (g-C/km) w/trap
Honda Insight (M)	Gas	53	28.0	
Honda Insight (A)	Gas	47	31.5	
Toyota Prius (A)	Gas/electric	46.5	31.9	
Honda Civic (A)	Gas/electric	42.5	34.9	
Honda Civic (A)	Gas	31	47.9	
Toyota Corolla (A)	Gas	30.5	48.6	
VW Golf, Jetta (M)	Diesel	35.5	48.5	50.9
VW N. Beetle, Jetta (A)	Diesel	34	50.6	53.1

(A) denotes automatic transmission; (M) denotes manual transmission. The table assumes a gasoline and diesel density of 737 g/L and 840 g/L, respectively, a gasoline and diesel carbon content of 85.5% and 87.0%, respectively, and an increase in fuel use with a trap+filter of 5% (see text). Source of fuel economy: Ref. 37.

Figure 3 illustrates the net effect of diesel versus gasoline vehicles on climate for a range of mileage differences between diesel and gasoline (up to 30% better mileage for diesel). The figure examines the time-dependent impacts on climate of diesel versus gasoline vehicles, accounting for carbon dioxide and fossil-fuel soot (primarily black carbon plus organic matter) emissions from both.

Figure 3a shows that, when diesel vehicles have 15% better mileage than gasoline vehicles, the diesel vehicles cause more global warming over 100 years, regardless of whether they are emitting fossil-fuel soot at a particulate matter emission standard of 10 milligrams per mile (mg/mi), 40 mg/mi, or 80 mg/mi and regardless of the atmospheric lifetime of carbon dioxide (30 or 50 years). This conclusion applies to diesel vehicles having 0-15% better mileage as well.

Figure 3. Comparison of the calculated ratio of the CO_2-C emission reduction required per unit of fossil-fuel (FF) soot (BC+OM) emitted for diesel vehicles to cool global climate with the actual ratio of CO_2-C emission reduction per unit mass fossil-fuel soot emission when diesel achieves (a) 15% and (b) 30% better mileage than gasoline and when diesel has different fossil-fuel soot emission rates. The three solid, straight lines in each figure represent the actual ratios of CO_2-C saved to FF soot emitted for a modern diesel vehicle emitting 0.08, 0.04, and 0.01 g/mi soot. The intersection of each straight line with each modeled curve indicates the period during which diesel vehicles enhance global warming in comparison with gasoline vehicles under the given emission standard. For example, in the case of the 0.08 g/mi standard, diesel warms climate in comparison with gasoline for >100 yr for both CO_2 lifetimes and for both differences in diesel versus gasoline mileage. Although gasoline soot emissions are low, the figure can be applied correctly only when the PM standard numbers in the figure represent the difference between diesel and gasoline soot emissions. From Ref. 21.
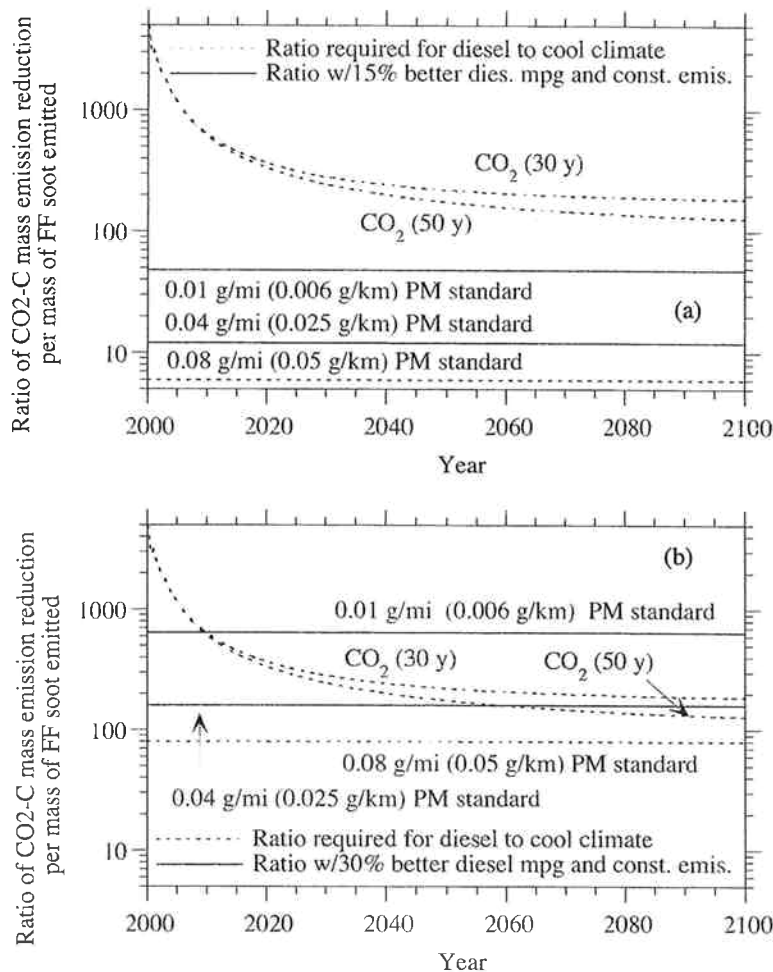
Figure 3b shows that, when diesel vehicles have 30% better mileage than gasoline vehicles, diesel vehicles emitting particles continuously at a particulate matter emission standard of 40 mg/mi or 80 mg/mi may warm climate more than gasoline vehicles for more than 100 yr for a CO_2 lifetime of 30 years, which is close to the actual data-constrained lifetime of CO_2 of 30-43 years[20,21]. However, diesel emitting at 10 mg/mi (Tier 2, bins 2-6 emission standard) may warm climate relative to gasoline for about 10 yr at 30% higher mileage.

However, because no diesel vehicle available in the U.S. in 2006, 2005, or 2004 emitted less CO_2 than did the best gasoline vehicle available (Table 7 for 2006), the 30% scenario in not applicable to the best available vehicles in the United States. As such, 2006 and earlier diesel vehicles sold in the U.S. all caused more global warming than did the best gasoline cars available, over a 100-year period.

Table 7 shows that the highest-mileage diesel vehicles (manual-transmission VW Golf and Jetta) obtained only 14.5% better mileage than did the automatic-transmission gasoline-powered Honda Civic. However, this translated into greater CO_2 emissions for the highest-mileage diesel vehicles since diesel fuel has a greater density and carbon content than does gasoline (Table 7, footnote). The addition of a particle trap to a diesel vehicle increases its fuel use by 3.5-8.5%[33-35]. Assuming a 5% increase, diesels with a trap emit even more CO_2 per unit distance than do the gasoline vehicles in Table 7. In all cases, gasoline-electric hybrid vehicles available in the U.S. in 2006 emitted less CO_2 than did diesel with or without a trap or gasoline vehicles, aside from the Honda Insight, which was a smaller gasoline vehicle than the others.

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In 2007, subcompact diesel vehicles appear to have been removed from the United States market, most likely because none could meet the Tier-2, bin 2-6 emission standard of 10 mg/mi without adding a particle trap. This appears to have been beneficial from a climate perspective based on the results described above. However, lower-mileage diesel passenger cars as well as diesel trucks, buses, farm equipment, and contruction machines are still sold.

In sum, there is not an advantage and a potential disadvantage of diesel versus gasoline in terms of climate and air pollution impacts. However, neither type of vehicle is satisfactory or useful for solving climate and health problems as the emissions from both are very high. Even modest improvements in mileage standards for all vehicles are beneficial, but will only delay the eventual increase in emissions due to a larger population.

Conversion of the Vehicle Fleet
A more certain method of reducing global warming caused by both fossil-fuel soot and carbon dioxide is to convert vehicles from fossil fuel to electric, plug-in-hybrid, or hydrogen fuel cell vehicles, where the electricity or hydrogen is produced by a renewable energy sources, such as wind, solar, geothermal, hydroelectric, wave, or tidal power.

In the case of replacing all onroad vehicles with electric and/or hydrogen fuel cell vehicles powered by renewables, the vehicles would emit zero carbon dioxide, particles, nitrogen oxides, and hydrocarbons. Such a conversion would eliminate 160 Gg/yr (24%) of U.S. (or 1.5% of world) fossil-fuel soot (Table 5) and about 26% of U.S. (or 5.5% of world) carbon dioxide (Figure 4a). This sum of the two would eliminate about 0.06 K (about 7.7%) of global warming. However, the elimination of hydrocarbons and nitrogen oxides would also eliminate some cooling particles, reducing the net benefit by at most, half, but improving human health.

Figure 4. (a) Sources of U.S. CO_2 and (b) thousands of 5 MW wind turbines needed, placed in locations where the mean annual wind speed is 7.5 m/s (high number) to 8.5 m/s (low number), to displace 100% of CO_2 from each source (2005). Onroad vehicles include light and heavy-duty vehicles. Data from Ref. 38.
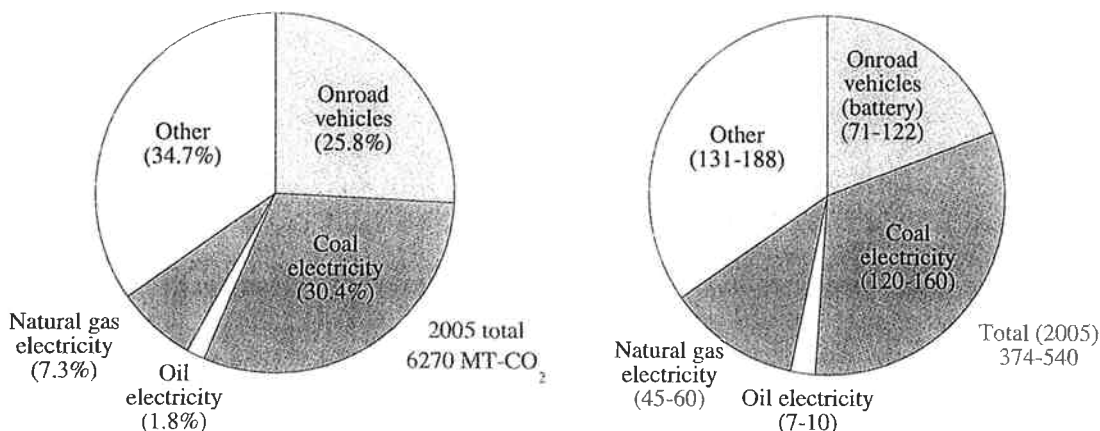
Is enough renewable energy available to power all U.S. onroad vehicles?. Recently, global wind speeds at 80 meters above the ground, the hub height of many modern wind turbines, were mapped for the first time from data[39]. The figure below shows the resulting map for North America. The Great Plains has long been known to be a region of strong winds, but the figure identifies some areas of intense winds that were previously unknown, including off the southern and southeastern coasts of the United States, along the coasts of Texas, California, Washington State, and Alaska, and over/around the Great Lakes.

Figure 5. Annually-averaged wind speeds 80 meters above the ground in North America. Wind speeds greater than 6.9 meters per second (m/s) are economically viable. From Ref. 38.
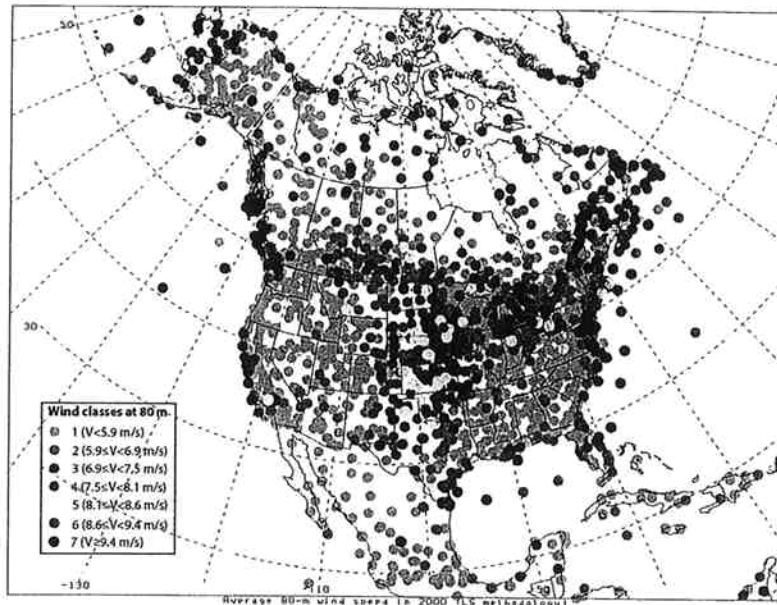
For wind energy to be economically viable, the annual-average wind speed at 80 meters must be at least 6.9 meters per second (15.4 miles per hour). Based on the mapping analysis just discussed, 15 percent of United States land area (and 17 percent of land plus coastal offshore area) may have wind speeds above this threshold (globally, 13 percent of land area is above the threshold).

From the numbers above, the total energy available from the wind in the United States (onshore plus coastal offshore) over economically-viable wind areas is about 55,000 TWh, or twice the total energy consumed by all energy sources in the United States (28,000 TWh[40] and more than ten times the electricity consumed (3700 TWh). In other words, if the United States could capture only a fraction of the available wind at 80 meters, wind could supply a significant portion of U.S. electric power, including that used to supply electricity for all onroad vehicles converted to battery-electric vehicles.

Figure 4 shows that the U.S. would need only about 71,000-122,000 5 MW turbines to power all onroad (light and heavy-duty) vehicles in the U.S. converted to battery-electric vehicles. The word "only" is used since this number is much less than the 300,000 airplanes the U.S. manufactured during World War II.

Figure 6 shows that the land area required for wind turbines to provide electricity for batteries to replace all U.S. onroad vehicles is only 0.35-0.6% of the U.S. (with the turbine area touching the ground only 1-2 square kilometers). The area required for wind is about 1/30th that required for corn-ethanol (E85) and 1/20th that required for cellulosic ethanol (E85), on average, to replace the same vehicles. The land area for wind to produce electricity for hydrogen for fuel cell vehicles is about three times greater than that for wind producing electricity for batteries, but the climate benefits of the exhaust gases from the vehicles are the same in both cases. The land area required for solar energy to provide electricity for batteries is about 1/5th that of wind turbines in terms of their spacing but much greater than that in terms of the wind turbine area touching the ground.

Figure 6. Percent of U.S. land required to replace all U.S. onroad vehicles with other vehicle types. Data from Ref. 38.
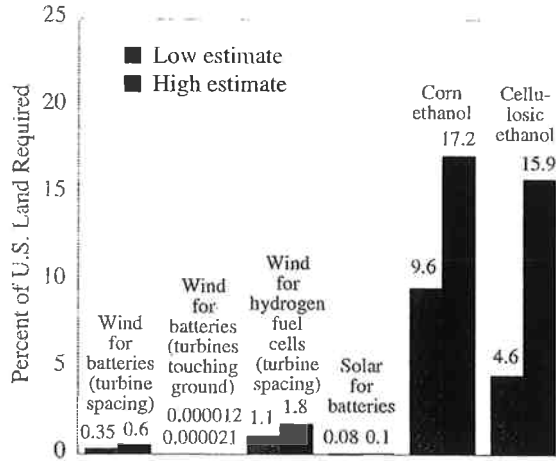

Figure 7 shows the percent decrease in total U.S. carbon dioxide emissions due to converting to different vehicle types or fuels. Conversion to battery-electrics or hydrogen fuel cell vehicles powered by renewable energy would provide better benefits than converting to corn or cellulosic ethanol fueled vehicles.

Figure 7. Percent decrease in total U.S. carbon dioxide emissions upon replacing 100% of onroad vehicles. Data from Ref. 38. Corn and cellulosic ethanol lifecycle carbon reductions relative to gasoline were calculated by multiplying reductions from Ref. 41 as 2% and 50%, respectively, by 26%, the percent of U.S. CO_2 from onroad vehicles. These numbers were multiplied by 30% to account for the landuse limits of corn and cellulosic crops in the U.S., estimated from Figure 6. Wind turbines were assumed to have 2% embedded carbon. Photovoltaics were assumed to have 10% embedded carbon.
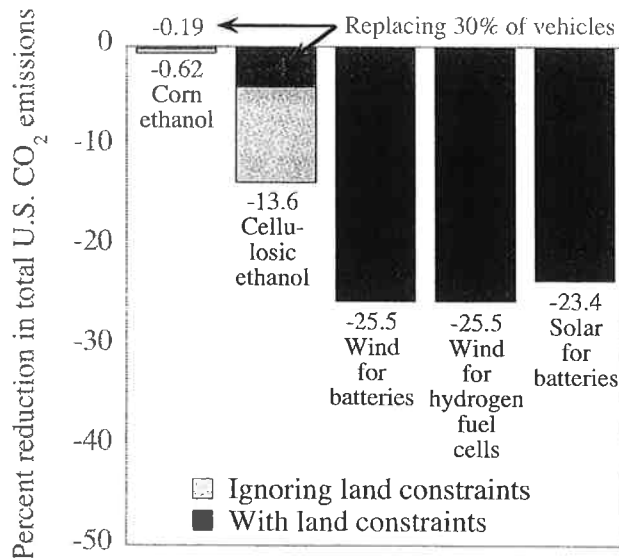

Figure 8 shows the estimated number of deaths per year in 2020 due to converting to different vehicle types or fuels. This death rate is conservative, particularly with respect to

particulate matter health effects. Conversion to battery-electrics or hydrogen fuel cell vehicles powered by renewable energy would eliminate all motor-vehicle tailpipe air pollution deaths[43].

Figure 8. Conservative estimate of future (c. 2020) U.S. deaths per year from onroad vehicles assuming full penetration of the vehicles. Data from Refs. 38, 42.
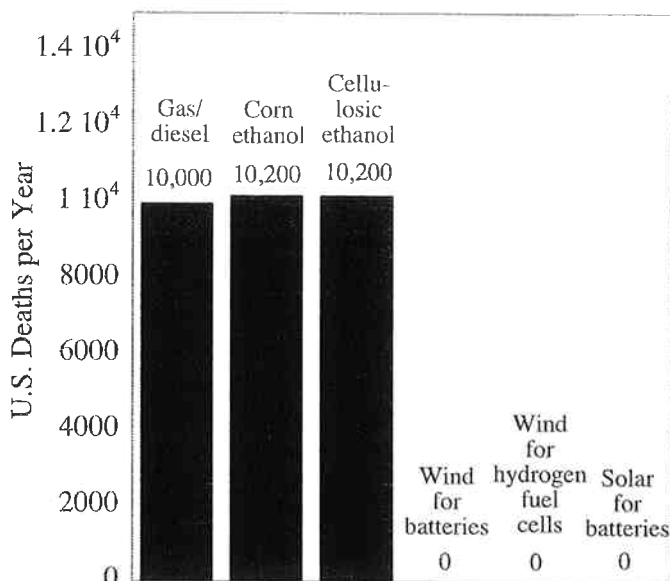
In sum, the best solution to the problem of health- and climate-relevant emissions from vehicles is the large scale conversion from liquid fuel to electric vehicles powered by renewable energy and hydrogen fuel cell vehicles, where the hydrogen is produced by renewable energy, as such vehicles emit no carbon dioxide, soot particles, nitrogen oxides, or hydrocarbons.

Summary

- Fossil-fuel soot plus biofuel-soot have a strong probability of being the second-leading cause of global warming after carbon dioxide and ahead of methane. Such soot may account for 16% of gross global warming (warming due to greenhouse gases, soot, and the urban heat island effect) and 40% of net warming (gross warming minus the cooling due to non-soot aerosol particles).

- Due to the short atmospheric lifetime of soot, its control appears to be the fastest method of slowing global warming for a specific period.

- The control of soot will not only slow global warming but also improve human health.

- The best method of reducing the combined effects of carbon dioxide and soot on climate and health problems is to convert as many onroad and nonroad vehicles to vehicles powered by renewable energy (e.g., battery-electrics, plug-in-hybrids, and hydrogen fuel cell vehicles) and to replace as much electric power as possible with renewable electric power sources.

- For example, the U.S. could theoretically replace all onroad vehicles with battery-electric vehicles powered by electricity from 71,000-122,000 5-MW wind turbines, less than the 300,000 airplanes the U.S. produced during World War II.

- Use of electric vehicles for short commutes and hydrogen-fuel-cell vehicles or plug-in-hybrid vehicles for long commutes would be one approach.

- The addition of particle traps to existing diesel vehicles is a secondary strategy that will reduce soot emissions but will slightly increase carbon dioxide emissions.

- The conversion of gasoline to diesel vehicles is a poor strategy for addressing global warming since such a conversion increases particle soot emissions and can decrease carbon dioxide emissions only under sufficiently large mileage differences between the two.

Thank you for considering this information,

Sincerely,

Mark Z. Jacobson

References
1) Jacobson, M.Z. (2002), Control of fossil-fuel particulate black carbon plus organic matter, possibly the most effective method of slowing global warming, J. Geophys. Res., 107, (D19), 4410, doi:10.1029/ 2001JD001376, www.stanford.edu/group/efmh/fossil/fossil.html.
2) Jacobson, M.Z. (2004), The climate response of fossil-fuel and biofuel soot, accounting for soot's feedback to snow and sea ice albedo and emissivity, J. Geophys. Res., 109, D21201, doi:10.1029/2004JD004945, www.stanford.edu/group/efmh/jacobson/VIIIc.html.
3) Hansen, J., and L. Nazarenko (2004), Soot climate forcing via snow and ice albedos, Proc. Natl. Acad. Sci., 101(2), 423–428.
4) Flanner, M.G., C.S. Zender, J.T. Randerson, and P.J. Rasch (2007), Present-day climate forcing and response from black carbon in snow, J. Geophys. Res., 112, D11202, doi:10.1029/2006JD008003.
5) Ackerman, T. P. and O. B. Toon (1981), Absorption of visible radiation in atmosphere containing mixtures of absorbing and nonabsorbing particles, Appl. Optics, 20, 3661-3667.
6) Jacobson, M. Z. (1997), Development and application of a new air pollution modeling system. Part II: Aerosol module structure and design, Atmos. Environ., 31A, 131–144, www.stanford.edu/group/efmh/jacobson/IIb.html.
7) Jacobson, M. Z. (1997), Development and application of a new air pollution modeling system. Part III: Aerosol-phase simulations, Atmos. Environ., 31A, 587–608, www.stanford.edu/group/efmh/jacobson/IIa.html.
8) Jacobson, M. Z. (2000), A physically-based treatment of elemental carbon optics: Implications for global direct forcing of aerosols, Geophys. Res. Lett., 27, 217-220, www.stanford.edu/group/efmh/jacobson/IVa.html.

9) Schnaiter, M., H. Horvath, O. Mohler, K.-H. Naumann, H. Saathoff, and O.W. Schock (2003), UV-VIS-NIR spectral optical properties of soot and soot-containing aerosols, J. Aerosol Sci., 34, 1421-1444.

10) Schnaiter, M., C. Linke, O. Mohler, K.-H. Naumann, H. Saathoff, R. Wagner, U. Schurath, and B. Wehner (2005), Absorption amplification of black carbon internally mixed with secondary organic aerosol, J. Geophys. Res., 110, D19204, doi:10.1029/2005JD006046.

11) Chylek, P., V. Ramaswamy, and R. J. Cheng (1984), Effect of graphitic carbon on the albedo of clouds, J. Atmos. Sci. 41, 3076-3084.

12) Chylek, P., and J. Hallett (1992), Enhanced absorption of solar radiation by cloud droplets containing soot particles in their surface, Q. J. R. Meteorol. Soc., 118, 167-172.

13) Jacobson, M.Z. (2006), Effects of absorption by soot inclusions within clouds and precipitation on global climate, J. Phys. Chem., 110, 6860-6873, www.stanford.edu/group/efmh/jacobson/soot_incl_clouds.htm.

14) Intergovernmental Panel on Climate Change (IPPC) (2007). The physical science basis of climate change, Cambridge University Press, New York, http://ipcc-wg1.ucar.edu/wg1/.

15) Jacobson, M. Z. (2001), Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols, Nature, 409, 695-697, www.stanford.edu/group/efmh/jacobson/IVb.html.

16) Hansen, J., M. Sato, R. Ruedy, A. Lacis, and V. Oinas (2000), Global warming in the twenty-first century: An alternative scenario, Proc. Natl. Acad. Sci., 97, 9875-9880.

17) Jacobson, M.Z (2001), Global direct radiative forcing due to multicomponent anthropogenic and natural aerosols, J. Geophys. Res., 106, 1551-1568, 2001, www.stanford.edu/group/efmh/jacobson/IVc.html.

18) Chung, S.H., and J.H. Seinfeld (2002), Global distribution and climate forcing of carbonaceous aerosols, J. Geophys. Res. 107, doi:10.1029/2001JD001397.

19) Jacobson, M.Z. (2004) The short-term cooling but long-term global warming due to biomass burning, J. Clim., 17 (15), 2909-2926, www.stanford.edu/group/efmh/bioburn/index.html.

20) Gaffin, S.R., B.C. O'Neill, and M. Oppenheimer (1995), Comment on "The lifetime of excess atmospheric carbon dioxide" by Berrien Moore III and B.H. Braswell, Global Biogeochemical Cycles, 9, 167-169..

21) Jacobson, M.Z. (2005), Correction to "Control of fossil-fuel particulate black carbon and organic matter," J. Geophys. Res., 110, D14105, doi:10.1029/2005JD005888.

22) Menon, S., J. Hansen, L. Nazarenko, and Y. Luo (2002), Climate effects of black carbon aerosols in China and India, Science, 297, 2250-2253.

23) Ramanathan, V., C. Chung, D. Kim, T. Bettge, L. Buja, J.T. Kiehl, W.M. Washington, Q. Fu, D.R. Sikka, and M. Wild (2005), Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle, PNAS, 102, 5326-5333.

24) Ramanathan, V., M.V. Ramana, G. Roberts, D. Kim, C. Corrigan, C. Chung, and D. Winker (2007), Warming trends in Asia amplified by brown cloud solar absorption, Nature, 448, 575-578.

25) Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M., Woo, J.-H. & Klimont, Z. (2004), A technology-based global inventory of black and organic carbon emissions from combustion, J. Geophys. Res., 109, D14203, doi: 10.1029/2003JD003697.

26) United States Environmental Protection Agency (USEPA) (2007). Clearinghouse for Inventories and Emission Factors, http://www.epa.gov/ttn/chief/.

27) Jacobson, M.Z., and D.G. Streets (2007), The influence of future anthropogenic emissions on climate, natural emissions, and air quality, manuscript in review.

28) Petzold, A., A. Dopelheuer, C.A. Brock, and F. Schroder (1999), In situ observations and model calculations of black carbon emission by aircraft at cruise altitude, J. Geophys. Res., 104, 22,171-22,181.

29) Mortlock, A.M., and R. Van Alstyne (1998), Military, Charter, Unreported Domestic Traffic and General Aviation: 1976, 1984, 1992, and 2015 Emission Scenarios, NASA CR- 1998-207639. (available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19980047346_1998120131.pdf)..

30) Sutkus, D.J., S.L. Baughcum, and D.P. DuBois (2001), Scheduled Civil Aircraft Emission Inventories for 1999: Database Development and Analysis, NASA/CR-2001-211216, http://gltrs.grc.nasa.gov/reports/2001/CR-2001-211216.pdf.

31) Corbett, J.J., P.S. Fischbeck, and S.N. Pandis (1999), Global nitrogen and sulfur emissions inventories for oceangoing ships, J. Geophys. Res., 104, 3457-3470.

32) Corbett, J.J., and H.W. Koehler (2003), Updated emissions from ocean shipping, J. Geophys. Res., 108 (D20), 4650, doi:10.1029/2003JD003751.

33) Salvat, O., P. Marez, and G. Belot (2000), Passenger car serial application of a particulate filter system on a common rail direct injection diesel engine, SAE 2000-01-0473.

34) Ullman, T. L., L. R. Smith, J. W. Anthony (2002), Exhaust emissions from school buses in compressed natural gas, low emitting diesel, and conventional diesel engine configurations, Southwest Research Institute Report 08.05303.

35) Durbin, and Norbeck (2002).

36) Jacobson, M. Z., J. H. Seinfeld, G. R. Carmichael, and D.G. Streets (2004), The effect on photochemical smog of converting the U.S. fleet of gasoline vehicles to modern diesel vehicles, Geophys. Res. Lett., 31, L02116, doi:10.1029/2003GL018448, www.stanford.edu/group/efmh/jacobson/effPhoto.html

37) Department of Energy (DOE) (2007), Fuel Economy Ratings, www.fueleconomy.gov.

38) Jacobson, M.Z. (2007), Wind versus biofuels for addressing climate, health, and energy, www.stanford.edu/group/efmh/jacobson/E85vWindSol.

39) Archer, C.L., and M.Z. Jacobson (2005), Evaluation of global wind power, J. Geophys. Res., 110, D12110, doi:10.1029/2004JD005462, 2005, http://www.stanford.edu/group/efmh/winds/global_winds.html.

40) Energy Information Administration (2005) http://www.eia.doe.gov/emeu/states/sep_use/total/use_tot_us.html.

41) Dulucchi, M. (2006), www.its.ucdavis.edu/publications/2006/UCD-ITS-RR-06-08.pdf.

42) Jacobson, M.Z. (2007a) Effects of ethanol (E85) versus gasoline on cancer and mortality in the United States, Environ. Sci. Technol., 41 (11), 4150-4157, doi:10.1021/es062085v. www.stanford.edu/group/efmh/jacobson/E85vWindSol.

43) Jacobson, M.Z., W.C. Colella, and D.M. Golden (2005), Cleaning the air and improving health with hydrogen fuel cell vehicles, Science, 308, 1901-1905, www.stanford.edu/group/efmh/jacobson/fuelcellhybrid.html.