GREENHOUSE GAS EMISSIONS FROM AVIATION AND MARINE TRANSPORTATION: MITIGATION POTENTIAL AND POLICIES

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PEW CENTER ON Global CLIMATE CHANGE

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Prepared for the Pew Center on Global Climate Change

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Contents

1. Introduction and Summary

This paper provides an overview of greenhouse gas (GHG) emissions from aviation and marine transportation and the various mitigation options to reduce these emissions. Reducing global emissions by 50 to 80 percent below 1990 levels by 2050—reductions scientific studies suggest are necessary to stabilize the climate and avoid the most destructive impacts of climate change (IPCC 2007)—will require lowering GHG emissions across all sectors of the economy. Aviation and marine transportation combined are responsible for approximately 5 percent of total GHG emissions in the United States and 3 percent globally[1] and are among the fastest growing modes in the transportation sector. Controlling the growth in aviation and marine transportation GHG emissions will be an important part of reducing emissions from the transportation sector. The Intergovernmental Panel on Climate Change (IPCC) reports that global demand for aviation increased by 5.9 percent and demand for marine transportation by 5.1 percent, during 2005 alone (IPCC 2007). Business-as-usual (BAU) projections for CO_2 emissions from global aviation are estimated at 3.1 percent per year over the next 40 years, resulting in a 300 percent increase in emissions by 2050 (IEA 2008b). The projected growth rate of global marine transportation emissions is more uncertain. BAU growth projections by the IEA (2008b) and IMO (2008) are between 1 and 2 percent per year. By 2050, international marine transportation emissions are estimated to increase by at least 50 percent over 2007 levels.

There are several determinants of greenhouse gas emissions from any transportation mode. Schipper et al.'s (2001) "ASIF" identity (shown below) provides a useful framework for thinking about these drivers.

$$\textit{Transportation sector GHG Emissions} = A \cdot S_i \cdot I_i \cdot F_{i,j}$$

In the identity, GHGs are a product of the following:

- A: the transportation sector's total activity,
- S_i: each subsector's share of total activity,
- I_i: the energy intensity of vehicles used in each subsector, and
- $F_{i,j}$: the carbon intensity of the fuel types used in each subsector, where i: mode of transportation, j: fuel type.

Reducing parameters A, I_i, or $F_{i,j}$ reduces overall transportation sector emissions. Reducing S_i reduces the emissions from that particular subsector; however, whether it reduces overall emissions depends on whether that subsector's share of transportation activity is shifted to a higher or lower GHG emitting mode. In the context of aviation and marine shipping, GHGs can be mitigated by reducing overall activity (A) (e.g., passenger-miles or freight-miles); reducing the mode share (S_i) of a carbon-intensive mode by shifting to a transportation mode with lower emissions; increasing the mode share of a less carbon-intensive mode (S_i) by shifting away from a transportation mode with higher emissions; reducing energy intensity (I_i) through improving vehicle fuel efficiency; and reducing the carbon intensity of the fuel used ($F_{i,j}$) by switching to low- or no- carbon energy sources such as biofuels, hydrogen, wind, and solar.

While aviation and marine shipping efficiencies have been steadily increasing over the past several decades, demand has grown more rapidly than efficiency improvements, causing GHG emissions from these subsectors to continue to increase (IEA 2008b; IMO 2008). Under a BAU scenario where the global economy continues to grow and there are no specific policies targeting aviation and marine transportation GHG emissions, these trends are expected to continue.

A range of near-, medium- and long-term mitigation options are available to slow the growth of energy consumption and GHG emissions from aviation and marine shipping. Improvements in operational efficiency (e.g., advanced navigation and air traffic management systems for aviation and slower marine vessel speeds) have the potential to reduce GHG emissions below BAU projections by about 5 percent for aviation and up to 27 percent for marine shipping in the near to medium term (to 2025). Looking out to 2050, advanced propulsion systems and new airframe designs could further reduce aviation CO_2 emissions by up to 35 percent below BAU projections. For marine transport, larger ships, new combined cycle or diesel-electric engines, and optimized hull and propeller designs could provide an additional 17 percent reduction in emissions below BAU projections by 2050.

Reducing the carbon intensity of the energy sources used in aviation and marine transportation, by transitioning to alternative fuels and power sources, also could reduce GHG emissions over the medium to long term, although the level of potential reductions is uncertain. Aircraft and marine vessels could be powered by low-carbon biofuels or perhaps even hydrogen. While numerous technical challenges still exist, the main challenge to the use of alternative fuels will be the ability of aviation and shipping to compete with other transportation subsectors for a potentially limited supply of low-carbon biofuels. This could particularly be an issue with marine shipping, where the industry currently consumes the lowest-cost fuels available, namely residual fuel oil. Marine vessels could also benefit from switching to lower-carbon, conventional fossil fuels (e.g., liquefied natural gas and marine diesel oil) or to other renewable energy sources, such as wind or solar power.

Beyond technical measures, reducing the demand for aviation and shipping could achieve GHG reductions, though the potential impacts are probably limited. The challenge for these subsectors is that there are few suitable alternatives for the services provided by aviation and marine shipping. High speed rail could replace some passenger air travel, but currently there are few alternatives to marine shipping. Marine shipping is already the most efficient, lowest-cost form of transportation, aside from pipelines, which compete with shipping in just a few markets. With only modest cost increases likely to be achievable through policy intervention,[2] and a limited number of alternatives, a large reduction in demand compared to BAU seems unlikely from these subsectors.

Globally, the majority of GHG emissions from the aviation and marine transportation are still unregulated. While some countries have enacted domestic policies, most have not. Independently, New Zealand, Australia, and the European Union have already taken steps to include aviation in their domestic GHG cap-and-trade programs. The United States does not yet regulate GHGs at the national level, although the U.S. Environmental Protection Agency may soon initiate such regulation under the federal Clean Air Act and there are legislative proposals under consideration in the U.S. Congress to incorporate these emissions in a domestic, economy-wide, GHG cap-and-trade program.

Addressing GHG emissions from international aviation and marine shipping is especially challenging, because they are produced along routes where no single nation has regulatory authority. Internationally, unlike other sources of GHG emissions, the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) specifically excludes international emissions from aviation and marine transport from developed countries' national targets. Instead, the Protocol calls for limitations or reductions in emissions from these sectors to be achieved by working through the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO). In response to this mandate, both organizations have initiated activities aimed at addressing emissions from their respective sectors, but thus far neither has reached agreement on substantive binding actions aimed at limiting GHG emissions, and many of the key issues remain unresolved. In response to the stalemate on this issue, some countries have proposed alternative options for addressing these emissions in a future climate agreement scheduled for conclusion in late 2009. Meanwhile, the EU has taken a unilateral measure to include international aviation in its GHG emission trading system (i.e., by covering emissions from all flights either landing at or departing from airports within the European Union).

In summary, the potential for mitigating GHG emissions from aircraft and marine vessels is considerable—reductions of more than 50 percent below BAU levels by 2050 from global aviation and more than 60 percent for global marine shipping are possible. For these reductions to be realized, however, international and domestic policy intervention is required. Developing an effective path forward that facilitates the adoption of meaningful policies remains both a challenge and an opportunity.

2. Overview of Aviation and Marine Transportation

There are three major types and uses of aircraft and marine[3] vessels: commercial, recreational, and military. While all contribute to GHG emissions, of the three, commercial aviation and marine transportation account for the large majority of total aviation and marine emissions and are thus the focus of this paper. Commercial aviation and marine transportation demand and GHG emissions are also growing rapidly as a result of increasing international trade and economic growth (Table 1). Military and recreational aviation and marine transportation have vastly different objectives and employ somewhat different technologies; however, some of the mitigation options and policy solutions discussed herein may apply to these transportation modes as well.

Virtually all the fuels used in aviation and marine transport are petroleum-based. Kerosene-type jet fuel is by far the predominant aircraft fuel, accounting for about 99 percent of all aviation fuel consumed (EPA 2006). Domestic marine vessels consume a mix of distillate (diesel) fuel and residual fuel oil. International marine vessels predominantly use residual fuel oil. Aviation and marine fuels consumed during international trips are commonly referred to as "bunker fuels" to differentiate them from domestic uses of such fuels.[4]

2.1 Current Emissions and Trends

Domestic GHG emissions from ships and aircraft are those produced during trips between origins and destinations within the same country; emissions from trips between two different countries are considered international emissions. Emissions from domestic U.S. aviation and marine transport have been relatively stable since 1990 (Table 1), despite a lack of any policies regulating GHGs at the national level (EPA 2008a). Increasing energy efficiency in aviation (primarily motivated by market forces, e.g., fuel prices), and a decline in domestic shipping (driven by increasing competition from other modes), largely explain why this has been the case. Worldwide, international aviation and marine transportation emissions have been increasing steadily. This is largely due to globalization of the world economy and economic growth, which has made air travel affordable for a larger share of the population and contributed to an increased demand for traded goods, most of which are transported by marine vessels at some point in their supply chain, particularly to and from developing countries.

Table 1: U.S. And World Greenhouse Gas Emissions

			Year		% Change (1990 to 2005)	Notes
		Units: million metric tonnes CO_2-eq	1990	2005		
World	Total	All Anthropogenic Sources	39,400.0	49,000.0	24%	a, b
		Fossil Fuel Combustion Only	20,987.6	27,146.3	29%	c
	Aviation	Total (Domestic + International)	—	641.0	—	d
		International Bunkers	255.4	388.8	52%	
	Marine	Total (Domestic + International)	—	651.0		
		International Bunkers	357.9	551.6	54%	
United States	Total	All Anthropogenic Sources, Domestic	6,148.3	7,129.9	16%	e
		Fossil Fuel Combustion Only, Domestic	4,724.1	5,731.0	21%	e, f
	Transport	All Subsectors, Domestic	1,488.1	1,874.5	26%	e, f
		All Subsectors, Domestic + International	1,601.8	1,997.1	25%	f
	Aviation	Commercial, Domestic	136.7	150.4	10%	e, f
		Military, Domestic	33.9	16.9	-50%	e, f
		General Aviation, Domestic	9.4	13.8	47%	e, f
		International Bunkers	46.2	68.2	48%	
		Total, Domestic	180.0	181.1	1%	e, f
		Total, Domestic + International	226.2	249.3	10%	
	Marine	Ships and Other Boats, Domestic	32.5	28.1	-14%	e, f
		Recreational Boats, Domestic	14.0	17.4	24%	e, f
		International Bunkers	68.6	55.6	-19%	g
		Total, Domestic	46.5	45.5	-2%	e, f, g
		Total, Domestic + International	115.1	101.1	-12%	g

Notes

a Includes all GHG emissions due to human activities throughout the world: CO_2 from fossil fuel use and other sources; CO_2 from deforestation, decay and peat; CH_4 from agriculture, waste and energy; N_2O from agriculture and others; and F-gases

b Data for 2005 not available; uses 2004 data instead

c Includes all GHG emissions due to fossil fuel combustion throughout the world

d Does not include military or general aviation

e Does not include international aviation or marine bunker fuels, in keeping with UNFCCC guidelines

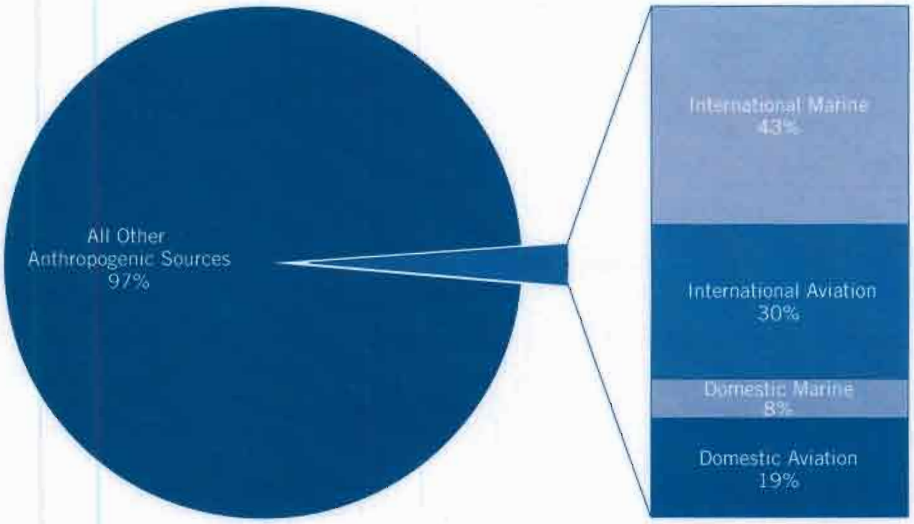
f Includes only CO_2 emissions due to fossil fuel combustion. Does not include CH_4, N_2O, and HFCs, PFCs, or SF_6

g Figures are not completely reliable due to potential data collection problems on reported residual fuel oil consumption and the difficulty in differentiating between domestic and international fuel consumption

Sources: EPA 2008a; IEA 2008a; IPCC 2007

The International Energy Agency (IEA) reports that combined aviation and marine transport produce three percent of all anthropogenic GHG emissions globally, with each mode contributing to half of this share (Figure 1). Within this 3 percent, over two-thirds of the total emissions are caused by international transport (*i.e.*, trips between two or more countries), with international marine shipping comprising the larger share of this (Figure 1 and Figure 2). However, the magnitude of marine transportation emissions is highly uncertain and potentially much greater than IEA estimates. Marine fuel sales data reported to IEA and used in top-down emission estimates are widely believed to be unreliable because of inconsistent reporting methods in non-OECD member countries. Bottom-up, activity-based methods (Corbett and Koehler 2003; Corbett and Koehler 2004; IMO 2008) estimate fuel consumption by considering the number of ships in the world fleet and estimating how often they are used (hours of operation), their power requirements, and how much fuel would be used to meet these requirements. While the data used in bottom-up methods may be more reliable than IEA fuel statistics, both methods contain many uncertainties, resulting in some debate about what is actually the best estimate of marine fuel use (Endresen, Sørgård et al. 2004). According to the most recent study, which relies on a bottom-up approach, CO_2 emissions from marine transportation may be 50 percent greater than the IEA estimates shown here (IMO 2008), thus representing about three percent of global CO_2 emissions in 2007.

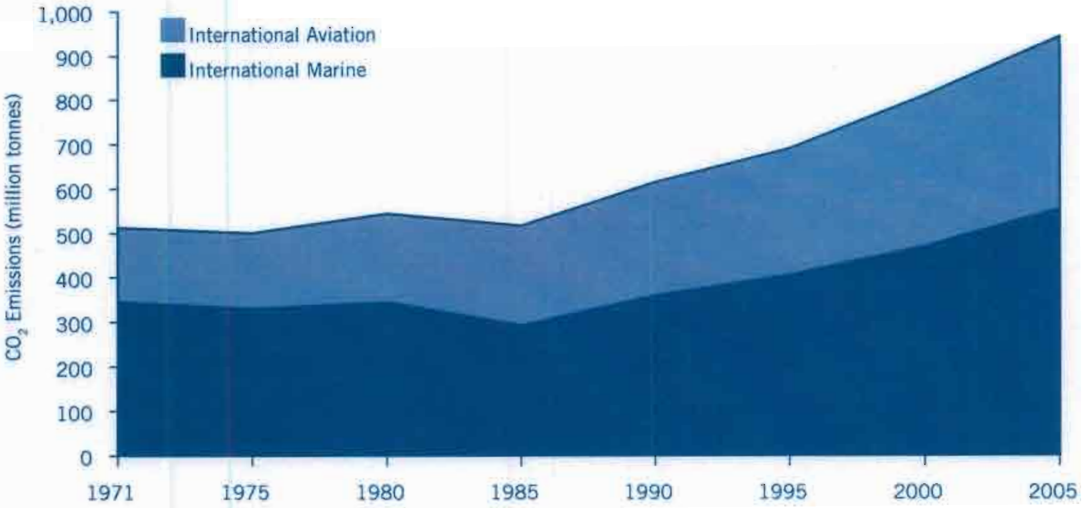
Figure 1: Global GHG Emissions from Domestic and International Aviation and Marine Transportation in 2005



Source: IEA 2008a; IPCC 2007; Kim, Fleming et al. 2007

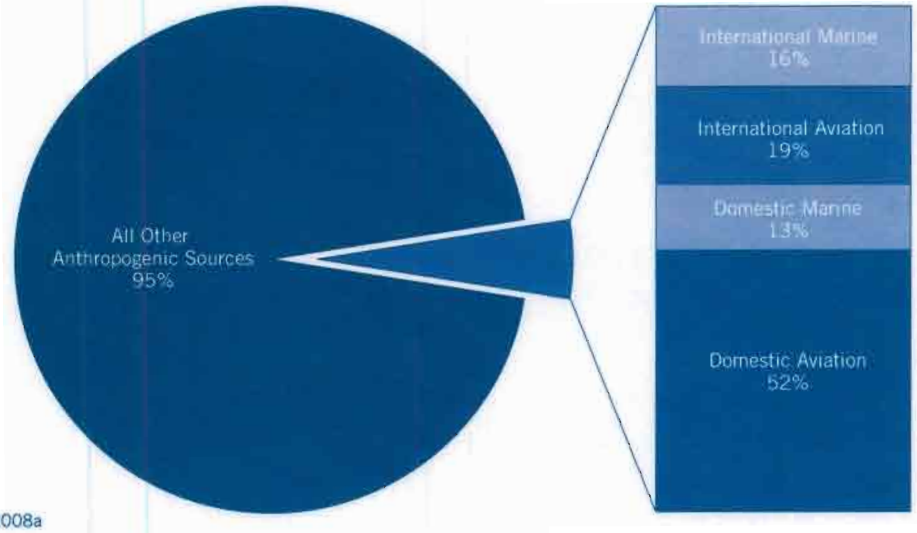
In the United States, aviation and marine transportation—both domestic (within the United States) and international (travel between the United States and another country)—contribute five percent to total reported GHG emissions (Figure 3). In contrast to the global picture, U.S. emissions are dominated by domestic travel, specifically domestic aviation. However, the method for calculating the international portion of U.S. marine transport emissions may not offer an accurate estimate of the total share of international GHGs for which the United States is responsible. Currently, as specified per UNFCCC guidelines, international emissions attributed to the United States are based solely on U.S. sales of international bunker fuels. This may misrepresent the potential U.S. contribution to international marine transportation emissions, since ships can visit U.S. ports without refueling.

Figure 2: Global Growth in International Aviation and Marine CO_2 Emissions



Source: IEA 2008a

Figure 3: U.S. GHG Emissions from Domestic and International Aviation and Marine Transportation in 2005



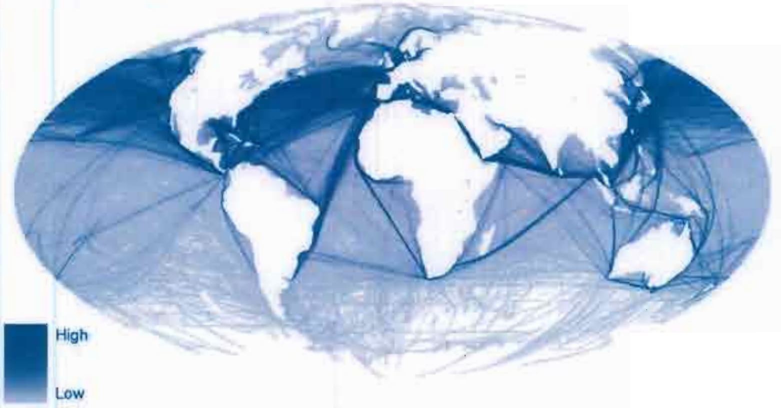
Source: EPA 2008a

2.2 Aviation and Marine Transportation Demand

Demand for commercial aviation and marine transportation is growing rapidly, driven largely by increasing economic growth, globalization, and international trade (Boeing 2008; UN 2008).

Developing regions, notably Asia, account for the largest share of marine transportation demand through the export of manufactured goods and the import of petroleum products, grains, and raw materials (UN 2008). The principal trading partners of these regions are developed countries in North America and Europe, although

Figure 4: Global Marine Shipping Traffic Density* for Ships Greater than 1000 Gross Tonnes During 2005. (Dark Shading Indicates A Higher Concentration of Ships.)†



*Traffic density is the amount of traffic per shipping area and used as a proxy for illustrating marine transportation emissions. It is calculated as the number of ships per area weighted by the installed power capacity for each ship.

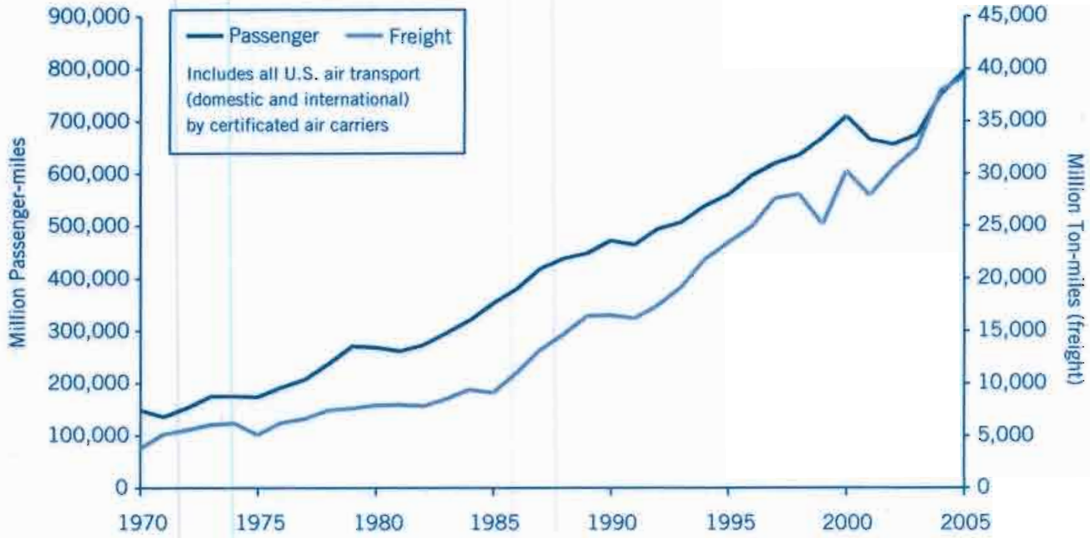
†GIS map data are from the National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara. More information available at http://www.nceas.ucsb.edu/GlobalMarine/impacts. A similar map in color using this data has previously been published by Halpern, B.S., S. Walbridge, et al. (2008).

Figure 5: Growth in U.S. Domestic and international Marine Transportation Demand, 1970–2005

Source: ORNL 2008

intra-regional trade, especially within Asia, is increasing as well. In 2007, as a group, Asia, the United States, and Europe accounted for most of the world's international trade—81 percent of global exports and 94 percent of global imports on a tonnage shipped basis. Asia alone accounts for slightly more than half of this share—more than the United States and Europe combined. Global shipping patterns clearly indicate the vast amount of trade that occurs between Asia and the United States and Europe (Figure 4). Between 2000 and 2007, as the global economy grew rapidly, the volume of world merchandise exports increased at an average rate of 5.5 percent per year, nearly twice as fast as world GDP (WTO 2008); over 80 percent of this volume

Figure 6: Growth in U.S. Aviation Transportation Demand, 1970–2005*



Source: ORNL 2008

*"Passenger-miles" (or passenger-km) and "Ton-miles" (or tonne-km) are calculated by multiplying the total number of passengers or weight aboard a vehicle by the distance traveled.

was transported by marine vessels (UN 2008). International trade continues to drive growth in demand for international shipping in to and from the United States as well, which increased at a rate of 2 percent per year between 2000 and 2005 (Figure 5) (ORNL 2008).

Demand for air travel (passenger and freight^5) is driven by both domestic and international leisure and business travel, as well as economic growth and international trade. Air travel experienced exceptionally high growth over the past several years. Between 2000 and 2006, global demand for passenger aviation grew at an average annual rate of 3.8 percent (Boeing 2008), with much of this growth taking place outside the United States. For example, demand for domestic air transport within China grew at 15.5 percent per year from 2000 to 2006 (Boeing 2008), while demand within the United States grew at just 2.2 percent per year (Figure 6) (ORNL 2008). Globally, most air traffic occurs within and between North America, Europe, and Asia (Kim, Fleming et al. 2007). With a slowing in global economic activity in 2008 and 2009, demand for air travel has also declined; however, it is still expected to continue to grow in the future.

2.3 Business-As-Usual Growth Projections

Demand for aviation and marine transportation is expected to grow substantially in the long term. Since most growth will take place outside the United States, the U.S. percentage contribution to aviation and marine shipping emissions is expected to gradually decline over time (Table 2).

The rising demand for aviation and shipping is expected to significantly increase GHG emissions from these sectors under a BAU scenario where no new policies are adopted to control GHG emissions. This will happen

Table 2: Aviation and Marine Sector Demand Projections

Sector	Market	Annual Growth Rate (%/yr)	Total Growth from Current Levels
Aviation	U.S. domestic passenger	0.8	27% by 2030
	U.S. international passenger	2.7	95% by 2030
	Rest of World passenger (domestic + international)	4	146% by 2030
	U.S. air freight (domestic + international)	3.5	124% by 2030
	Rest of World air freight (domestic + international)	5	199% by 2030
Marine	U.S. domestic	1	27% by 2030
	Global international	2.1–3.3	150–300% by 2050

Source: EIA 2009; IMO 2008.

Table 3: Aviation and Marine Greenhouse Gas Emission Projections

Sector	Market	Total Growth from Current Levels
Aviation	U.S. passenger and freight (domestic + international)	31–35% by 2030
	Global passenger and freight (domestic + international)	60% by 2030 300% by 2050
Marine	Global shipping	120–220% by 2050

Source: EIA 2009; FAA 2009; IEA 2008b; IEA 2008c; IMO 2008.

because growth rates for aviation and marine travel are higher than energy efficiency improvements. Furthermore, low-carbon fuels are not expected to achieve significant enough market penetration to lower GHG emissions, from the aviation and marine transportation sectors in a BAU scenario due to their relatively high costs (Table 3).

Advances in the efficiency of the aviation sector have been substantial; however, annual improvements have significantly slowed over the past two decades (IEA 2008b; ORNL 2008). A variety of technological and operational efficiency improvements, including changes in new aircraft and engines, as well as increased load factors (number of passengers per plane) led to these efficiency gains. Market forces (i.e., fuel costs) and government-sponsored research and development (R&D) efforts were primarily responsible for motivating these technological and operational improvements. These motivating factors are likely to continue in a BAU future, as fuel is a significant component of airline costs—historically 25 to 65 percent of combined direct operating and investment costs (DOC+I), or 12.5 to 32.5 percent of total airline costs (Lee, Lukachko et al. 2001).[6] However, to drive aviation advancements beyond BAU, policies and incentives will be required.[7]

The global shipping fleet relies almost entirely on diesel engines, which have gradually grown more efficient over the years (IMO 2008). However, there is little information available on historical trends in overall shipping energy efficiency. While new diesel engines have made new ships more energy efficient, changes in operations (for example increased speeds) have countered these improvements to some extent. What little research has been conducted suggests there has been little change in marine shipping efficiency over the past 20 to 30 years (Faber, Boon et al. 2007).

Non-CO_2 Emissions from Aircraft and Marine Vessels

In addition to carbon dioxide emissions, other, non-CO_2 emissions from aircraft and marine vessels have a significant impact on radiative forcing (RF)[*] and climate change (Endresen, Sørgård et al. 2003; IPCC 1999; Schäfer, Heywood et al. 2009). The principal GHG emitted by ships and planes, and the main focus of this paper, is CO_2. However, aircraft and marine vessels also emit other chemical compounds that impact RF. These include methane (CH_4) and nitrous oxide (N_2O), as well as hydrocarbons (HC), particulate matter (PM), sulfur oxides (SO_x), and nitrogen oxides (NO_x). In some cases, these emissions are a function of more than just fuel consumption: altitude, humidity, fuel quality, and engine operating conditions also play a role. In addition, aircraft emit water vapor (H_2O) as a result of fuel combustion, which forms "contrails" (or condensation trails) under certain atmospheric conditions. Non-CO_2 emissions and contrails tend to be much shorter-lived than CO_2 emissions, and depending on where they occur may have a positive (warming) or negative (cooling) RF.

Aircraft and marine vessels emit significant amounts of NO_x, which at high altitudes promote the formation of ozone (O_3), a radiatively active gas with a regional warming effect (Endresen, Sørgård et al. 2003; Schäfer, Heywood et al. 2009). Yet, NO_x emissions can also accelerate the removal of atmospheric methane. Since methane has a strong warming effect, removing methane has a cooling effect on the climate that is believed to be global in nature. In addition, aircraft and marine vessels emit large amounts of particulate matter and water vapor; this can promote cloud formation with varying impacts on RF. Water vapor and fine particulates from aircraft flying at high altitudes in cold, moist air produce contrails. Once formed, contrails can spread and eventually form clouds resembling natural cirrus. The increased cirrus cloud cover alters the atmosphere's radiation budget, because contrails trap outgoing radiation at a greater rate than they reflect incoming radiation. While subject to considerable uncertainty, this is generally thought to have a regional net warming effect (Ponater, Marquart et al. 2005; Schäfer, Heywood et al. 2009). A similar phenomenon referred to as "ship tracks" has been observed with oceangoing marine vessels (Durkee, Noone et al. 2000; Lauer, Eyring et al. 2007). Although the exact physics are not well understood, it appears that black carbon and sulfate particle emissions from diesel exhaust promote cloud formation in the marine boundary layer (a thin layer of air near the ocean surface). The low elevation of ship tracks results in less trapping of infrared radiation than for contrails, resulting in a cooling effect (Endresen, Sørgård et al. 2003). The total radiative forcing of contrails, ship tracks, and other emissions from airplanes and ships remains highly uncertain and is an area of active research (Brasseur 2008; Endresen, Sørgård et al. 2003).

Lee et al. (2009) estimate that if aviation-induced cirrus cloud formation is ignored, radiative forcing due all global aviation emissions accounted for 3.5 percent of total RF from all anthropogenic sources in 2005. If aviation-induced cirrus clouds are considered, this figure rises to 4.9 percent. When these estimates are compared to aviation's 1.5 percent share of global anthropogenic CO_2 emissions, it becomes clear that non-CO_2 emissions from airplanes and ships are very important. Dealing with these emissions through policy has proven to be especially challenging, however, due to scientific uncertainties and a lack of consensus in preferred policy approaches. Hence, CO_2 is still the main focus of existing GHG policies.

To date, no agreement has been reached on a suitable metric for calculating the radiative forcing effects of non-CO_2 emissions on an equivalent basis to CO_2 (Lee, Fahey et al. 2009). This is due to the inherent difficulty in treating short-lived (non-CO_2) and long-lived (CO_2) species the same way (Marbaix, Ferrone et al. 2008). Taking into account the potentially significant RF effects of contrail formation, nitrogen oxides, and other non-CO_2 compounds, as well as their lifetimes, the climate change impacts of high-altitude aircraft emissions (H_2O, NO_x, SO_x, and PM) are likely 50 to 300 percent greater than if the same emissions were released at ground level—though it is important to note that these estimates are still highly uncertain and are the subject of considerable debate. Because of the difficulty in comparing non-CO_2 and CO_2 emissions, some have proposed more direct policy instruments that deal with such emissions on a case-by-case basis as the best option for dealing with the non-CO_2 effects of aviation and marine transportation (Lee, Fahey et al. 2009).

* Radiative forcing refers to an externally imposed perturbation in the radiative energy budget of the Earth's climate system, which may lead to changes in climate parameters.

3. Technological Mitigation Options and Potential

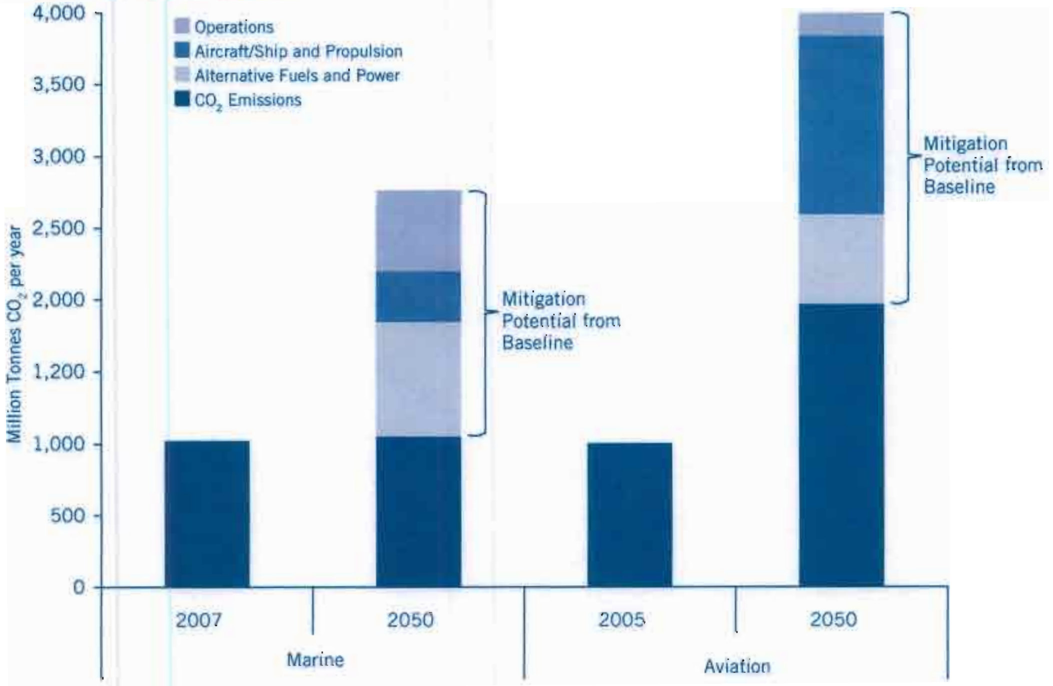
GHG emissions from aviation and marine transportation are a product of each mode's activity (distance traveled), energy efficiency of the vehicles, and the fuel carbon intensity. This section provides an overview of technological options to reduce GHG emissions. For a more detailed discussion of aviation technologies, as well as alternative fuel options in both the aviation and marine transportation sectors, see Appendix I.

In the short term, efficiency can be increased through system improvements that reduce travel distances and congestion, and by optimizing the way each aircraft or ship is operated in order to save fuel. Improving efficiency through the design of new aircraft, ships, and propulsion systems offers potentially significant, though more uncertain, medium- (2025) to long-term (2050) GHG reductions. The potential GHG benefits from reducing the carbon intensity of energy used in the aviation and marine transportation sectors, primarily through switching to lower-carbon fuels such as biofuels, natural gas, or hydrogen, is also uncertain but could be significant. The success of shifting to low-carbon fuels will depend on their availability and the ability of the aviation and shipping sectors to compete with other modes and sectors for them. Ensuring that biofuels can be produced with low lifecycle GHG emissions will also determine their success, though significant uncertainty still remains (Peña 2008).

Reducing the demand for aviation and shipping could help mitigate GHG emissions to some extent. This could be accomplished either through shifting to less GHG-intensive transportation modes or by reducing total transportation demand. Market-based policies, such as a cap-and-trade program that includes transportation, may have little impact on reducing transportation demand unless carbon prices are very high. For example, the European Union has estimated the reduction in transportation demand from including aviation in its GHG Emissions Trading Scheme, and initial results show only small changes (Batchelor 2008). In terms of mode shifting, there is some potential to reduce the demand for passenger air travel by switching to high speed rail; however, high speed rail is not a substitute for long-distance or transoceanic flights. Finally, while advanced telecommunications and teleconferencing technologies have also been discussed as a possible substitute for air travel, the extent to which they can substitute on a global scale is unknown (Mokhtarian and Salomon 2002).

An estimation of the GHG mitigation potential from the global aviation and marine transportation subsectors is summarized in Figure 7 and Table 4. Combining the various abatement options, the potential exists to reduce annual emissions from global aviation by more than 50 percent below BAU in 2050. Reductions of more than 60 percent are possible from global marine shipping. This potential is moderately optimistic in terms of technological innovation—it only includes technologies that are currently envisioned, though does depend on their full utilization. In the authors' judgment, these levels of mitigation should be achievable in a future world with emission prices of $50 to $100 per metric ton of CO_2. Even with a price on carbon dioxide, a concerted R&D effort to bring these technologies to fruition will be necessary. Higher levels of GHG reductions could be achieved if the aviation and marine transportation subsectors are able to make much greater use of low-carbon alternative fuels than what is assumed here, which would also likely necessitate strong policy intervention.

Figure 7: Global GHG Mitigation Potential from Aviation and Marine Transportation (Based on Authors' Calculations Using Multiple Sources, see Text and Table 4)



3.1 Aviation

A number of technological and operational options are available to limit the rapid growth in aviation GHG emissions expected in a business-as-usual future. These include improved navigation systems in the near to medium term and advanced propulsion systems, lightweight materials, improved aerodynamics, new airframe designs, and alternative fuels over the medium to long term. Combining the various abatement options, the potential exists to reduce annual GHG emissions from global aviation by more than 50 percent below BAU projections in 2050 (Figure 7 and Table 4).

Table 4: Summary of GHG Reduction Potentials in 2050 by Abatement Option and Sector

Sector	Category	Measure	Reductions under BAU Conditions (% in 2050)	Additional Reductions from BAU emissions in 2050 (%)	Combined Reduction Potential (% in 2050)
Aviation	Operations	Advanced CNS/ATM systems (e.g., NextGen, SESAR)	0	5	5
	Airframe Design and Propulsion	More efficient turbofan (jet) engines, Advanced lightweight materials, Improved aerodynamics (e.g., winglets, increased wingspans)	30	0	30
		Unducted fan (open rotor) engines where feasible, Greater application of advanced lightweight materials, Improved aerodynamics (e.g., laminar flow control), New airframe designs (e.g., blended wing body)	0	35	35
	Alternative Fuels	Medium term: Biofuels; Long term: Biofuels, Hydrogen	0	24	24
	Total Reduction from BAU Emissions in 2050			53	
Marine	Operations	Speed reduction, Optimized routing, Reduced port time	20	27	47
	Ship Design and Propulsion	Novel hull coatings, propellers, Fuel efficiency optimization, Combined cycle operation and Multiple engines	20	17	37
	Alternative Fuels and Power	Marine diesel oil (MDO), Liquefied natural gas (LNG), Wind power (sails)	2	38	40
	Total Reduction from BAU Emissions in 2050			62	

Notes

* BAU reductions are the expected effeciency improvements and corresponding GHG reductions under a business as usual scenario. Additional reductions are those emission reductions that can be achieved under more agressive technology penetration and alternative fuel use scenarios; they are shown as percentage reduction in 2050 emissions from the BAU baseline.

* Within each sub-sector, total GHG reduction is multiplicative in order to avoid double counting (e.g., (1-0.1)*(1-0.2) = 0.72 = 1-0.28, a 28 percent reduction rather than a 30 percent reduction).

* Technological and operational mitigation potentials are based on authors' calculations. Marine estimates are from MARINTEK (2000), and BAU projections from IMO (2008). Aviation estimates are from various sources discussed in text, and BAU projections from IEA (2008b).

* Alternative fuels consumption in aviation sector assumes that 30 percent of global petroleum-based jet fuel demand in 2050 is replaced with biofuels (no hydrogen) and that the lifecycle GHG emissions of biofuels are 80 percent lower than petroleum fuels (both assumptions consistent with IEA (2008b)). Annual biofuels demand in 2050 is roughly 9,420 PJ (66 billion gallons), requiring approximately 18,839 PJ (1.26 billion dry tonnes) of biomass, or 12.6 percent of the estimated annual global supply of sustainable biomass in 2050 (IEA, 2008b).

Operational Efficiency

In the near term, the most promising strategies for improving the efficiency of aircraft operations are improvements to the aviation system: advanced communications, navigation and surveillance (CNS) and air traffic management (ATM), as opposed to changes to the aircraft itself. In the United States, these improvements are embodied in the Next Generation Air Transportation System (NextGen) initiative, which has the potential to decrease aircraft fuel consumption and improve aviation operations by shortening travel distances and reducing congestion in the air and on the ground (GAO 2008). A similar project, Single European Sky ATM Research (SESAR), is being developed in Europe. ICAO estimates that by 2015, airlines in the United States and Europe will achieve a five percent fuel savings as a result of currently planned changes in their CNS/

ATM systems (GBD 2005). Even greater savings—5 to 10 percent—are possible in the medium term (Schäfer, Heywood et al. 2009).

Under a BAU scenario, market forces are unlikely to drive the adoption of these systems; hence policy will be needed. Aircraft infrastructure and CNS/ATM systems are heavily regulated and, in the case of NextGen and SESAR, dependent on government support (see Section 4). The development of NextGen is one of the main R&D goals of the U.S. Federal Aviation Administration (FAA), as stated in its annual report to Congress, the National Aviation Research Plan (NARP).[8]

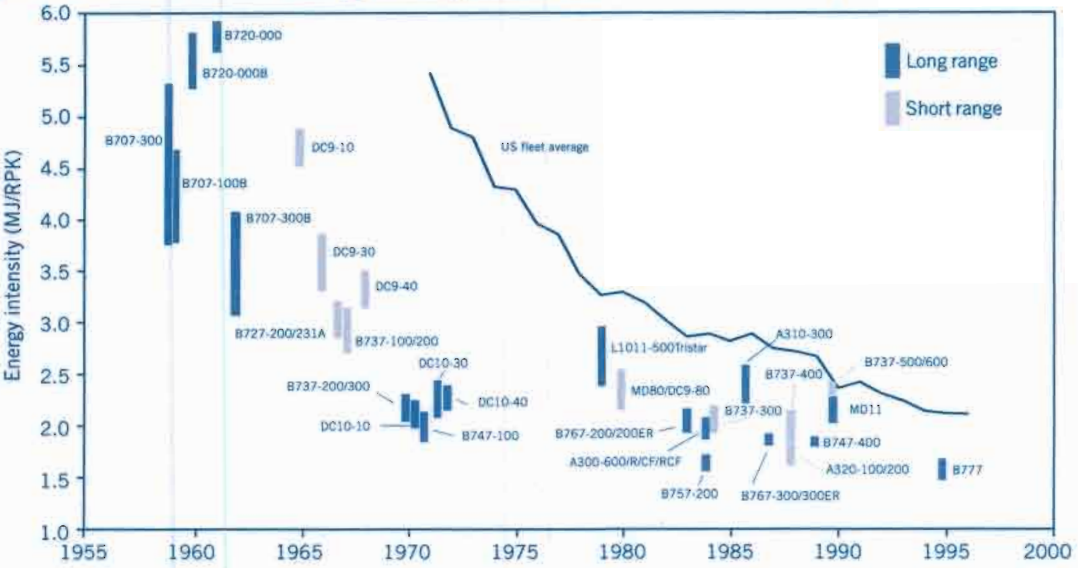
Moreover, it is important to note that the bulk of fuel savings reported for advanced CNS/ATM systems will be achieved upon initial implementation—i.e., a step-change in operational efficiency will be followed only by incremental further improvements. In addition, GHG reductions from the increase in system efficiency will be negated to some extent by the higher demand caused by the increase in capacity that these systems will create. This is similar to what is typically observed when highway capacity is increased by adding more lanes. Faber et al. (2008) estimate that in the European Union, for example, half of the benefits of the SESAR initiative will be offset by an increase in demand.

Aircraft Efficiency

As conventional aircraft move closer to an optimal configuration, annual efficiency improvements are slowing (Figure 8) (IEA 2008b; ORNL 2008). However, the efficiency of the U.S. and global aircraft fleets will continue to improve as older, less efficient aircraft are retired and then replaced with new, more efficient aircraft. The Air Transportation Association of America (ATA), which represents the nation's leading airlines, has set a goal of increasing the industry's fuel efficiency by 30 percent from 2005 to 2025 (ATA 2009); this translates into a 23 percent reduction in energy intensity. According to Lee, Lukachko et al. (2001), if historical trends in technology continue to 2025, a decline in new airplane energy intensity of 1.2 to 2.2 percent per year could be expected. Due to long aircraft lifetimes (typically 20 to 30 years), new technology that is commercially available by 2025 is expected to represent the fleet average by 2050 (Lee, Lukachko et al. 2001). Hence, under a BAU scenario, the energy intensity of U.S. aviation (e.g., fleet-average megajoules per passenger-mile) is expected to decrease by at least 30 percent between now and 2050. This reduction will be achieved by utilizing currently known technologies: more efficient propulsion systems (engines), advanced lightweight materials, and improved aerodynamics (e.g., winglets, increased wingspans) (IEA 2008b; Lee, Lukachko et al. 2001; Schäfer, Heywood et al. 2009). Varying combinations of these technologies have already been employed on existing state-of-the-art aircraft, such as the existing Airbus A380, and they will also be utilized on the future Airbus A350 and Boeing 787.[9]

Going beyond BAU is possible with further energy efficiency improvements. Widespread application of current state-of-the-art technology combined with the adoption of more advanced technologies (e.g., laminar

Figure 8: Evolution of Aircraft Energy Intensity, New Aircraft and U.S. Fleet Average



Notes: 1) The bar for each aircraft reflects varying configurations; the line shows estimated fleet average for the United States across all existing aircraft. 2) RPK = revenue passenger kilometer = number of passengers carried x distance flown (in km).

Source: IEA 2008b

flow control and new engine designs) could increase reductions in energy intensity to 50 percent below current levels, or 20 percentage points beyond BAU by 2050 (IEA 2008b; Lee, Lukachko et al. 2001; Morris, Rowbotham et al. 2009; QinetiQ 2008). The most advanced, and thus most uncertain, technologies (e.g., full body laminar flow control and blended wing body airframes) have the longer-term potential to contribute an additional 10 to 15 percentage point reduction by 2050. In total by 2050, global adoption of these more advanced aircraft technologies could reduce aviation GHG emissions by as much as 35 percent below what is expected under BAU projections (Figure 7 and Table 4).

Early aircraft retirement programs might be able to push this mitigation potential slightly higher by 2050. However, given that early aircraft retirement is one of the most expensive GHG abatement options, either fuel or carbon prices (or both) will need to be quite high for this mitigation strategy to become attractive (Morris, Rowbotham et al. 2009). Airlines already change older aircraft engines for new ones and modify the airframes (e.g., by adding winglets) of their aircraft fleets on a periodic basis, and this will continue in a BAU future. Thus, the added benefits of early retirement programs (beyond BAU) may not be large.

The costs of achieving GHG reductions through the abatement options described above are still uncertain in many cases (Dray, Evans et al. 2009; Morris, Rowbotham et al. 2009). Morris et al. (2009) have conducted the most comprehensive and rigorous study to date on marginal abatement costs (MAC) in the aviation sector. Their analysis, which focuses on the UK and European aviation fleets, finds that MACs range widely depending on abatement option and timeframe: in the case of Europe in 2025, costs range from -£148 to +£205 per ton of CO_2 (-\$222 to +\$308 per metric ton CO_2),[10] assuming an oil price of \$75 per barrel. Actually, most of the abatement options, accounting for greater than half of all potential GHG reductions, can be achieved at MACs below £73 (\$110) per ton. These include all abatement options except for biofuels and early aircraft retirement. In fact, many technologies and strategies have negative costs (i.e., they yield net positive economic benefits through fuel savings over their lifetimes)—for example, CNS/ATM improvements and increased use of turboprops, winglets, and lightweight materials. Examples of abatement options with positive costs, though still less than £73 (\$110) per metric ton CO_2, include engine upgrades or replacement, open rotor (UDF) engines, and blended wing body airframes.

3.2 Marine Transportation

GHG emissions can be mitigated from shipping by increasing efficiency (i.e., decreasing fuel consumption/ton-mile) and using less GHG-intensive fuels or power sources. Operational measures, such as speed reduction, offer a large and near-term mitigation option, while improving the energy efficiency of new ships and switching to alternative fuels provide longer-term potential. However, absent a technological breakthrough, application of all available technological mitigation options could slow, but is not likely to be enough to stop, the rising emissions caused by increasing demand for shipping (IMO 2008).

Operational Efficiency

Immediate reductions in GHG emissions are available from all ships by reducing speed. For example, a 50 percent reduction in viscous resistance (resistance between the hull and water) is achieved by just a 3 knot (3.5 MPH) reduction in speed for a typical container ship (MARINTEK 2000). Some shippers have reduced their speeds in response to high fuel prices (Corbett, Wang et al. 2009). However, reducing speed also reduces shipping capacity. To maintain shipping supply, more frequent trips or increasing ship utilization (the load factor) is required. The extra trips or cargo also increase fuel consumption, but overall the result is a net reduction in fuel consumption and CO_2 emissions. Corbett et al. (2009) find that reducing speeds by 10 to 50 percent can reduce CO_2 emissions from container ships by 20 to 70 percent if no extra ships are needed to maintain supply, or 5 to 40 percent when they are. However, high carbon prices from \$36 to \$200 per metric ton of CO_2 would be required to drive these changes (carbon prices on the European ECX have been \$10 to \$40 per ton of CO_2 over the past year). Reductions for other types of ships would be less, due to their already slower speeds. The reduction in shipping supply from reduced speeds can also be countered by increasing port efficiency and by optimization of complementary land-side intermodal transport systems, allowing for faster ship turnaround times. For the entire shipping sector, the maximum feasible mitigation potential from speed reduction, considering the requirements of shippers and their customers, has been estimated at 40 percent (MARINTEK 2000).

Additional optimization of shipping logistics, routing and maintenance could reduce CO_2 emissions by 3 to 12 percent (MARINTEK 2000). Efficiency could be improved through increased ship utilization (increased load factor), improved and more consistent maintenance practices, optimized ship control, and route planning optimized for current weather conditions and ocean currents (IMO 2008; MARINTEK 2000). The maximum mitigation potential available from all operational improvements is about 27 percent after accounting for expected BAU improvements out to 2050.

Ship Efficiency

Technological mitigation options for new ships, aside from alternative fuels and power, include larger ship sizes, hull and propeller optimization, more efficient engines, and novel low-resistance hull coatings.

Larger ship sizes improve efficiency by exploiting economies of scale (IMO 2008)—one large ship with the volume of two smaller ships weighs less and has less hull area in contact with the water, reducing resistance. Doubling the size of a ship could increase energy efficiency by up to 30 percent (Interlaboratory Working Group 2000). Thus far, the industry trend has been towards massive container and cargo ships (UN 2008). However, practical limitations to increasing ship size exist: canal size, harbor depths, port cargo handling equipment, ability to aggregate cargo into fewer larger shipments, and capacity of ground transportation networks (IMO 2008; MARINTEK 2000). To some extent, these limitations are being overcome, but they are costly and take time to implement (UN 2008).[11]

Hull and propeller optimization is available for new ships, and has the potential to reduce CO_2 emission by a combined 28 percent for each new ship (MARINTEK 2000). The relative costs would be minimal for larger ships, but the full mitigation potential will not be realized until the current fleet of ships is retired (ships have a typical life time of 20 or more years) (MARINTEK 2000).

Ninety-six percent of commercial shipping power is produced by highly efficient low- to medium- speed diesel engines (Eyring, Köhler et al. 2005). These engines commonly achieve efficiencies near 50 percent, which is higher than most diesel engine applications, since ships typically operate at steady state under high load conditions (Interlaboratory Working Group 2000; Lovins, Datta et al. 2005). However, there still is some potential for further gains. Currently, engines are optimized for a specific ship design speed, and operation outside of optimized conditions results in reduced efficiency (IMO 2008). A more flexible design utilizing a series of smaller diesel-electric engines, each optimized for a single speed, that power an electric drive may lead to greater efficiencies. This type of configuration is currently the trend in fuel-efficient diesel locomotive design (EPA 2008b); however, there seems to be some disagreement over the potential benefits when applied to ships (Eyring, Köhler et al. 2005; MARINTEK 2000). Combined-cycle diesel engines, which recover energy from waste heat, as is current practice in many stationary power plants, could also increase the efficiency of ships (MARINTEK 2000).

Technological mitigation options are available for the existing fleet include tuning engines for energy efficiency and novel hull coatings. Increasing the efficiency of existing engines could reduce their energy consumption by up to 7 percent (MARINTEK 2000). Novel hull coatings and similar technologies, which reduce resistance (for example, perhaps by using special polymers or tiny air bubbles), have a large mitigation potential, but such coatings are still under development and are thus considered a longer-term option. Most diesel engines are also optimized for NO_x reduction, which consequently decreases fuel efficiency. Development of advanced NO_x after-treatment retrofit technologies could allow engines to be re-optimized to save fuel (Eyring, Köhler et al. 2005; MARINTEK 2000).

Overall, the potential to reduce GHG emissions from marine transportation is large (Figure 7 and Table 4). Changes in operations (mainly speed reduction) could reduce marine transportation emissions by up to 47 percent from today's shipping fleet (MARINTEK 2000). Additional technical fixes (e.g., upgrading current engines) for the existing fleet could reduce emissions by up to 7 percent. For new ships, increased size, optimized hull and propeller designs and even more efficient diesel engines could reduce emissions by up to 37 percent from today's shipping fleet (MARINTEK 2000). A recent IMO (2008) study estimates that by 2050 under a BAU scenario, operational efficiency improvements and ship and engine efficiency improvements will each yield a 20 percent reduction in emissions. That leaves an additional 27 percent mitigation potential available from operational efficiency improvements and 17 percent from ship and engine efficiency improvements. However, the costs of most mitigation options for marine transportation are not well understood or reported. Improved estimates of mitigation potential and costs should be available in a new study by the IMO, scheduled to be completed by mid-2009.

3.3 Alternative Fuels and Power

Alternative fuels and power sources also have the potential to significantly reduce or eliminate GHG emissions from ships and aircraft (Figure 7 and Table 4). Yet as with other sectors, alternative aviation and marine fuels face numerous challenges with respect to their production, distribution, and cost, and it is not entirely clear what quantity of these fuels will be available and when, or what magnitude of GHG benefits can ultimately be achieved by using them (Fargione, Hill et al. 2008; IPCC 2007; Peña 2008; Searchinger, Heimlich et al. 2008). The availability of alternative fuels (particularly the biological feedstocks needed for biofuel production) and the ability of aviation and marine transportation to compete with other modes and sectors for them are uncertain. Additionally, to significantly contribute to GHG mitigation, the lifecycle carbon footprints of these fuels needs to be significantly lower than the conventional fuels they replace.

The marine transportation sector could also utilize alternative energy sources currently in use or under development for application in other sectors. (Eyring, Köhler et al. 2005; IMO 2008; MARINTEK 2000). In the near to medium term, a 4 to 15 percent reduction in GHGs can be achieved by substituting marine diesel oil or liquefied natural gas for heavy fuel oil (i.e., residual fuel oil). The IMO study implies that under a BAU scenario, the use of LNG will result in a small 2 percent reduction in CO_2 emissions from current levels by 2050. However, there appears to be a much greater potential to use LNG aboard most ships if constraints on the availability of LNG at ports can be overcome. The use of LNG, coupled with alternative energy sources, such as wind power (sails), can reduce emissions by up to 40 percent from current levels by 2050. Other alternative fuel and power sources, such as biofuels, solar photovoltaic cells and fuel cells, appear to be more uncertain, longer-term options.

The potential for fuel switching on jet aircraft is rather limited in the near to medium term, at least compared to on-road vehicles (Lee, Fahey et al. 2009; Saynor, Bauen et al. 2003). The only feasible options for "drop-in" replacements to petroleum-based jet fuels include hydroprocessed renewable jet fuel (HRJ)[12] and Fischer-Tropsch (FT) fuels.[13] A plant- or animal-based oil can be hydroprocessed to create a synthetic bio-based fuel that is chemically identical to petroleum-based jet fuel. The FT process can also use any of several biomass or fossil feedstocks (potentially with carbon capture and storage at the point of fuel production) to produce a jet fuel replacement. It is important to note that these types of jet fuel-like alternative fuels are not the same as those being discussed for road transport applications (e.g., ethanol and biodiesel). Liquid hydrogen (via any number of low-carbon pathways) may offer a potentially longer-term alternative fuel option, though significant challenges exist, such as the redesign of aircraft and engines to use hydrogen fuel (GBD 2005; Janic 2008; Saynor, Bauen et al. 2003). There is significant interest from airlines and aircraft manufacturers in using alternative fuels. The International Air Transport Association (IATA) has set a goal for its member airlines to use 10 percent "alternative" fuels by 2017 (IATA 2009). Over the past year, several airlines and aircraft manufacturers have successfully conducted test flights with bio-based HRJ.

3.4 Alternative Modes of Transportation

Shifting air or marine transportation to alternative modes has some additional potential to reduce GHG emissions.

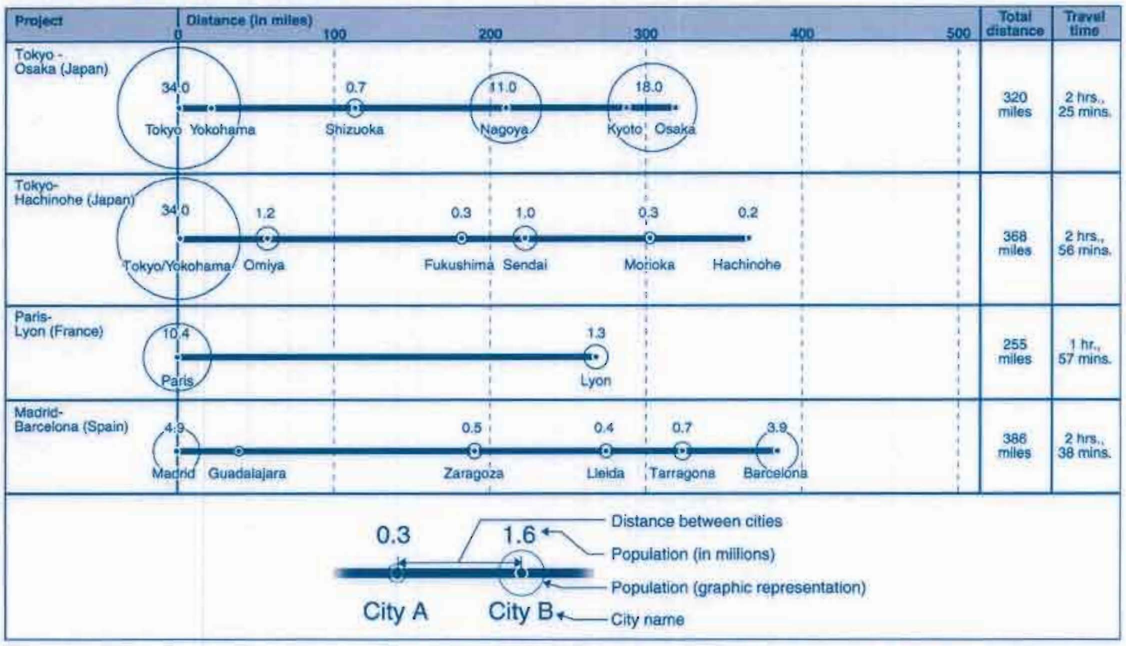
High speed rail (HSR) can potentially substitute for short-distance passenger air travel, mitigating GHG emissions through greater efficiency and use of less carbon-intensive energy (e.g., electricity from renewables) (Givoni 2007; IEA 2008b). The energy use per passenger-mile for HSR could be as much as 65 to 80 percent less than air travel. However, the energy intensity and carbon footprint of HSR depend strongly on the design of the system, namely operating speeds and distances between stops, and passenger load factors, which depend on demand for HSR service between cities (CHSRA 2009; IEA 2008b). The European and Japanese experience has shown high speed rail to generally be competitive with air travel on routes of up to 300-500 miles (500-800 km), where there is existing high demand for intercity travel and where several high-population areas can be connected along a single corridor (de Rus and Nombela 2007; GAO 2009; Givoni 2007; IEA 2008b; Jamin, Schäfer et al. 2004; Park and Ha 2006).

In the United States, there are several dozen proposals for HSR projects in 44 specific transportation corridors; some of these corridors have the characteristics of existing, successful HSR corridors elsewhere in the world (Figure 9). A rigorous study by Jamin et al. (2004) shows that if high speed rail systems were to connect major metropolitan areas throughout the United States, the energy and emissions benefits would be relatively modest due to insufficient traffic volumes in many cases: less than a 3 percent reduction in total U.S. domestic air traffic volume would be achieved, with consequently modest reductions in energy use and emissions. On the other hand, recognizing that connecting major downtowns is not the only potential market for HSR, Johnson et al. (1989) argued that high speed rail should be thought of as a complement to air travel rather than as a competitor with it. The authors estimated that if U.S. airlines integrated HSR into their hub-and-spoke networks, substituting HSR for feeder service flights to major hubs, domestic airlines could achieve fuel savings of 12 to 17 percent.[14]

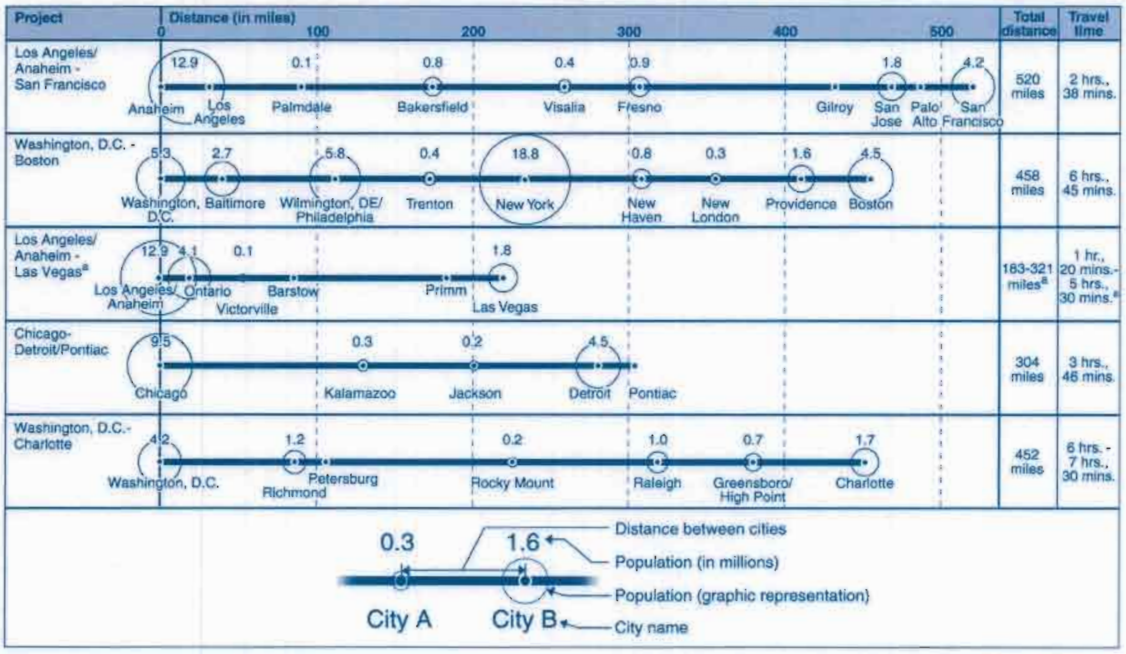
In addition, high speed rail may provide other benefits compared to air travel, such as reductions in local air pollution, noise, and air and roadway congestion; moreover, combined with strong land-use and urban planning policies, HSR has the potential to re-structure urban development patterns. The American Recovery and Reinvestment Act of 2009 (i.e., the economic stimulus package) includes more than $8 billion to help finance high speed rail corridors throughout the United States (P.L.-111-5 2009). This represents only a fraction of what would be needed to build an expansive HSR network; for example, California's proposed high speed rail line between San Francisco and Los Angeles is estimated to cost $45 billion[15] (GAO 2009). HSR also holds promise as a mitigation strategy for the developing world, where adequate on-land transportation infrastructure often does not exist.

GHG emissions can also be reduced by shifting goods movement and transportation from more energy-intensive modes (e.g., trucks and freight rail) to ships, where feasible. The concept is known as short sea shipping and is defined as the relatively short distance transport of goods by smaller ships between ports (TEMS 2008). This would increase emissions from marine transportation but would have an overall effect of reducing total emissions from goods movement. The main challenge facing short sea shipping is its slow speed compared to other modes. However, this gap can be reduced through the use of roll-on/roll-off ships (known as ROROs, ships that trucks can drive on and off of, similar to a ferry) and by off-loading large container or bulk carrier ships directly onto smaller ships for delivery to nearby ports, both of which can reduce cargo handling times at ports (drayage). While short sea shipping is unlikely to achieve comparable speeds to land-based transportation, it potentially offers large cost savings due to its energy efficiency and reduced drayage costs. The mitigation potential of a mode shift to shipping from land-based freight ultimately depends on the balance of shipper preferences for speed vs. low costs.

Figure 9: Population of Cities Along Selected Foreign (Top) and Current and Proposed U.S. (Bottom) High Speed Rail Lines



Source: GAO analysis of data from domestic project sponsors, foreign transportation officials, the U.S. Census Bureau, and Demographia.



Source: GAO analysis of data from domestic project sponsors, foreign transportation officials, the U.S. Census Bureau, and Demographia.

4. Policy Options: Achieving Deep and Durable Reductions

As this paper has discussed, the technological and operational potential for reducing international and domestic GHG emissions from aircraft and marine vessels is considerable; however, the rate of improvement under business-as-usual conditions is unlikely to be sufficient to eliminate the projected growth in emissions from steadily increasing demand (Eyring, Köhler et al. 2005; IEA 2008b; IMO 2008). To slow and eventually reverse this growth, policy intervention is required in the form of regulations or incentives to accelerate the adoption of fuel-saving advanced technologies and operational measures. This section outlines domestic and international policy options for reducing GHG emissions from aviation and marine transportation. Whereas GHG emissions from domestic aviation and shipping are clearly the responsibility of the nations where those emissions occur, the assignment of responsibility and the determination of the relative merits of policy options for international emissions are less straightforward.

4.1 Domestic Emissions

Greenhouse gas emissions from a given country's domestic aviation and shipping sectors are undisputedly the responsibility of the country where those emissions occur. In the United States, a recent Supreme Court decision clarified that the U.S. Environmental Protection Agency (EPA) has the authority to regulate GHG emissions under the existing federal Clean Air Act (*Massachusetts v. Environmental Protection Agency*, 549 U.S. 497 (2007)). Domestic regulations could take the form of emission, aircraft or engine efficiency standards, limits on the carbon intensity of fuel, or possibly the inclusion of aviation and shipping and other GHG sources in a comprehensive cap-and-trade regime. In fact, EPA has been petitioned specifically to begin regulating GHGs from aviation and marine transportation under the Clean Air Act.[16] In legislation recently debated in Congress, domestic GHG cap-and-trade programs would cover all transportation fuels, including all jet and marine fuels, sold in the United States—thus, both domestic GHGs and a portion of international aviation and marine shipping GHGs would be covered under the proposed system.

Other countries have recently begun to develop policies to regulate GHG emissions from domestic aviation under their national programs. For example, New Zealand, Australia, and the European Union have already taken steps to include domestic aviation in their domestic GHG cap-and-trade programs. The European Union has acted to expand its GHG trading system to include emissions from the aviation sector beginning in 2012. The EU regulations include emissions from all flights either landing at or departing from airports within EU member countries. As a result, the EU system would include all domestic aviation emissions and the portion of international emissions with origins or destinations in the EU, regardless of where the fuel was purchased or the nationality of the airline.[17]

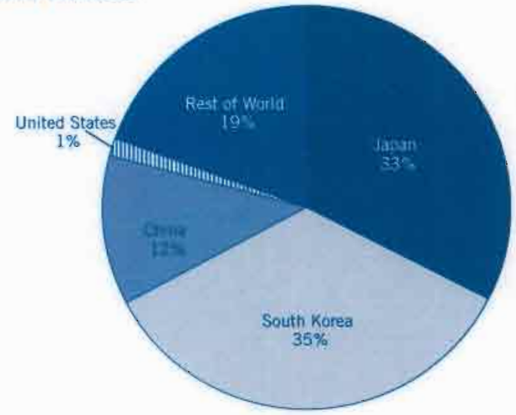
In addition to possible regulations, government-sponsored research and development (R&D) can be an effective driver of innovation, especially when it is targeted at basic research that is beneficial to many industries (e.g., low-carbon fuels and advanced lightweight materials) or is focused on risky projects (e.g., radical changes to airframe designs and novel hull coatings for ships) that individual companies may not be willing to fund. Public R&D has been a particularly important driver of aviation innovation in the past (GAO 2008), and while this has raised trade concerns and World Trade Organization challenges at the international level, an increase in U.S. R&D funding could accelerate the rate of innovation. Current R&D programs in the United States include the FAA's Continuous Lower Energy Emissions and Noise (CLEEN) program and NASA's Environmentally Responsible Aviation (ERA) project. Moreover, expanded federal R&D support for the aviation industry in the United States would have both domestic and global impacts, particularly due to U.S.-based Boeing's position as one of the world's two dominant commercial aircraft manufacturers, along with the European Airbus. Increasing federal government funding for marine vessel R&D, if carefully targeted, could also be effective. While only a small share of global ship building actually takes place in the United States (Figure 10), R&D efforts could focus on technological innovations aimed at making ship components that are manufactured here more fuel efficient. Moreover, international collaboration and technology transfer could be a possible option to facilitate R&D across countries.

Finally, increased government spending on infrastructure could also play a role in mitigating GHG emissions. In the case of aviation, certain strategies to reduce congestion, such as airport expansion and advanced CNS/ATM systems, are beyond the direct control of airlines and are strongly dependent on government regulation and support. For this reason, the funding provided to NASA in the economic stimulus package of 2009 for the development of NextGen technologies is helpful (P.L.-111-5 2009), but more resources from both the public and private sector are needed to make this system an operational reality. Similarly, while plans for the SESAR project will continue to progress in Europe, incentives may be needed to motivate all aircraft to comply with SESAR requirements and adapt to its usage (Dray, Evans et al. 2009). Airport congestion could also be reduced by greater regulation of aircraft arrival and departure times, possibly via pricing and/or auctioning strategies (Janic 1999). Finally, in some cases marine transportation emissions could be reduced through dredging of ports and waterways to accommodate larger vessels. Improvements in cargo handling equipment and land transportation networks could also reduce delays.

4.2 International Emissions

The current structure for addressing GHG emissions from international aviation and maritime sources was established as part of the 1997 Kyoto Protocol and related decisions under the UNFCCC. In accordance with IPCC and UNFCCC reporting guidelines, emissions from international bunker fuels (i.e., emissions from fuels used in international aviation and maritime shipping), to the extent possible, are to be included as part of Parties' national GHG inventories, but are to be excluded from national totals and reported separately. These emissions are not subject to the limitation and reduction commitment of Annex I Parties under the Convention and the Kyoto Protocol. Unlike GHG emissions from all other sources, which were included under the national targets for developed countries established under the Protocol, Article 2.2 carved out a different approach for international emissions from aviation and marine shipping.

Figure 10: Orders Received for Manufacturing of New Ships by Country During 2003 (Percent of Global DWTS Ordered)



Source: Birkler, Rushworth et al. 2005

> *'The Parties included in Annex[18] I shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organization and the International Maritime Organization, respectively.'*
>
> [Article 2.2 of the Kyoto Protocol to the United Nations Framework Convention on Climate Change, 1998]

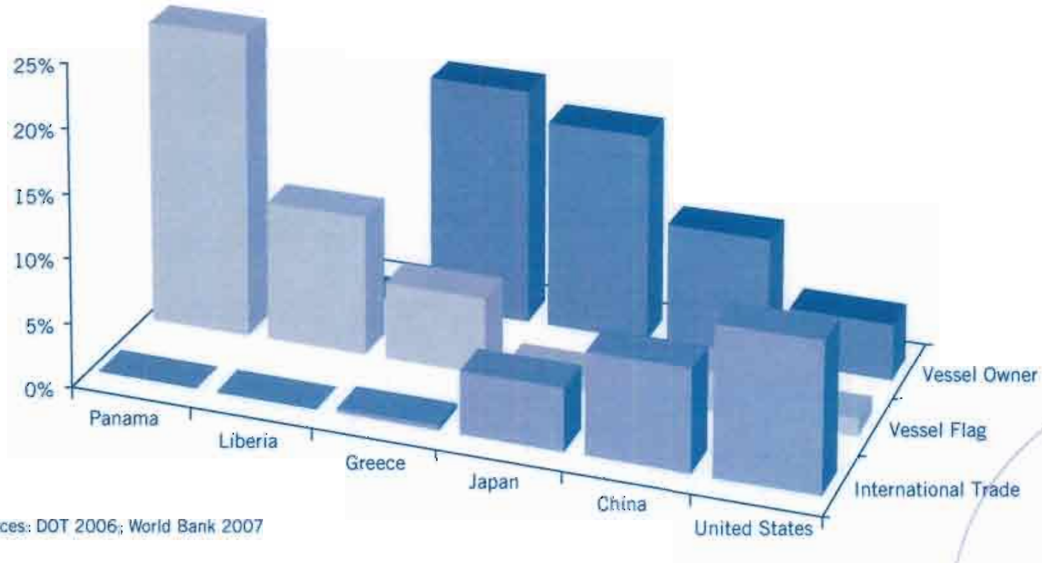
ICAO[19] and the IMO[20] have traditionally been the international organizations responsible for the development of policies affecting these sectors. For example, they have implemented standards for emissions of conventional pollutants and to limit noise from aircraft, and they have also set fuel quality standards (Annex 16, Volume II of the Chicago Convention and Annex VI, MARPOL respectively). Leading up to the global climate agreement reached in Kyoto, an important, unresolved methodological issue concerned how best to assign international GHG emissions from these sectors to specific countries. An agreed rule governing how to calculate international emissions in national inventories would be required in order for these emissions to be assigned to and dealt with under countries' national GHG policies. The UNFCCC's Subsidiary Body on Science and Technological Advice (SBSTA) set forth a number of options in a working paper it issued in 2003 (UNFCCC 2003). But in the six years since this issue was first discussed, little progress has been made on what is the appropriate methodology for assigning responsibility for international emissions to countries.[21] The most promising option appears to be dividing the emissions between the countries of origin and destination for either the aircraft/ship or its passengers/cargo (Faber, Boon et al. 2007). Other options, such as assignments based on national fuel sales, the nationality of the carrier or shipper, or country of vehicle registration could cause serious market distortions and evasive behavior. For instance, national emissions could be "mitigated" by purchasing fuel elsewhere, changing the nationality of carriers and shippers, or registering aircraft and marine vessels in another country.

Market distortions and evasive behavior would be most severe for maritime shipping. The majority of shipping capacity is comprised of vessels flagged in countries that engage in relatively little international trade, and similarly the ownership of a large portion of the global shipping fleet does not correspond to international trade flows (Figure 11). The potential for evasion is also high in the marine sector since changing vessel flags is easy and large quantities of fuel can be bunkered onboard a ship, affording great flexibility in choosing where to flag a vessel and purchase fuel in order to minimize costs.

While dividing international transport emissions between origins and destinations provides the least opportunity for evasion and market distortions, the approach is still hindered by practical and political issues: how to split emissions from multi-stop trips, how to estimate emissions produced during a trip, and how to treat emissions from developing nations.

For the specific purposes of reporting emissions under the Framework Convention, countries have been instructed to report based on the sales of bunker fuels within their countries, regardless of where the fuel is actually consumed or by whom it is consumed. This method is not the most representative of international trade and travel, especially in the case of international marine transport where fuel can readily be bunkered (ships, for example, need not refuel at every port they visit). It is important to note that this method is used for the purposes of reporting only, as required of Annex 1 Parties, and that the emissions from international bunker fuels are not currently included in calculating or accounting with respect to a country's target for GHG reductions.[22]

Figure 11: Comparison of International Trade (Percent of Global Value of Merchandise Trade), Vessel Flag (Percent of Global Deadweight Tons, DWTs), and Vessel Owner (Percent of Global DWTs) by Country



Sources: DOT 2006; World Bank 2007

Policy Activities to Date—ICAO

ICAO responded to the mandate from the Kyoto Protocol and incorporated activities related to measures to reduce GHG emissions in its work program soon after the Kyoto Protocol was adopted. ICAO staff and public and private sector experts participated in the development of the IPCC's Special Report on Aviation (IPCC 1999) and have worked with other experts on methodological issues related to modeling and reporting of GHG emissions from aviation. ICAO has also explored a number of policy options including: encouraging voluntary programs; developing and evaluating designs for an emissions trading program for aviation emissions and issuing draft guidance for incorporating international aviation emissions into national emissions trading schemes; analyzing the possible use of a fuel tax or charge; examining the potential for improved operational measures to reduce fuel burn, and exploring the possible design and use of emissions or efficiency standards.

At the 36th Session of the ICAO Assembly in 2007, the member countries discussed a range of policy options along with issues related to reconciling the concept of "common but differentiated responsibilities" contained in the UNFCCC with the concept of non-discrimination contained in the Chicago Convention under which ICAO operates. This issue specifically arose in the context of the European Union's emissions trading scheme, which is designed to apply to all airlines flying into or out of EU airports. The countries at the Assembly adopted guidelines for countries to use in developing their own national emissions trading schemes. A key element of these guidelines was that participation in any national emissions trading regimes should only be on the basis of the mutual consent of the countries involved. Because of the potential conflict with the European Union's emission trading system, 42 European countries reserved their position regarding this element of the resolution (ICAO 2007). Moreover, a number of nations have expressed concern that the EU decision was not based on the mutual consent of the countries involved and may seek to challenge the legality of including aviation emissions within the European Union's emissions trading regime under the terms of the Chicago Convention. In seeking to advance efforts to address GHG emissions from the aviation sector under ICAO, the 36th Session of the Assembly also established a Group on International Aviation and Climate Change (GIACC) with the task of developing a program of action to address this issue. This group was to establish a possible global aircraft fuel efficiency goal and a menu of options for achieving this goal from which countries can choose (ICAO 2007).

Following a series of meetings, GIACC issued a final report in June 2009 (ICAO 2009a). This report recommends an approach where individual countries develop action plans to suit their circumstances guided by a global aspirational goal for GHG emissions. GIACC recommends an aspirational goal of 2 percent per year improvement in fuel efficiency. For context, average passenger growth is forecasted to be 5 percent per year, with emissions growth at 3 percent, under business as usual conditions. Thus, GIACC's aspirational goal would slow but not offset the expected growth in emissions. The Group discussed options related to carbon-neutral growth or goals aimed at reducing total emissions over time, but the group did not achieve consensus in support of these proposals. In addition, GIACC recommended that countries select from the basket of measures developed by ICAO, which include aircraft-related technology development, improved air traffic management and infrastructure use, more efficient operations, economic/market-based measures, and regulatory measures. GIACC also recommended that ICAO continue to develop a CO_2 standard for new aircraft types. While reaching agreement on the Programme of Action, no consensus emerged from the GIACC discussions on issues related to the extent of involvement of developing countries or the need for market-based strategies (ICAO 2009a).

Furthermore, in October 2009, members of the airline industry trade group, the International Air Transport Association (IATA), also announced fuel efficiency improvement targets. IATA pledged that the industry would improve fuel efficiency by 1.5 percent a year through 2020. As a long-term goal, the industry would aim to reduce GHGs by 50 percent from 2005 levels by 2050.

Finally, some UNFCCC parties have proposed levies on international aviation to provide new financial resources for mitigation and adaption. ICAO has expressed concern over the proliferation of charges and taxes on air traffic and has drawn attention to the need to recognize existing ICAO policies on charges and taxes (ICAO 2009a).

Policy Activities to Date—IMO

IMO also initiated a work program in response to the mandate contained in the Kyoto Protocol. It created a Working Group on Greenhouse Gas Emissions from Ships to develop proposals aimed at reducing this subsector's emissions. Its work has focused on possible technical measures, operational measures, and market-based measures (e.g., fuel taxes and emissions trading) to reduce GHG emissions. The working group developed an initial estimate of GHG emissions from shipping in 2000 and has developed an Energy Efficiency Design Index for new ships aimed at guiding the design of more efficient ships in the future. Several years ago, the IMO developed and encouraged Member States to begin pilot testing an Energy Efficiency Operational Index (now renamed the Energy Efficiency Operational Indicator) aimed at measuring over time the energy efficiency of ships. However, at present the IMO has not concluded that this tool is suitable for conducting comparisons for similar ships of their relative fuel efficiency. Finally, the working group discussed a draft Ship Energy Management Plan that provides guidance on best practices for improving fuel efficiency. These proposals, as well as the work on market-based options, considerations of the impacts on developing countries of possible IMO measures, and the final update of IMO's GHG study was presented to the IMO's Marine Environmental Protection Committee[23] for consideration at its 59th Session in July 2009.

Policy Options—Post Kyoto

Activities within IMO and ICAO and by individual countries and regions will provide the backdrop for any decisions taken by the UNFCCC that will determine how international emissions from aviation and marine shipping will be incorporated into future international agreements. Two broad options appear most likely:

1) International aviation and maritime emissions continue to be excluded from national limitation and reduction commitments and work continues under ICAO and IMO. Under this option, the existing language in Article 2.2 of the Kyoto Protocol would simply be carried forward under the Kyoto Protocol or into a new agreement, and ICAO and IMO would continue to have broad discretion about the magnitude and timing of any specific measures to reduce GHG emissions in these sectors. Alternatively, to bring emissions from these sectors in line with restrictions on other sectors, the UNFCCC could request ICAO and IMO to achieve targets, standards and timetables similar to those reached in any new international climate agreement. If work continues under this option, it is likely that ICAO and IMO would continue to explore the use of a wide range of policy tools for countries to employ. These might include voluntary agreements; emissions trading and other market-based mechanisms; levies; efficiency or emissions standards or indices; operational and system-wide efficiency measures; and fuel standards. These organizations would also continue to seek ways to reconcile the common but differentiated responsibilities principle mandated under the UNFCCC with their own organizations' approaches to dealing with actions by developed and developing countries.

2) Responsibility for international aviation and maritime emissions is assigned to nations and included in national limitation or reduction commitments or national plans, to be addressed as part of countries' national efforts.[24] Under this option, countries would first resolve the issue of how to assign international aviation and shipping emissions, and then these emissions would be incorporated into national commitments or plans under a post-2012 agreement. One advantage of this approach is that by including emissions from aviation and marine shipping in their national commitments, countries would be able to decide what policies they believe are appropriate to enact over time. Under this option, whatever obligations are taken on by developed and developing countries would also apply to aviation and maritime emissions and therefore would avoid any conflicts with the UNFCCC principle of common but differentiated responsibilities. The range of policy tools available to nations includes the same suite of options that have been considered by ICAO and IMO, but consideration would have to be given to possible disadvantages if individual nations took disparate or conflicting approaches. Alternatively, nations could decide to work cooperatively to develop a sector-based approach for international shipping and aviation, in which case they would likely turn to ICAO and IMO to assist in this effort. For example, agreements among interested nations could be reached on aircraft or engine efficiency standards or low carbon fuel standards. But any reductions from these sectoral agreements would be counted as part of a nation's efforts to achieve its overall commitments under a post-2012 agreement.

Countries have a number of options that could be considered when implementing controls on aviation and shipping. One option has already been adopted by the European Union as part of the implementation of its emissions trading regime. This regime requires that all airlines flying into or out of airports in EU territory must hold allowances to cover emissions resulting from those flights. If all OECD nations implemented similar measures that cover shipping and aviation emissions for any trip beginning or ending in its territory, 57 percent of all international emissions from these sectors would be covered (IEA 2008a). Such a route-based approach (e.g., restrictions placed on all routes beginning or ending in a developed country or region) could begin to address concerns that restrictions on only developed country airlines or ships would put them at a competitive disadvantage against developing country counterparts. At the same time, however, this approach could also raise objections from developing countries and their airlines. An alternative would be to require allowances only for those companies owned or licensed in a developed country. Under this approach, for example, a British- or American-owned airline would be required to hold allowances for emissions that result from flights that begin or end in a developed country airport, but a developing country airline would not be required to hold allowances in this case. In order to avoid competitiveness concerns, these airlines from developed nations could be granted free allowances to cover some or all of their emissions in the time period prior to when firms in developing countries are restricted. This approach is similar to that which was adopted in order to minimize competitive impacts on energy-intensive, trade-exposed industries (e.g., iron and steel and aluminum manufacturing) in a cap-and-trade program in the European Union and is under consideration in the United States as well. This approach would cover fewer emissions than the first option but would potentially raise fewer concerns from developing country interests.

5. Conclusion

The technological and operational potential for mitigating international and domestic GHG emissions from aircraft and marine vessels is considerable, and there is a range of mitigation options over the near, medium, and long term to slow the growth in energy consumption and GHG emissions.

In the near to medium term, improvements in operational efficiency have the potential to reduce CO_2 emissions below BAU projections by about 5 percent for aviation and up to 27 percent for marine shipping. For aviation, these improvements include advanced air traffic management systems. In marine transportation, slower marine vessel speeds, optimized routing, and reduced port time can improve shipping operations. Over the long term, technological options, such as advanced propulsion systems and new airframe designs, could reduce aviation CO_2 emissions by up to 35 percent below BAU projections. Larger ships, new combined cycle or diesel-electric engines, and optimized hull and propeller designs could provide an additional 17 percent reduction in marine transportation emissions, below BAU projections, by 2050.

Switching to alternative fuels and power sources is another potential route to reducing GHG emissions over the medium to long term. Aircraft and marine vessels could be powered by low-carbon biofuels or perhaps even hydrogen. Marine vessels could benefit from switching to lower-carbon, conventional fossil fuels (e.g., liquefied natural gas and marine diesel oil), or to other renewable energy sources, such as wind or solar power. While numerous technical issues still exist, the main challenge to the use of alternative fuels will be the ability of aviation and shipping to compete with other modes and sectors for a potentially limited supply of low-carbon biofuels. This could particularly be an issue with shipping, where the industry currently consumes the lowest-cost fuels available, namely residual fuel oil.

Combining the various abatement options, the potential exists to reduce annual emissions from global aviation by more than 50 percent below business-as-usual (BAU) in 2050. Reductions of more than 60 percent are possible from the global marine sector (see Table 4 and Figure 7). For these reductions to be realized, however, policy intervention is required. The rate of technological improvement under BAU conditions is unlikely to be sufficient to eliminate the projected growth in emissions from steadily increasing demand. Furthermore, based on current studies and technology, it appears unlikely that currently available options will be able to achieve absolute reductions in emissions from these subsectors. If absolute reductions were achievable, they would likely come from greater use of alternative fuels than assumed in the mitigation estimates presented in this paper and strong policy intervention to drive such use.

While the policies to regulate domestic GHG emissions are relatively straightforward, as these emissions are undisputedly the responsibility of the countries where they occur, international aviation and maritime shipping pose a greater challenge. Two broad policy options are available for controlling emissions from international transportation: The status quo of excluding international aviation and maritime emissions from national totals and continuing work under ICAO and IMO; or assigning responsibility for these emissions to parties for inclusion in national commitments or national plans, to be addressed individually as part of countries' national efforts or collectively through sectoral approaches. How international aviation and marine emissions will be dealt with in any post-2012 agreement remains uncertain. A number of potentially attractive technological and operational measures appear feasible, but developing an effective path forward that facilitates the adoption of meaningful policies remains a challenge.

Appendix I—Expanded Discussion of Mitigation Technologies

A. Aviation

To sustain flight, airplanes must produce lift and overcome aerodynamic drag. This operation is driven either by propellers, fan blades, or turbines, which provide thrust via the combustion of liquid fuels. More than 98 percent of modern commercial aircraft are of the conventional tube and wing (i.e., swept-winged) design powered by two or four high bypass (ducted) turbofans (a type of jet engine). Propeller-driven turboprops account for a far smaller share of aircraft in use (Kim, Fleming et al. 2007).[25] The amount of energy an airplane needs to sustain flight is determined by its size, weight, range, speed, engine configuration, and other performance characteristics. Maximizing efficiency entails optimization of these factors. Yet efficiency depends on more than just aircraft design alone: logistics and operations also play a role in shortening route distances, reducing congestion, and decreasing fuel burn.

Reducing aviation fuel use directly reduces CO_2 emissions. Through a variety of technological and operational improvements, the energy intensity of the U.S. commercial aircraft fleet (fuel consumption per passenger-kilometer) decreased 70 percent from 1970 to 2006, averaging 3.2 percent decrease per year (ORNL 2008). This allowed a significant increase in aviation demand, while GHG emissions grew only moderately. These efficiency gains were not motivated by regulation, but rather by market forces and government-sponsored R&D efforts. Fuel costs have historically comprised 25 to 65 percent of airlines' combined direct operating and investment costs (DOC+I), or 12.5 to 32.5 percent of total airline costs (Lee, Lukachko et al. 2001).[26] Thus reducing fuel use can lower airlines' operating costs significantly.

Operational Efficiency

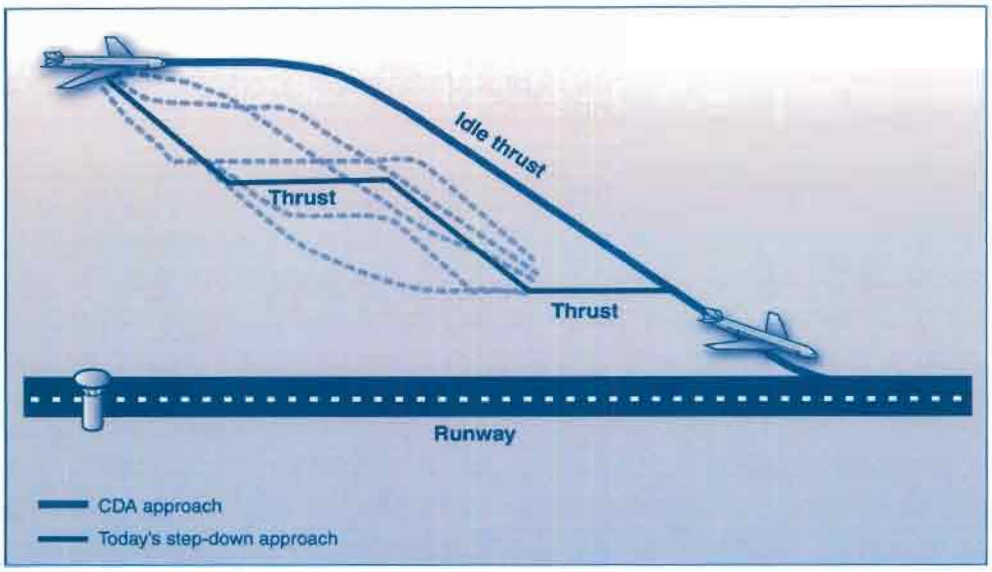
A key operational strategy that airlines have employed to save fuel is to achieve high average load factors on their flights (number of passengers per plane), which have approached 80 percent in recent years. This was made possible by their now-ubiquitous hub-and-spoke networks, which airline industry deregulation helped to motivate. At the same time, this network structure also led to the use of smaller, less efficient aircraft (e.g., regional jets), offsetting some of the efficiency gains that higher load factors achieved. While it may be possible for airlines to reduce travel distances by restructuring their network configurations and offering more point-to-point service, such a strategy would not necessarily reduce fuel consumption, as load factors would probably also fall.

In the near term, promising strategies for operational efficiency gains are advanced communications, navigation and surveillance (CNS) and air traffic management (ATM) systems. In the United States, these improvements are embodied in the Next Generation Air Transportation System (NextGen) initiative, which has the potential to decrease aircraft fuel consumption and improve aviation operations by shortening travel distances and reducing congestion. The centerpiece of NextGen is the Automatic Dependent Surveillance-Broadcast (ADS-B) satellite aircraft navigation system, which will allow for more precise control of aircraft during en-route flight, take-off, and landing; more direct routing; improved situation awareness in the cockpit; and closer, safer separation distances (GAO 2008). ADS-B will facilitate the expanded use of Continuous Descent Arrivals (CDA), which compared to the conventional step-down approach, allow aircraft to remain at cruise altitudes longer as they approach a destination airport and then descend at near-idle power levels to touchdown, thus reducing fuel burn (see Figure 12). Only a limited number of U.S. airports currently incorporate CDA into their operations (GAO 2008). Other CNS/ATM advancements allowing aircraft to descend on more precise, efficient routes include Area Navigation (RNAV) and Required Navigation Performance (RNP), which are already being utilized by at least 54 U.S. airports. In addition, while still in an early stage of development, the FAA's High-Density Terminal and Airport Operations initiative should help to reduce ground taxiing times, as well as separation requirements during take-offs and landings (GAO 2008).[27]

The government has an important role in the development of advanced CNS/ATM systems and in ensuring that aviation policy and regulations do not hinder their adoption. To this end, the U.S. Federal Aviation Administration (FAA)—along with the European Commission and a number of airlines, aircraft manufacturers, and providers of aviation navigation services—is a member of both the Asia and South Pacific Initiative to Reduce Emissions (ASPIRE) and the Atlantic Interoperability Initiative to Reduce Emissions (AIRE), two multinational consortiums which have performed several test flights in the past two years (with more planned), demonstrating the capability and facilitating the development of advanced CNS/ATM systems.[28] As an example, in November 2008, a United Airlines flight from Sydney, Australia, to San Francisco, California (USA), implemented CNS/ATM technology to save more than 15,000 liters of fuel and 19 metric tons of carbon emissions by periodically updating its route based on wind and weather conditions (something that is generally not possible with today's technology) and utilizing a smooth, continuous descent approach rather than a traditional step-down approach.

A second option to achieve small, near-term GHG reductions is through improved airport ground operations, which account for about 1 percent or less of total aviation emissions (Hansen, Smirti et al. 2008; Vigilante 2009). Strategies include supplying parked aircraft with ground-based auxiliary power (for electricity, heating, and cooling), instead of generating it with the jet fuel in the airplane's engines, and operating ground equipment (tractors, conveyor, etc.) with alternative fuels. On-site production of renewable electricity at airports is also an option. In fact, several U.S. airports (e.g., Denver, Fresno, and Boston) are cutting their emissions by

Figure 12: Comparison of Continuous Descent Arrivals (CDA) and the Conventional Step-Down Approach



Sources: Naverus and AVTECH.

installing on-site wind turbines and solar panels (Vigilante 2009). The FAA is funding many of these projects in the United States through its innovative Voluntary Airport Low Emissions Program (VALE) program.[29]

Aircraft Efficiency

As the conventional swept-winged aircraft has moved closer to an optimal configuration, the potential for efficiency gains has become exceedingly limited, and annual improvements have slowed (IEA 2008b; ORNL 2008). According to Lee, Lukachko et al. (2001), if historical trends in technology continue to 2025, a decline in new airplane energy intensity of 1.2 to 2.2 percent per year could be expected (i.e., a 30 to 50 percent cumulative reduction below 2000 levels by 2025). Similar estimates are provided by QinetiQ (2008), IEA (2008b), and Morris et al. (2009). This will require advanced technologies in the following areas: propulsion (engines), lightweight materials, aerodynamics and new airframe designs, and operations and navigation systems. State-of-the-art aircraft, such as the currently operating Airbus A380 and the future Airbus A350 and Boeing 787, make use of a number of advanced technologies. Widespread adoption of these aircraft, and the even more advanced designs that follow, will be needed to ensure that trends in declining energy intensity continue. Due to the long lifetimes for aircraft (typically 20-30 years), new technology commercially available by 2025 could be expected to represent the fleet average by 2050 under a BAU scenario (Lee, Lukachko et al. 2001).

Opportunities exist to improve the energy efficiency of aircraft propulsion systems through new designs. Theoretically, the fuel consumption of modern jet engines can still be reduced by approximately 30 percent through higher pressure ratios and combustion temperatures, strategies that led to past efficiency gains (Karagozian, Dahm et al. 2006). Yet higher pressures and temperatures also increase emissions of nitrogen oxides (NO_x), unless there is also a change in combustor technology (Allyn 2008). While the science is still uncertain, increased NO_x emissions potentially negate some of the CO_2 reduction benefits (see Box 1). Additionally, the adoption of increasingly stringent NO_x emission standards for air pollution reasons will limit the potential engine efficiency gains to 20 to 25 percent, unless revolutionary NO_x control technologies can be developed (IPCC 2007). General Electric (GE), Rolls-Royce, and Pratt & Whitney are all currently developing more efficient, lower-NO_x aircraft engines.[30] For example, GE's goal for its new GEnx jet engine, which will be used on many of the new Boeing 787s, is for it to achieve NO_x emission levels that are 50 percent lower than the ICAO standards approved in 2005 while reducing fuel consumption by 15 percent compared to its previous generation engine technology (the CF6).[31,32] Similarly, the new Rolls-Royce Trent 1000 jet engine, which Virgin Atlantic will employ on its fleet of Boeing 787s, will reduce fuel consumption 15 percent compared to its previous generation engine (the Trent 800).[33] This will be achieved through improved compressor operation and advances enabling the engine to run more efficiently at slower speeds, which is especially important during aircraft descent.[34] Finally, Pratt & Whitney has developed a geared turbofan engine, which they claim will achieve a 12 percent reduction in fuel consumption while halving NO_x emissions, compared to current engines. After extensive flight testing, the engine is expected to be introduced into service in 2012.[35]

Similar reductions in fuel consumption (20 to 30 percent) may be achieved from unducted fan (UDF) engines with contra-rotating blades (Figure 13)—also known as propfans, open rotors, or ultra high bypass turbofans (Lee, Lukachko et al. 2001). UDF technology combines certain benefits of a turbofan with the fuel efficiency of a turboprop and represents the theoretical limit of propulsive efficiency (GBD 2005). Despite the UDF's benefits, it is unclear whether the technology will gain public acceptance. UDF engines can be loud, and the public may view propeller-driven aircraft, in general, as old-fashioned and dangerous (IPCC 2007). In addition, the efficiency of UDFs comes with a speed penalty. Maximum cruising speeds of an UDF airplane would be less than 400 miles per hour (mph) compared to 550 mph (885 km/h) for conventional turbofan aircraft. Therefore, UDFs are likely limited to operations where speed is less important, such as short- and medium-haul flights (less than 2500 km) which account for about half of all aircraft fuel use worldwide (GBD 2005).

Figure 13: Pratt & Whitney–Allison Unducted Fan Engine

Source: www.flightglobal.com

Reducing aircraft weight using advanced materials is perhaps the most straightforward approach to improve efficiency and has recently been a major focus of aircraft manufacturers. Since aircraft have lifetimes of 20 to 30 years, this strategy offers longer-term mitigation potential. A typical aircraft operating in today's fleet is constructed of 65 percent aluminum, 15 percent steel, 15 percent composites, and 5 percent titanium (GBD 2005). Replacing aluminum and steel with composites (carbon-fiber reinforced plastics), which are lighter and stronger, is one option (IEA 2008b). Both the new Boeing 787 and Airbus A350 will replace aluminum with composites in the wings and fuselage. In fact, fifty percent (by weight) of the 787 will be constructed of composite material, accounting for an estimated one-third of its 20 percent total fuel efficiency gain. Another option is fiber metal laminate (FML), a layer of fiber sandwiched between one or more thick layers of aluminum. The first civil aviation application of FML is for the fuselage skin of the new Airbus A380 (IEA 2008b). It is likely that all future aircraft designs will incorporate at least some amount of advanced lightweight materials (GBD 2005).

Improving an airplane's aerodynamics, in particular increasing the lift-to-drag (L/D) ratio,[36] offers perhaps the greatest potential for reducing aircraft fuel burn and GHG emissions over the long term (IEA 2008b). There are several ways to raise an aircraft's L/D ratio including increased wingspans, winglets, laminar flow control, and flying wing or blended wing body (BWB) airframe designs. The addition of winglets to wingtips is one of the most likely near-term strategies. Winglets were developed by NASA in the 1970s and 80s and are now quite common on newer aircraft.[37] As they are added to more aircraft in the existing fleet, their GHG reduction benefits will accumulate over time. Winglets reduce aerodynamic drag caused by vortices that develop at the wingtips and also provide a small amount of extra thrust from otherwise wasted energy, much like a sailboat traveling upwind (Figure 14). Winglets can reduce fuel consumption by up to 7 percent, but they also add weight which reduces the savings for short flights where a greater portion of time is spent climbing (NASA 2004). They come in several different shapes and sizes and can be installed on newly built aircraft or as retrofits to existing planes (Airline world 2008).

Figure 14: Winglets and Their Effect on Vortices at Wingtips

Source: Airline world 2008

Laminar flow control (LFC) is a medium- to long-term option that could also provide significant efficiency improvement. LFC increases efficiency by smoothing an aircraft's boundary layer (the thin layer of air that clings to its surface), which is generally turbulent. This reduces aerodynamic drag and, consequently, fuel burn

(NASA 2009). One option is to use natural (passive) LFC by shaping the wing profile to achieve laminar flow conditions on the front half of the wing. A more advanced option is hybrid (active) LFC, in which mechanical suction devices are used to remove a portion of the boundary layer through porous material, slots in the wing, or tiny perforations in the wing skin (NASA 2009). Maximum efficiency gain could be achieved by applying hybrid LFC over the entirety of an aircraft's surface; however, cost, reliability, and susceptibility to inclement weather are important considerations that must be addressed (GBD 2005). When applied to just the wings, tail, fins, and engine housing, hybrid LFC could potentially reduce the fuel burn of a medium-range aircraft by up to 16.5 percent (GBD 2001), while more modest and less costly applications could yield efficiency improvements of 2 to 5 percent (GBD 2005).

New airframe designs present the most revolutionary and long-term approach to increasing efficiency through improved aerodynamics. These include flying wing or blended wing body (BWB) aircraft. BWBs, a hybrid between a flying wing and a conventional tube and wing aircraft, smoothly blend together the wings, fuselage, and engines, reducing aerodynamic drag and generating lift with the entire airplane instead of just the wings (Leifsson and Mason 2004). A design study by Boeing found that a 32 percent reduction in fuel burn could be achieved by a large, long-range BWB aircraft similar in size and performance to an Airbus A380 (Liebeck 2004). However, capital costs of the BWB are not yet known, and passenger acceptance issues (e.g., fewer windows) could impact its commercial success (GBD 2007). A substantial research and engineering effort will be needed to bring the BWB concept to reality (Leifsson and Mason 2004). NASA, Boeing, and the U.S. Air Force are collaborating in this area (Risch 2008). The technology might first be used in military or freight applications; a civil passenger BWB aircraft will not likely be seen before 2030 (GBD 2007). The long time horizon would limit fleet-wide energy intensity reductions from BWBs to 10 to 15 percent by 2050 (IEA 2008b).

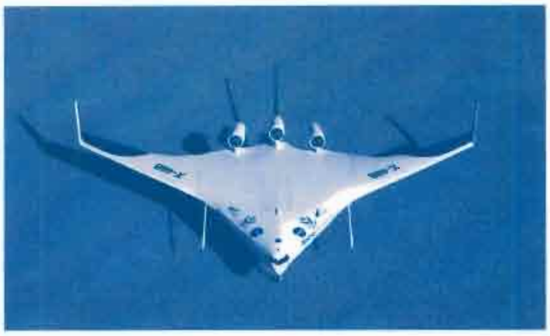
As the older, less efficient airplanes are retired and newer, more efficient ones come into service, fleetwide efficiencies will improve. Under business-as-usual (BAU) conditions, the fleet average energy intensity of U.S. aviation (e.g., fleet-average megajoules per passenger-km) can probably be expected to decrease by at least 30 percent between now and 2050 utilizing known technologies, including more efficient propulsion systems (engines), advanced lightweight materials, and improved aerodynamics (e.g., winglets, increased wingspans) (IEA 2008b; Lee, Lukachko et al. 2001; QinetiQ 2008; Schäfer, Heywood et al. 2009). Widespread application and success with these technologies combined with the adoption of the more advanced technologies (e.g., laminar flow control) and navigation systems (e.g., NextGen) could extend the energy intensity reductions to 50 percent below current levels, or 20 percentage points beyond BAU. However, this is unlikely without policy intervention in the form of incentives or regulation. The most advanced, and thus most uncertain, technologies (e.g., full body laminar flow control, blended wing body airframes) have the longer-term potential to contribute an additional 10 to 15 percentage point reduction beyond BAU by 2050. In total by 2050, global adoption of these more advanced aircraft technologies could potentially reduce aviation GHG emissions by as much as 35 percent below what is expected in a BAU future.

B. Alternative Fuels and Power

Aviation

Decarbonization of aviation fuels offers a potential path to low-carbon flight. The options for fuel switching on jet aircraft are more limited than for road vehicles, however, where liquid and gaseous fuels and electricity all can be used as energy sources. These limitations are due to the demanding requirements of aircraft and jet engines, as well as challenges with fuel storage. An energy- dense liquid fuel is thought to be needed. Synthetic bio-based fuels, Fischer-Tropsch (FT)[38] kerosene-type jet fuels, and liquid hydrogen are considered to be the only feasible options (Lee, Fahey et al. 2009; Saynor, Bauen et al. 2003). As in other sectors, alternative fuels face numerous challenges with respect to their production, distribution, and cost, and it is not entirely clear what quantity of these fuels will be available and when, or what magnitude of GHG benefits can ultimately be achieved by using them (Fargione, Hill et al. 2008; IPCC 2007; Peña 2008; Searchinger, Heimlich et al. 2008). To contribute to considerable GHG mitigation, the carbon footprint of jet fuel substitutes will need to be significantly lower than conventional petroleum-based jet fuel, and they will eventually need to achieve cost-competitiveness—both of which are possible with concerted research, development, demonstration, and deployment (RDD&D) efforts. The U.S. EPA has developed a comprehensive methodology to determine the lifecycle GHG emissions, including direct and indirect land use change effects, for a range of biofuels under the Renewable Fuel Standard program.[39] A recent ICAO report summarizes lifecycle GHG emissions estimates for a number of alternative jet fuel production pathways (ICAO 2009b).

Figure 15: Boeing X-48B Blended Wing Body Experimental Aircraft



Source: Boeing/NASA

Synthetic bio-based fuels include bio-based jet fuels, derived from oils from plants such as *Jatropha* and *Camelina* and also from algae and other feedstocks. Any of these plant- or animal-sourced oils can be hydroprocessed to create jet fuel (HRJ) that is chemically identical to (i.e., a "drop in" replacement for) petroleum jet fuel. If able to meet the stringent specifications of high altitude flight, bio-jet fuels could become a drop-in replacement for petroleum-based jet fuel. Other bio-derived hydrocarbon fuels produced through advanced fermentation processes are also under development. And finally, FT jet fuel (via thermochemical gasification) can be produced from biomass or a mixture of fossil fuel and biomass, possibly employing carbon capture and sequestration.

Liquid hydrogen produced from renewable sources (e.g., renewable electricity or biomass) offers a potentially longer-term alternative fuel option as it would require new airframe designs to accommodate a large volume of hydrogen stored onboard the aircraft (GBD 2005; Janic 2008; Saynor, Bauen et al. 2003). The added storage space would likely increase aerodynamic drag and aircraft weight, although the latter would be compensated for by the much lower weight of liquid hydrogen. Hydrogen aircraft could use conventional jet engines modified for cryogenic operation[40] (Janic 2008). However, emissions of H_2O at high altitudes would increase, potentially negating some of the CO_2 reduction benefits of hydrogen aircraft through increased contrail formation (Saynor, Bauen et al. 2003). In addition, as in other sectors, the challenge and expense associated with developing a hydrogen supply infrastructure would be considerable.

The aviation industry is moving forward in its search for a drop-in jet fuel replacement. The International Air Transport Association's (IATA) has set a goal for its member airlines to be using 10 percent "alternative" fuels by 2017 (IATA 2009). Over the past year, several airlines have successfully conducted test flights with bio-based HRJ. The Commercial Aviation Alternative Fuels Initiative (CAAFI), a consortium of airlines, airports, and aircraft manufacturers, is leading some of these efforts.[41] CAAFI's goals are to certify a 50 percent synthetic FT aircraft fuel (i.e., non-petroleum based, but possibly from natural gas or coal) by late 2009, a 100 percent synthetic fuel by 2010, and an HRJ biofuel by 2013, though the latter could happen as soon as 2010 (GAO 2008). It is important to note that unless made in part by biomass or other low-carbon sources (e.g., low-carbon hydrogen in the long term), some synthetic fuels might provide little or no climate benefit, and in the worst case they could generate even greater lifecycle emissions than the jet fuels they replace (e.g., those from FT synthesis using coal). Still, demonstrating the feasibility and reliability of all synthetic aviation fuels is an initial step along the path towards the utilization of those fuels, which have markedly lower carbon footprints.

Marine

Alternative fuels and power sources also have the potential to significantly reduce or eliminate GHG emissions from ships. In a sense, large shipping vessels are power plants on water. Hence, most alternative energy sources currently in use or under development for application in other sectors could be applied to ships as well: biofuels, solar, wind, and hydrogen fuel cells (Eyring, Köhler et al. 2005; IMO 2008; MARINTEK 2000). However, as in aviation and other sectors, large uncertainties still remain.

The most promising near-term options are substitution of current marine fuels with lower-carbon, fossil-based fuels. Residual fuel oil (also called heavy fuel oil (HFO)) can be replaced by diesel (also called marine diesel oil (MDO)) or liquefied natural gas (LNG), both of which produce lower carbon emissions per unit of energy. Replacing HFO with MDO can reduce CO_2 emissions by 4 to 5 percent (MARINTEK 2000), and replacing HFO and MDO with LNG can reduce GHG emissions by 15 percent (IMO 2008). Vegetable oil and biodiesel can also replace HFO and MDO (MARINTEK 2000). Limitations to fuel switching are mainly posed by the comparatively low cost of traditional fuels. Currently, MDO prices are 70 percent, LNG prices 20 percent and biodiesel prices 480 percent higher than HFO which costs $0.95/gallon.[42] Storage space for LNG may also be a limitation on certain types of ships because it requires 2.5- to 3-times the space as HFO, although tankers could potentially store LNG above deck without compromising cargo space (IMO 2008; MARINTEK 2000).

Alternative power plant technologies are also feasible for ships. Nuclear power is promising because it produces virtually no carbon emissions, but at present the technology is largely reserved to military use because of security and safety concerns and high costs (Eyring, Köhler et al. 2005; IMO 2008). Solar photovoltaic cells are also an attractive option because they produce no GHG emissions during operation, but they are currently impractical because of their high costs and the limited surface area aboard ships available to generate sufficient power (Eyring, Köhler et al. 2005). Solar cells might find niche applications in offsetting a portion of ships' auxiliary power needs. Wind power generated by large sails has also been considered, and some limited tests have shown mitigation potential of 10 to 50 percent (Eyring, Köhler et al. 2005; MARINTEK 2000). In the long term, introduction of fuel cells could offer a large mitigation potential, but ultimately this depends on the success of ongoing research. Studies by the U.S. military and U.S. Department of Transportation (DOT) estimate that fuel cells using either diesel or natural gas could reduce ship fuel consumption by 17 to 30 percent (Interlaboratory Working Group 2000). Hydrogen can offer even greater mitigation potential, depending on the availability of low-carbon or carbon-free hydrogen production. It could be used directly in marine engines or in a fuel cell to power ships (Eyring, Köhler et al. 2005; MARINTEK 2000). In fact, a few very small ships are currently powered by hydrogen fuel cells (Eyring, Köhler et al. 2005). Based on the current state of fuel cell technology, the biggest limitations for shipping applications are fuel storage space, weight, and cost (MARINTEK 2000). However, marine vessels may offer an attractive initial application of hydrogen as a transportation fuel. Farrell et al. (2003) argue that the costs of introducing hydrogen fuel are lowest for modes with few, large vehicles that are operated by highly trained workers and which transit between few points—e.g., shipping.

References

Airline world. (2008, January 15, 2009). "Aircraft winglets." Retrieved from http://airlineworld.wordpress.com/2008/10/01/aircraft-winglets/.

Allyn, D. (2008). Technical Design Interrelationships. 2008 Aviation and the Environment: A Primer for North American Stakeholders, Boeing and ICCAIA Chairman.

ATA (2009). "Alternative Aviation Fuels Q&A." Retrieved from http://www.airlines.org/economics/energy/altfuelsqanda.htm.

Batchelor, D. (2008). Extending the EU Emissions Trading Scheme to Aviation. Air Transport Emissions Trading Scheme Workshop, UK Department for Transport, European Commission, Directorate-General for Energy and Transport.

Birkler, J., D. Rushworth, et al. (2005). Differences Between Military and Commercial Shipbuilding. Santa Monica, CA, RAND.

Boeing (2008). Current Market Outlook 2008-2027. Retrieved from http://www.boeing.com/commercial/cmo/index.html

Brasseur, G. P. (2008). A Report on the Way Forward: Based on the Review of Research Gaps and Priorities, Federal Aviation Administration (FAA), Aviation Climate Change Research Initiative (ACCRI), Sponsored by the Environmental Working Group of the U.S. NextGen Joint Planning and Development Office.

CHSRA (2009). "Questions & Answers: Protecting Our Environment." Retrieved January 21, 2009, from http://www.cahighspeedrail.ca.gov/faqs/environment.htm.

Corbett, J. and H. Koehler (2003). "Updated emissions from ocean shipping." *Journal of Geophysical Research* 108(D20): 4650-64.

Corbett, J. and H. Koehler (2004). "Considering alternative input parameters in an activity-based ship fuel consumption and emissions model: Reply to comment by Øyvind Endresen et al. on "Updated emissions from ocean shipping." *J. Geophys. Res* 109(D23).

Corbett, J., H. Wang, et al. (2009). The Impacts of Speed Redcutions on Vessel-Based Emissions for International Shipping. Proceedings of the 88th Annual Meeting of the Transportation Research Board, Washington, DC.

de Rus, G. and G. Nombela (2007). "Is Investment in High Speed Rail Socially Profitable?" Journal of Transport Economics and Policy 41(1): 3.

DOT (2006). "Fleet Statistics (10,000 Deadweight Tons or Greater)." U.S. Department of Transportation. Retrieved from http://www.marad.dot.gov/library_landing_page/data_and_statistics/Data_and_Statistics.htm.

Dray, L. M., A. Evans, et al. (2009). Opportunities for Reducing Aviation-Related GHG Emissions: A Systems Analysis for Europe, Omega, University of Cambridge Institute for Aviation and the Environment.

Durkee, P. A., K. J. Noone, et al. (2000). "The Monterey Area Ship Track Experiment." *Journal of the Atmospheric Sciences* 57(16): 2523-2541.

Endresen, Ø., E. Sørgård, et al. (2004). "Substantiation of a lower estimate for the bunker inventory: Comment on "Updated emissions from ocean shipping" by James J. Corbett and Horst W. Koehler." *J. Geophys. Res* 109.

Endresen, Ø., E. Sørgård, et al. (2003). "Emission from international sea transportation and environmental impact." *J. Geophys. Res* 108(D17): 4560.

EPA (2006). Greenhouse Gas Emissions from the U.S. Transportation Sector, 1990-2003. Washington, DC, Environmental Protection Agency, Office of Transportation and Air Quality. EPA420-R-06-003.

EPA (2008a). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006. Washington, DC, U.S. Environmental Protection Agency. EPA430-R-08-005.

EPA (2008b). Regulatory Impact Analysis: Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression Ignition Engines Less than 30 Liters Per Cylinder, US Environmental Protection Agency. EPA420-R-08-001.

Eyring, V., H. W. Köhler, et al. (2005). "Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050." *J. Geophys. Res.* 110.

Faber, J., B. Boon, et al. (2007). Aviation and maritime transport in a post 2012 climate policy regime, Netherlands Environmental Assessment Agency.

Faber, J., D. Greenwood, et al. (2008). Lower NOx at Higher Altitudes: Policies to Reduce the Climate Impact of Aviation NOx emission, CE Delft.

Fargione, J., J. Hill, et al. (2008). "Land Clearing and the Biofuel Carbon Debt." *Science* 319(5867): 1235-1238.

Farrell, A. E., D. W. Keith, et al. (2003). "A strategy for introducing hydrogen into transportation." *Energy Policy* 31(13): 1357-1367.

GAO (2008). Aviation and the Environment: NextGen and Research and Development Are Keys to Reducing Emissions and Their Impact on Health and Climate. Washington, D.C., Government Accountability Office, Statement of Gerald L. Dillingham.

GAO (2009). High Speed Passenger Rail: Future Development Will Depend on Addressing Financial and Other Challenges and Establishing a Clear Federal Role. Washington, D.C., Government Accountability Office.

GBD (2001). The Technology Challenge. Report of the Technology Sub-Group, Greener by Design.

GBD (2005). Mitigating the Environmental Impact of Aviation: Opportunities and Priorities. Report of the Greener by Design Science and Technology Sub-Group, Greener by Design.

GBD (2007). Annual Report 2007-2008, Greener by Design.

Givoni, M. (2007). "Environmental benefits from mode substitution: comparison of the environmental impact from aircraft and High-Speed Train operations." *International Journal of Sustainable Transportation* 1(4): 209-230.

Halpern, B. S., S. Walbridge, et al. (2008). "A Global Map of Human Impact on Marine Ecosystems." *Science* 319(5865): 948-952

Hansen, M., M. Smirti, et al. (2008). A Comparative Evaluation of Greenhouse Gas Emission Reduction Strategies for the Maritime Shipping and Aviation Sectors, University of California, Berkeley.

IATA (2009). "Fact Sheet: Alternative Fuels." Retrieved March 23, 2009, from http://www.iata.org/pressroom/facts_figures/fact_sheets/alt_fuels.htm.

ICAO (2007). Resolutions Adopted at the 36th Session of the Assembly. Montreal, International Civil Aviation Organization.

ICAO (2009a). Group on International Aviation and Climate Change (GIACC) Report, International Civil Aviation Organization.

ICAO (2009b). Review of aviation emissions related activities within ICAO and internationally: Opportunities for Mitigating Climate Impacts, International Civil Aviation Organization, Presented by the U.S. Member to ICAO, Group on International Aviation and Climate Change (GIACC) Third Meeting.

IEA (2008a). CO_2 Emissions from Fuel Combustion (2008 Edition). Paris, France, International Energy Agency, Organization for Economic Co-operation and Development (OECD).

IEA (2008b). Energy Technology Perspectives 2008: Scenarios and Strategies to 2050. Paris, France, International Energy Agency, Organization for Economic Co-operation and Development (OECD).

IMO (2008). Updated Study on Greenhouse Gas Emissions from Ships, International Maritime Organization (IMO).

Interlaboratory Working Group (2000). Scenarios for a Clean Energy Future. Oak Ridge, TN and Berkeley, CA, Oak Ridge National Laboratory and Lawrence Berkeley National Laboratory.

IPCC (1999). Aviation and the Global Atmosphere. Cambridge, UK, Cambridge University Press.

IPCC (2007). Climate Change 2007—Fourth Assessment Report. Geneva, Intergovernmental Panel on Climate Change.

Jamin, S., A. Schäfer, et al. (2004). "Aviation emissions and abatement policies in the United States: a city-pair analysis." *Transportation Research Part D: Transport and Environment* 9(4): 295-317.

Janic, M. (1999). "Aviation and externalities: the accomplishments and problems." *Transportation Research Part D: Transport and Environment* 4(3): 159-180.

Janic, M. (2008). "The potential of liquid hydrogen for the future 'carbon-neutral' air transport system." *Transportation Research Part D: Transport and Environment* 13(7): 428-435.

Johnson, L. R., D. M. Rote, et al. (1989). Maglev vehicles and superconductor technology: Integration of high-speed ground transportation into the air travel system. Argonne, IL. Argonne National Laboratory.

Karagozian, A., W. Dahm, et al. (2006). Technology Options for Improved Air Vehicle Fuel Efficiency: Executive Summary and Annotated Brief. Washington, D.C., United States Air Force Scientific Advisory Board.

Kim, B. Y., G. G. Fleming, et al. (2007). "System for assessing Aviation's Global Emissions (SAGE), Part 1: Model description and inventory results." *Transportation Research Part D: Transport and Environment* 12(5): 325-346.

Lauer, A., V. Eyring, et al. (2007). "Global model simulations of the impact of ocean-going ships on aerosols, clouds, and the radiation budget." *Atmospheric Chemistry and Physics* 7(19): 5016-5079.

Lee, D. S., D. W. Fahey, et al. (2009). "Aviation and global climate change in the 21st century." *Atmospheric Environment* In Press, Corrected Proof.

Lee, J. J., S. P. Lukachko, et al. (2001). "Historical and Future Trends in Aircraft Performance, Cost, and Emissions." *Annual Review of Energy and the Environment* 26(1): 167-200.

Leifsson, L. T. and W. H. Mason (2004). The Blended Wing Body Aircraft. Blacksburg, VA, Virginia Polytechnic Institute and State University.

Liebeck, R. H. (2004). "Design of the Blended Wing Body Subsonic Transport." *Journal of Aircraft* 41(1): 10-25.

Lovins, A. B., E. K. Datta, et al. (2005). Winning the Oil Endgame. Snowmass, CO, Rocky Mountain Institute.

Marbaix, P., A. Ferrone, et al. (2008). Inclusion of non-CO_2 effects of aviation in the ETS: a summary, Aviation and the Belgian Climate Policy : Integration Options and Impacts (ABC Impacts), Centre d'Etudes Economiques et Sociales de l'Environnement, Université libre de Bruxelles.

MARINTEK (2000). Study of Greenhouse Gas Emissions from Ships. Final Report to the International Maritime Organization. Trondheim, Norway, Performed by Norwegain Marine Technology Research Institute (MARINTEK) for the International Maritime Organization.

Mokhtarian, P. L. and I. Salomon (2002). Emerging Travel Patterns: Do Telecommunications Make a Difference? In *Perpetual motion: travel behavior research opportunities and application challenges*, edited by Hani S. Mahmassani, 143-182, Oxford: Elsevier Science Ltd.

Morris, J., A. Rowbotham, et al. (2009). A Framework for Estimating the Marginal Costs of Environmental Abatement for the Aviation Sector, Omega, Cranfield University.

NASA (2004). Technology Facts, U.S. National Aeronautics and Space Administration.

NASA (2009). "Fact Sheets." U.S. National Aeronautics and Space Administration. Retrieved from http://www.nasa.gov/centers/dryden/about/Organizations/Technology/Facts/TF-2004-12-DFRC.html.

ORNL (2008). Transportation Energy Data Book, Edition 27. US Department of Energy, Oak Ridge National Laboratory.

P.L.-111-5 (2009). American Recovery and Reinvestment Act of 2009 (H.R.1). Washington, D.C., 111th Congress of the United States of America.

Park, Y. and H. Ha (2006). "Analysis of the impact of high-speed railroad service on air transport demand." *Transportation Research Part E* 42(2): 95-104.

Peña, N. (2008). Biofuels for Transportation: A Climate Perspective, Pew Center on Global Climate Change.

Ponater, M., S. Marquart, et al. (2005). "On contrail climate sensitivity." *Geophys. Res. Lett.* 32.

QinetiQ (2008). Aviation CO2 Emissions Abatement Potential from Technology Innovation, Final Report to the Committee on Climate Change, Department of Environment, Food and Rural Affairs, London.

Risch, T. K. (2008). X-48B Flight Research Progress Overview, Dryden Flight Research Center.

Saynor, B., A. Bauen, et al. (2003). The Potential for Renewable Energy Sources in Aviation, Imperial College London.

Schäfer, A., J. B. Heywood, et al. (2009). Transportation in a Climate-Constrained World. Cambridge, Massachusetts, The MIT Press.

Schipper, L., F. Unander, et al. (2001). "Indicators of energy use and carbon emissions: explaining the energy economy link." *Annual Review of Energy and Environment* 26: 49-81.

Searchinger, T., R. Heimlich, et al. (2008). "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change." *Science* 319(5867): 1238 - 1240.

TEMS (2008). Impact of High Oil Prices on Freight Transportation: Modal Shift Potential in Five Corridors Technical Report, Prepared by TEMS for the Marine Administration, U.S. Department of Transportation.

UN (2008). Review of Maritime Transport 2008. New York, United Nations.

UNFCCC (2003). Emissions Resulting from Fuel Used in International Aviation and Maritime Transportation, United Nations Framework Convention on Climate Change.

Vigilante, M. (2009). Reducing the Carbon Footprint—What Works. Transportation Research Board Annual Meeting, Washington, D.C., Synergy Consultants.

World Bank (2007). "Trade Statistics." Retrieved February 26, 2009, from http://go.worldbank.org/VDYJ5GA960.

WTO (2008). International Trade Statistics 2008, World Trade Organization.

Endnotes

1. The actual effect of aviation and marine transportation emissions on the climate is potentially much greater, considering the radiative forcing effects of non-CO_2 emissions (see Box 1) and the large uncertainties in marine transportation emissions (see Section 2.1).

2. Many policies, which aim to control GHGs from these and other subsectors—either directly or indirectly through taxes and allowances or technology and efficiency standards—increase the cost of transportation. In theory, increased costs will reduce demand as some of the costs are passed on to customers who then take the higher price into consideration in their transportation decisions.

3. The terms "marine" and "shipping" are used in this paper to refer to all types of waterborne vessels utilized at sea and on inland waterways and lakes.

4. Traditionally, bunker fuels were considered to be those used aboard ships (e.g., heavy fuel oil and residual fuel oil) because they were stored in the ships' bunkers. However, for purposes of GHG accounting, it has become quite common to refer to the fuel consumed for both international air travel and marine voyages as international bunker fuel.

5. A large share of freight traffic is carried in the bellies of passenger airplanes during normal commercial passenger service.

6. In 2007, fuel costs accounted for over 40 percent of U.S. airline operating expenses (DOC+I), up from 25 percent just a few years earlier (Boeing 2008). Current Market Outlook 2008-2027.]

7. See Section 3, Figure 8 for a graph showing the declining trend in aircraft energy intensity over time.

8. For more information, see the following webpage: http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/nextgen/research_planning/narp/.

9. The Boeing 787 Dreamliner is currently under development and is scheduled to enter service in 2010. The Airbus A350 is currently under development and is scheduled to enter service in 2013.

10. Using a conversion rate of 1.5 US dollars per British pound (consistent with early 2009 exchange rates).

11. For example, the expansion of the Panama Canal is estimated to cost $5.2 billion. See http://www.pancanal.com/eng/plan/documentos/propuesta/acp-expansion-proposal.pdf for more information.

12. Hydroprocessing a plant- or animal-based oil is similar to the process of conventional crude oil refining. First, the oil is "hydrotreated" by adding hydrogen, which increases the oil's hydrogen-to-carbon ratio. Then, the molecules that result are "cracked," yielding a finished jet fuel product.

13. Fischer-Tropsch synthesis of transportation fuels involves gasification of a carbon-containing feedstock (e.g., biomass, coal) and production of a synthetic crude oil, which can then be processed into refined liquid fuel products.

14. This level of reduction is more optimistic than current estimates and not included in Table 4.

15. Latest California High Speed Rail Authority estimate, available at http://www.cahighspeedrail.ca.gov/faqs/financing.htm.

16. For a description of these petitions, see Section VI. Mobile Source Authorities, Petitions, and Potential Regulation, Subsection C. Nonroad Sector Sources in Regulating Greenhouse Gas Emissions Under the Clean Air Act, Advance Notice of Proposed Rulemaking, 73 *Federal Register* 44354–44520 (July 30, 2008).

17. Note, the legality of this policy may be challenged by one or more nations under the terms of the ICAO's Chicago Convention.

18. Signatories to the UNFCCC are split into three main groups: Annex I countries (developed countries); Annex II countries (a subset of Annex I developed countries that have a special obligation to provide new and additional financial resources and facilitate the transfer of climate-friendly technologies to developing countries to help them tackle climate change); and developing countries.

19. ICAO has 190 Contracting States. For more information see http://www.icao.int

20. IMO has 168 Member States. For more information see http://www.imo.org

21. For more information on the SBSTA's work on "Emissions Resulting from Fuel Used for International Transport: Aviation and Marine (Bunker Fuels)," see http://unfccc.int/methods_and_science/emissions_from_intl_transport/items/1057.php.

22. Statement from the International Civil Aviation Organization (ICAO) to the Twenty-Sixth Session of the UNFCCC Subsidiary Body for Science and Technological Advice (SBSTA); Bonn 7-18 May 2007.

23. IMO's Marine Environmental Protection Committee is responsible for marine environmental concerns, including GHG emissions.

24. Statement without prejudice to the outcome/s of the UNFCCC Ad-Hoc Working Groups on Long-term Cooperative Action and the Kyoto Protocol.

25. Piston-powered (reciprocating engine) aircraft account for only 2 percent of commercial propeller aircraft (piston and turboprops) and just 0.05 percent of global commercial aircraft fuel burn.

26. In 2007, fuel costs accounted for over 40 percent of U.S. airline operating expenses (DOC+I), up from 25 percent just a few years earlier [Boeing (2008). Current Market Outlook 2008-2027.]

27. Under the High-Density Terminal and Airport Operations, busy airports would be able to better and more safely assign arriving and departing aircraft to multiple runways, especially in bad weather or low visibility conditions. Enhanced navigation capabilities and automated controllers will be needed to bring this initiative to fruition.

28. For more information on ASPIRE, see the following webpage: http://www.aspire-green.com/default.asp. For more information on AIRE, see the following webpage: http://ec.europa.eu/transport/air/environment/aire_en.htm.

29. For more information on VALE, see the following webpage: http://www.faa.gov/airports_airtraffic/airports/environmental/vale/.

30. For more information on these advanced engine technologies, see the original source from which this discussion was summarized: EPA's "Regulating Greenhouse Gas Emissions Under the Clean Air Act", Advance Notice of Proposed Rulemaking, 73 *Federal Register* 44470 (July 30, 2008).

31. General Electric, Press Release, *Driving GE Ecomagination with the Low-Emission GEnx Jet Engine*, July 20, 2005, available at http://www.geae.com/aboutgeae/presscenter/genx/genx_20050720.html.

32. The NOx standards adopted at the sixth meeting of ICAO's Committee on Aviation Environmental Protection (CAEP) in February 2004 were approved by ICAO in 2005.

33. Rolls-Royce, *Trent and the environment*, available at www.rolls-royce.com/community/downloads/trent_env.pdf and the Rolls-Royce environmental report, *Powering a better world: Rolls-Royce and the environment*, 2007, available at http://www.rolls-royce.com/community/environment/default.jsp

34. Green Car Congress, *Rolls-Royce Wins $2.6B Trent 1000 Order from Virgin Atlantic; The Two Launch Joint Environmental Initiative*, March 3, 2008, available at http://www.greencarcongress.com/2008/03/rolls-royce-win.html.

35. Engine Yearbook, *Pratt & Whitney changing the game with geared turbofan engine*, 2008, at page 96.

36. The L/D ratio is a measure relating the forces that provide an aircraft with lift (L) compared to the frictional drag (D) forces that slow it down. The higher the ratio, the less energy is needed to fly the aircraft.

37. For example, Aviation Partners Boeing claims that their winglets have been sold to 140 airlines and that 95 percent of all Boeing 737NG airplanes are fitted with them [Airline world. (2008, January 15, 2009). "Aircraft winglets." from http://airlineworld.wordpress.com/2008/10/01/aircraft-winglets/.]

38. Fischer-Tropsch synthesis of transportation fuels involves gasification of a carbon-containing feedstock (e.g., biomass, coal) and production of a synthetic crude oil, which can then be processed into refined liquid fuel products.

39. See the Renewable Fuel Standard Program (RFS2): Notice of Proposed Rulemaking (found at http://www.epa.gov/otaq/renewablefuels/index.htm#regulations).

40. Cryogenic operation means operation at extremely low temperatures. In the case of hydrogen aircraft, the hydrogen would have to be stored at a temperature less than -253 degrees Celsius (-423 degrees Fahrenheit) in order to keep it in the liquid phase.

41. For more information on CAAFI, see the following webpage: http://www.caafi.org/.

42. Comparison made between costs per BTU based on the authors' calculations. Fuel prices from EIA Spot Prices and bunkerworld.com for 2/26/2009, biodiesel prices from DOE (http://www.afdc.energy.gov/afdc/pdfs/afpr_oct_08.pdf).

This paper provides an overview of greenhouse gas (GHG) emissions from aviation and marine transportation and the various mitigation options to reduce these emissions. The Pew Center on Global Climate Change was established in 1998 in order to bring a cooperative approach to the debate on global climate change. The Pew Center continues to inform the debate by publishing reports in the areas of policy (domestic and international), economics, environment, and solutions.

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