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Reducing pollution from aviation and ocean shipping

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IN

ENGINEERING & PUBLIC POLICY

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ABSTRACT

International aviation and ocean shipping are significant and potentially fast growing sources of greenhouse gas emissions. Both sectors also contribute to poor local and regional air quality. This thesis analyzes three interventions aimed at reducing air emissions from airplanes and ships. The first is the use of tugs, or an electric motor embedded in the landing gear, to propel the aircraft on the ground. If airlines were to tow all large narrowbody aircraft on domestic service from the gate to the edge of the runway before take off at 41 of the 50 busiest airports in the U.S., CO_2 emissions would fall by 0.5 million tonnes annually. In addition, the switch would produce $150 million in annual air quality benefits from reduced emissions of particulate matter, hydrocarbons and the oxides of nitrogen. Using embedded electric motors to taxi large narrowbody aircraft would cut CO_2 emissions by nearly 2 million tonnes per year. The second intervention is the market based mechanism, designed to cap CO_2 emissions from international aviation at 2020 levels, currently being designed at ICAO. An analysis of an early draft of this mechanism suggests that it would require airlines to offset an average of 270 million tonnes in CO_2 emissions during each of the years between 2021 and 2035 when it will be active. The analysis suggests that the current proposal is complex, and poorly specified. We recommend that the mechanism be made much simpler: for example, by simply determining an airline's offset obligations on the basis of its carbon footprint in that year. Finally, we study the costs and benefits of a more widespread use of grid electricity to energize berthed vessels. We use mixed-integer linear programming to identify combinations of ports and vessels where using shore power would produce the greatest benefit to society. We conclude that the practice could reduce CO_2 emissions by 0.2 million tonnes per year and yield air quality improvements worth $80-200 million per year at no net cost to society.

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Chapter 1: INTRODUCTION

1.1 Greenhouse gas emissions from international aviation and ocean shipping

International transport, which includes ocean shipping and aviation, is among the fastest-growing sources of human-generated greenhouse gas emissions. Between 2009 and 2010, carbon dioxide (CO_2) emissions from international marine shipping and aviation grew faster—at 7%[1] and 6.5%, respectively—than those from China, which grew by 6% (IEA 2012a). Although 2010 was a year of especially rapid growth as global trade and travel bounced back from the 2009 recession, emissions from this activity are expected to grow to between two and three times their current level by 2050 (IMO 2009, Leggett 2012).

This growth will occur from a small but substantial base: if the sector were a country, its current emissions would be roughly the size of those of Japan or Germany. Aviation is currently responsible for about 2 per cent of annual anthropogenic emissions of CO_2, but 3.5 per cent (90% confidence interval: 1.3-10%) of current anthropogenic forcing if the effect of changes in cirrus cloud formation is ignored.[2] Aviation's contribution is 4.9 per cent (90% CI: 2-14%) if this effect is included. (Lee et

[1] A recent report by the International Maritime Organization (IMO, Smith et al. 2014) suggests that these numbers may not be reliable. This growth rate corresponds to the top-down estimates of emissions – which are based on estimates of marine bunker fuel sales allocated to international shipping – in Smith et al. (2014). When a bottom-up methodology – in which fuel use is estimated based on the actual voyages undertaken by the vessels, and which accounts for the fact that engine loads and fuel consumption drop significantly when speed is lowered – is applied, the figures indicate that fuel use (and therefore, emissions) fell by 10% during that time (Tables 2 and 3 of Smith et al. (2014)). That emissions are likely to grow substantially in the medium to long term is, however, not in dispute.

[2] Until 2004, the International Civil Aviation Organization (ICAO) quantified the impact of aviation on global warming based on estimates of radiative forcing (e.g., by saying, "aircraft are estimated to contribute about 3.5 per cent of the total radiative forcing…" (ICAO 2004, I–45) Since 2010, it has referred only to the contribution of CO_2 by saying that international aviation currently accounts for "less than 2 per cent of total global CO_2 emissions…"(ICAO 2010, I–68) No reason is given to this shift, and no attention drawn to it. It is the case that the level of scientific understanding of non-CO_2 impacts of aviation is "low" for water vapor, sulfate aerosol, soot aerosol, and linear contrails and "very low" for changes in cirrus cloud formation. (Lee et al. 2010, 4714), and

al. 2010) As of 2012, international shipping accounted for 2.2% of global CO_2 emissions and 2.1% of greenhouse gas emissions (Smith et al. 2014).[3]

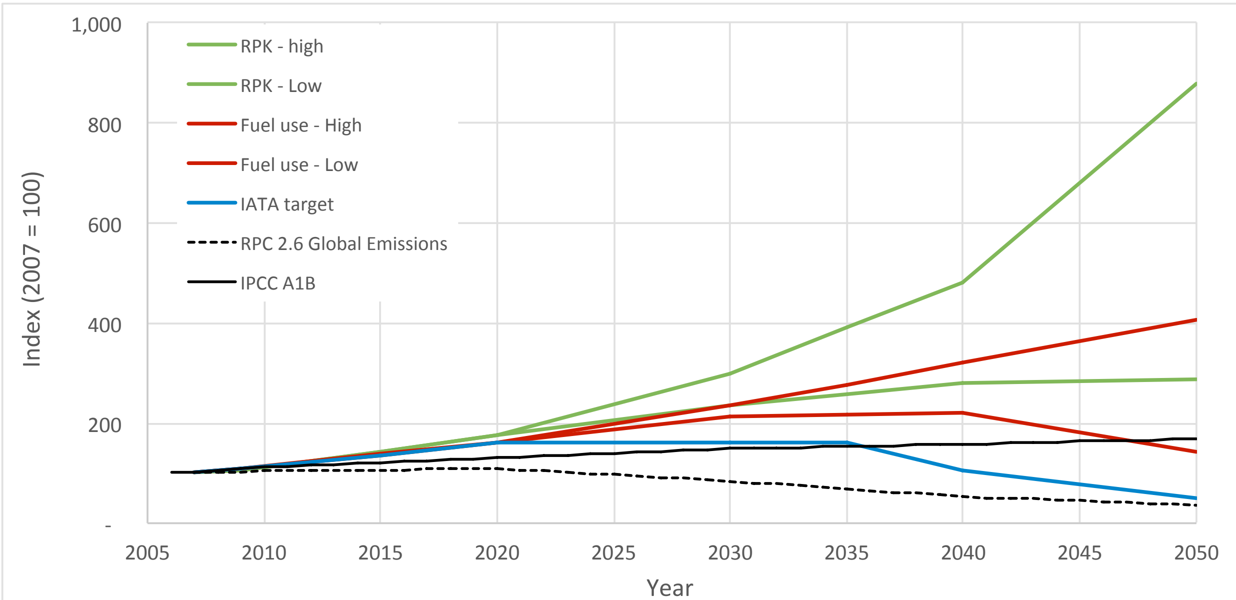

Figure 1.1: ICAO's high and low estimates of the demand for air travel in revenue passenger kilometers (RPK), as well as ICAO's high and low estimates of fuel use (ICAO 2009a). Without offsets, emissions from aviation will not meet either of the International Air Travel Association's (IATA, the industry's representative) targets: zero growth in emissions from 2020, and halving annual 2050 emissions compared to 2005 levels (IATA 2013). Also shown (solid black line) is the trend for global fossil fuel CO_2 emissions from all sources, which are set to rise more slowly than emissions from aviation (IEA 2012b). The dotted black line represents the trajectory that emissions must follow for there to be a significant (20-70%) chance that global temperature rise compared to pre-industrial times will remain below 2 degrees C (van Vuuren et al. 2007).

Analysis by the International Civil Aviation Organization (ICAO 2009a, Figure 1.1) and International Maritime Organization (IMO, Figure 1.2) suggests that within-sector approaches such as improved efficiency and new technologies will not stem the projected growth in greenhouse gas

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recent studies have found that the non-CO_2 impact of aviation on equilibrium global-mean temperature is likely to be very low. (Rap et al. 2010), (Olivier Boucher et al. 2012).

[3] In addition to carbon dioxide, ships emit significant quantities of NO_X and sulfate aerosol. The atmospheric chemistry of these species is complex, and the indirect effects very poorly understood. Sulfate aerosol produces a cooling effect. NO_X emissions induce the production of ozone, which produces warming but also promotes the oxidation of methane, thus removing a potent warming agent from the atmosphere. (Eyring et al. 2010) These processes operate on very different time scales. The net effect is that a pulse of emissions in one year is likely to produce net cooling for several decades, as the atmospheric chemistry of the non-CO_2 species plays out. The temperature response switches to net warming, as only the CO_2 survives and dominates, after 55 years. (Fuglestvedt et al. 2008)

emissions from international transport, let alone reduce them to well below current levels. If the impact of alternative fuels is not accounted for, aviation fuel burn is likely to grow by between 40% and over 300% between the present and 2050, even as the passenger-miles flown grow much more rapidly. This rate of growth will likely be faster than the growth in global emissions even in a "business as usual" scenario and far in excess of the International Air Transport Association's (IATA) target of carbon-neutral growth after 2020 and a 50% reduction in emissions relative to a 2005 baseline.

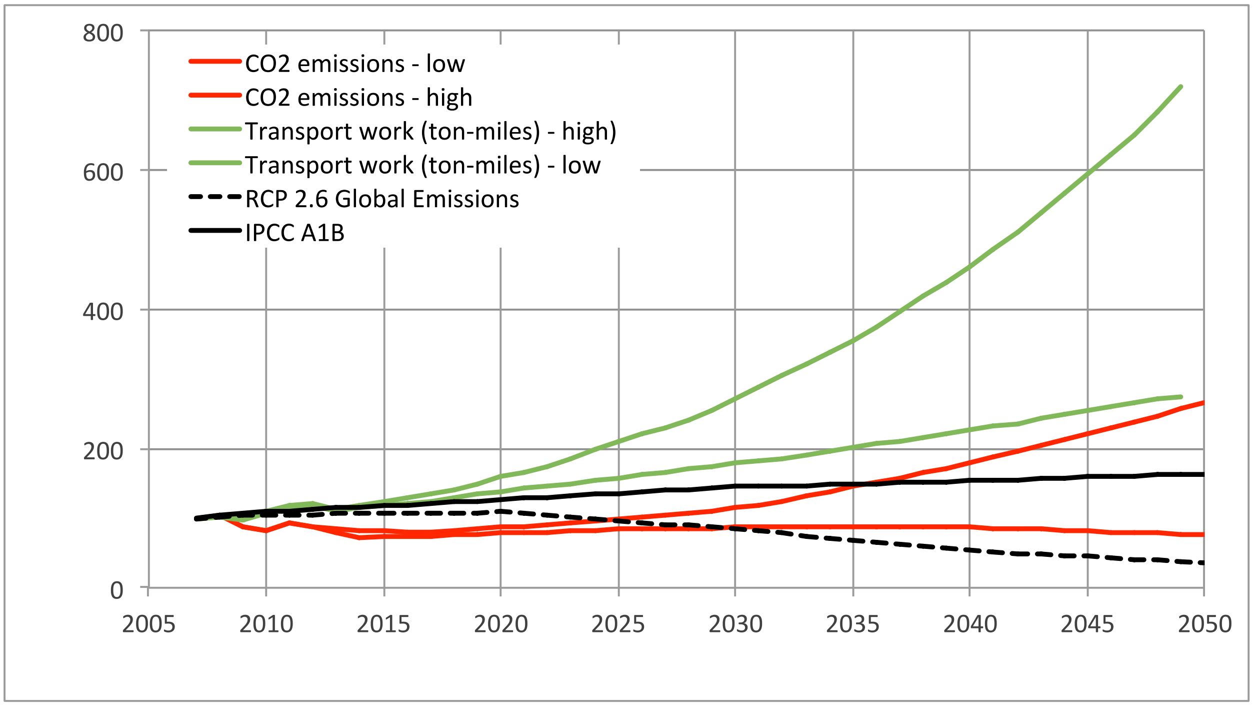

Figure 1.2: IMO's high and low estimates of the demand for ocean transport in tonne miles, as well as IMO's high and low estimates of CO_2 emissions (Smith et al. 2014). Also shown (solid black line) is the trend for global fossil fuel CO_2 emissions from all sources (IEA 2012b), which are set to rise more slowly than emissions from shipping in the long run. The dotted black line represents the trajectory that emissions must follow for there to be a significant (20-70%) chance that the global temperature rise compared to pre-industrial times will remain below 2 degrees C (van Vuuren et al. 2007).

In its business as usual scenarios, the IMO forecasts that emissions in 2050 will be 50-250% greater than those in 2012. In only one scenario would emissions in 2050 return to current levels, after having risen slightly in the interim. This scenario is optimistic. It assumes that future global and sectorial fossil fuel use is low (RCP 4.5, Wise et al. 2009), that liquefied natural gas constitutes

25% by mass of all shipping fuel used in 2050, that aggressive measures are taken to reduce the emission factors for oxides of nitrogen from liquid fuels, that high improvements in efficiency are obtained, and that prospects for the economic growth in emerging nations are poor.

It is this expectation of rapid growth in international transport, and the fear that it would undermine hard won emissions reductions from other sectors, that has compelled environmental policymakers to focus their efforts on the sector. This concern is naturally more salient in jurisdictions that have put in place potentially costly measures to reduce emissions from other sectors of the economy. For example, the European Union (EU) directive ordering the inclusion of aviation in the EU's Emissions Trading Scheme (ETS) says, "If the climate change impact of the aviation sector continues to grow at the current rate, it would significantly undermine reductions made by other sectors to combat climate change…" (The European Parliament and Council 2008) A recent regulatory proposal aimed at including in the EU-ETS maritime transport within, as well as in and out of, Europe declares, "The projected increase of CO_2 emissions from shipping is not in line with the EU objectives,[4] leading to negative impacts on climate change." (European Commission 2013a)

A hypothetical example illustrates such concerns. Consider the case of the United Kingdom. In 2013, the U.K. emitted about 570 million tons CO_2 equivalent of greenhouse gases (DECC 2014). Domestic and international flights departing from the UK in that year emitted 35 million tons, or about 6% of the total. (Committee on Climate Change 2014) The UK has instituted a legally binding commitment to reduce its annual greenhouse gas emissions in 2050 to a fifth of their level in 1990 (Parliament of the UK 2008). This means that in 2050, the UK ought to emit a mere 120 million tons of CO_2. The UK Department of Energy and Climate Change has forecast that under current

[4] An EU White Paper (European Commission 2011, para. 1.29) on Transport recommends that the EU's CO_2 emissions from maritime transport be reduced at least by 40% relative to 2005 levels by 2050, and – if feasible – by 50%.

policies to control their rise, CO_2 emissions from aviation in the UK will rise to about 50 million tons (Department for Transport 2013), or an untenable 42% of the total. This example is hypothetical because it is not clear that the United Kingdom will be successful in fulfilling its commitment to a drastic cut in its emissions by 2050, and – in any case – such an obligation might be met at least in part by the purchase of offsets generated by emissions reductions in other countries. Nonetheless, this thought experiment demonstrates that if unchecked, emissions from aviation could make the country's efforts to meet its obligations significantly more difficult.

While forecasts suggest that growth in emissions from aviation and – eventually – shipping will outpace that of total global emissions of CO_2, recent trends (Figure 1.3) suggest that emissions from aviation have merely kept pace with those of the economy as a whole, while those from shipping have actually fallen even as the volume of world seaborne trade has grown.

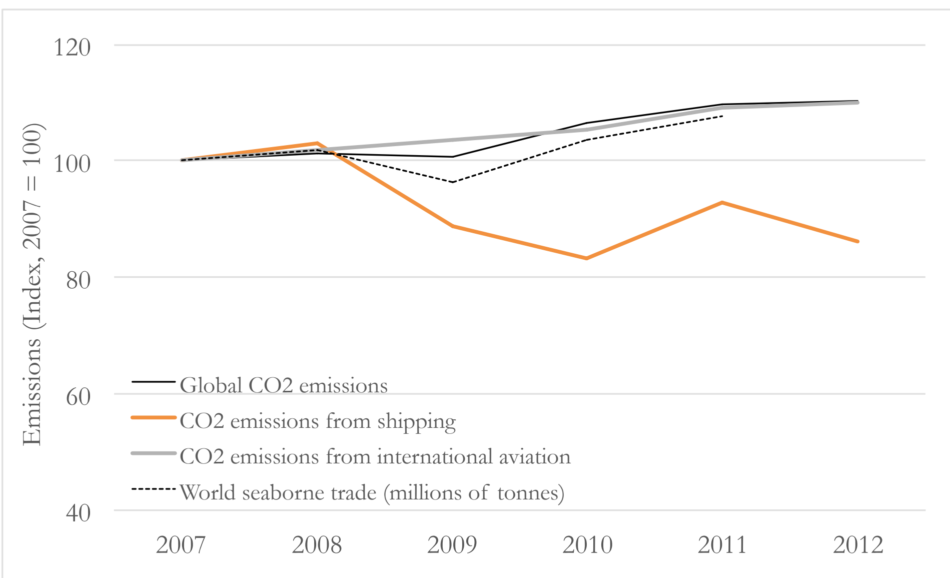

Figure 1.3: In the six years between 2007 and 2012, emissions from international aviation grew at roughly the same pace as emissions from the global economy as a whole. World seaborne trade has lagged global emissions somewhat, and emissions from shipping have in fact fallen. Sources: International aviation bunker sales from IEA (2013). Global CO_2 emissions from (EIA 2015b). CO_2 emissions from shipping from Smith et al. (2014). World seaborne trade from UNCTAD (2015).

As will be discussed in Chapter 6:, this lull in the growth of emissions from international transport is the result of a number of factors such as high fuel prices, a sluggish world economy, gains in operational efficiency, overcapacity in shipping, and low interest rates. Some of these factors may reverse themselves and sources of efficiency gains (e.g., improvements in passenger load factors in aviation) might be close to exhausting themselves.

The risks associated with a warming climate are well documented (e.g., Melillo, Richmond, and Yohe, Eds., 2014), and increasing greenhouse gas emissions from international transport would contribute to these risks. Some of these risks affect the sector directly. In its annual report, Delta Air Lines (2013) warns investors that, "increases in frequency, severity or duration of thunderstorms, hurricanes, typhoons or other severe weather events, including from changes in the global climate, could result in increases in fuel consumption to avoid such weather, turbulence-related injuries, delays and cancellations, any of which would increase the potential for greater loss of revenue and higher costs." The IPCC cautions, "Hotter air is less dense. In summer months, especially at airports located at high altitudes, this may result in limitations for freight capacity, safety, and weather-related delays, unless runways are lengthened." (Arent et al. 2013, 18)

The IPCC report goes on to predict, "Increased storminess at airports, particularly those located in coastal regions, may increase the number of weather related delays and cancellations and increase maintenance and repair costs. Clear-air turbulence will increase in the Atlantic corridor leading to longer and bumpier trips. The impact of climate change on airport pavement is very similar to paved roads. The effect of temperature and increased precipitation intensity on airports imposes a risk to the entire facility if pavements are not adapted to these increases."(see also National Research Council 2008, 88)

The impact of a warming climate on shipping will be more mixed. The Arctic Marine Shipping Assessment concluded that due to the decrease "in extent and thickness [of Arctic ice] during the second half of the 20th century and early 21st century, " and because "Global Climate Model simulations indicate a continuing retreat of sea ice…It is highly plausible there will be greater marine access and longer seasons of navigation…" (Arctic Council 2009, 4) Apart from making port cities more vulnerable, more intense floods could cause "waterway closures and [damage or destroy] ports and locks." (Melillo, Richmond, and Yohe 2014, 85) In addition, inland navigation might be adversely affected by droughts, which could reduce channel depths.

Some large shipping lines recognize the need to reduce their greenhouse gas footprints: AP Moller Maersk – by some margin the largest container shipping line – has committed itself to reducing CO_2 emissions per container by 60% by 2020 relative to a 2007 baseline, and had cut per-container emissions by 39% by 2014. The firm expects to carry 80% more containers in 2020 relative to 2007, and therefore anticipates that its total emissions will rise significantly. It sees lowering the carbon intensity of its shipping activities as intimately tied to reducing operating costs. (A.P. Møller - Mærsk A/S 2014) The World Shipping Council (WSC) argues that "an emissions cap applicable to shipping could be meaningful [only] in the context of a global, cross-sectoral emissions trading regime, which would cap carbon emissions and provide for trading of emission allowances in a broad, defined, and commonly regulated international market." (WSC 2010) The WSC did, however support the energy efficiency measures put in place by IMO and discussed in 0.

1.2 Effects on local air quality

This thesis is motivated primarily by a desire to understand and contribute to the effort currently under way at, among others, the European Union, as well as ICAO and IMO to reduce greenhouse gas emissions from international transport. However, these activities produce other pollutants that have a more immediate impact on air quality and human health. Corbett and Fischbeck (1997) showed that ocean shipping is a significant contributor to emissions of the oxides of nitrogen and sulfur, and that their residence time in the atmosphere is long enough for some of the emissions on the high seas to be transported to shore. Corbett et al. (2007) found that "shipping-related PM [particulate matter] emissions are responsible for approximately 60,000 cardiopulmonary and lung cancer deaths annually…" Aviation fuel contains between 500 and 1000 parts per million (ppm) of sulfur, and jet fuel specifications allow that content to be up to 3000ppm. (Chevron Corporation 2006) As such, exhaust from jet engines contains significant concentrations of the oxides of sulfur and nitrogen. These combine with ammonia[5] in the atmosphere to produce fine particulate matter, which contributes to about 10,000 annual premature deaths globally, of which 450 occur in the United States. (Barrett, Britter, and Waitz 2010) Of these, 200 deaths are likely to occur in near-airport areas. (Brunelle-Yeung et al. 2014)

1.3 Outline of thesis

This chapter has laid out our motivation for undertaking this research. Chapter 2 will outline the history of efforts to reduce greenhouse gas emissions from international aviation (at ICAO and by the European Union) and ocean shipping (at the IMO and by the EU).

Morgan (1978) defines policy analysis as the effort to "evaluate, order and structure incomplete knowledge so as to allow decisions to be made with as complete an understanding as possible of the current state of knowledge, its limitations and implications." This thesis consists of three analyses – two of technological interventions, and one of a policy intervention – that endeavor to meet that definition.

Chapter 3 assesses the benefits and costs of two interventions to reduce fuel use and air emissions from aircraft while they are taxiing. Chapter 4: evaluates the offset obligations that an ICAO proposal for a market-based mechanism to cap CO_2 emissions from international aviation at 2020 levels would place on real airlines, as well as the effectiveness of the proposal in meeting its own goals. Chapter 5: assesses the benefits and costs of cold ironing, the use of electricity from the shore – in place of on-board diesel generators, which are almost always used in current practice – to

[5] The ammonia comes from-among other things-fertilizer use. (Barrett, Britter, and Waitz 2010)

energize a ship's systems while it is in port. Chapter 6 concludes by synthesizing the insights generated in the previous three chapters, and discusses avenues for further research.

Chapter 2: EFFORTS TO REDUCE GREENHOUSE GAS EMISSIONS FROM INTERNATIONAL TRANSPORT

Article 2.1, paragraph (a)(vii) of the Kyoto Protocol (Parties to the UNFCCC 1997) states that "Each Party included in Annex I…shall…[take] measures to limit and/or reduce emissions of greenhouse gases not controlled by the Montreal Protocol in the transport sector," which includes domestic aviation and water transport. The problem of how to allocate emissions from international transport proved, and has remained, intractable. (Haites 2009) To see why, consider a ship that is registered in Liberia, operated by a Danish shipping line, and is making a voyage from Shanghai to Los Angeles carrying products made in China by a European firm for sale in North America. The ship will carry on to the Port of Newark through the Panama Canal, en route taking on fuel at the Port of Colón. How and to whom should the emissions from this voyage be allocated, and who should be assigned responsibility for reducing them? (Vaishnav 2014)

Recognizing this, Article 2.2 of the protocol says that the Parties in Annex 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." Both organizations have been criticized for the glacial pace of their progress (e.g., see Oberthür 2006) on this matter and the European Union has felt compelled to take, or at least to declare that it will take, unilateral action in response. (The European Parliament and Council 2008) (European Commission 2013a)

This chapter traces the ICAO and IMO's efforts to fulfill their mandate under the Kyoto Protocol. The story is interwoven with the history of other (mainly, the European Union) actors' efforts to establish mechanisms to control emissions.

2.1 Greenhouse gas emissions from international aviation

ICAO consists of three organs. The Secretariat is the administrative organ. The Assembly of all its 191 current member States, which meets every three years, represents the "supreme authority in the organization." Decisions of the Assembly are taken by a majority of the votes cast, and a majority of 191 contracting States is needed to constitute a quorum for a meeting of the Assembly. The ICAO Council is a body consisting of 36 member states, which are elected by the Assembly. (Milde 2012, 138) The Council "adopts…international standards and recommended practices," which are designated as Annexes to the Chicago Convention. (ICAO 2006, Article 54(l)) This mandatory function makes the Council a "quasi-legislative" body. (Milde 2012, 149) Annex 16 deals with environmental protection, and it is possible that any new standard or mechanism related to environmental protection will be added to this Annex. Council decisions "require approval by a majority of its members and a majority of the members of the Council constitutes the quorum." However, unless a Member of the Council requests that this rule apply, decisions can be taken by a majority of the votes *cast*. (Milde 2012, 154–155) As such, 19 member States constitute a quorum, and it is conceivable that a rule may be adopted by an affirmative vote by ten States. Any market-based measure or efficiency standard will have to be approved by a majority vote of the Council, which will refer it to the Assembly. The rule would then be adopted by a majority of the votes cast in the Assembly. In practice, most decisions in ICAO have been taken by consensus. A significant measure like a market-based mechanism for CO_2 control would, in all probability, require very broad support to be adopted.[6]

The Chicago Convention, ICAO's founding charter, does not list environmental protection as one of the organization's responsibilities. Assembly Resolution A22-12, the first to refer to aviation's impact on the human environment – as opposed to a specific aspect of that impact, such as noise –

[6] Annie Petsonk, personal communication, February 1, 2015.

appears to draw its authority from Article 44 of the Convention, which states that ICAO should, among other things, "meet the needs of the peoples of the world for safe, regular, efficient, and economical air transport." The Resolution goes on to acknowledge that "advancing technology has caused civil aviation to become a significant influence in the human environment." (ICAO 1977, I–38) ICAO's willingness to engage with environmental issues, a responsibility that its founding Convention does not place upon it, is arguably motivated by its concern that ceding the initiative on such issues would create a vacuum that other national, regional, and international agencies might seek to fill with more stringent, potentially fragmented, regulations of their own.[7] Such regulations might slow the sector's growth. As such, Resolution 22-12 goes on to request the Council of the ICAO to "maintain its vigilance in the pursuit of aviation interests related to the environment and also maintain the initiative in developing policy guidance on all aviation matters related to the human environment, and not leave such initiatives to other organizations."[8] (ICAO 1977, I–39)

The first reference to climate change is made in Appendix F of Resolution A31-11, which acknowledges "growing concerns about environmental problems in the upper atmosphere such as global warming and depletion of the ozone layer." (ICAO 1995) This resolution, which was adopted before the 1997 Kyoto Protocol was signed (but with knowledge of the ongoing negotiations, and in anticipation that they would result in some agreement), pointed out that "the extent to which international civil aviation contributes to these problems is still being ascertained" but accepted that "ICAO is recognized as the primary organization responsible for…developing policy guidance on

[7] For example, Resolution A23-10, which addresses noise and engine emissions from subsonic jet aircraft, notes that "restrictions on the utilization of [excessively noisy] aircraft operated by carriers of the Member States of ICAO constitute a problem of general interest which must be solved by the international aeronautical community" and "unilateral measures in this field pose a serious risk for the stability of air transport…" (ICAO 1980, 49)

[8] In the case of ICAO (and IMO) efforts to control climate change pollution, Oberthür (2003) asserts, "To the extent that progress has been achieved, it appears to have been driven by the danger to lose regulatory authority to the climate change regime as well as the threat of unilateral action by major players."

possible means of minimizing any undesirable effects of international civil aviation on the environment."(1995, I–36)

In 1996, the European Commission "recommended that the exemption [from taxation] of aviation kerosene be abolished, as soon as the international situation allowed duty to be charged on all carriers including those from *third* countries."(Seely 2012, 5) Noting that "the subject of environmental charges or taxes on air transport has also been raised in other international policy-making bodies," (ICAO 1996) a Council resolution on environmental charges and taxes strongly recommended that such charges be narrowly targeted at the damage cause by emissions from aircraft engines, where such damages could be identified.[9] Establishing such a link is clearly not straightforward. The resolution also urged states to ensure that their charges "take into account the non-discrimination principle" (that aircraft from all States be treated equally) and that charges do not discriminate against air transport compared with other modes of transport. Since ICAO's remit only includes international aviation, this last exhortation could be interpreted as saying that international aviation ought not to be taxed before international shipping is. Given the vast differences in their relative costs and environmental footprints (per ton-mile of service provided),[10] as well as the equally wide gap in the value of the goods transported by each,[11] it is hard to conceive of aviation and shipping as competing modes. As such, the idea that aviation would be placed at a relative

[9] Other recommended uses for such charges were the funding of scientific research into the environmental impact of aviation, or reducing such impacts through developments in technology and aircraft operations.

[10] Transporting goods by ships produces between 0.5 and 90 grams CO_2 per tonne-mile, whereas air transport produces between 900-4000 grams CO_2 per tonne-mile. It is also worth noting that ships are responsible for 57% of global freight activity, against 0.4% for aircraft. (Wang 2013) Air transport costs $0.59 per ton-mile, whereas water transport costs $0.01. (Rodrigue and Notteboom 2013)

[11] Analysis of Japanese imports that were denominated in kilograms in 2014 showed that goods imported by sea container had a median value of ¥1000 per kg, and 90% of the values lay between ¥120 and ¥8,500. The median value for cargo imported by air was ¥5500 per kg, with 90% of the values lying between ¥700 and ¥75,500. (Ministry of Finance 2014)

disadvantage if it were taxed while shipping is not is somewhat fanciful. This exhortation is arguably designed to serve as an impediment to a Pigovian tax and not as an attempt to level the playing field.

Assembly Resolution 32-8 (ICAO 1998) acknowledged the role the Kyoto Protocol assigned ICAO in addressing the issue of climate change. The resolution also declared that ICAO had requested the Intergovernmental Panel on Climate Change (IPCC) to prepare a scientific assessment of the impact of aviation on the global atmosphere. The same resolution requested the ICAO Council to "study policy options to limit or reduce the greenhouse gas emissions from civil aviation."(1998, 17) Appendix H of the Resolution requested its Committee on Aviation Environmental Protection (CAEP) "to focus on an en-route levy or a fuel levy to address global emissions." In doing so, it added to the myriad qualifications that ICAO (1996) placed on any potential environmental levy the condition that CAEP take into account "ICAO's policy regarding reciprocal exemption from taxation of aviation fuel"[12]Finally, Appendix H also requested CAEP to take into account "other market-based options such as emissions trading." (ICAO 1998, 18)

In 2001, Assembly Resolution 33-7 (ICAO 2001, 27) acknowledged the findings of an IPCC report on the impact of aviation on the global atmosphere (Penner et al. 1999), including the conclusion that "aircraft are estimated to contribute about 3.5 per cent of the total radiative forcing (a measure of change in climate) by all human activities and this percentage, which excludes the effects of possible changes in cirrus clouds, is projected to grow," and that "although improvements in aircraft and engine technology and the efficiency of the air traffic system will bring environmental benefits, they will not fully offset the effects of the increased emissions resulting from the projected

[12] ICAO policy on this subject is as follows: "When an aircraft registered in one State or leased or chartered by an operator of that State engaged in international air navigation makes successive stops at two or more international airports in one customs territory of another State on its way to another customs territory of that State or to the territory of any other State, the fuel, lubricants and other consumable technical supplies taken on board at any of the airports referred to above shall be exempt from customs and other duties on a reciprocal basis."(ICAO 1994, 7)

growth in aviation." (2001, 27) As such, the ICAO Assembly endorsed "the development of an open emissions trading system for international aviation…" (ICAO 2001, 31) "Open", in this context, refers to a scheme in which the international aviation sector could purchase (and sell) greenhouse gas emissions permits from (and to) other sectors.

A month later, the "EU Environmental Council declared that the EU should take action if no concrete measures were agreed on within ICAO by 2002." (Oberthür 2006, 63)[13] In 2003, the European Commission produced a communication, which stated that "it is not realistic to expect ICAO to take global decisions on uniform, specific measures to be implemented by all nations." (Commission of the European Communities 2005, para. 4.3) The communication went on to note that the inclusion of aviation in the EU-ETS would be a cost-effective way for the sector to meet its emissions reduction goals, and that the sector's inclusion in the scheme would be "compatible with the current international legal framework for aviation." (Commission of the European Communities 2005, para. 6.3) At its sixth meeting in February 2004, the ICAO Committee on Aviation Environmental Protection (CAEP/6), declared that an aviation-specific emissions trading system based on a new legal instrument created by ICAO "…seemed sufficiently unattractive that it should not be pursued further." (European Commission 2006)

Perhaps in anticipation of the EU's response to this finding, Assembly Resolution 35-5 (ICAO 2004) urged "contracting States[14] to refrain from unilateral implementation of greenhouse gas emissions charges prior to the next regular session of the Assembly in 2007, where this matter [would] be considered and discussed again." The Resolution also provided some guidance by asking

[13] In 2003, the European Council permitted Member States to impose taxes on jet fuel sold for domestic flights, and – by mutual agreement – for flights between two Member States. (Council of the European Union 2003, para. Article 14, Paragraph 2)

[14] The European Union is not a State, and therefore not a member of the ICAO, though all the Members States of the EU are. A full discussion of the EU's role at ICAO can be found at: http://ec.europa.eu/transport/modes/air/international_aviation/european_community_icao/index_en.htm

the Council to focus on two approaches. One was a voluntary international trading scheme run by ICAO, and the second a set of guidelines under which States would incorporate emissions from international aviation in their own emissions trading schemes.

In 2006, the European Commission put forth a proposal for the inclusion of aviation in its ETS. Crucially, the proposal recommended, "From 2012, emissions from all flights arriving at and departing from Community airports should be included."(Commission of the European Communities 2006, para. 5(11)) As such, the EU was asserting that its directive would apply even to flights with origins or destinations in non-EU countries,[15] and even if such flights were operated by carriers from outside the EU. The Commission noted that the proposed directive would not come into force until after the next Assembly session in 2007, in which the ICAO would "discuss and consider" the matter of the market-based mechanism to control greenhouse gas emissions from international aviation. The proposal noted that the ICAO's guidance would be taken into account in developing the EU's final directive, and that it was meant to serve as "a model for aviation emissions trading that [could] be a point of reference in the EU's contacts with key international partners and to promote the development of similar systems worldwide." It also said that the Commission supported "the objective of a global agreement aimed at effectively tackling aviation emissions." (2006, para. 1)

In Assembly Resolution 36-22 (ICAO 2007, Appendix J), note is taken that "different regions of the world are experiencing wide differences in absolute levels of aviation emissions and aviation emissions growth rates both internationally and domestically," and that the "Kyoto Protocol provides for different flexible instruments (such as the Clean Development Mechanism — CDM) which would benefit projects involving developing States." While previous resolutions invoked

[15] If the flight had both origin and destination outside the EU, it would not be included in the ETS.

ICAO's non-discrimination principle, Resolution 36-22 appears to acknowledge that developing countries' contributions to the problem are different from those of developed countries, and that special attention would have to be paid to their needs to insure their participation in any ICAO mechanism. The resolution requested the ICAO council to form a broadly representative Group on International Aviation and Climate Change (GIACC) which would make consensus recommendations to the Council on an "aggressive" program of action, which would include voluntary measures, equipment, operational efficiency and air traffic management improvements, as well as "positive economic incentives" and market-based measures. On the latter, the Assembly urged "Contracting States [presumably members of the European Union] not to implement an emissions trading system on other Contracting States' aircraft operators except on the basis of mutual agreement between those States." (2007, Appendix L) Appendix L of the resolution asked the Council to examine the potential of carbon offset mechanisms, while also inviting Contracting States to explore the use of the Clean Development Mechanism in this context. In response, Portugal, on behalf of the European Community (EC) and States Members of the European Civil Aviation Conference (ECAC), expressed "in the strongest terms…great disappointment with the lack of ambition and concrete actions in the resolutions tackling greenhouse gas emissions being adopted" by the ICAO Assembly (ICAO 2008b, 2). They declared "no meaningful effort has been made to reflect in Appendix L the views" of the EC and the ECAC; and therefore, they "reserve the right under the Chicago Convention to enact and apply market-based measures… on a non-discriminatory basis to all operators of all States providing services to, from or within their territory." (2008b, 2)

ICAO then issued a series of guidelines on the use of emissions trading for aviation. Among other things, the guidance recommended that the "accountable entities" under an emissions trading scheme be aircraft operators[16] (ICAO 2008a, 2–4). The guidance also made recommendations for the setting of *de minimis* thresholds,[17]and suggested that at least initially, trading schemes be based on CO_2 emissions rather than those of other species (e.g., oxides of nitrogen). (ICAO 2008a, 2–8)

In 2009, the GIACC outlined a gamut of measures - running from technology development, to improved air traffic management and infrastructure use, more efficient operations, and market-based measures - and argued that ICAO ought to consider these in its quest to control greenhouse gas emissions from international aviation. (ICAO 2009b) A high-level ICAO meeting declared that the aviation sector would work "through ICAO to achieve a global annual average fuel efficiency improvement of 2 per cent over the medium term until 2020 and an aspirational global fuel efficiency improvement rate of 2 per cent per annum in the long term from 2021 to 2050, calculated on the basis of volume of fuel used per revenue tonne kilometer performed," while asserting that these or other "aspirational" efficiency goals would not "attribute specific obligations to individual States." Furthermore, ICAO said that it would "establish a process to develop a framework for market based measures in international aviation." (ICAO 2009c, A–2) The same document noted "the collective commitments announced by ACI, CANSO, IATA and ICCAIA[18] on behalf of the international air transport industry to continuously improve CO_2 efficiency by an average of 1.5 per cent per annum from 2009 until 2020, to achieve carbon neutral growth from 2020 and reducing its carbon emissions by 50 per cent by 2050 compared to 2005 levels."(ICAO 2009c, A–1,2) Finally, it

[16] As opposed to, say, national regulators, fuel suppliers or airports. The aircraft operator could be identified by the ICAO designator (a three-letter code given each airline) used in the flight plan, or the holder of the Air Operations Certificate (AOC) of the aircraft. Such elaborate guidelines were needed to ensure that rules were in place to attribute emissions for, for example, code-sharing arrangements.

[17] These choices are consequential, as is demonstrated in Chapter 4:.

[18] Airports Council International (ACI), Civil Air Navigation Services Organization (CANSO), International Air Transport Association (IATA), International Coordinating Council of Aerospace Industries Associations (ICCAIA).

was recommended that the ICAO council “seek to develop a global CO_2 Standard for new aircraft types consistent with CAEP recommendations.” (ICAO 2009c, B–1)

In July 2010, the Air Transport Association (ATA) of America, along with United, Continental and American Airlines had sued The [British][19] Secretary of State for Energy and Climate Change in a UK High Court, questioning the legality of the EU’s right to regulate foreign airlines under the EU-ETS. The case was referred to the European Court of Justice (ECJ), which was asked to determine whether one or more of a large number of “rules of international law [were] capable of being relied upon…to challenge the validity” of the EU Directive’s attempt “to include aviation activities within the EU Emissions Trading Scheme.”(European Court of Justice 2010) In order to have the Directive pronounced contrary to international law, the applicants in the case hoped to invoke principles including the sovereignty of a country over its air space, the freedom to flyover the high seas, several articles of the Chicago Convention, the Open Skies Agreement between the EU and the US, as well as Article 2.2 of the Kyoto Protocol.

In Assembly Resolution A37-19, ICAO recognized that its aspirational goals were “unlikely to deliver the level of reduction necessary to stabilize and then reduce aviation’s absolute emissions contribution to climate change, and that goals of more ambition will need to be considered to deliver a sustainable path for aviation.”(ICAO 2010, I–68) The Assembly recommended that the Council place emphasis on those policy options, which would reduce emissions without retarding the growth of air transport, “especially in developing economies.”(2010, I–70) The Resolution also requested the ICAO Council to develop a framework for market-based measures (MBM) based on certain guiding principles that were listed in an Annex to the Resolution. These included a recommendation that the proposed MBM “recognize past and future achievements and investments

[19] Under provisions of the EU-ETS, the responsibility for administering the EU-ETS for US airlines fell upon the Department of Energy and Climate Change (DECC) of the government of the United Kingdom. As such, in the first instance, ATA and the three US airlines sued the Secretary of State for DECC in a British court.

in aviation fuel efficiency and in other measures to reduce aviation emissions," that it enable "appropriate access to all carbon markets," and that any revenues generated from such measures "be applied…to mitigating the environmental impact of aircraft engine emissions, including mitigation and adaptation, as well as assistance to and support for developing States."(2010, I–74)

In a November 2011 meeting the ICAO Council, which consists of several members of the European Union, declared its opposition to the EU's plan to extend the EU-ETS to flights by non-EU carriers if they landed in or took off from airports in the territory of EU Member States on the grounds that it was "inconsistent with applicable international law." (ICAO 2011, Appendix, p26) The European States registered a reservation to this declaration, clearly indicating that they intended to proceed with the implementation of their plan to include a portion of international aviation activity in the EU-ETS.

In December 2011, the European Court of Justice ruled that its examination of the EU's directive to include aviation in the ETS had "disclosed no factor of such a kind as to affect its validity," thereby declaring it compatible with international law. (European Court of Justice 2011) In February 2012 (IISD Reporting Services 2012), 23 countries (including the United States, India, and China), after meeting in Moscow, adopted the position that "the EU and its Member States must cease application of the [EU-ETS] to airlines/ aircraft operators registered in third States" and strongly urged "EU Member States to work constructively forthwith in ICAO on a multilateral approach to address international civil aviation emissions."[20]Significantly, the United States Senate passed S.1956 (Thune 2012), an act to "prohibit operators of civil aircraft of the United States from participating in the European Union's emissions trading scheme," which required the US Secretary of Transport to not only order such a prohibition but also hold US airlines harmless from the fines

[20] The authentic text of this declaration is in Russian, and is available at the website of the Ministry of Transport of the Russian Federation (http://www.mintrans.ru/news/detail.php?ELEMENT_ID=17629) The translation quoted here is from the commercial website http://www.ruaviation.com/docs/1/2012/2/22/50/

they would accrue on account of their non-participation in the EU-ETS. China threatened to withhold aircraft orders from Airbus. (Lewis and Volcovici 2012)

The impasse was broken by an ICAO Council decision "to prepare and deliver both the MBM Framework and Feasibility Report for consideration by its next triennial Assembly in October 2013." (ICAO 2012b) In response, the EU "stopped the clock" on the mechanism, meaning that it would not "require allowances to be surrendered in April 2013 for emissions from such flights during the whole of 2012," while warning that if ICAO failed "to move forward," the EU Directive would be applied in full from 2013 onwards. (European Commission 2012)

A 2013 feasibility report (ICAO 2013a) evaluated three potential mechanisms[21] and found that all could be implemented without a large economic cost. In particular, the traffic level under a mechanism that stabilized net emissions at 2020 levels would be at most 1 percent lower than that without it, and revenues would be less than 1 percent lower. The study also found that the differences in impacts between regions would be small; in particular, least-developed countries would not be disproportionately affected.

In response to Resolution A37-19, CAEP had published a fact sheet on an aircraft CO_2 emissions standard metric. (ICAO 2012a) Resolution 38-18 of the ICAO Assembly requested the Council to finalize the analysis needed to develop a standard by 2015, so that it could be adopted in 2016. (ICAO 2013c, I–75) The Resolution also requested the Council to present a market-based mechanism for the Assembly's consideration the next time it met (in 2016), with a view to making it effective from 2020 onwards. As before, the Resolution laid out guiding principles for the design and implementation of market-based measures. These were identical to the principles laid out in Resolution 37-19, except for the additional provision that the mechanism "take into account the principle of common but differentiated responsibilities and respective capabilities, the special

[21] Mandatory offsetting, mandatory offsetting with revenue (for instance, by applying a CO_2 "fee"), and global emissions trading

circumstances and respective capabilities, and the principle of non-discrimination and equal and fair opportunities." (ICAO 2013c, I–77) While past Resolutions (e.g., A36-22, ICAO 2007, I–68) have acknowledged common but differentiated responsibilities (CBDR) as a principle of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, as well as differences between the contributions of different States to past and future emissions, Resolution 38-18 represents the first time CBDR has been explicitly presented as a guiding principle for ICAO policy.

The European Union, after considering (European Commission 2013c) the possibility of applying the EU-ETS to all flights within the EU as well as those portions of flights to and from Europe that take place in EU airspace, has – until 2016 – restricted the application of the scheme to flights within the European Community. (The European Parliament and Council 2014)

Since then, ICAO has drawn a "strawman" document, which describes an initial proposal for its market-based mechanism. The implications of this document are analyzed in Chapter 4:.

2.2 Greenhouse gas emissions from international shipping

Article 1(a) of the Convention on the International Maritime Organization (IMO) declares that the purpose of the organization is "to encourage and facilitate the general adoption of the highest practicable standards in matters concerning the maritime safety, efficiency of navigation and prevention and control of marine pollution from ships." (IMO 2002) In 1973, the International Convention for the Prevention of Pollution from Ships (MARPOL) was adopted at IMO, and dealt with "pollution by oil, chemicals, harmful substances in packaged form, sewage and garbage."[22] Before MARPOL came into force, the Protocol of 1978 -- which was concerned with the safety of

[22] See IMO's history of amendments to the MARPOL at: http://tinyurl.com/mzsne2b

tankers -- was adopted in response to accidental spillages.[23]The first five annexes of MARPOL, which dealt with either liquid or solid discharges of pollutants into the water, came into force between 1983 and 2003.[24]

In 1979, the United Nations Economic Commission for Europe (UN ECE) recognized in its Convention on Long-range Transboundary Air Pollution the adverse "effects of sulphur compounds and other major air pollutants on human health and the environment," and resolved to monitor and evaluate the long-range transmission of air pollutants in Europe. In particular, such long range transmission included pollutants whose physical origin was in one jurisdiction, but whose effects were felt in an "area under the jurisdiction of another State at such a distance that it is not generally possible to distinguish the contribution of individual emission sources or groups of sources." (UN ECE 1979) Recognizing that ships were a significant source of the types of pollutants described in the 1979 Convention as well as sources of ozone-depleting substances, in 1991 the IMO Assembly passed Resolution A.719(17), which asked the IMO's Marine Environment Protection Committee (MEPC) as well as governments to take measures to reduce the emissions of such pollutants from ships. These measures included the establishment of standards to reduce the sulfur content of marine fuels. Importantly, the Resolution asked the MEPC to draft a new annex to the MARPOL to codify its regulations on the control of air pollution from ships. (IMO 1991)

Annex VI to MARPOL, which was adopted in 1997 and came into force in 2005, sets standards for the fuel content and mode of operation of marine engines in order to limit and progressively

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[23] The EU successfully pushed the IMO to bring these regulations into force sooner than it had originally planned. (van Leeuwen and Kern 2012) As in the case of ICAO, environmental regulation at the IMO has often gained impetus by the threat of regulatory competition from the European Union.

[24] See IMO's page on MARPOL at: http://tinyurl.com/pqhucqs

reduce their emissions of the oxides of nitrogen and sulfur.[25] Resolution 8 on the CO_2 emissions from ships of the 1997 MARPOL Conference resulted in the production of a report (Skjølsvik et al. 2000), which concluded that in 1996 marine shipping was responsible for 1.8% of all global CO_2 emissions.[26]The report demonstrated, through a case study, that technical and operational measures would not be able to offset the growth in shipping emissions anticipated as a result of the growth in the global economy and global trade. However, it described various avenues by which the IMO could catalyze the pursuit of such measures. In addition to recommending that ship owners enter into voluntary agreements with the IMO to reduce emissions and that the IMO produce an efficiency standard for new and perhaps even existing ships, the report proposed a mechanism by which those who implemented "additional abatement measures…on new and possibly also on existing vessels" (2000, 9) would receive tradable credits.

The report triggered a series of efforts at the IMO to address the problem of greenhouse gas emissions from ocean shipping. The work done in this area by the IMO up to October 2011 is documented in great detail in IMO (2011) - a document produced at the time of the 61st meeting of the Marine Environmental Protection Committee (MEPC), which the interested reader is referred to – and will not be described here.

By July 2011, IMO had adopted a new chapter to Annex VI of MARPOL that defined mandatory measures to reduce greenhouse gas emissions from shipping. (IMO 2011a) These include an Energy Efficiency Design Index (EEDI) that would quantify the efficiency of new ships, and a Ship Energy Efficiency Management Plan (SEEMP) that would apply to the operation of existing ships. The new regulations, which would come into force in Jan 2013, required that by 2025, large

[25] See IMO's outline of MARPOL Annex VI at: http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx

[26] By 2007, shipping's contribution had risen to 3.3% of global CO_2 emissions (Ø. Buhaug et al. 2009), and – over the 2007-12 period – shipping accounted for, on average, 3.1% of annual global CO_2 emissions. (Smith et al. 2014)

new ships be 30% more efficient than a pre-defined baseline. While they required existing ships to have an SEEMP, and various measures were to be put in place to educate ship owners and operators and encourage them to operate their vessels more efficiently, the regulations set no compulsory targets for existing ships. The IMO's own studies showed that, even in an optimistic scenario – that is, one in which fuel prices remained high, and both EEDI and SEEMP measures enjoyed a high level of uptake – CO_2 emissions from shipping would rise to well over two times their 2010 levels by 2050. (Bazari and Longva 2011)

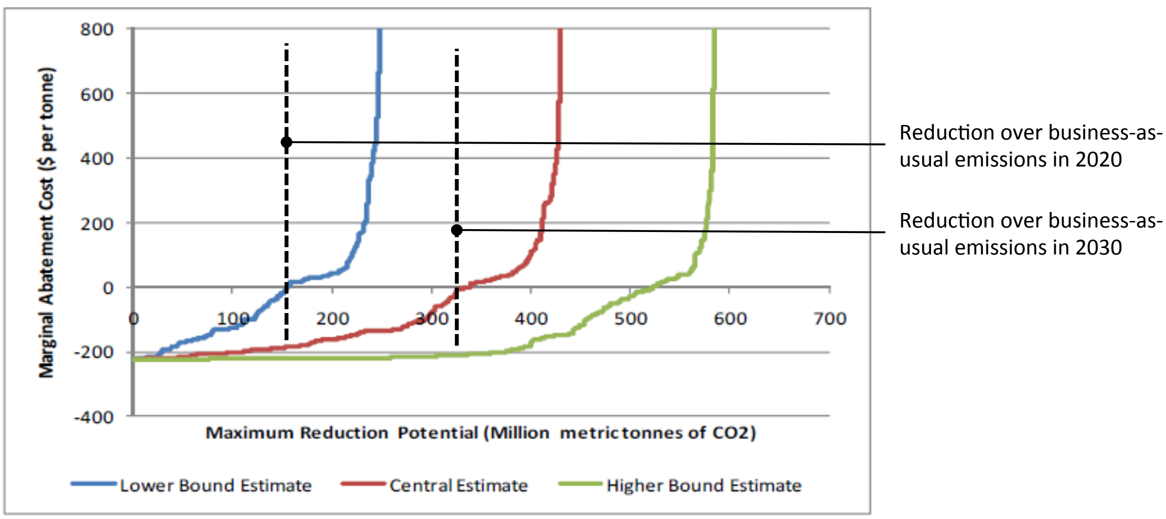

Figure 6-1: Aggregated MACC in 2020 with $700 per ton fuel price and 10% discount rate for all ship types.

Figure 2.1: The IMO anticipates that its mandatory measures will reduce CO_2 emissions relative to business as usual by 150 million tonnes a year by 2020 and 330 million tonnes a year by 2030 (Bazari and Longva 2011, Table iii (page 4)). Reductions of this magnitude would likely be accompanied by economic savings, based on a marginal abatement cost curve for 2020 that assumes a fuel price of $700 per tonne. (Wang et al. 2011)

Work on marginal abatement cost curves (Figure 2.1) for shipping (Wang et al. 2011, 70) shows that – up to 2020, and perhaps as far out as 2030 - the reduction in CO_2 emissions that would be achieved by the two mandatory measures would most likely be accompanied by a monetary saving. That is, the efficiency standards were set so that it would be in the economic interests of ship owners and operators to achieve them even if they were not mandatory. Of course, this analysis assumed a certain fuel price ($700 per ton). The incentive to become more efficient would be reduced if the price were to fall substantially below this level, and the mandatory rules would ensure that the efficiency gains were made even in this case. A 2010 study (IMO 2010) by an expert group had concluded that a wide variety of market-based mechanisms to control shipping emissions would be feasible. Even so, at the 63rd meeting of the MEPC, several developing countries emphasized the need for further analysis of the impact of any cap on greenhouse gas emissions on their trade activities.[27] (IMO 2012a, para. 5.10, 5.13.1) Interestingly, unlike ICAO, the IMO MEPC expressed a "general preference" (IMO 2012a, para. 5.31) for a mechanism that generated revenues that fed into climate change funds set up under the auspices of the UNFCCC, although the view that an IMO mechanism should not be used as a source for general climate finance was also expressed. (IMO 2012a, para. 5.34.3) Finally, while the Secretariat of the World Trade Organization expressed the view that an IMO market-based mechanism was compatible with the Organization's rules, a number of delegations to the IMO (notably, India) maintained that there could possibly be an incompatibility between an MBM and WTO rules. (IMO 2012a, para. 5.38–5.39)

The 64th Meeting of the MEPC, held in October 2012, discussed the progress (in terms of defining standards, and availability of facilities) of providing shore power (the subject of Chapter 5:) and concluded that "ports equipped with on-shore power supply are limited and mandatory requirements for the on-shore power supply should not be developed at this stage." (IMO 2012b, para. 4.57)

In the context of market-based mechanisms, the delegations from Brazil, China, India, Peru, Saudi Arabia, and South Africa emphasized the importance of making decisions by consensus and

[27] Independent researchers have conducted such analyses, with an emphasis on developing country impacts, and found that such impacts would be slight. (e.g., Anger et al. 2013) Analysis by the UN's high-level advisory group of climate change financing (AGF), suggested that putting a price of $45 on each ton of CO_2 emissions from marine transport would have a minimal impact on the prices of commodities. For low-value commodities such as jute shipped from Bangladesh to Europe, the price would rise by about 2%. For high-value commodities such as coffee, the rise in price would be about 0.2%. (AGF 2010b, 38)

respecting the principle of common but differentiated responsibilities (CBDR). The delegations asked that priority be given to "an ambitious MEPC resolution to ensure that financial, technological and capacity-building support from developed countries for the implementation of regulations on energy efficiency for ships by developing countries is provided," (IMO 2012b, para. 5.12) and that further decisions on market-based mechanisms be taken only after such a resolution was adopted. In light of this request, further discussion of market-based mechanisms was postponed to the next meeting of the MEPC. (2012b, para. 5.15) The 65th meeting of the MEPC, held in May 2013, continued to refine the mandatory performance measures adopted in 2011, but "agreed to suspend discussions on Market-Based Measures and related issues to a future session…" (IMO 2013, para. 5.1) The 66th meeting (IMO 2014a) of the MEPC focused on the terms of reference for the Third IMO Greenhouse Gas Study (Smith et al. 2014) and the 67th meeting (IMO 2014b) discussed its results. While both meetings featured discussions about the implementation and design of the measures to improve the efficiency of ships, no mention was made at either meeting of a market-based mechanism. A key finding of Smith et al. (2014) is that during the 2007-12 period, ships had slowed by 12%, resulting in a drop in daily fuel consumption of 27%. Clearly, the reduction in fuel use per unit of transport service (e.g., tonne-mile) was smaller (as cargo was transported more slowly) but still substantial (~(1-27%)/(1-12%) = 20%). This trend was bolstered by high fuel prices during this period and the availability of capacity (i.e., historically low fleet productivity). Both trends could be reversed, setting emissions on a higher trajectory.

In 2009, the European Union had declared that, if no international emissions reductions targets were set by the IMO by the end of December 2011, it would initiate a process to include international shipping in the EU ETS. As a first step, the EU proposed that it would set up a mandatory monitoring, reporting, and verification (MRV) system for voyages within the European Union, as well as all voyages into and out of EU ports. It was anticipated that such a regulation would induce a 2% reduction greenhouse gas emissions, accompanied by cumulative savings of up to €1.2 billion by 2030. (European Commission 2013a)

As such, as things stand, the maritime transport sector has achieved a potentially temporary stabilization in CO_2 emissions mainly by reducing speed. Mandatory efficiency standards mean that emissions will grow somewhat more slowly than they otherwise might have, but are still very likely to more than double by 2050. A market-based mechanism that, for example, allowed the sector to offset its emissions by paying for reductions in other sectors where such reductions are less expensive to make does not seem to be in the offing.

Chapter 3: THE COSTS AND BENEFITS OF REDUCING FUEL BURN AND EMISSIONS FROM TAXIING AIRCRAFT

Abstract

Aircraft are powered by their main engines while taxiing. This paper estimates the cost and emissions reductions that could be achieved by using tugs, or an electric motor embedded in the landing gear, to propel the aircraft on the ground. The use of tugs would result in a saving of $20 per tonne of CO_2 emissions avoided, if the measure were adopted for all domestic flights. Estimates of average net savings for airlines vary from $100 per flight at JFK to a loss of $160 per flight at Honolulu. Electric taxi would save between $30 and $240 per tonne of CO_2 emissions avoided. Either approach could reduce CO_2 emissions from domestic flights in the U.S. by about 1.5 million tonnes each year, or about 1.1% of the total emissions from domestic aviation in 2006. If the switch were limited to large narrowbody aircraft on domestic service at the busiest airports in the U.S., the total reduction in emissions would be 0.5 million tonnes CO_2 annually, accompanied by a saving of $100 per tonne. Air quality benefits associated with lower main engine use were monetized using the Air Pollution Emission Experiments and Policy (APEEP) model, and ranged from over $500 per flight in the New York area to just over $20 per flight in the Dallas Fort Worth area. The analysis also demonstrates that emissions reductions from different interventions (e.g., single-engine taxi and the use of tugs) are often not independent of each other, and therefore cannot be combined in a simple way.

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3.1 Introduction

As discussed in Chapter 1:, there are compelling environmental reasons for airlines to seek ways in which to reduce their fuel consumption. Airlines also have a strong economic incentive to reduce fuel consumption. In 2010, fuel costs constituted 30% of US airlines' expenses, and consumed 29% of passenger revenue. (BTS 2011a) The pressure on airlines to reduce their environmental footprint is likely to continue to grow.

In this context, it is important for airlines and policymakers to understand the magnitude of emissions reductions that could be achieved by different measures, as well as what it would cost to achieve such reductions.

3.2 Prior work

McKinsey & Company (2009) estimates that, in the global aviation industry, "measures costing less than €60 per tonne of CO_2 have an abatement potential of 0.36GtCO_2 per year in 2030, or 24 per cent [of total emissions]…"

Schäfer et al. (2011) estimate the emissions reductions and associated costs of three technological improvements: (a) A more advanced narrow-body aircraft: 17g CO_2[28] of savings per passenger kilometer (pkm) at zero marginal cost per tonne of emissions avoided, (b) Fast open-rotor aircraft: 27.2g CO_2 per pkm at a cost of €171 per tCO_2, and (c) Reduced-speed open-rotor aircraft: 34g CO_2 per pkm at €158 per tCO_2.

Morris et al. (2009) calculate that 0.6 million tonnes, or 23% of the UK's total emissions from domestic aviation in 2020, could be cut in ways that reduce costs. Projected savings ranged from £187[29] per tCO_2 emissions avoided through the better use of capacity to £20 per tonne of emissions avoided by more efficient air traffic management. Of the measures with a positive cost, the least

[28] Baseline emissions are 76gCO_2 per passenger kilometer

[29] Morris et al. assumed an exchange rate of \$1.86 to £1

expensive was the fitting of winglets wherever possible, at a cost of £20 per tCO_2. The most expensive measures included the replacement of old engines with the newest ones (£206 per tCO_2) and the early retirement of aircraft (£497 per tCO_2). The full range of measures considered would result in emissions reductions of 1.4 million tCO_2, or about 54% of the total.

This paper estimates the reduction in fuel burn and CO_2 emissions that could be achieved if aircraft were to taxi without the use of their main engines, as well as the costs of two alternatives. The first is the use of a tug to tow the aircraft from the gate to the start of the runway. The second is an electric taxi (e-taxi) system, which uses an electric motor – embedded in the aircraft's landing gear, and powered by its auxiliary power unit (APU) – to propel the aircraft on the ground. The comparison is made by considering domestic flights operated by major airlines in the United States in 2011.

Deonandan and Balakrishnan (2010) estimate reductions in fuel burn that accrue from using only one engine while taxiing out. They consider domestic commercial flights departing from the fifty busiest airports in the United States, and conclude that fuel use and emissions from ground operations could be cut by between 25% and 40% by taxiing out with only one engine running. They also calculate that towing aircraft out to the runway before take-off would reduce jet fuel burn by about 75%. Fuchte et al. (2011) estimate that an electric taxi system installed on a Boeing 737 or Airbus A320 aircraft on domestic service would reduce fuel burn by between 1.1% and 3.9%.

3.3 METHODS & DATA

The scenarios compared in this paper are described below.

3.3.1 Baseline scenario

Over half the commercial pilots surveyed by Clewlow, Balakrishnan, and Reynolds (2010) said that more than 75% of the time, they taxied in (after landing) with only one engine running.

However, a majority of pilots reported that, more than 90% of the time, they taxied out (before take-off) with both[30] engines running. Clewlow, Balakrishnan, and Reynolds (2010) also found that pilots ran both engines for an average of three minutes after landing, to allow them to cool down. As such, it is assumed in the Baseline scenario (Figure 3.1) that aircraft taxied out with both main engines operating, but that while taxiing in - after the cool-down period - only one engine was run until the aircraft reached the gate. It was also assumed that the aircraft was pushed back from the gate by a tractor, a process that took two minutes.

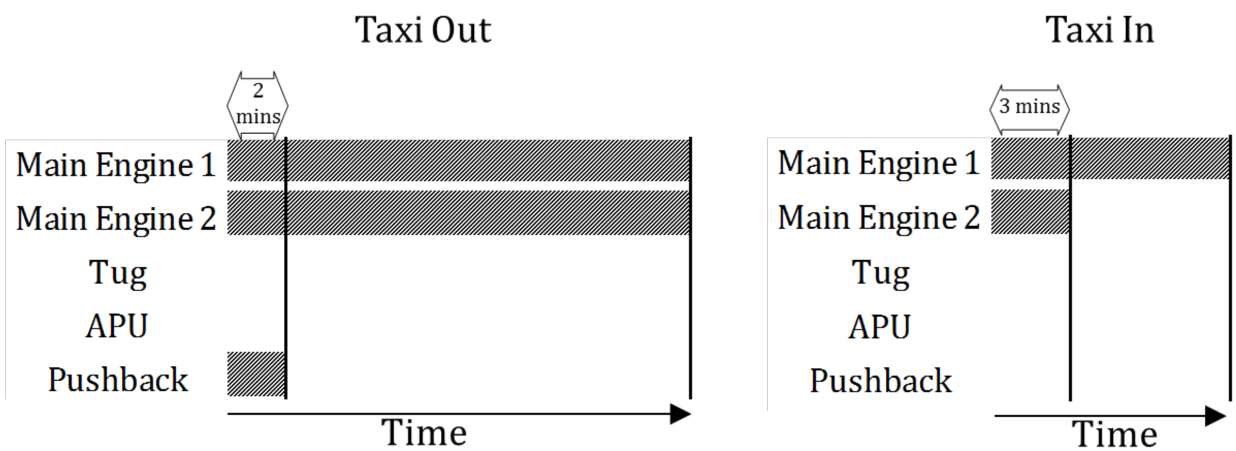

Figure 3.1: Schematic of Baseline scenario. Both engines are operated when the aircraft taxies out. However, both engines are run only for three minutes when the aircraft taxies in, after which the second engine is switched off.

3.3.2 Single-engine taxi scenario

While the practice is currently rare,[31] a variant of the Baseline scenario (Figure 3.2) in which pilots taxied out with one engine was also considered. Tedrow (2008) indicates that airlines instruct pilots to taxi with one engine as often as possible, and it is likely that the approach will become more widely adopted. It was assumed that both engines were run for an average of five minutes before take-off, a duration called the spool-up time. (Clewlow, Balakrishnan, and Reynolds 2010)

[30] In the dataset used in this analysis, all aircraft on domestic service were two-engined.
[31] In addition to Clewlow et al., research by Page et al. (2009, 10) suggests that single-engine taxi-out is relatively rare

The time for which the main engines must be run was calculated for each flight. For example, if an aircraft taxied for precisely three minutes on its way in, it was assumed that both its engines would be operated throughout the duration of taxi. Fuel burn and emissions were calculated for a total of six minutes (three times two engines) of main engine operation. If it taxied for longer – say, five minutes - it was assumed that one engine was run for the entire five minutes, while the other was run for only two. As such, fuel burn and emissions were calculated for a total of seven minutes of engine run-time. In the Baseline and Single-engine taxi scenarios, it was assumed that both engines were or one engine was, respectively, operating at the moment the aircraft backed away from the gate.

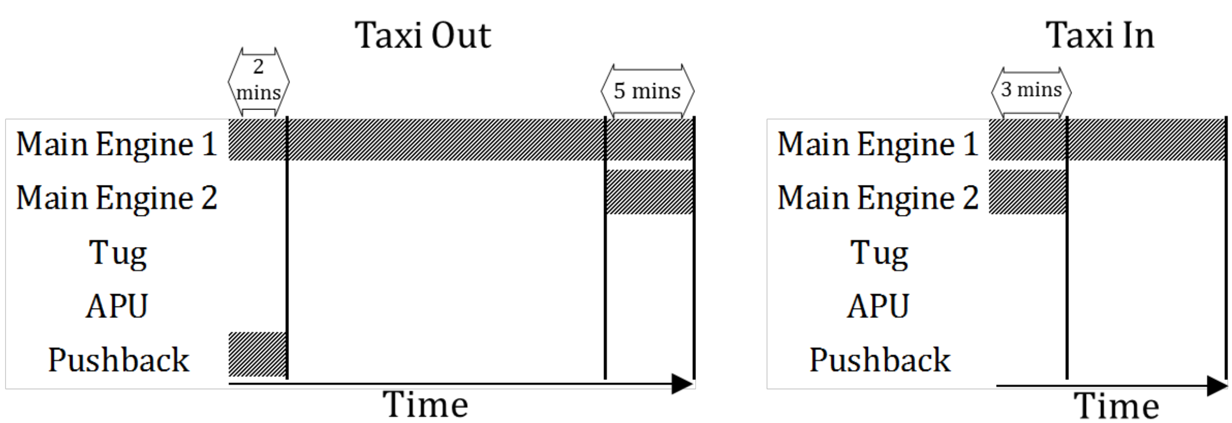

Figure 3.2: Schematic of the Single-engine taxi scenario. One of the main engines is used only for five minutes before take-off (to allow it to warm up) and for three minutes after landing (to allow it to cool down).

3.3.3 Tug scenario

In the Tug scenario (Figure 3.3), it was assumed that aircraft were towed from the gate to the runway by a tug powered by diesel. This process is called dispatch towing.[32] It was also assumed that the aircraft's APU, which is typically turned off during taxi if either of the main engines is on, was

[32] Aircraft taxi-in times are significantly shorter than taxi-out times, and the use of single-engine taxi is much more common during taxi-in than taxi-out. (Clewlow, Balakrishnan, and Reynolds 2010) As such, the fuel savings from using tugs for taxi-in would be small. Furthermore, ensuring that a tug is available to meet an aircraft a few minutes after it lands is operationally complex. As such, I assume that tugs would only be used to tow aircraft out to the runway before take-off, and not back to the gate after landing.

operated. The APU supplies bleed air to run the aircraft's air cycle machine, and power for its electrical systems.

Two variants of the Tug scenario were considered. The first assumed that tugs would be used to tow every domestic flight.

In fact, the use of tugs would likely be curtailed by two factors. First, as described in the section on operational issues below, only one manufacturer produces a tug that is designed to be used for operational dispatch towing. This tug is engineered to operate only with aircraft that are at least as large as the Airbus A318. Second, it costs $1.5 million to acquire and is expensive to maintain. As such, for flights with short taxi times (e.g., those departing from uncongested airports), the capital and maintenance costs of the tug are likely to exceed the fuel savings its use generates. As such, a second variant of the tug scenario was considered, in which tugs were only used to tow aircraft at least as large as the Airbus A318, and were deployed only at those of the 50 busiest airports in the U.S. where it was economical to do so.

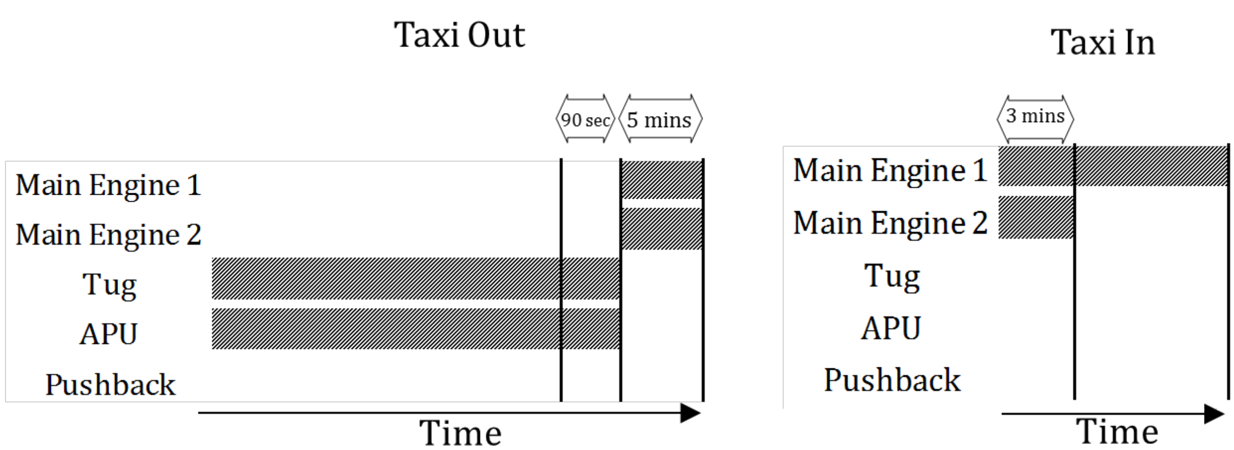

Figure 3.3: Schematic of Tug scenario. The main engines are used only for five minutes before take-off and for three minutes after landing. It is assumed that an additional 90 seconds are needed to detach the tug during taxi out.

3.3.4 Electric taxi scenario

A number of firms (see Honeywell 2011, Crane Aerospace 2012, WheelTug plc 2011, Airbus 2013b) are working on an electric-taxi (e-taxi) system. This analysis estimated the fuel and cost savings that would be achieved by such a system, whose operation is described by the schematic in Figure 3.4: both main engines would be run for a minimum of five minutes on the way out, and three on the way in. The APU would be run the rest of the time. No pushback tractor would be needed as the electric motor would be able to propel the aircraft both backwards and forwards.[33] It was assumed that all aircraft on domestic service are equipped with an electric taxi system with the Baseline and Single-engine taxi scenarios.

In practice, an electric taxi system would be phased in over time, and restricted to aircraft that are operated on routes for which the aircraft spends a significant fraction of the total flight time on the ground.

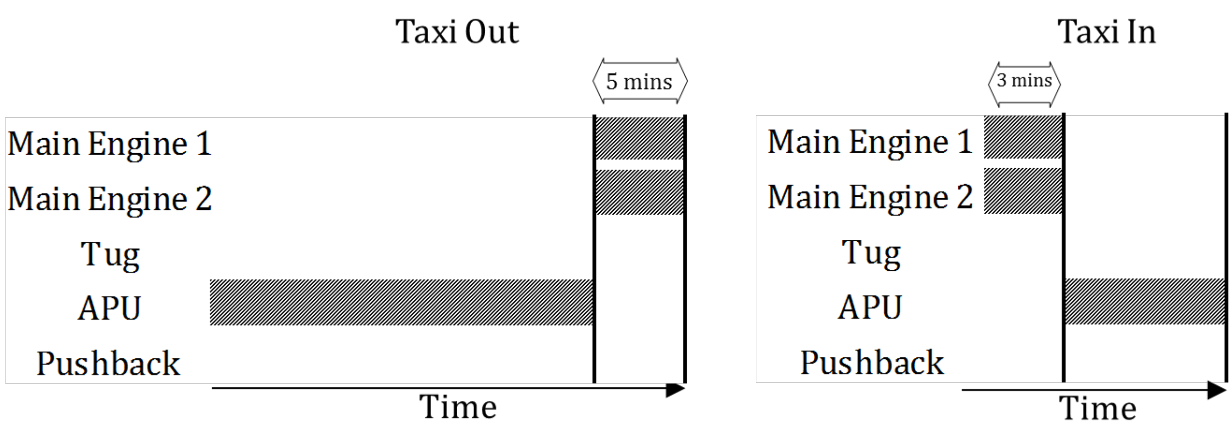

Figure 3.4: Schematic of e-taxi scenario. The main engines are used only for five minutes before take-off and for three minutes after landing.

3.3.5 Costs and benefits

The reduction in main engine fuel burn for each flight was calculated assuming that it went from being propelled by its main engines during taxi to either using a tug or electric taxi. This change in

[33] In fact, this might initially require wing walkers to guide the pilot and prevent tail strikes. Eventually, it may be possible for the aircraft to reverse autonomously, perhaps with the help of a rear-facing camera mounted on the aircraft to assist the pilot.

fuel use was multiplied by the price of jet fuel to arrive at the change in jet fuel cost for the main engines.

This saving was offset by an increase in the cost of jet fuel for the APU in both the Tug and Electric taxi scenarios. The analysis accounted for the capital cost associated with purchasing the tugs or electric taxi systems, and their operating costs. These operating costs included the cost of fuel and maintenance. In the case of the tugs, the cost of employing the personnel required to operate the tug was accounted for. In the case of e-taxi systems, the cost of additional fuel burn associated with carrying the extra weight of the system during cruise was also estimated.

These costs were subtracted from the saving in main engine fuel burn costs to calculate a net saving.

In most cases, there was a net reduction in fuel burn, even when the additional fuel burn for the APU and tug were taken into account. This resulted in lower emissions of CO_2, NO_X, hydrocarbons (HC), and particulate matter (PM).

The cost per tonne of CO_2 emissions avoided was calculated as the negative of the net saving, divided by the quantity of CO_2 emissions avoided in tonnes. This method of quantifying the benefits (or costs) associated with a reduction in CO_2 emissions was used because it facilitates comparison with other ways of reducing greenhouse gas emissions, both in aviation and other sectors.

The benefits associated with a reduction in the emissions of the other pollutants were monetized using the Air Pollution Emission Experiments and Policy analysis model (APEEP, Muller and Mendelsohn 2008). This model gives the marginal cost of emitting an additional ton of NO_x, volatile organic compounds (VOCs, or for the purposes of this analysis, HCs), and PM[34] in each county in the United States. The counties in which each of the 50 busiest airports in the US is situated were

[34] The APEEP model also gives the marginal cost of SO_2 and ammonia emissions, but these are not accounted for in the analysis here (however, see Footnote 105).

identified, and the benefit in improved air quality was calculated based on the APEEP model and the previously-described estimate of the reduction in emissions.

3.3.6 Taxi time

The Bureau of Transportation Statistics (BTS) defines taxi-out time as, "the time elapsed between departure from the origin airport gate and wheels off," and taxi-in time as that "between wheels down and arrival at the destination airport gate."(BTS 2012b)

The taxi times of all domestic flights operated by major airlines – defined as those that "that account for at least one percent of domestic scheduled passenger revenues" – are published by BTS. (BTS 2011b) For 2011, data are available for six million flights, out of a grand total of nine million domestic flights. (BTS 2012a) The latter number includes flights operated by minor airlines.

3.3.7 Main engine fuel burn and emissions

The BTS data (BTS 2011b) include the tail numbers of the aircraft that undertook each flight.[35] A Federal Aviation Administration database (FAA 2012) was used to identify the aircraft type based on the tail number. The engine most commonly associated with a particular aircraft type was identified in a study done by Energy and Environmental Analysis, Inc. (EEA 1995) for the US Environmental Protection Agency (EPA), as well as by referring to the airframe manufacturers' websites.

The International Civil Aviation Organisation (2010) maintains a database of specific fuel consumption and emission indices for a large number of aircraft jet engines. The data are provided

[35] For 14% of the flights, the tail number was not available. For such flights, a "typical" aircraft was assumed. The fuel burn rate for this hypothetical aircraft was calculated by weighting the burn rate for all the other aircraft by the number of flights performed by them, and averaging. Characteristics of all aircraft, including the "typical" aircraft, are given in Table 3.1.

for four levels of thrust, the lowest of which is "idle" or 7% of maximum. The analysis assumed that, when in operation during taxi, main engines were set to this level of thrust.[36]

Table 3.1: Aircraft types on which domestic flights were operated in 2011. The fuel burn for the DeHavilland Dash 8 was calculated based on data provided by the European Environmental Agency (EUEA 2009). The EUEA reports fuel burn for a range of flight durations. The fuel burn per minute for each data point was calculated, and the average used in the model.

Aircraft	Flights	% flights	APU	APU Fuel Burn rate	Engine	Fuel Burn Rate	Number of engines
				kg / min		kg / min / engine	
Airbus A319	332,215	6%	GTCP 36-300	2.1	CFM56-5A1	6.1	2
Airbus A320-100/200	445,963	7%	GTCP 36-300	2.1	CFM56-5A1	6.1	2
Airbus A321	60,653	1%	GTCP 36-300	2.1	CFM56-5-A1	6.1	2
Boeing 717-200	231,595	4%	GTCP 85	1.8	BR700-715C1-30	6.3	2
Boeing 737-300	366,526	6%	GTCP 85-129	1.8	CFM56-3B-2	7.1	2
Boeing 737-400	103,000	2%	GTCP 85-129	1.8	CFM56-3C-1	7.4	2
Boeing 737-500	75,286	1%	GTCP 85-129	1.8	CFM56-3B	7.1	2
Boeing 737-700/700lr	872,162	15%	APU 131-9	1.8	CFM56-7B26	6.8	2
Boeing 737-800	237,196	4%	APU 131-9	1.8	CFM 56-7B27	7	2
Boeing 737-900	58,662	1%	APU 131-9	1.8	CFM 56-7B27	7	2
Boeing 757-200	296,494	5%	GTCP 331-200ER	2	PW2040	9.5	2
Boeing 757-300	37,826	1%	GTCP 331-200ER	2	PW2040	9.5	2
Boeing 767-200/Er/Em	13,784	0%	GTCP 331-200ER	2	CF6-80C2B2	11.5	2
Boeing 767-300/300er	39,510	1%	GTCP 331-200ER	2	CF6-80C2B6	12.4	2
Boeing 767-400/Er	3,601	0%	GTCP 331-200ER	2	CF6-80C2B2	11.5	2
Boeing 777-200/200lr/233lr	7,638	0%	GTCP 331-500	4.1	GE90-77B	18	2
Canadair Crj 900	125,402	2%	GTCP 85	1.8	CF34-8C5	3.9	2
Canadair Rj-100/Rj-100er	536,545	9%	GTCP 36-150	1.1	CF34-3A1	3	2
Canadair Rj-700	246,940	4%	GTCP 85	1.8	CF34-8C1	4.1	2
Embraer 170	4	0%	GTCP 36-150	0.9	CF34-8E	3.7	2
DeHavilland Dash 8	11,799	0%	T-62T-46C1	1.8	PW150A0	7.0[1]	2
Embraer 190	98,990	2%	GTCP 36-150	0.9	CF34-10E	5	2
Embraer-140	122,860	2%	GTCP 36-150	0.9	AE3007C1	2.5	2
Embraer-145	397,899	7%	GTCP 36-150	0.5	AE3007C1	2.5	2
McDonnell Douglas Dc9 Super 80/Md81/82/83/88	314,076	5%	GTCP 85-98	1.8	JT8D-217C	8.2	2
McDonnell Douglas Dc-9-50	44,159	1%	GTCP 85-98	1.8	JT8D-17	8.8	2
McDonnell Douglas Md-90	29,609	0%	APU 131-9	1.8	V2525-D5	7.7	2
"Typical" Aircraft	860,014	14%		1.7		6	Assumed 2

After considering the marginal impact of stops and turns, Khadilkar and Balakrishnan (2011) conclude that fuel burn is determined almost entirely by total taxi time. The emissions of CO_2 are determined by the quantity of fuel burnt. The CO_2 emission index of jet fuel is obtained from a study by the Intergovernmental Panel on Climate Change (IPCC). (Penner et al. 1999) As such, it

[36] Nikoleris, Gupta, and Kistler (2011) have pointed out that the actual thrust setting during taxi may vary between 4% and 9%. However, a study of flight recorder data by Khadilkar and Balakrishnan (2011) suggests that – with the exception of large Airbus aircraft such as the A330 and A340, which are not included in my dataset - assuming a constant thrust level of 7% during taxi yields a good estimate of actual fuel burn, as measured by the flight data recorder.

was assumed throughout the analysis that main engine fuel burn and emissions are determined by the time for which engines are run. The emissions indices for other pollutants (NO_x, HC, and PM) were obtained from Wade (2002).

3.3.8 APU and tug operation time

The APU and tug operation times are a function of taxi time, and engine spool up and cool-down times, as shown in Figure 3.3 and Figure 3.4. They are calculated separately for each flight.

3.3.9 APU fuel consumption and emissions

The models of APU most commonly associated with particular aircraft types were identified using the study by Energy and Environmental Analysis, Inc. (EEA 1995) as well as a more recent study done for Zurich airport. (Fleuti and Hofmann 2005) The rate of fuel burn of the APUs was obtained from these studies, whereas the emissions index was obtained from Wade (2002). These were combined with the estimated run times of the APU in each of the scenarios to calculate fuel burn and emissions.

3.3.10 Tug fuel burn and emissions

As discussed in the section on operational issues, only one manufacturer currently produces a tug that is designed for operational dispatch towing. This tug is powered by diesel. Statistics on fuel burn and emissions for the tug were obtained from the manufacturer. CO_2 emissions were calculated directly based on the fuel burn. (Penner et al. 1999)

3.3.11 Fuel price

For jet fuel and diesel, price data were obtained from the Energy Information Administration. (EIA 2013), (EIA 2011)

3.3.12 Tug capital costs

Each tug costs $1.5 million. This estimate was obtained from the manufacturer, and was amortized over a 10-year period, assuming a discount rate of 7%.[37]

3.3.13 Electric taxi system capital costs

The capital expense associated with retrofitting the system to existing aircraft, or incorporating it into new ones, is not publicly available. Therefore, this value was parameterized and the cost per tonne of CO_2 emissions avoided was calculated, assuming that the system costs between $250,000 and $1,000,000 per aircraft. It was assumed that the system's capital cost is amortized over 20 years at a discount rate of 7% (see footnote 37). Finally, it was assumed that each aircraft performs an average of 3.5 flights per day (Airline Data Project 2013a; Airline Data Project 2013b), 365 days a year.

3.3.14 Tug operating and maintenance costs

Based on discussions with the manufacturer, it was assumed that during its operational life the tug would undergo two major overhauls: one in the fifth year after purchase and another in the tenth. Assuming a discount rate of 7%, the cost of each overhaul was amortized over five years to arrive at an annual cost. In addition, it was assumed that the tug incurs an annual routine maintenance cost of 7.5% of the price of a new tug. Finally, it was assumed that each tug is manned 18 hours a day, and that the tug operator is paid $40 per hour.[38]

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[37] This is the coupon rate of a US Airways bond that matures in 2020 (Morningstar.com 2012).

[38] The analysis is not very sensitive to this assumption: halving the hourly rate increases the average per-flight saving by about 30%.

3.3.15 Electric taxi systems operating and maintenance costs

Maintenance costs were assumed to be 20% of annualized capital expense. It was assumed that the electric taxi system would draw on APU power; as such, the fuel costs associated with using the system were included in APU fuel burn.

3.3.16 Number of tugs needed

Two different versions of the Tug scenario were evaluated. In the first, it was assumed that tugs would be deployed at 300 airports and virtually every domestic flight would be towed from the gate to the runway. In the second it was assumed that tugs would be deployed only at those of the 50 busiest airports in the United States where they saved airlines money. In this second variant of the Tug scenario, it was assumed that tugs would only be used to tow aircraft larger than the Airbus A318.

The following procedure was used to evaluate the number of tugs needed in the first variant of the Tug scenario.

All the domestic flights that departed from each of the 31 busiest airports in July[39] were arranged in chronological order. It was assumed that the tug assigned to the first flight would be unavailable for the duration of time it took for the tug to tow the aircraft to some point close to the edge of the runway, to detach from the aircraft, and then drive back.[40] Each flight that started taxiing between the time that the first tug left from, and returned to, the gate would have to be towed by other tugs. The number of such flights would be an estimate of the number of tugs needed at that point of

[39] July was chosen because aircraft taxied the longest in July for virtually all the airports considered. As such, it was assumed that analysing July data would yield a conservative estimate.

[40] I assumed that this point of detachment was five minutes' taxiing time away from the runway, as the engines would need to be run for this period of time before take-off, in any case. As such, if a flight in the dataset had taxied for 10 minutes, I assume that using a tug to tow it to the edge of the runway would require the use of the tug for 11.5 minutes: 5 (=10-5) minutes to tow the aircraft, 1.5 minutes to detach from it, and 5 minutes to drive back to the gate. In practice, the drive back to the gate should not take very long, as the tug would likely not have to spend any time waiting in the take-off queue, as it would while towing the aircraft out. As such, this is a conservative assumption.

time. Such estimates were obtained for every flight, and analyzed to arrive at the number of tugs that would have been sufficient to meet demand in 95% of the cases.

Once this number was obtained for the 31 busiest airports, an ordinary least squares (OLS) regression model was built to express the number of tugs needed at an airport as a function of the number of departures and the average taxi time there. The model was used to arrive at an estimate of the number of tugs needed at the remaining 270 airports in the dataset (see Section 3.7).[41]

For the second variant of the Tug scenario, the calculation outlined above for each of the 50 busiest airports was repeated. Only domestic flights that were operated on aircraft larger than the Airbus A318 were considered. Initial calculations assuming a 95% service level were performed. However, the service level was then adjusted to ensure that the net saving was maximized. Note that this calculation did not account for the social benefit produced by the reduction in pollution: it was assumed that whoever operated the tugs would operate them to maximize the financial benefit to themselves.

3.3.17 Weight penalty of the electric taxi system

Boeing (2004) published estimates of the percentage change in fuel burn associated with a 1000lb change in the zero fuel take-off weight of each of its major aircraft types. There is a strong correlation between these percentage reductions and the zero fuel weight of the aircraft, as shown in Figure 3.5.

[41] When the model estimated that a non-integer number of tugs was needed, I rounded up to the nearest integer.

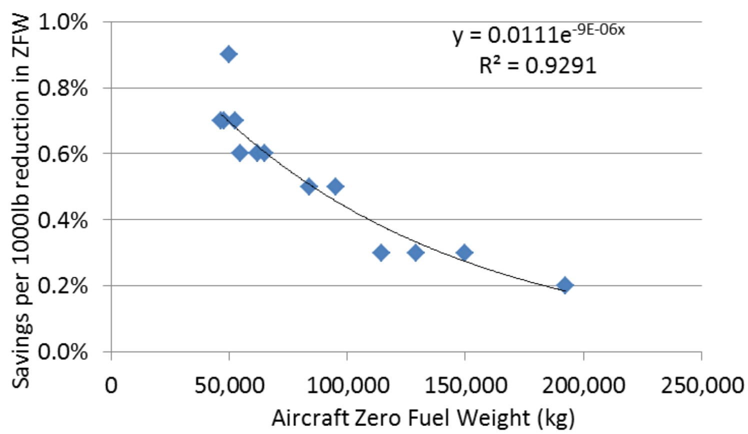

Figure 3.5: Relating the percentage change in fuel burn associated with a 1000lb reduction in zero fuel weight (ZFW) to the total ZFW of the aircraft

Table 3.2: Comparing the model's and Airbus's estimates of weight penalty. According to Airbus the A321 is the most fuel efficient of the A320 class of aircraft (Airbus 2012b), which also includes the A319 and A320. However, baseline fuel burn data were available for the A320 family and not individual members, and this might have contributed to an overestimation of the fuel penalty for this aircraft.

Aircraft	Additional weight (kg)	Stage length (nm)	Fuel penalty – *Airbus data* (kg)	Fuel penalty – *model prediction* (kg)
A319	590	1000	50	52
A320	735	1000	60	62
A321	890	1000	55	68

This correlation was applied to other aircraft types to estimate how much their fuel burn would change with increase in weight. Baseline fuel burn associated with each flight is based on the European Environment Agency's (EUEA 2009) air emissions inventory, which provides typical fuel burn for various aircraft and mission lengths. Additional fuel burn due to the weight of the e-taxi equipment was calculated on the basis of baseline fuel burn and the percentage increase estimated from the Boeing data. It was assumed that a practical electric taxi system would weigh 1000lb, and that the percentage change in fuel burn would vary linearly with weight. In order to validate the model, its predictions were checked against estimates Airbus (2004, 12) published of additional fuel burn associated with a given increase in weight for a number of its aircraft. Meaningful comparisons could be made for only three aircraft types, but the agreement between the model and Airbus's estimates was good. (Table 3.2)

3.4 RESULTS

3.4.1 Switching from the Baseline scenario to the Tug scenario for all domestic flights

If it is assumed that all 6 million domestic flights in the U.S. in the dataset taxied out powered by both engines, using tugs to tow virtually[42] all of them from the gate to the runway would reduce fuel burn by 0.5 million tonnes each year, and CO_2 emissions by 1.7 million tonnes. This would be accompanied by a net saving of $36 million each year. As such, cutting CO_2 emissions in this way would *save* $20 per tonne. This number varies considerably from airport to airport: the cost would be over $1000 per tonne of CO_2 abated at Guam, but the use of tugs would *save* $100 per tonne at Philadelphia International Airport.

3.4.2 Switching from the Single-engine taxi out scenario to the Tug scenario for all domestic flights

If all the domestic flights analyzed were assumed to have taxied out with only one engine save for the final five minutes before take-off, a switch to dispatch towing would reduce fuel use by 0.2 million tonnes per year, and CO_2 emissions by 0.6 million tonnes. However, because of the costs of buying and operating the tugs, net costs would increase by $300 million each year, resulting in a cost of $500 per tonne of CO_2 abated. Clearly, in cases where single-engine taxi-out is the current practice, a switch to using tugs is not economical.

3.4.3 Switching from the Baseline scenario to Tug scenario for large narrowbody aircraft at select airports

An overview of the results of this analysis is given in Table 3.3. The results for Newark Liberty International Airport are discussed in detail here.

[42] Virtually all, because tugs would not be used to tow out the extremely small number of flights (<1% of the total) that have a taxi-out time of less than 5 minutes, and because it is assumed that we only have enough tugs to provide a service level of 95%.

In 2011, about 60,000 flights departed from Newark that were operated on large narrowbody aircraft. Assuming that these taxied out using two engines, this analysis concludes that total net savings would have been maximized if 65%, or 39,000, of these flights had been towed out using a tug. To provide this level of service, seven tugs would have been needed. This would have resulted in a net cost saving of, on average, $80 per flight. This translates to a saving of $3 million each year at Newark.[43] Because taxi times vary considerably between flights, so would the savings. Figure 3.6 illustrates this, and shows that – even at 65% service level – about 30% of the flights that are towed would lose money.

Table 3.3: Net fuel savings of up to $100 per flight would be achieved compared to the Baseline scenario (two-engine taxi-out and one-engine taxi-in) if tugs were used for dispatch taxi. Benefits from improvements in air quality would be dominated by the health benefits associated with the reduction in PM emissions. At airports near densely populated cities such as New York City, these benefits can be almost an order of magnitude higher than those associated with fuel savings. The APEEP model does not give the marginal cost for a ton of emissions for Honolulu County.

Airport	Service level	Tugs	Flights	Avg. per flight benefit from				Average per flight reduction in CO_2 emissions (tonnes)	Cost per tonne CO_2
				Fuel savings	reduction in the emissions of				
					PM	NOx	HC		
ATL	75%	15	86,000	$80	$70	$3	$5	0.6	-130
ORD	75%	8	55,000	$50	$130	$3	$7	0.4	-110
DFW	60%	2	12,000	$20	$40	$5	$4	0.4	-50
DEN	60%	9	90,000	$30	$40	$3	$3	0.3	-90
LAX	55%	5	57,000	$50	$150	$1	$10	0.3	-140
PHX	45%	6	63,000	$30	$20	$3	$2	0.3	-100
IAH	65%	9	48,000	$30	$40	$4	$6	0.5	-70
LAS	75%	9	93,000	$40	$20	$1	$2	0.3	-130
SFO	60%	6	46,000	$60	$110	$2	$10	0.4	-130
CLT	60%	11	50,000	$20	$60	$10	$7	0.5	-40
MCO	55%	5	48,000	$30	$40	$1	$4	0.3	-100
SLC	45%	3	20,000	$40	$60	$3	$5	0.4	-90
EWR	65%	7	39,000	$80	$290	-$2	$30	0.6	-130
BOS	75%	8	45,000	$40	$80	$1	$30	0.5	-90
BWI	60%	4	46,000	$30	$40	$2	$20	0.3	-100
MSP	60%	5	32,000	$30	$60	$30	$20	0.4	-70
SEA	60%	6	51,000	$40	$40	$1	$20	0.4	-110
LGA	65%	7	29,000	$70	$640	-$10	$250	0.7	-100
JFK	70%	8	35,000	$100	$720	-$6	$40	0.8	-130

[43] Note that modifications might need to be made to airport layout and procedures to enable the use of tugs (see the section on operational issues below). I have not accounted for these costs.

DTW	45%	4	21,000	$30	$100	$1	$9	0.5	-70
MDW	60%	4	49,000	$10	$50	-$2	$8	0.2	-60
PHL	45%	5	28,000	$60	$160	$0	$20	0.6	-110
MIA	65%	2	12,000	$40	$25	$1	$2	0.5	-90
SAN	55%	3	32,000	$30	$50	$1	$5	0.3	-100
IAD	55%	3	16,000	$10	$90	$1	$8	0.4	-20
DCA	55%	3	19,000	$40	$70	$1	$4	0.4	-100
TPA	75%	4	39,000	$10	$50	$1	$4	0.2	-50
FLL	70%	5	35,000	$10	$50	$1	$5	0.3	-30
STL	35%	1	12,000	$1	$20	$3	$2	0.2	0
PDX	55%	2	21,000	$20	$20	$2	$2	0.3	-80
BNA	40%	1	12,000	-$2	$10	$1	$1	0.2	10
HOU	35%	1	16,000	$1	$10	$1	$2	0.1	-10
HNL	75%	2	4,000	-$160	-	-	-	0.5	320
MCI	40%	1	11,000	$0	$10	$3	$1	0.2	0
CLE	40%	1	7,000	-$1	$50	$7	$8	0.3	0
MEM	30%	1	3,000	-$120	$30	$3	$2	0.3	330
OAK	40%	1	17,000	$10	$30	$0	$4	0.1	-50
SMF	45%	1	15,000	$10	$20	$2	$2	0.2	-40
DAL	70%	2	29,000	$1	$20	$2	$1	0.1	-10
MKE	45%	1	8,000	-$2	$50	$7	$5	0.2	10
AUS	45%	1	11,000	$10	$10	$2	$1	0.2	-40
RDU	55%	1	9,000	$20	$20	$2	$2	0.3	-60
SNA	65%	2	22,000	$20	$60	$0	$6	0.2	-70
SJC	45%	1	14,000	$2	$30	$1	$4	0.1	-10
SAT	45%	1	10,000	$0	$10	$2	$1	0.2	0
MSY	45%	1	12,000	$2	$10	$2	$0	0.2	-10
ABQ	55%	1	11,000	-$10	$5	$1	$1	0.1	70
PIT	45%	1	8,000	$10	$60	$2	$6	0.3	-30
IND	55%	1	7,000	-$20	$30	$3	$4	0.2	70
JAX	55%	1	8,000	$3	$20	$1	$2	0.3	-10

This assumes that it is not possible to cherry-pick flights with long taxi times. This is reasonable because flights with the longest taxi times are likely to occur during times of congestion. Selectively towing all these flights would result in a larger saving in fuel costs, but also require the purchase of a large number of tugs that would sit idle at other times, reducing net savings. Using a tug could most likely be used to push the aircraft back from the gate, though this would depend on whether there was enough space between the aircraft and the gate for a tug to maneuver. Another determining factor would be the maneuverability of the tug itself: for example, a tug with four-wheel steering would be able to "crawl" sideways under the jet bridges and position itself to push back aircraft as needed. Airlines may currently pay up to $90 per flight for pushback services. As such, the elimination of the need for a separate pushback service could yield a significant saving.

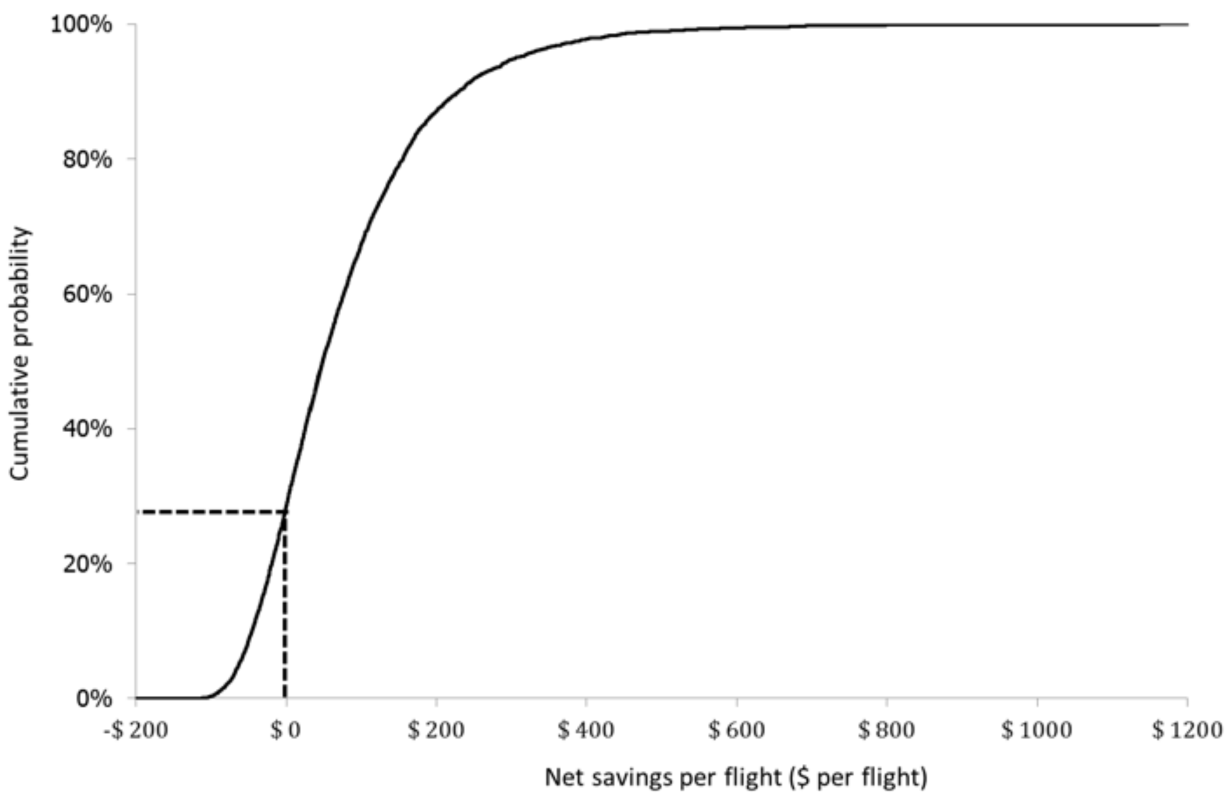

Figure 3.6: Even at a service level of 65%, about 30% of the flights departing from Newark would lose money if towed by tugs. Towing flights which do not taxi very long would reduce savings, whereas towing flights with long taxi times would increase savings. This analysis assumes that it is not possible to cherry-pick flights with long taxi times. This is reasonable because flights with the longest taxi times are likely to occur during times of congestion. Selectively towing all these flights would result in a larger saving in fuel costs, but also require the purchase of a large number of tugs that would sit idle at other times, reducing net savings.

The analysis indicated that the switch to using tugs would reduce emissions of particulate matter by an average of 0.5kg per flight. The APEEP model described above estimates that the mean value of a marginal ton of PM emissions in Union County, NJ is $360,000. As such, the switch to using tugs would generate – on average – a $180 per flight benefit due to reduced PM emissions. Similarly, reducing NO_x emissions is associated with a *cost* of $1,500 per ton, and switching to dispatch towing would reduce them by 0.7 kg per flight. As such, the average *damage* done by using tugs instead of main engines would be $1.10 per flight. Hydrocarbon emissions are valued at $32,000 per marginal ton, and would be reduced by, on average, 0.5kg per flight. As such, using tugs would produce a mean benefit of $16 per flight. Overall, the average air quality benefit at Newark of using tugs would be about $200 per flight. In fact, the marginal cost of emitting a pollutant is highly uncertain, and the APEEP model provides the fifth and ninety-fifth percentile estimates of this cost for each pollutant. To quantify the impact of this uncertainty, this information was used along with the mean, and the marginal cost was assumed to follow a triangular distribution. The air quality benefits per flight also depend on the duration of taxi-out. A log-normal distribution was fitted to the taxi times observed for large narrowbody aircraft at Newark in 2011. A 10,000-run Monte-Carlo simulation was performed in which the marginal cost of each pollutant and the duration of taxi-out was varied with each run. The results are shown in Figure 3.7.

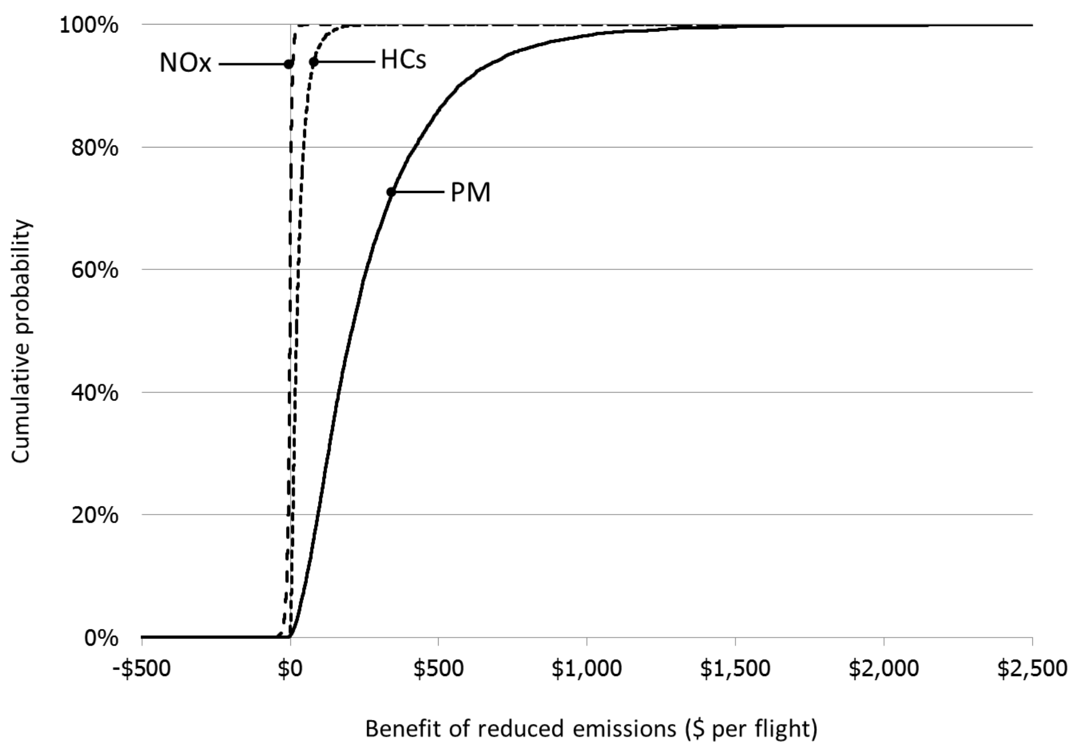

Figure 3.7: Benefits from reduced emission of particulate matter dominate. For about 80% of the flights, these benefits exceed $100 in value.

Using tugs reduces CO_2 emissions from each flight by an average of 0.6 tonnes. This translates to savings of $130 per tonne of CO_2 emissions. The 90% confidence interval for the emissions reduction is 0.15 to 1.33 tonnes of CO_2 per flight, while that for the net cost is from a saving of $230 to a cost of $400 per flight. Apart from the marginal benefits of reducing pollutants and taxi times, the values of other parameters are either uncertain or liable to fluctuate (e.g., the price of jet fuel). A sensitivity analysis was performed to determine the impact that each of these parameters have on the average net savings. The results for Newark are shown in Figure 3.8. Savings are most sensitive to the taxi out time, the price of jet fuel and the main engine fuel burn rate. A 30% reduction in any of these would reduce average net savings to zero. Future attempts to cut down taxi times – by, for example, holding aircraft at the gate during times of runway congestion – would be detrimental to the economics of tugs, as would the introduction of increasingly efficient engines. The economic savings would also fall dramatically if the cost of the tug could only be amortized over three or fewer years. Finally, changes in the price of the tug and the price of diesel do not have a dramatic impact on the net savings.

Finally, if the switch from two-engine taxi-out to dispatch towing were made for large narrowbody aircraft on domestic service at all the 41 of the 50 busiest airports in the U.S., the total net savings would amount to $50 million each year. CO_2 emissions would fall by 0.5 million tonnes each year. As such, this reduction in emissions would be accompanied by a saving of $100 per tonne. In addition to the net savings from reduced fuel burn, the switch would produce $150 million in annual air quality benefits from reduced PM, HC, and NO_x emissions. About 90% of these air quality benefits ($130 million annually) would come from reduced PM emissions.

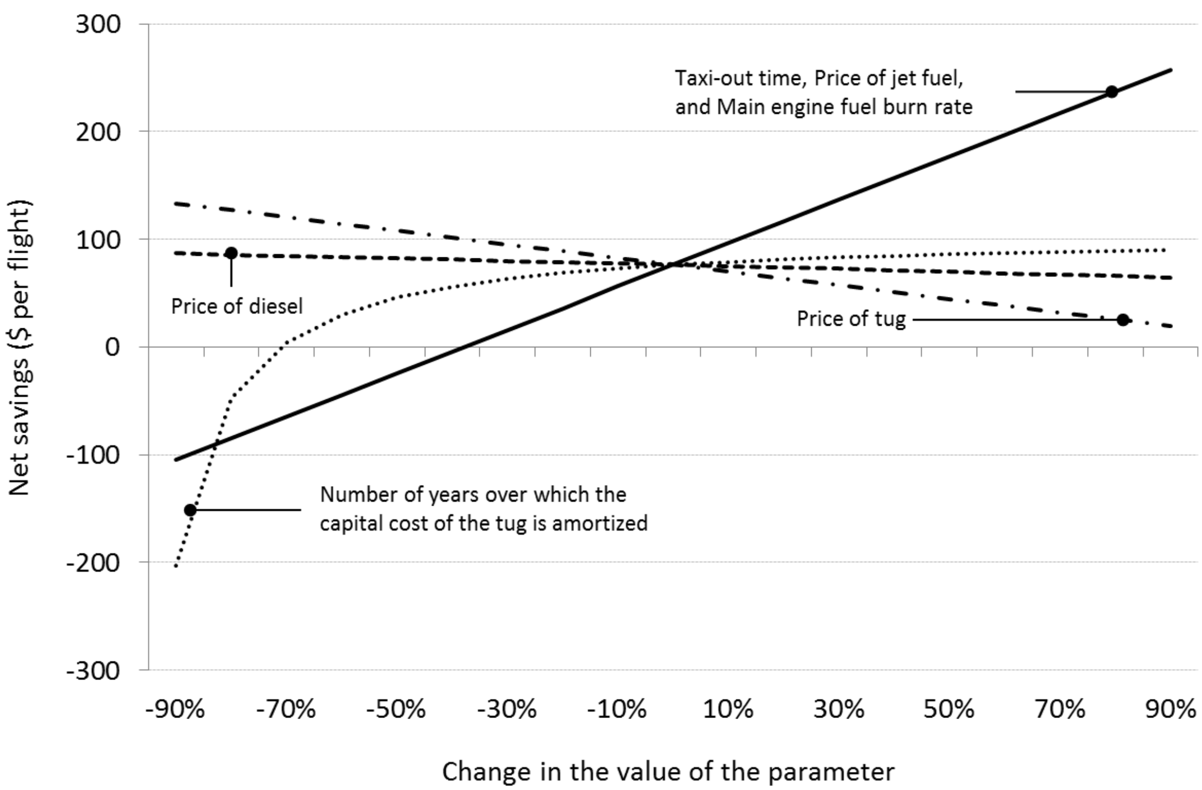

Figure 3.8: Savings are most sensitive to the taxi out time, the price of jet fuel and the main engine fuel burn rate. A 30% reduction in any of these would reduce average net savings to zero. The economic savings would also fall dramatically if the cost of the tug could only be amortized over three or fewer years. Finally, the price of the tug and the price of diesel do not have a dramatic impact on the net savings.

3.4.4 Switching from the Single-engine taxi to Tug scenario for large narrowbody aircraft at select airports

If single engine taxi-out is assumed to be the baseline, the use of tugs is not economical anywhere (Table 3.4), unless a $90 per flight saving is realized from avoiding pushback. Assuming the same levels of service (and therefore, number of tugs) as in the previous scenario, such a switch made at all of the 50 busies airports in the U.S. would increase costs by $60 million each year. However, there would still be a 0.2 million tonne reduction in CO_2 emissions, albeit at a cost of $300 per tonne of CO_2 abated. The total increase in hydrocarbon emissions would produce a loss of $2 million each year, but this would be offset by a $1 million worth of benefits from reduced NO_x emissions, and $60 million in benefits from reduced PM emissions. As such, if air quality benefits were accounted for, the total impact of a switch from single engine taxi to using tugs would still be a small positive number (<$1 million annually). [44,45]

Table 3.4: A net fuel cost of up to $170 per flight would be incurred compared to the Single-engine taxi scenario (one-engine taxi-out and one-engine taxi-in) if tugs were used for dispatch taxi.

Airport	Service level	Tugs	Flights	Avg. per flight benefit from				Average per flight reduction in CO_2 emissions (tonnes)	Cost per tonne CO_2
				Fuel savings	reduction in the emissions of				
					PM	NOx	HC		
ATL	75%	15	86,000	-$30	$30	$0	$0	0.2	$200
ORD	75%	8	55,000	-$40	$60	$0	$0	0.2	$300
DFW	60%	2	12,000	-$50	$10	$0	$0	0.1	$400
DEN	60%	9	90,000	-$30	$10	$0	$0	0.1	$300
LAX	55%	5	57,000	-$10	$60	$0	$10	0.1	$200
PHX	45%	6	63,000	-$20	$0	$0	$0	0.1	$300
IAH	65%	9	48,000	-$70	$40	$0	$0	0.1	$500
LAS	75%	9	93,000	-$20	$0	$0	$0	0.1	$200
SFO	60%	6	46,000	-$30	$50	$0	$0	0.2	$200
CLT	60%	11	50,000	-$80	$20	$0	-$10	0.2	$500
MCO	55%	5	48,000	-$30	$10	$0	$0	0.1	$300
SLC	45%	3	20,000	-$40	$20	$0	$0	0.2	$300
EWR	65%	7	39,000	-$40	$130	$0	$10	0.2	$200
BOS	75%	8	45,000	-$50	$30	$0	-$20	0.2	$300
BWI	60%	4	46,000	-$20	$10	$0	-$10	0.1	$300
MSP	60%	5	32,000	-$50	$20	$10	-$10	0.1	$400
SEA	60%	6	51,000	-$20	$10	$0	-$10	0.1	$200
LGA	65%	7	29,000	-$60	$270	$0	-$110	0.3	$300
JFK	70%	8	35,000	-$50	$330	$0	$20	0.3	$200
DTW	45%	4	21,000	-$60	$40	$0	$0	0.2	$400
MDW	60%	4	49,000	-$20	$20	$0	$0	0.1	$400
PHL	45%	5	28,000	-$40	$70	$0	$10	0.2	$200
MIA	65%	2	12,000	-$50	$14	$0	$1	0.2	$300
SAN	55%	3	32,000	-$20	$20	$0	$0	0.1	$300
IAD	55%	3	16,000	-$70	$40	$0	$0	0.1	$500
DCA	55%	3	19,000	-$40	$30	$0	$0	0.2	$300

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[44] If the switch were made only at airports where the sum of the net savings and the air quality benefits was positive, the total reduction in CO_2 emissions would be 0.06 million tonnes, and this would be accompanied by a monetary loss of $11 million. Total benefit, including that from improvement in air quality would be $24 million annually.

[45] These calculations assume that each main engine consumes the same amount of fuel regardless of whether the aircraft is powered by one or two engines. In fact, during single-engine taxi, the one engine powering the aircraft would likely need to be operated at elevated levels of thrust. Measurements by Presto et al. (2011) suggest that increasing engine load from 4% to 7% raises fuel burn by about 10%. Assuming that during single-engine-taxi the main engine burns 10% more fuel does not qualitatively change the results: shifting from single-engine taxi to tug use would not be economical unless savings from avoiding pushback were accounted for.

TPA	75%	4	39,000	-$30	$20	$0	$0	0.1	$400
FLL	70%	5	35,000	-$50	$20	$0	$0	0.1	$500
STL	35%	1	12,000	-$30	$0	$0	$0	0.1	$600
PDX	55%	2	21,000	-$20	$0	$0	$0	0.1	$300
BNA	40%	1	12,000	-$30	$0	$0	$0	0.1	$600
HOU	35%	1	16,000	-$20	$0	$0	$0	0.0	$600
HNL	75%	2	4,000	-$170	-	-	-	0.2	$900
MCI	40%	1	11,000	-$30	$0	$0	$0	0.1	$600
CLE	40%	1	7,000	-$50	$20	$0	$0	0.1	$500
MEM	30%	1	3,000	-$180	$10	$0	$0	0.1	$1,700
OAK	40%	1	17,000	-$20	$10	$0	$0	0.0	$400
SMF	45%	1	15,000	-$20	$10	$0	$0	0.1	$500
DAL	70%	2	29,000	-$20	$0	$0	$0	0.0	$600
MKE	45%	1	8,000	-$50	$20	$0	$0	0.1	$600
AUS	45%	1	11,000	-$30	$0	$0	$0	0.1	$500
RDU	55%	1	9,000	-$30	$0	$0	$0	0.1	$400
SNA	65%	2	22,000	-$30	$20	$0	$0	0.1	$400
SJC	45%	1	14,000	-$20	$10	$0	$0	0.1	$600
SAT	45%	1	10,000	-$30	$0	$0	$0	0.1	$600
MSY	45%	1	12,000	-$30	$0	$0	$0	0.1	$500
ABQ	55%	1	11,000	-$30	$0	$0	$0	0.1	$800
PIT	45%	1	8,000	$40	$20	$0	$0	0.1	$500
IND	55%	1	7,000	-$60	$10	$0	$0	0.1	$800
JAX	55%	1	8,000	-$40	$10	$0	$0	0.1	$500

3.4.5 Switching from main engine taxi to electric taxi

Table 3.5 shows the economics of shifting all flights to electric taxi, relative to the baseline and single-engine taxi scenarios. For a random sample of 500,000 domestic flights, the fuel and cost savings that would accrue from using electric taxi were calculated. This distribution of per flight cost savings associated with different assumptions about capital costs are shown in Figure 3.9.

An electric taxi system would likely eliminate the need for a separate pushback tractor, saving up to $90 per flight. If the electric taxi system cost $1 million per aircraft to put in place, and this cost were amortized over 20 years at 7% per year, and if we assumed that the aircraft performed 3.5 departures per day, then the capital cost per flight would be $75. If it were assumed that maintenance was 20% of capital cost, the total fixed cost of the system would be $90 per flight, which would be fully paid for by the elimination of pushback services.

Table 3.5: Relative to two-engine taxi-out and one-engine taxi-in, electric taxi would save money system-wide even if the system cost $1 million per aircraft to install. Relative to single-engine taxi, electric taxi systems would save money only if they were very cheap to install or if significant savings could be realized from eliminating pushback

Per aircraft cost of installing system	$1,000,000	$500,000	$250,000
Relative to two-engine taxi-out and one-engine taxi-in			
Total CO_2 emissions reductions (tonnes CO_2)	1,900,000	1,900,000	1,900,000
Per flight CO_2 emissions reductions (tonnes CO_2)	0.31	0.31	0.31
Total annual savings	$50,000,000	$320,000,000	$454,000,000
Average savings per flight	$10	$50	$70
Cost per tonne of emissions reductions ($ per tonne CO_2)	-$30	-$170	-$240
Proportion of flights that would lose money	70%	40%	30%
Relative to one-engine taxi-out and one-engine taxi-in			
Total CO_2 emissions reductions (tonnes CO_2)	700,000	700,000	700,000
Per flight CO_2 emissions reductions (tonnes CO_2)	0.11	0.11	0.11
Total annual savings	-$329,000,000	-$59,000,000	$75,000,000
Average savings per flight	-$50	-$10	$10
Cost per tonne of emissions reductions ($ per tonne CO_2)	$490	$90	-$110
Proportion of flights that would lose money	90%	80%	60%

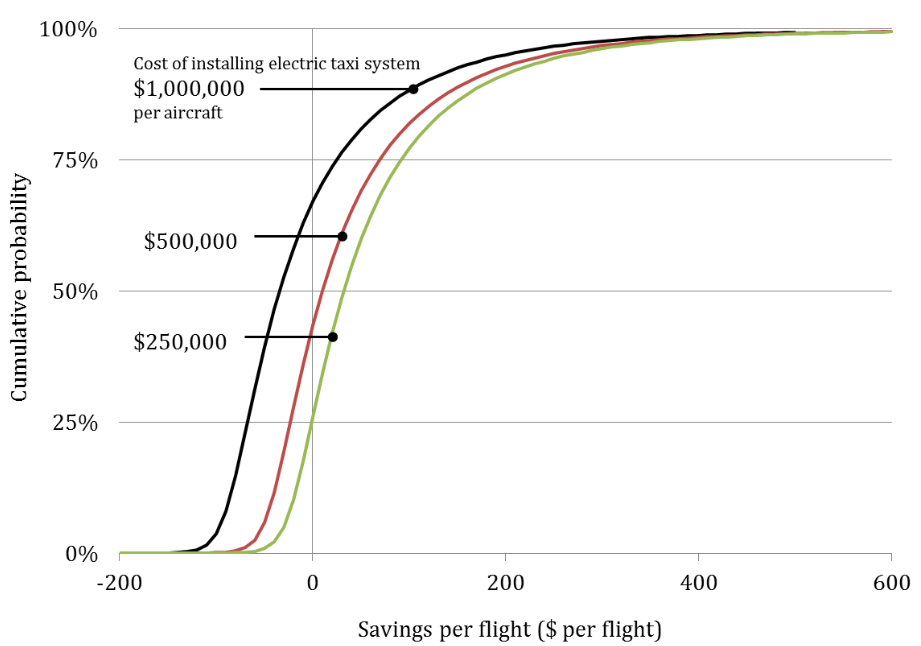
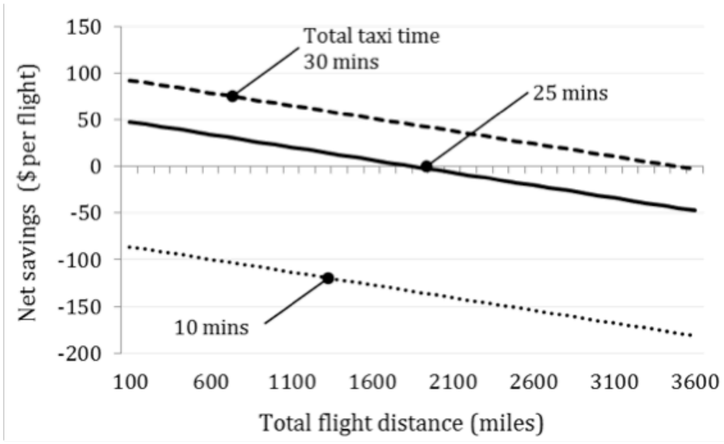
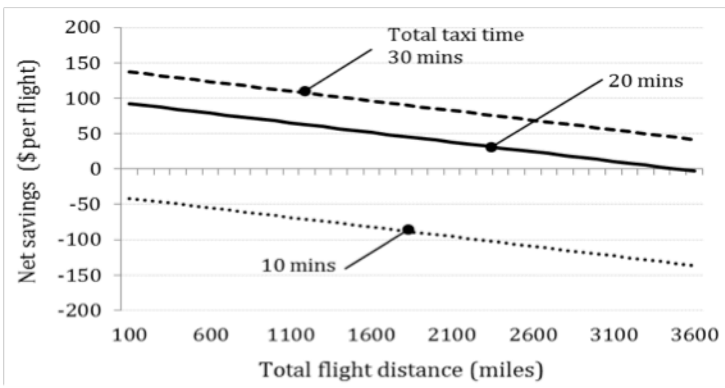


Figure 3.9: Depending on what the system costs to install, between 25-70% of all flights would lose money if operated with en electric taxi system



(a)



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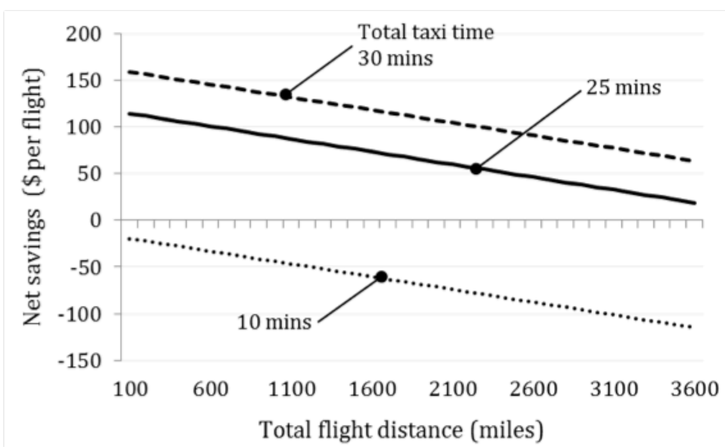

(c)

Figure 3.10: (a) Capital cost of $1 million per plane. On A320 aircraft in the dataset, an electric taxi system would lose money only if the flight were longer than 2000 miles, assuming that the aircraft taxied for the average duration of 25 minutes. (b) Capital cost of $500,000 per plane. If the electric taxi system cost only $500,000, only flights that taxi for the average 25 minutes and fly for about 3500 miles – close to the maximum range of the A320 family – would lose money. (c) Capital cost of $250,000 per plane. If the electric taxi system cost $250,000 flights that taxi 20 minutes would have to be over 3600 miles for the capex, maintenance cost, and weight penalty to exceed fuel savings on the ground.

For the A320 family of aircraft, an ordinary least squares model was estimated to explain the total reduction in fuel burn as a function of total flight distance (in miles) and total taxi time (in minutes). Compared to the Baseline scenario of two-engine taxi-out and one-engine taxi-in, the model was as follows.

Reduction in fuel burn = 8.92 x Total taxi time – 0.03 x Total flight distance – 83.85[46]

Using this relationship, the net average saving per flight was calculated for different assumptions about the capital expense associated with equipping an aircraft with the electric taxi system, and the total taxi time.

Figure 3.10 shows the results of this calculation. The average flight distance and average taxi and for the A320 family aircraft in my dataset are 990 miles and 24.5 minutes, respectively. The analysis suggests that, for the average 25-minute total taxi time, the e-taxi system – even if it were expensive to install – would reduce fuel costs for flights of up to 2000 miles. It is apparent that flights that taxi less than 10 minutes would lose money regardless of how cheap it is to install the e-taxi system.

3.5 OPERATIONAL ISSUES

3.5.1 Tugs

A recent TRB report (Quinn 2012) briefly discussed the problems associated with dispatch towing:

> Dispatch towing has been used at some airports in the U.S. However, a number of issues related to dispatch towing have been identified that limit widespread use. First, TBLT [tow bar-less tractor] towing places heavy stress loads on the nose gear. Tests conducted by Virgin Atlantic and Boeing found that dispatch towing with TBLTs resulted in a reduced operational life of aircraft nose gear because of the additional stress. Additionally, the TBLT must disconnect from the aircraft near the end of the runway and return to the terminal. This return trip represents an additional vehicle

[46] All coefficients are highly significant ($p < 2x10^{-16}$), and the model has an R^2 of 0.94. This is unsurprising, since this regression essentially involved running in reverse the model used to estimate fuel savings.

> on the airfield with which ATC must maintain contact until such a point that the TBLT exits the movement area or can use a vehicle service road. (Quinn 2012)

These issues are elaborated upon in this section, and possible solutions discussed.

First, using currently available tugs for dispatch taxi imposes fatigue load on the aircraft nose-wheel that reduces its life.

This load is greater than that experienced by the aircraft during maintenance towing. Aircraft are virtually empty when towed between hangars, and are typically full of fuel and passengers when taxiing out. An empty A320 weighs about 40 tonnes, whereas the maximum ramp weight of the same aircraft is 78 tonnes. Aircraft also need to brake more often when they are in a queue prior to take-off, especially if they have to cross active runways and taxiways and therefore wait for other aircraft to pass. Since current towbarless tractors (TBLTs) use their own brakes to stop the aircraft, they have to transmit through the nose landing gear a braking force large enough to arrest the momentum of the fully-laden aircraft within a reasonable distance. The braking distances are likely to be shorter – and the required forces correspondingly larger – if the aircraft were being towed on and across active taxiways than if it were being towed on maintenance roads. Finally, small narrowbody aircraft perform nearly five departures per day, whereas large narrowbodies perform over three. An aircraft might need to be towed from a maintenance area to a gate – or between maintenance areas – less frequently than that. As such, compared to maintenance towing, dispatch towing is more frequent, involves heavier aircraft, and is likely to involve more braking. As such, the fatigue loads imposed on the nose gear are greater for dispatch towing.

This issue has been addressed by the development of an advanced tug (Perry and Braier 2012; Perry et al. 2011) that limits fatigue loads on the nose gear in two ways. First, it allows the aircraft to be stopped using the aircraft's own brakes. As such, if power to the tug were cut when it detected that the aircraft was braking, the nosegear would only need to transmit enough force to stop the tug. Since the tug is considerably lighter (~25MT) than a fully laden aircraft (~75MT), this alone would significantly reduce the load on the landing gear. In fact, the tug is designed to further reduce the load by braking in tandem with the aircraft. It is also designed to apply a load that compensates for braking forces to ensure that – even if the load on the nose gear fluctuates – there is no reversal in the direction of the load, and that the amplitude of the fluctuations is kept to a minimum.

Second, airport rules may prohibit the operation of vehicles in movement areas. For example, the airport rules of the Port Authority of New York and New Jersey (PANYNJ 2009, 37) state:

> Non-Port Authority vehicles are prohibited from operating on any runway, taxiway and safety area unless under escort by the Port Authority or FAA maintenance. All vehicles shall obtain permission from the Control Tower before entering or operating on the movement areas.

If airlines want to use tugs for dispatch taxi, they will have to negotiate exemptions from such rules in a way that ensures that safety and operational efficiency are not compromised.

For example, aircraft would need to be towed to a location close to the edge of the departure runway. They would have to stop here for some few moments, while the tug decoupled from them. Such a location would have to be positioned so that the aircraft could leave and re-join the take-off queue safely: aircraft could not be permitted to stop and decouple while in the queue, as doing so would hold up the aircraft behind them. Such locations would need to be identified on a case-by-case basis, and permission would need to be sought to use them in this manner. For example, at Philadelphia International Airport (see Figure 3.11), there is a de-icing pad close to the edge of a runway, which could be used for decoupling. In this case, the tug could complete its entire journey without entering movement areas.[47]

While the tugs and the aircraft could be treated as a single entity while they are joined, the tug would become an additional object for ramp or active area controllers to manage after decoupling. As such, the use of tugs would require these controllers to agree to take on the additional

[47] Quinn (2012, 3) defines movement areas as "The airport runways, taxiways, and safety areas. The movement area does not include loading ramps or aircraft parking areas. Specific approval for entry onto the movement area must be obtained from [air traffic control] ATC.

workload,[48] and the development of procedures that permitted safe operations. The tug must be equipped with appropriate transponders so that controllers could "see" and communicate with them, and tug operators would have to be trained to be able to communicate with the air traffic control tower.

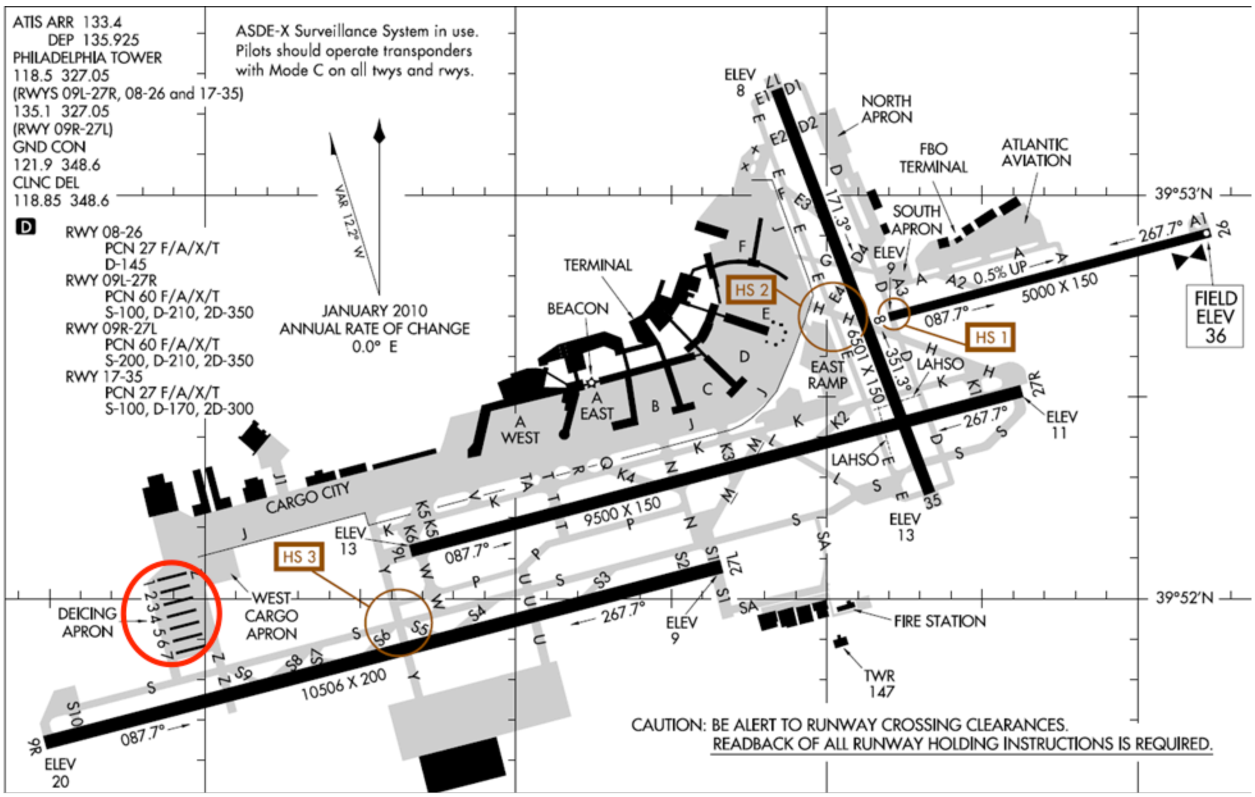

Figure 3.11: The layout of Philadelphia International Airport is such that aircraft taking off eastward from runway 9R could exit the take-off queue, and decouple from the tug at the de-icing apron (circled).

In the case of other airports, both an area for decoupling the aircraft and a service road to return the tug might need to be constructed. Tug operations would lower fuel costs, and reduce pollution and noise. As such, airlines and airport operators (which, in the US, are invariably public bodies) stand to benefit from their use. They would have to establish a way of sharing the costs of any new

[48] If the tug stayed on the ramp at all times, its movements would have to be managed by ramp controllers, who are often airline employees and potentially more amenable to adopting a procedure that benefits the airline economically.

infrastructure that might need to be put in place to enable such operation. One potential source of funding could be the FAA's Voluntary Airport Low Emissions Program (VALE).

3.5.2 Electric taxi

Consider a narrowbody aircraft with mass 75 tonnes (e.g., the Airbus A320 family (Airbus 2012a)), rolling on a flat taxiway – with coefficient of friction 0.03 (Nicolai 2009)– at 20mph, a typical taxiing speed. This would require about 200kW,[49] or 270hp, of power. To climb slopes and to accelerate the aircraft sufficiently quickly, the APU would need to provide even more power, or another source of power would need to be found. Any such modification is likely to incur both cost and weight penalties. The calculations above are therefore a "best-case" estimate of the economics of electric taxi.

3.6 CONCLUSIONS AND IMPLICATIONS FOR PRACTICE

The costs and benefits were estimated of two measures to curtail the use of main engines, and therefore fuel burn and emissions, while taxiing – the use of tugs and embedding an electric motor in the aircraft landing gear.

If the switch from two-engine taxi-out to dispatch towing were made for large narrowbody aircraft on domestic service at all the 41 of the 50 busiest airports in the U.S., the total net savings would amount to $50 million each year. CO_2 emissions would fall by 0.5 million tonnes each year, or about 0.3% of the 144 million tonnes CO_2 equivalent emitted each year by domestic civil aviation. (US Department of Transport 2010) Though relatively small, this reduction in emissions would be accompanied by a saving of $100 per tonne CO_2, employing technology that is already available.[50] In

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[49] The power requirement is calculated as force times velocity, where the force is given by the weight of the aircraft times co-efficient of friction. As such, Power required $= 75{,}000 \text{ kg} \times 9.81 \text{ m/s}^2 \times 0.03 \times 9 \text{ m/s} = 198\text{kW}$

[50] The tugs described in this chapter were first used for commercial flight operations by Lufthansa at Frankfurt in February 2015. (Lufthansa Group 2015)

addition to the savings from reduced fuel burn, the switch would produce $150 million in annual air quality benefits from reduced PM, HC, and NOx emissions.

Even if it were assumed that aircraft typically taxi out with only one engine running, a switch to the use of tugs would result in a reduction in CO_2 emissions. However, these incremental reductions would come at a cost of over $300 per tonne CO_2 abated. If air quality benefits were accounted for, the total impact of a switch from single engine taxi to using tugs would still be a small positive number (<$1 million annually).

Electric taxi could be an attractive way of cutting both emissions and costs, provided the cost of incorporating such a system into airplanes, and its weight, were kept low.

This analysis also demonstrates the dangers of aggregating emissions reductions obtained in different ways. For instance, the results make it apparent that single-engine taxiing and the use of tugs are both attractive ways of reducing emissions when considered in isolation, and compared to taxiing with both engines running. However, even though an airline that is successful in exploiting savings from single-engine taxiing could further reduce its emissions by using a tug, that reduction would likely remain unrealized because the incremental cost associated with making the change would be too large. Clearly, the wide range of costs obtained with different assumptions suggests that sweeping statements about the potential and cost of emissions reduction may be unreliable guides to decision-making, and might even be misleading.

The range of logistical challenges associated with the use of tugs and single-engine taxiing suggests that the efficacy of any measure depends strongly on the operating environment. This may well be different for each combination of location, aircraft type and airline. For instance, 2011 taxi data shows that the average taxi out time for Boeing 737 aircraft operated by SouthWest airlines is just over 10 minutes. Boeing 737 aircraft operated by all other airlines taxi out for much longer: on average, 17 minutes. Clearly, SouthWest would have a smaller incentive to adopt the measures discussed above than would other airlines.

A potential implication for policymakers seeking to reduce greenhouse gas emissions from aviation is that putting a price on emissions but leaving airlines to decide where and how to achieve reductions could be both more effective and more efficient than prescribing – or trying to build a consensus for the adoption of – specific measures.

3.7 Appendix: Regression model to calculate the number of tugs needed at smaller airports

For the 31 busiest airports, the number of tugs needed was calculated using a queuing model as described in the main text. Based on the results, the coefficients of the following equation were estimated using ordinary least squares regression.

log(number of tugs) = $\boldsymbol{\beta_0}$ + $\boldsymbol{\beta_1}$×*log(number of departures from the airport in July)* + $\boldsymbol{\beta_2}$×*(mean taxi-out time in July)*

The resultant model had an R^2 of 0.92, and all the variables were found to be significant predictors of the number of tugs needed (Table 3.6). The model was then used to estimate the number of tugs that would be needed at other airports.

Table 3.6: Average taxi times and the number of departures at an airport are both significant predictors of the number of tugs required

Coefficient	Estimate	Std. Error	t value	Pr(>|t|)
β_0	-5.575	0.454	-12	9E-13
β_2	0.054	0.004	14	2E-14
β_1	0.839	0.050	17	3E-16

Chapter 4: POLICY ANALYSIS OF A MARKET-BASED MECHANISM FOR INTERNATIONAL AVIATION

Abstract

In October 2013, the International Civil Aviation organization (ICAO) announced that it would put in place a market-based mechanism to cap net greenhouse gas emissions from international civil aviation at 2020 levels. This chapter analyzes the obligations ICAO's initial proposal for the mechanism would create for real airlines, and whether it would indeed succeed in keeping emissions at or below the desired level. In order to protect commercial sensitivities, the analysis begins by using hierarchical cluster analysis to identify groups of different types of airlines. The provisions of the ICAO proposal are then applied to these groups. We find that the ICAO proposal is somewhat poorly specified and ambiguous. Further, it is possible to interpret it in a way that would prevent net sectorial emissions from remaining capped at 2020 levels. We also find that, depending on their size and rate of growth, airlines will be required to offset very different proportions of their emissions from international flights. Exemptions from the scheme are poorly targeted. We conclude by recommending that ICAO design and implement a much simpler scheme, and target its exemptions more intelligently.

This chapter draws on work done during a summer internship in 2014 at the Environmental Defense Fund with Annie Petsonk. It benefited greatly from feedback by and discussions with Annie, Pedro Piris-Cabezas, and Rafael Grillo Avilla. Any errors and omissions in this chapter are, however, entirely my own, as are the opinions and recommendations.

4.1 Introduction

In October 2013, the International Civil Aviation organization (ICAO) announced that it would put in place a market-based mechanism to address greenhouse gas emissions from international civil aviation. (ICAO 2013b) ICAO's Council, a 36-member Executive Body, has formed a subsidiary Environmental Advisory Group (EAG). The EAG has published an initial 'strawman' document[51] outlining one possible structure for the MBM; various nations are in the process of formulating their own proposals. The EAG strawman and the various national proposals provide alternatives for structuring a mechanism in which airlines would offset their emissions in such a way that "net" sectorial[52] emissions – actual emissions less offsets – would remain capped at 2020 levels.

The purpose of EAG's strawman was to generate "discussion on advantages and disadvantages of design elements and allowing for the improvements of the Strawman." (ICAO 2014, 3) Such an "iterative" approach is meant to "ensure the full engagement of States and other stakeholders, taking into account inputs from different sources." (ICAO 2014, 3) It is in this spirit of providing inputs into an iterative process that the present analysis was undertaken during an internship – in summer 2014 – at the Environmental Defense Fund, which – through the International Coalition for Sustainable Aviation (ICSA) – participates in the ICAO's Committee on Aviation Environmental Protection (CAEP).

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[51] This text of this document is available from: http://clacsec.lima.icao.int/Reuniones/2014/GEPEJTA33/NE/NERstgd/33GENE18.pdf

[52] In this case, the "sector" is defined as international civil aviation, including passenger and freight transport. The IPCC treats flights where the origin and destination airports are in different countries as international. ICAO's definition is different: if an airline operates a flight whose origin *or* destination lie in any country other than the one that issued the airline its air operating certificate, the flight is classified as international. So, an Air Canada flight from Pittsburgh to New York (for example) would be considered an international flight. For a number of airlines, the volume of international emissions is significantly different depending on what definition is used. In the strawman, ICAO appears to have used IPCC's definition of international: "flights departing from an airport of a State and arriving at an airport of another State."

This analysis estimates the volume of offsets, in kilotonnes of carbon dioxide, which a large number of real airlines are likely to have to procure during each year (2012-35) in which the proposed scheme will apply. This will reveal whether airlines are required to offset a similar proportion of their emissions, or if this proportion varies by airline. The text of the strawman document makes it clear that the proposal is aimed at preferentially lowering the offset obligations of airlines that are either new, particularly efficient, or growing very fast. The latter accommodation is made, presumably, because fast-growing airlines are likely to be small and serving developing regions and the ICAO wants to avoid stifling their growth by placing too onerous a burden on them. The analysis of airline obligations will reveal if, and to what extent, these objectives have been met.

Due to commercial sensitivities, in this analysis airlines have been anonymized; pseudonyms such as A_1, A_2 etc. will be used to refer to them. Hierrchical cluster analysis will be used to identify airline types. The characteristics (e.g., size and growth rate) and offset obligations of different clusters of airlines[53] will then be compared to find out whether different *types* of airlines face systematically different obligations under the provisions of the strawman.

Later in the chapter I will propose alternatives to certain aspects of the strawman proposal. The integrity of an offset-based mechanism hinges on the integrity of the offsets that it permits participants to buy. The problems associated with maintaining this integrity are well documented.[54]In conclusion, this chapter will draw upon a framework from organizational science to explain why ensuring the integrity of emissions offsets in aviation might be particularly challenging.

[53] We will define the size of the cluster as the sum of the size of all the airlines in the cluster, its growth rate as the weighted average growth rate of the airlines in it, and its offset obligations as the sum of the offset obligations of all the airlines in the cluster.

[54] For example, for a discussion of the problems associated with the Clean Development Mechanism (CDM) of the Kyoto Protocol, see (Victor 2004).

4.2 Methods and Analysis

4.2.1 Description of Strawman v1.1

The Strawman Version 1.1 text[55] (under Section 4, Quantities of Offset for Each Operator) and accompanying sample calculations describe the method by which the offset obligations of an airline should be calculated in any given year.

The strawman defines *de minimis* exemptions in the following way.

> *(a) States are listed in increasing order from the lowest to the highest amount of emissions generated by all international flights to and from individual States.*
>
> *(b) Flights to and from the States in this list are exempted from the top State down to the State where the cumulative amount of emissions reaches y% of global emissions in the reference year.*
>
> *(c) This list is established in the first year of application, and revised after 5 years.*
>
> *(d) The exempted emissions are not included in the reference year and in the current year.*

This analysis will discuss the implications of this *de minimis* exemption in terms of how it would affect the coverage of the mechanism; that is, what proportion of current global emissions would exempt for different values of "y". We do not attempt to forecast how it would affect individual airlines going forward, as this would require forecasts at the level of airline *and route.* That is, a forecast of how many revenue passengers a particular airline would carry on a particular route. Such a forecast is beyond the scope of this analysis.

The strawman also exempts emissions from airlines whose flights collectively emit less than 10 kilotonnes of carbon dioxide each year, aircraft with a maximum take-off mass of less than 5.7 tonnes, as well as humanitarian, medical and fire-fighting operations. These are called "technical exemptions."

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[55] See Footnote 51.

For the rest of the sector, the strawman begins by defining reference year emissions as the average of emissions in 2018, 2019, and 2020. This number is calculated for the sector,[56] as well as for individual airlines.[57] For the sector, the difference between reference year emissions and 2020 emissions is held as a notional reserve. This reserve is defined at the start of the mechanism's implementation period – that is, by the end of 2020 – and does not change throughout its life.

In the first instance, the reference year emissions are treated as a "cap". Each year, an airline's offset obligations are calculated as the average of (a) the airline's share of sectorial emissions in a particular year times the absolute growth in sectorial emissions since the reference year, and (b) the absolute growth in the airline's own emissions relative to the reference year. In other words, in deciding what part of the sector's growth in emissions an airline is responsible for offsetting, the strawman takes into account its relative size as well as its direct contribution to the growth in emissions.

New entrants are exempt from having to offset their emissions for a period of five years after they begin operations, or until their annual emissions reach a certain – as yet undefined – fraction of the global emissions in the reference year.[58] The strawman explicitly says that other exemptions (e.g., the *de minimis* exemptions listed above) are not included in the sectorial reference emissions and in the annual emissions of the sector in each subsequent year. This suggests that emissions from new entrants must be included in the sectorial emissions for a particular year, and this analysis will proceed under that assumption.[59]

[56] See Footnote 52 on ICAO's definition of "sector."

[57] For an airline that does not exist in these years, reference emissions are zero for the first five years of its existence, after which "reference year" emissions are assumed to be the average of the airline's fourth and fifth year emissions.

[58] The strawman text does not make it clear whether this threshold will be set for *all* new entrants at a given time (i.e., the total exemptions granted to new entrants in a particular year cannot exceed x% of the reference year emissions) or for *each* new entrant.

[59] It is worth noting that if new entrants' emissions were included in calculating the annual sectorial emissions, they would represent a growth in sectorial emissions relative to the reference

This calculation is then adjusted to account for special categories of airlines. The obligations of fast growers – defined as airlines whose percentage growth relative to the reference year is twice or more the percentage growth of the sector – are somewhat reduced. The obligations of early movers – defined as those whose fuel efficiency is more than 10% higher than the global fuel efficiency[60] – would also be somewhat reduced for the period between 2021 and 2025. If the sum of all the reductions (termed as "compensation" by the strawman) offered to fast-growing airlines and early movers in any given year exceeds the size of the notional reserve, these reductions are proportionally trimmed so that their total magnitude is equal to that of the reserve.[61]

As such, the mechanism is designed to ensure that net emissions from international aviation stay capped at the sum of (a) emissions in the reference year, (b) emissions in the notional reserve, (c) emissions from other *de minimis* exemptions (small airlines and airplanes) and humanitarian missions. For this to be an effective cap, several aspects of the mechanism – for example, about the treatment of new entrants (Footnote 59) and alternative fuels (Footnote 60) – need to be fully defined.

year and would therefore have to be offset by other airlines, even if the new entrant itself were temporarily exempt. If, on the other hand, these emissions were not included in calculating the sector's annual emissions, no one would have to offset them. That is, unless (a) an upper limit were set to the volume of exemptions that all new entrants could collectively claim in a particular year, or (b) the emissions of new entrants were included in calculating the total sectorial emissions for a particular year, the sector would be obliged to offset less than the actual growth of emissions since the reference year, and net emissions would, in fact, keep growing.

[60] The strawman does not define what fuel efficiency means, or what global fuel efficiency means. The term itself might be somewhat misleading because, presumably, what ICAO wants to reward is low carbon intensity. For example, consider two airlines that use the same volume of fuel per passenger-mile or ton-mile. Assume further that one airline uses a 50-50 blend of conventional jet fuel and an advanced, low-carbon biofuel, while the second uses only conventional jet fuel. The first airline is surely more deserving of having its offset obligations reduced, but it is not clear that the strawman makes provision for this. As such, the "early mover" adjustment, while motivated by an admirable desire to give airlines an incentive to act on emissions reductions even before the mechanism is implemented, is very poorly defined. This, coupled with the fact that airline and sectorial fuel efficiencies are very difficult to determine based on the data we have available, means that this chapter will not analyze the impact of the "early mover" clause.

[61] The text of the strawman suggests that the reserve is available to offset the obligations of both fast growers and early movers, and no specific allocation is made between these two categories of airline. However, an accompanying sample calculation suggests that half the reserve is allocated to fast growers and the other half to early movers. This analysis is conducted with that assumption.

4.2.2 Data collection and verification

The analysis in this chapter depends critically on knowing each airline's annual emissions during the period that the mechanism is applied. As a starting point, we use a dataset of aviation activity for the year 2012, assembled by an industry expert (Southgate 2013).[62]

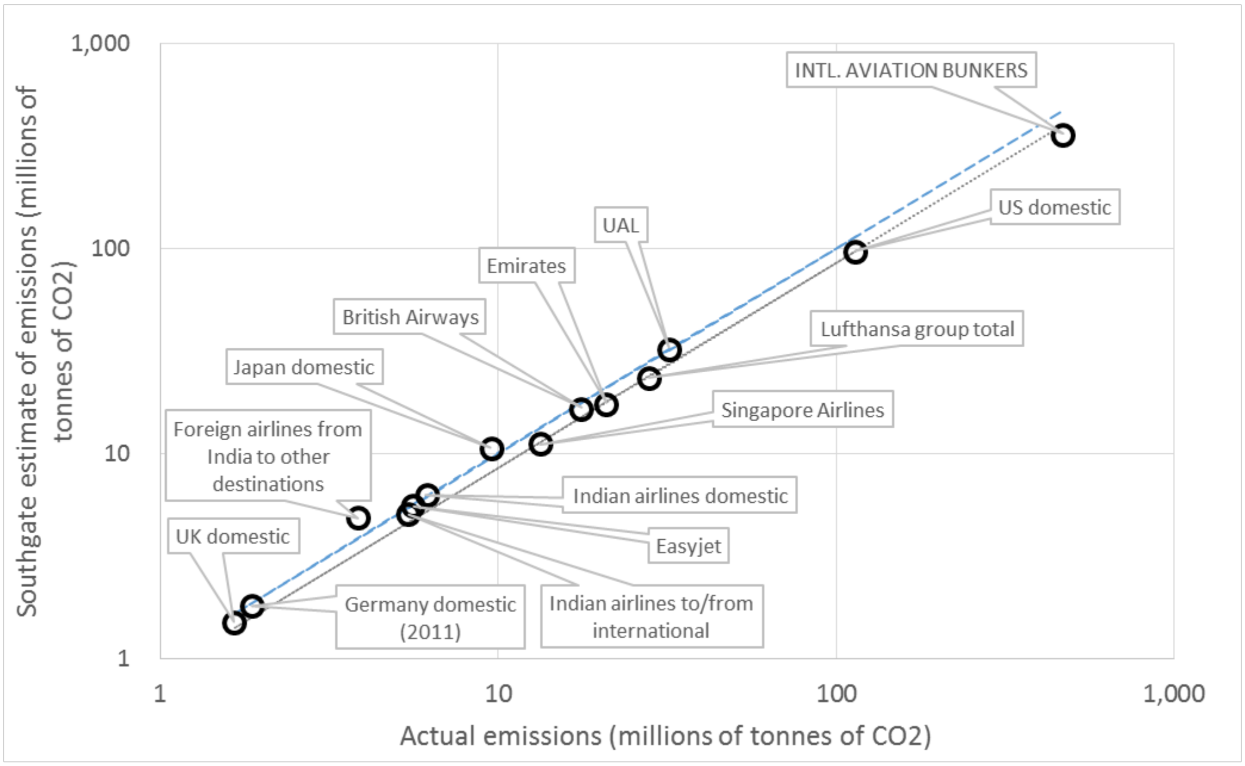

Figure 4.1: Data from independent sources aligns reasonably well with those compiled by David Southgate. The upper 45-degree line represents the equation (Actual emissions = Southgate estimate of emissions). The lower 45-degree line represents the equation (0.85xActual emissions = Southgate estimate of emissions). This line is meaningful because the Southgate data only include passenger emissions, whereas the "actual" emissions also include freight emissions. It is estimated that the latter are about 15% of total emissions: that is, passenger emissions are about 85% of total emissions from aviation.[63]

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[62] The data were assembled by David Southgate. "From 2004 to 2012 Dave was the Australian Government representative on the United Nations International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP). He pursued his interest in carbon footprinting while on CAEP and was a member of the group that oversaw the development of the ICAO Carbon Calculator." (Southgate 2014)

[63] The data sources for the independent estimates are as follows. All Indian estimates: (Directorate General of Civil Aviation 2013), Japan: (Greenhouse Gas Inventory Office of Japan 2014), United Airlines: (United Airlines 2014), easyJet: (easyJet plc 2014), Germany: (European Environment Agency 2014), British Airways: (British Airways 2013), United Kingdom: (Department of Energy & Climate Change 2014), United States: (EPA 2014), Singapore Airlines: (Singapore

The data contain actual information about the number of non-stop flights for each combination of origin airport, destination airport, airline, and aircraft operated. It was assumed that each international flight was 78% full, and flight fuel use and emissions were calculated based on this assumption. These data were partially validated against external sources where such sources were available. The Southgate (2013) data were found to be a reasonably complete record of civil passenger aviation activity in 2012 (Figure 4.1 and Figure 4.2).

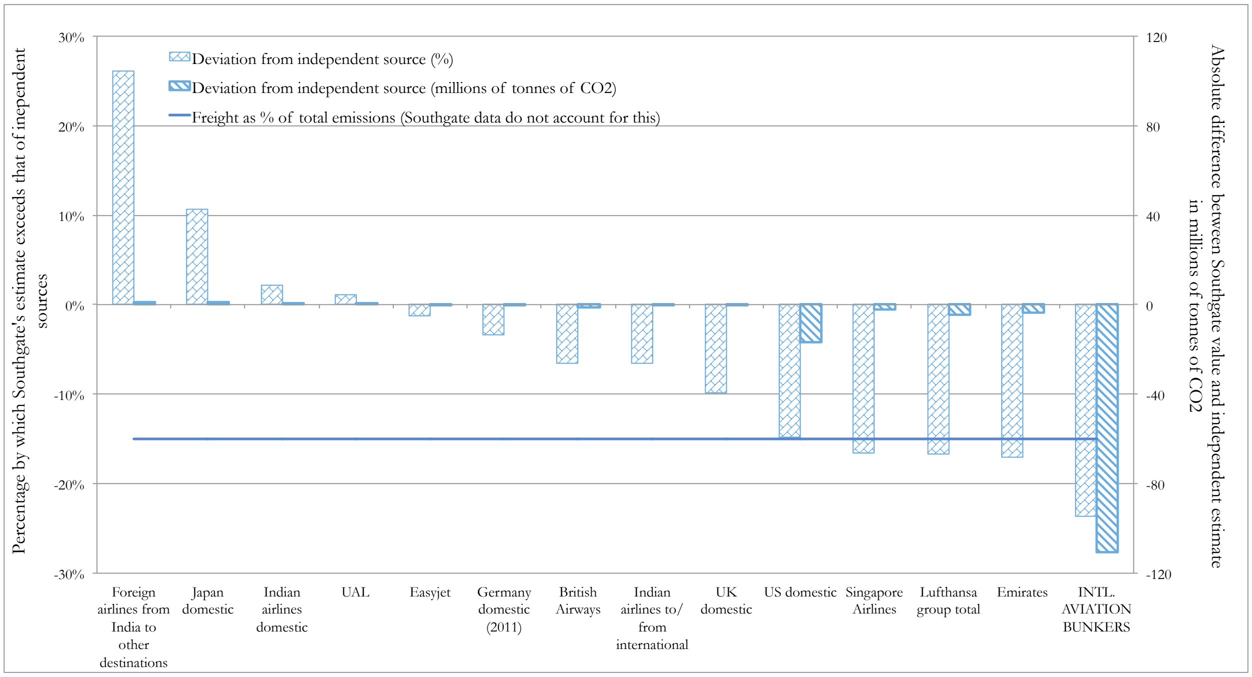

Figure 4.2: In most cases, Southgate somewhat underestimates emissions. His data cover only emissions related to passenger travel. Our calculations suggest that freight emissions are typically 15% of total emissions. As such, in a number of cases, the difference in Southgate and independent estimates could be explained by the exclusion of freight. Southgate's data underestimate the *total* sectorial fuel use (represented by "international aviation bunkers") by much more than 15%. Part of the explanation could be that the Southgate data are incomplete: some airlines or routes are missing from it. Southgate also calculates emissions based on a model, and assumes that all international flights are 78% full. Both the model and the assumption might be distorting the final numbers. Finally, the IMO's third report on greenhouse gas emissions from shipping (Smith et al. 2014) suggests a large discrepancy between a bottom-up estimate of emissions (such as the one taken by Southgate) and a top-down approach (i.e., an estimate derived from total fuel sales), with the former substantially exceeding the latter in the case of shipping. It may be that a similar discrepancy exists for aviation, with the direction reversed.

Airlines 2012), Lufthansa Group: (Lufthansa Group 2013), Emirates: (The Emirates Group 2014), International aviation bunkers: (IEA 2013)

Data for emissions from the carriage of freight were added to Southgate's estimates of the emissions from passenger aviation. Data for ton-miles of freight carried by airlines flying in and out of the United States by various airlines were obtained from form T-100 records maintained by the Bureau of Transportation Statistics (2014). For US airlines – both passenger and cargo – it was assumed that this represented the total volume of freight they carried.[64] Carbon dioxide emissions were estimated from this number by assuming that all airlines operated as efficiently as Federal Express (FedEx 2012) in terms of CO_2 emissions per *available* ton-mile, and at a load factor of 60%, which was the US average in 2010 (Donatelli and Belobaba 2014). For US airlines, it was possible to obtain this data for each combination of origin and destination country pair and airline. For other major carriers, information on revenue ton-miles was obtained from Donatelli and Belobaba (2014), and the same assumptions made as for the US airlines. Finally, for Cargolux (2014) and DHL (2013), data on emissions were obtained directly from publications by these companies.

In addition to data on activity, I gathered information about airline fleets. This included the size of the fleet, the average age of the fleet, and the number of aircraft on firm order (options were ignored). These data were gathered from airlines' webpages, investor relations materials, and Airbus and Boeing order books.

4.2.3 Projection of emissions

To assess the obligations that each of these airlines would face, it was necessary to forecast their emissions. Several approaches were considered in order to do this.

[64] The implicit assumption is that US airlines only carry freight in or out of the US, and not between two destinations within a second country or between a second and third country. The first of these activities is called cabotage (or the eighth freedom of the air), and is extremely rare outside the European Union. The latter of the two activities – a US airline carrying cargo or passengers between a second and third country – is called the seventh freedom of the air and is also rare outside Europe. As such, we are justified in assuming that these activities do not take place to a significant extent. See: http://www.icao.int/Pages/freedomsAir.aspx

The first approach was based on growth in traffic in the regions in which each airline chiefly operates. For each airline, I used at the Southgate data to identify the traffic flow regions in which the airline was active. I then identified the traffic growth rate for these regions based on Airbus's estimates for growth in 2012-32. (Airbus 2013a) The traffic-based estimate of airline's annual growth rate was calculated as the weighted average of these various regional growth rates, with the number of revenue passenger kilometers (RPKs) flown by the airline in a particular region in 2012 acting as the weight.

The second approach was to estimate the growth in RPK based on the projected growth in the fleet. The rate of growth of the fleet was calculated slightly differently depending on whether the ratio of the number of aircraft on order to the number of aircraft in the fleet was less than or greater than 0.75.[65] For clusters where the ratio was greater than 0.75, it was assumed that all the aircraft on order would be delivered by 2025. It was assumed that all carriers operate aircraft until they reach an age of 25 years. This "target" age was combined with the average age of the current fleet to calculate the annual rate of retirement. Consider an airline that aims to retain aircraft until their age is 25 years, whose current fleet has an average age of 13 years. Each aircraft in its fleet would, on average, have seven additional years of life. As such, one can estimate that each year, one-seventh (or 14%) of its fleet would retire. Based on this assumption, the total number of retirements up to 2025 were calculated, and subtracted from the sum of the number of aircraft in the current fleet and the number of aircraft on order. The resulting number was an estimate of the number of aircraft the airline would operate in 2025, and the growth rate in the RPK between now and 2025 was calculated

[65] With this assumption and the assumption that aircraft are operated for 25 years, we estimate that there will be about 20,000 jets in passenger service in 2020. By comparison, our analysis of forecasts by Airbus (2014) and Boeing (2014a) suggests that both they anticipate that there will be about 24,000 jet aircraft operating in that year. Allowing for the fact that some part of the global fleet is dedicated freighters (1,700 today and 2,730 forecast in 2033 according to (Boeing 2014b)), there is reasonable high-level agreement between out projection and that of the airframe manufacturers. The results of this analysis are not sensitive to this assumption.

on this basis. For airlines where the ratio of the number of aircraft on order to that in the fleet was less than 0.75, an analysis similar to the one described above was applied, except that it was assumed that all aircraft currently on order would be delivered by 2020.

In these calculations, it was assumed that the airline would grow at the larger of the two rates calculated above. This is akin to saying that if the routes on which the airline operates grow faster than its fleet, then it will acquire the aircraft necessary to serve those routes; and if the fleet grows faster than the routes, then the airline will fill its aircraft, perhaps at the expense of its competitors. Growth rates were assumed to fall to 80% of those assumed for 2013-2025 after 2025.[66]

This calculation produced forecasts of the growth in RPKs flown by each airline. It was assumed that if the age of an airline's fleet was less than five years, its emissions would grow at an annual rate that was 0.5% slower than its RPK. If the fleet was between 5-10 years old, we assumed that emissions would grow 1% per annum slower than RPK. If the fleet was more than 10 years old on average, we assumed that emissions would grow 1.5% slower per year than RPK. As such, it was assumed that airlines with older fleets had the ability to grow more efficiently in the future by switching to newer airplanes, and that airlines whose fleets were already new did not have this ability.

Regional growth rates for freight were also obtained from Airbus (2013a). For US cargo airlines, an average growth rate that was weighted by their regional footprint in 2012 could be obtained and was used in projecting emissions. For the two European cargo airlines, a simple average of all regional growth rates for routes in and out of Europe was used.

4.2.4 Hierarchical cluster analysis

To extract generic airline types from these data, I used a hierarchical cluster analysis, implemented in R, an environment for statistical computing. (Müllner 2013) Cluster analysis has been used to identify groups of airlines in the literature for market segmentation (e.g., Robles and

[66] This was based on assumptions made in Airbus fleet forecasts (Airbus 2014).

Sarathy 1986) and the identification of strategic groups (e.g., Kling and Smith 1995). Hierarchical clustering (as opposed to, say, k-means) was used because this approach makes it possible to visualize the structure of the cluster hierarchy and exercise judgment in defining each cluster at the appropriate level.

The following variables were included in the analysis for each airline: the number of international revenue passenger kilometers, the average age – in years – of the fleet, the fleet size, the number of airplanes on order for each airline, the maximum and average distances of the airline's services, the number of domestic and international destinations served by the airline, the number of aircraft variants operated by the airline, and the proportion of the airline's total RPK that were international. We had data for 111 airlines, but combined airlines that have merged and operate as single entities (e.g., American Airlines and US Airways) since 2012. After these combinations were made, 106 airlines remained.

Since the variables spanned an enormous range of values ($\sim 10^{11}$ for international RPK and ~1 for proportion of revenue passenger kilometers that were international), the data were normalized by conversion to z-scores. A Pearson correlation matrix (Figure 4.3) was then generated to see which variables were strongly correlated with each other. This correlation matrix is complex, with a number of variable pairs showing high, significant correlations. We therefore apply principal component analysis to generate mutually independent components that could be used in the cluster analysis. The resultant components are shown in Table 4.1.

		INTL_RPK	AVG_FLT_AGE	FLT_SIZE	FLT_ORDERS	MAX_DIST	AVG_DIST	NUM_INTL_RTS	NUM_DOM_RTS	NUM_VARIANTS	PROP_INTL_RPK
INTL_RPK											
AVG_FLT_AGE	|r|	16%									
	p	0.11									
FLT_SIZE	|r|	70%	14%								
	p	0.00	0.15								
FLT_ORDERS	|r|	51%	10%	66%							
	p	0.00	0.32	0.00							
MAX_DIST	|r|	49%	21%	33%	11%						
	p	0.00	0.03	0.00	0.28						
AVG_DIST	|r|	4%	19%	22%	14%	31%					
	p	0.67	0.05	0.02	0.16	0.00					
NUM_INTL_RTS	|r|	42%	10%	79%	35%	29%	29%				
	p	0.00	0.28	0.00	0.00	0.00	0.00				
NUM_DOM_RTS	|r|	55%	7%	52%	44%	11%	18%	26%			
	p	0.00	0.49	0.00	0.00	0.25	0.06	0.01			
NUM_VARIANTS	|r|	75%	34%	69%	30%	56%	16%	51%	34%		
	p	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00		
PROP_INTL_RPK	|r|	4%	18%	37%	32%	4%	39%	54%	7%	11%	
	p	0.67	0.06	0.00	0.00	0.66	0.00	0.00	0.46	0.28	

Figure 4.3: Pearson correlations between the z-scores of the variables used in the analysis. High absolute pair-wise correlations (|r|) are shown with a dark background, as are those with high significance (low p-value). As such, cells where both the upper and lower numbers are shaded with a dark color indicate pairs of variables with high, significant correlations.

Table 4.1: Results of a principle component analysis performed on the airline data. We retain the first four components, which explain 80% of the variation found between the airlines. They pertain to the size, network structure, and fleet characteristics of the airline. The variables with the highest absolute weight in each of the components are highlighted.

Variable	Comp.1	Comp.2	Comp.3	Comp.4	Comp.5	Comp.6	Comp.7	Comp.8	Comp.9	Comp.10
	Size	Network structure	Size	Fleet	Fleet	Size	Network structure	Network structure	Size	Size
INTL_RPK	-0.41	0.23	-0.22	0.08	-0.14	-0.18	0.30	-0.36	0.67	-0.11
AVG_FLT_AGE	-0.10	0.38	0.31	-0.60	0.55	-0.11	-0.20	0.04	0.17	-0.05
FLT_SIZE	-0.47	-0.09	0.01	0.01	0.14	0.08	0.28	0.15	-0.36	-0.72
FLT_ORDERS	-0.33	-0.18	-0.35	0.31	0.44	-0.46	-0.17	0.35	-0.01	0.29
MAX_DIST	-0.25	0.40	0.30	0.37	-0.34	0.08	-0.55	0.32	0.10	-0.13
AVG_DIST	0.11	0.50	0.03	0.52	0.45	0.25	0.20	-0.30	-0.23	0.12
NUM_DOM_RTS	-0.38	-0.21	0.35	-0.01	0.05	0.50	0.34	0.29	0.18	0.45
NUM_INTL_RTS	-0.30	0.03	-0.58	-0.24	0.01	0.54	-0.41	-0.20	-0.12	0.10
NUM_VARIANTS	-0.41	0.19	0.17	-0.18	-0.32	-0.35	0.09	-0.28	-0.53	0.38
PROP_INTL_RPK	0.17	0.51	-0.40	-0.20	-0.20	0.01	0.37	0.57	-0.07	0.08
Standard deviation	2.01	1.39	1.08	0.96	0.83	0.67	0.60	0.50	0.36	0.26
Proportion of variance	40%	19%	12%	9%	7%	4%	4%	2%	1%	1%
Cumulative proportion	40%	60%	71%	81%	87%	92%	96%	98%	99%	100%

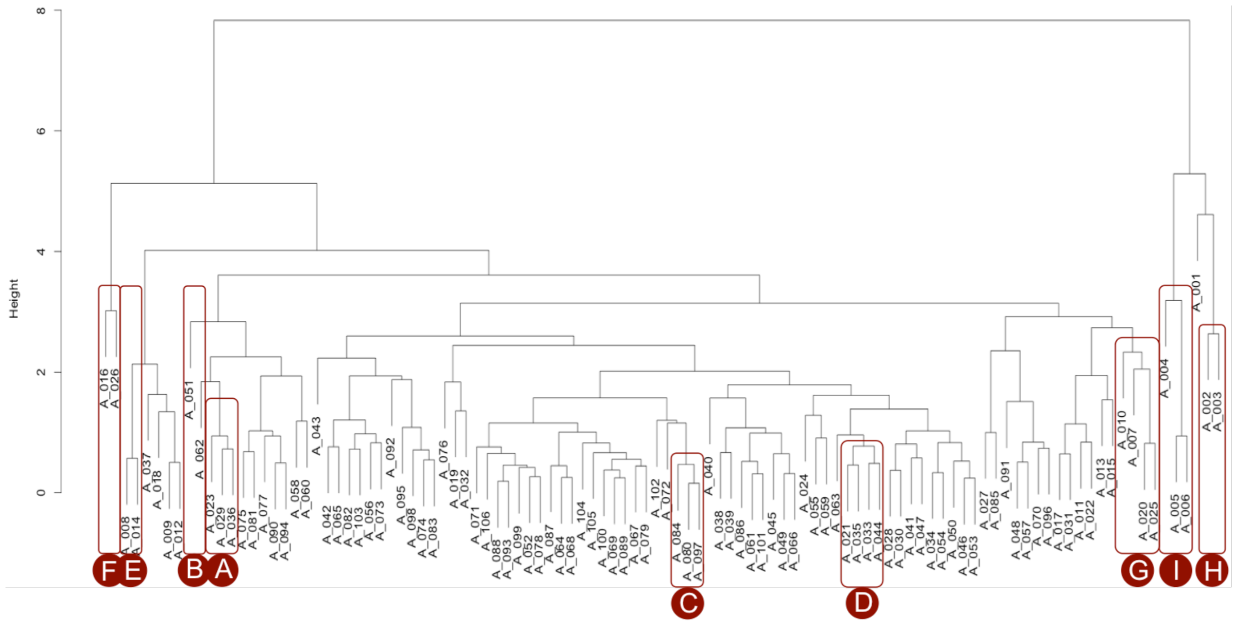

Figure 4.4: Clusters extracted based on the dendogram produced by hierarchical clustering. Clusters are selected so that a diversity of airline types is represented. Airlines are anonymized in this representation and throughout the rest of the document.

A hierarchical cluster analysis was performed; retaining the only the scores for the first four components identified in the principal component analysis for all airlines. The results of this cluster analysis are as shown in Figure 4.4. The individual clusters were selected in order to represent a diversity of airline types. To ensure that the clusters were meaningful – that is, that the airlines within each cluster were indeed similar to each other – the metric in Equation 4.2 was calculated for each cluster, as well as for the entire dataset.

$$d_C = \frac{1}{n_C} \sum_{j=1}^{10} \sum_{i=1}^{n_C} \left(z_i^j - \mu_C^j\right)^2 \qquad \text{Equation 4.1}$$

where

C refers to each of the clusters A to I, as well as the full dataset (which we refer to as cluster 0),

n_C is the number of airlines in cluster C,

z_i^j is the z-score of the jth variable[67] of the ith airline in cluster C, and

[67] The ten variables used in this analysis are listed in Figure 4.3 and Table 4.1.

μ^j_C is the mean z-score of the jth variable for cluster C.

$$\frac{d_C}{d_0}, where\ C \in \{A, B, C, D, E, F, G, H, I\} \qquad \text{Equation 4.2}$$

where d_C and d_0 are as defined in Equation 4.1.

Table 4.2: A diversity of airline clusters has been extracted from the dendogram in Figure 4.4. The international RPK for each cluster is a simple sum of all the airlines within each cluster, and the fleet ages and growth rates are weighted averages. The last column indicates that the cluster is meaningful, the ratio d_C/d_0 <<1 for all clusters, with the exception of cluster F.

Cluster	Network Footprint	Growth rate	Avg. age of fleet	International RPK (2012)	d_C/d_0
			(years)	*(billions)*	
A	90% Dom – 10% Intl	< Industry average	< 10	15	0.09
B	90% Dom – 10% Intl	> 2x industry average	< 5	5	0.44
C	100% Intl	> 2x industry average	< 5	14	0.01
D	20% Dom – 80% Intl	No growth	< 10	11	0.09
E	70% Dom – 30% Intl	~ Industry average	< 10	53	0.06
F	10% Dom – 90% Intl	< Industry average	~ 5	11	0.86
G	100% Intl	> Industry average[68]	< 10 years	37	0.48
H	50% Dom – 50% Intl	< Industry average	> 10 years	30	0.52
I	10% Dom – 90% Intl	< Industry average	> 10 years	60	0.51

The resultant clusters are presented in Table 4.2. Cluster D is composed of a group of airlines, which – based on their fleet orders – might be expected to shrink over the next 20 years. We have imposed an exogenous assumption that this cluster does not grow, to assess the impact of the strawman on such airlines. In its last column, which displays ratio d_C/d_0 as defined in Equation 4.2, Table 4.2 also shows that the clusters are indeed meaningful. Airlines within the cluster are significantly "closer" to each other than all the airlines in the dataset; i.e., d_C/d_0 << 1. The exception to this finding is cluster F, for which the ratio is 0.86. This is entirely due to the fact that A_016 in that cluster serves many more destinations than A_026, the other airline in the cluster. If the number

[68] While the weighted average growth rate of the cluster is greater than the industry average but less than twice industry average growth rate, two of the airlines in this cluster are forecast to grow at twice the industry average. These would therefore be eligible for the reduction offered fast growers.

of international destinations were ignored for both cluster F and for the entire dataset, d_F/d_0 would be 0.19.

4.3 Results

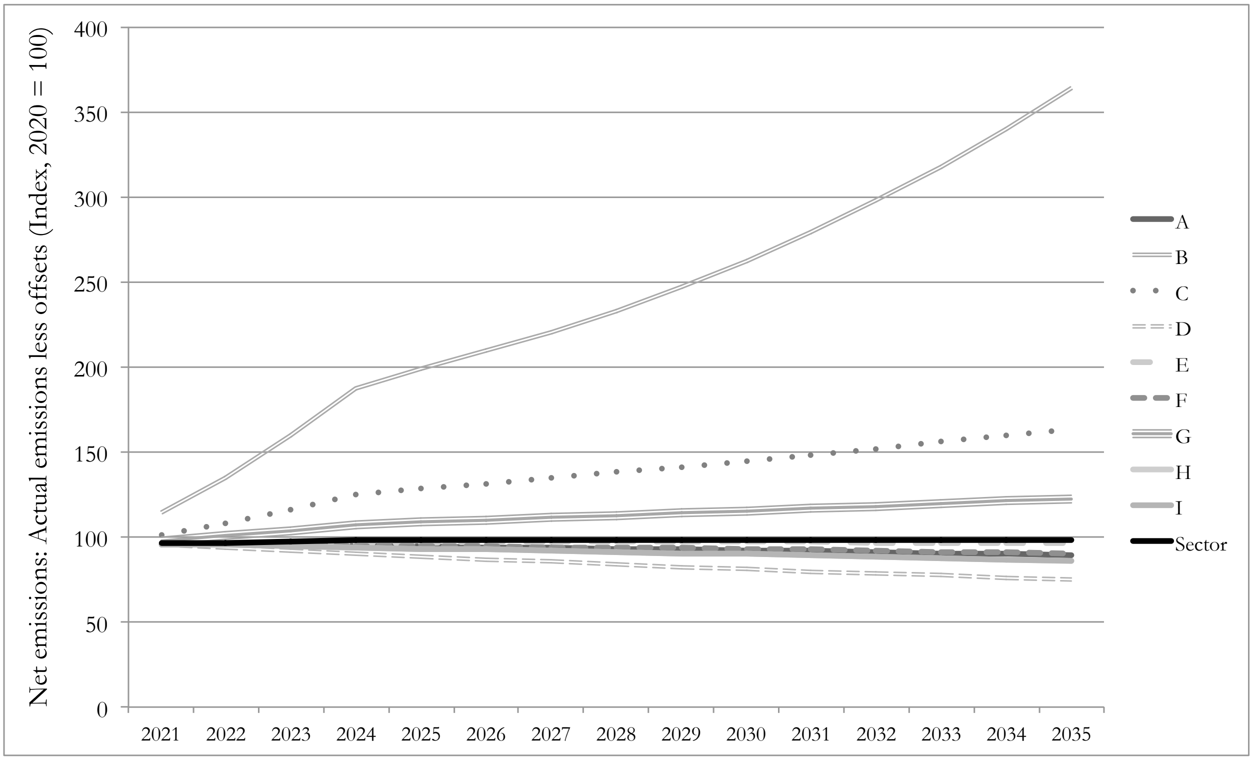

Figure 4.5: Assuming *de minimis* exemptions are kept small and new entrants' emissions are added when calculating the sectorial total, the strawman would cap emissions at or below 2020 levels. It would also create room for fast-growing airlines, whose current contribution to emissions from international aviation is small, to increase their net emissions very substantially by requiring much larger airlines to push their net emissions somewhat below 2020 levels.

The first question to ask of the strawman is whether it does what it is primarily designed to do: restrict net emissions (actual emissions less offsets) for international aviation to 2020 levels or below. With the assumptions made above – that new entrants' emissions are accounted for when total sectorial emissions are calculated and that *de minimis* exemptions are kept small[69] – Figure 4.5 suggests that it does. The rest of this section comments on the distribution of the obligations the strawman places on different airlines. However, Figure 4.5 gives an early glimpse: by forcing the very

[69] The *de minimis* exemption is discussed further at the end of this section.

large airlines of clusters H and I to slightly reduce their emissions relative to 2020, the mechanism creates room for smaller, faster-growing airlines such as those in groups B, C, and G to increase quite substantially.

The strawman imposes very different offset obligations – when expressed as a percentage of total international obligations – on different types of airlines. The trajectory taken by these obligations also varies greatly between clusters; for example, the airlines in Cluster B offset a comparatively small proportion of their international emissions in 2021, but – by 2035 – are required to offset a larger proportion of their emissions than any other cluster of airlines Figure 4.6.

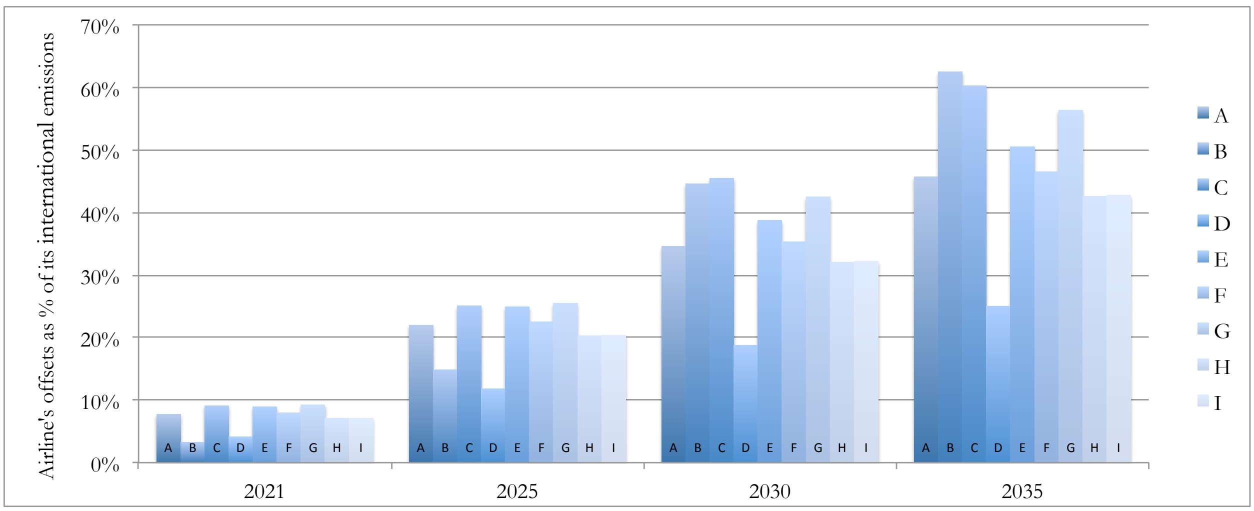

Figure 4.6: Different types of airlines are required to offset very different proportions of their emissions in each year. The trajectories that airlines' offset obligations follow over time are also very different: the airlines in Cluster G are obliged to offset among the highest proportions of their emissions in each of the years, whereas the airlines in Cluster B start off offsetting a comparatively small proportion of their emissions in 2021, but – by 2035 – are responsible for offsetting a higher proportion of their emissions than any other cluster.

This trajectory is explained by the fact that the airlines in Cluster B are eligible for reductions in their offset obligations due to their exceptionally fast growth. Until 2024, the total of such reductions is below the limit set for it in the strawman – that is, 50% of the emissions held in reserve (see Section 4.2.1) – and all airlines receive all the compensation they are eligible for. After 2024, this limit is breached, and airlines' total offset obligations grow while the reductions offered to them stay constant. As such, their offset obligations as a share of their international emissions rise rapidly after 2024 (see Figure 4.7).

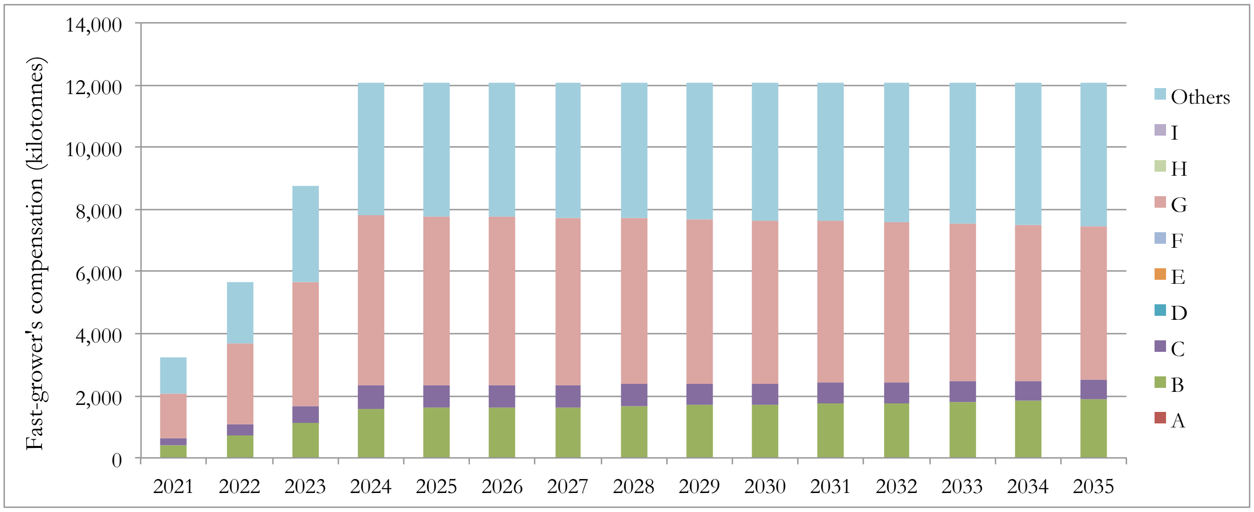

Figure 4.7: Most of the reductions due to fast growers are received by airlines that belong to clusters B, C, D, and G. The fast-growers reduction is such that it depends on its growth since the reference year as well as the absolute magnitude of its emissions in the reference year. As such, a bulk of this compensation is given to the relatively large airlines in Cluster G, rather than the small, but faster-growing, airlines in Clusters B and C. The reduction is limited by the size of the reserve allocated to fast growers. This limit is breached in 2024. Before this year, the airlines receive "full" reduction. After it, the reductions are trimmed to ensure that total compensation does not exceed the 50% of the reserve allocated to compensate fast growers.

It is possible that the purpose of the fast-grower's compensation is to ensure that small, rapidly growing airlines are not overly burdened by the need to buy offsets. Indeed, this compensation is a form of subsidy offered to fast-growing (presumably fledgling) airlines by their slower growing (presumably mature) competitors since it comes out of a reserve created by tightening the cap to below 2020 levels for airlines that receive no compensation. An interesting observation that can be made in Figure 4.7 is that a very large portion of the reductions goes to the relatively large airlines in Cluster G. This is a consequence of the fact that fast-grower's reductions are calculated based on both the growth rate and the size of the airlines emissions in the reference year. As such, the design of the strawman is such that it subsidizes already-large, fast-growing airlines at the expense of its comparably sized, slower-growing rivals. Against this, it must be said that – even after adjusting for the compensation they receive - the airlines in Cluster G offset a larger proportion of their international emissions than their larger or similarly-sized competitors in other clusters.

One criticism of the argument above is that the growth of airlines tends to slow as they grow larger: few airlines would remain eligible for fast-growers compensation as they grew larger. This line of reasoning would contend that we are being too optimistic in assuming that the comparatively large airlines of Cluster G will continue to grow rapidly enough to be eligible for reductions. This is a reasonable argument, but there have been historical outliers. One is Ryanair, which – in 2013 – was the world's largest airline in terms of passengers carried. (IATA 2014a) In terms of revenue passenger kilometers, Ryanair grew at an annual average rate of 28% between 1998-2013. Its growth slowed dramatically in 2012 and 2013.[70] Even so, during many of the years between 1998 and 2011, it was both a large, profitable airline and one that was growing fast enough to be eligible for a reduction in its obligations under the strawman.[71] Its competitors would not have been cheered by the prospect of subsidizing this rocketing growth.

Figure 4.8 sheds additional light on the issue. It shows that airlines that are growing faster than the sector – that is, airlines that are gaining market share – are required to offset a larger share of the sector's growth after 2020 than are airlines that are losing market share. The exceptions to this rule are the very fast-growing airlines in Cluster B, which – until 2026 – receive enough of a reduction in their offset obligations for their share of offsets to be lower than their share of international emissions.

[70] Data on historical growth rates of a large number of airlines were gathered by my colleague at the Environmental Defense Fund (EDF), Rafael Grillo, and I am grateful to him. The numbers for Ryanair come from the company's Form 20-F filings with the US Securities and Exchange Commission.

[71] In fact, since the reductions are based on percentage cumulative growth since a reference year, Ryanair would have remained eligible well after its growth slowed to or below industry average.

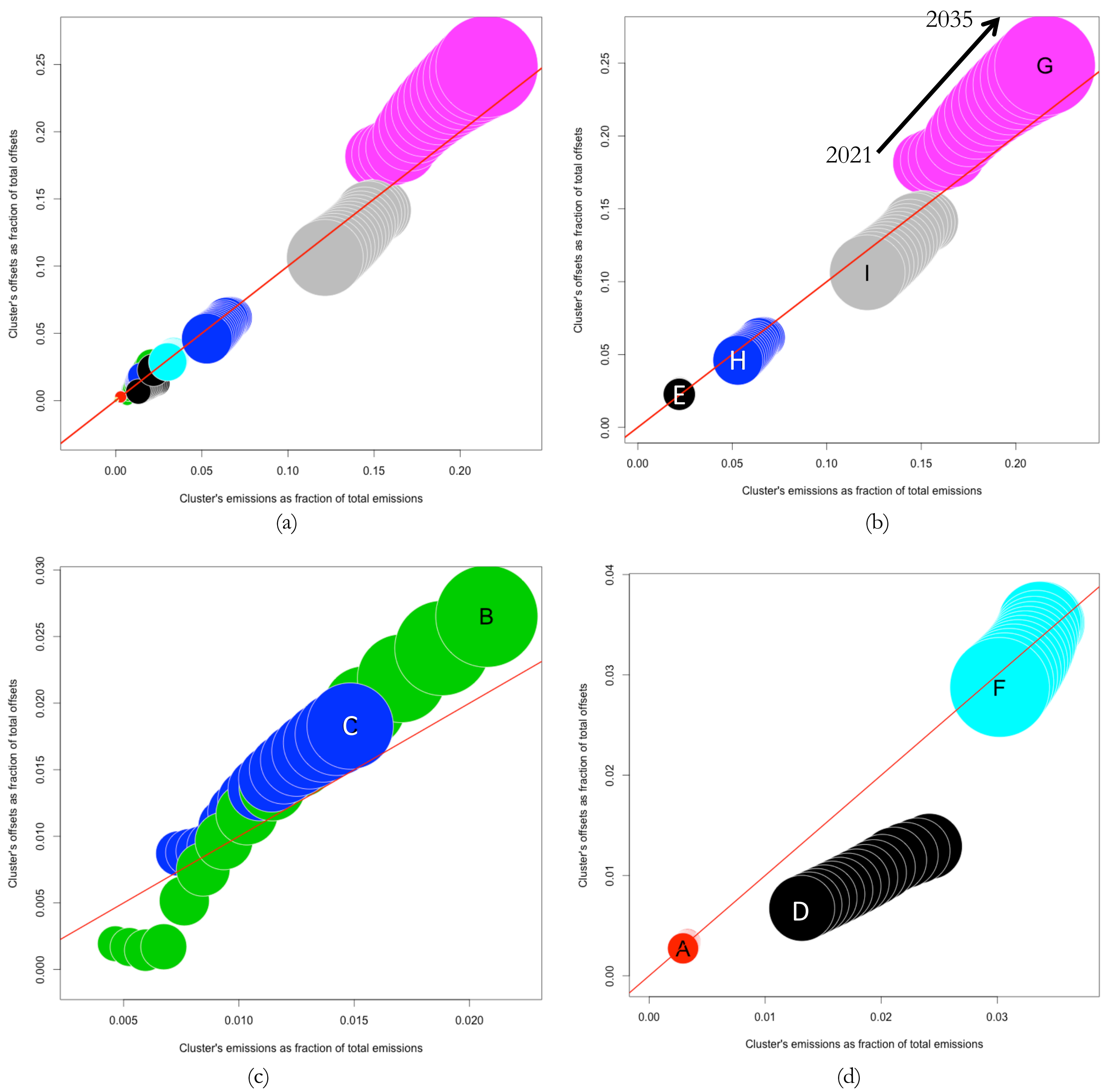

Figure 4.8: These plots show the relationship between a cluster's share of sectorial international emissions (x-axis) and its share of sectorial offsets (y-axis). The plots also show the evolution of this relationship: each bubble corresponds to the cluster's position in a particular year. In plot (a), the clusters are shown in different colors. In plots (b), (c), and (d), the clusters are named. The bubble containing the cluster's name indicates that bubble's position in 2035. The red line in each plot is a 45-degree line. If a bubble lies above this line, it suggests that, at that time, that cluster will be responsible for purchasing a larger share of sectorial offsets than its share of sectorial emissions. The size of the bubbles in each plot is proportional to the cluster's emissions. Note that the scale is constant within a plot, but not across plots. The plots indicate that airlines that gain are gaining market share will be responsible for offsetting a larger proportion of the sector's emissions growth than is their market share at any given time. An exception is cluster B, which – until 2024 – receives significant reductions in its obligations, and is share of offsets is consequently much smaller than its share of emissions. The situation is reversed after 2026-27.

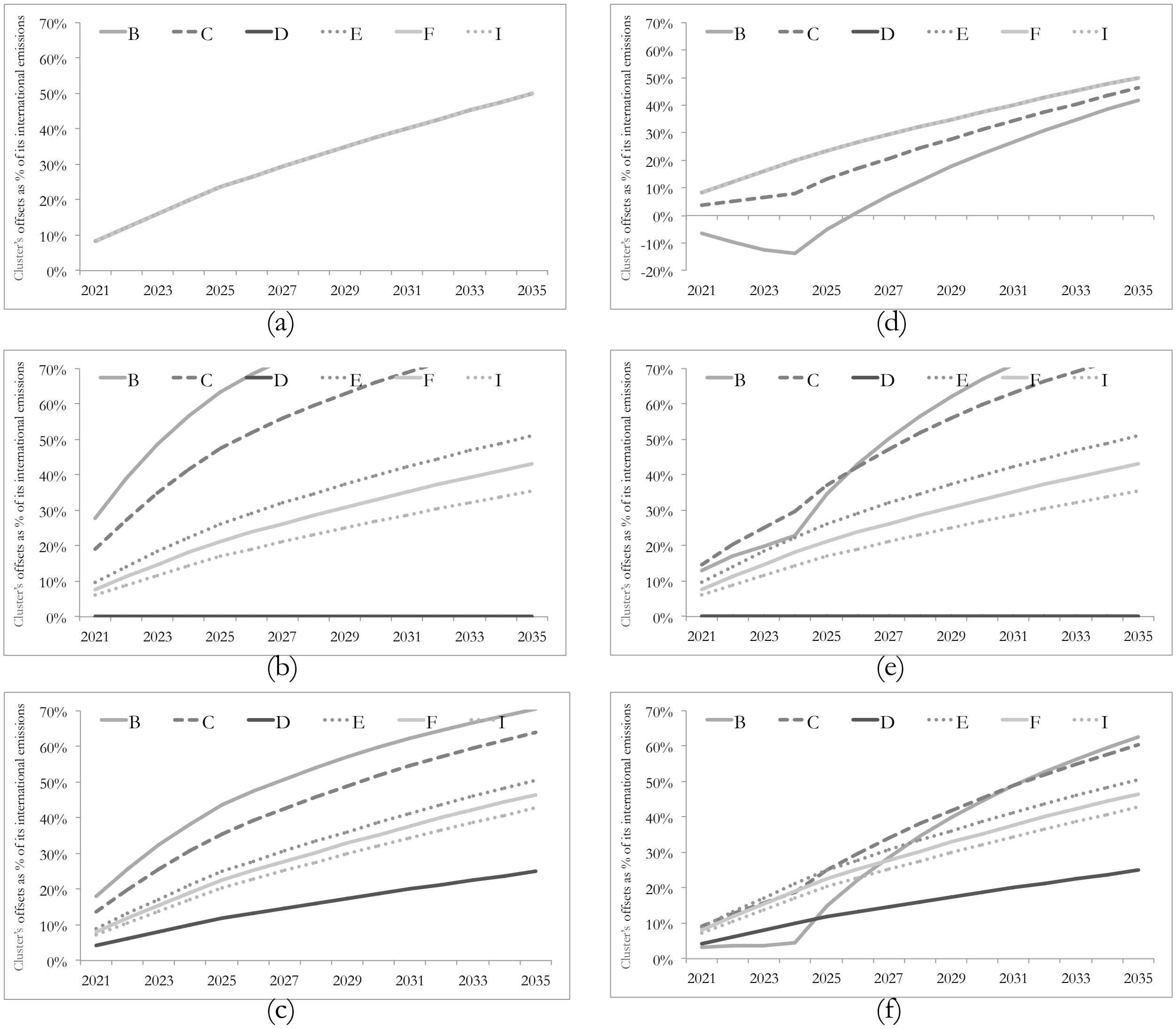

Figure 4.9: (a)-(e) illustrate the fraction of their international emissions different clusters would have to offset under different alternatives to the strawman, while (f) represents the strawman. (a), (b), (c) are scenarios where compensation is not made for fast growth, the remaining charts show scenarios where it is made. For visual clarity, only five of the nine clusters have been shown. <u>(a)</u> In this case, total sectorial growth since 2020 is calculated. Each year, each airline is required to offset a share of that growth equal to its share of sectorial emissions in that year. There is no compensation for fast growers. If the airlines were assumed to have access to a very large pool of identically-priced offsets, this situation closely resembles what would happen if a uniform carbon tax were imposed on airlines' international emissions: each airline's costs would be proportional to its international emissions. <u>(b)</u> If airlines were made to offset simply offset *their* growth in emissions since the reference year, the fast growers would be very hard hit, whereas airlines that did not grow would not have to offset anything. (c) represents a compromise – in fact, a literal averaging – of the approaches in (a) and (b). The while this raises the obligations for slow-growers and reduces them for fast-growers, the burden on the latter is still comparatively high. <u>(d)</u> is a version of (a), but one in which the obligation of fast growers is reduced, possibly to a point where they have no net obligation. <u>(e)</u> bases the offset obligation entirely on an airline's own growth since the reference year, but compromises by offering some relief to fast growers. <u>(f)</u> is a compromise – again, a literal average – between (d) and (e). (f) represents the strawman.

The analysis so far suggests that the strawman has produced diverging (i.e., different airlines are affected very differently) and complex outcomes, not all of which may have been anticipated by the document's designers. The deliberations of the Environmental Advisory Group are not made public, but it may be possible to gain insight into their thinking by considering counterfactuals to different elements of the strawman, as is done in Figure 4.9. The exercise illustrates that the strawman could be understood as a compromise.

The simplest starting point might have been Figure 4.9(a), in which each airline would be required to offset a portion of the industry's growth since the reference year that was directly in proportion to the airline's share of emissions in the current year. The fact that such an arrangement would resemble a Pigovian tax would make the approach attractive to economists, but legally fraught.[72] The approach might also be criticized for basing the penalty (i.e., the offset obligation) on the absolute size of the airline rather than its contribution to the sector's growth since 2020, when the latter might seem more salient in a mechanism designed to cap industry growth at 2020 levels. This criticism could be addressed by adopting the approach in Figure 4.9(b), where each airline is made to offset its own growth since the reference year. Such an approach would place a disproportionate burden on fast-growing (usually small) airlines, while letting airlines that are no longer growing (like those in Cluster D) completely off the hook, regardless of their current or past contributions to greenhouse gas pollution. Such an approach might be criticized because it penalizes (and might suppress) industry growth, and is likely to penalize fast-growing airlines, which are

[72] Article 24 on Customs duty of the Chicago Convention (ICAO 2006), which governs international civil aviation and is ICAO's founding charter, states that, "Fuel, lubricating oils, spare parts, regular equipment and aircraft stores on board an aircraft of a contracting State, on arrival in the territory of another contracting State and retained on board on leaving the territory of that State shall be exempt from customs duty, inspection fees or similar national or local duties and charges." This Article has always been interpreted to mean that fuel used for international aviation must be exempt from national taxes. Whether this extends to a similar prohibition on carbon offsets is a question that is still contested, even though the European Court of Justice (2011) has ruled that it does not.

predominantly – though not exclusively – based in developing countries. One possible compromise is to simply calculate offset obligations both ways, and to set actual obligations as the average of the two. In its basic calculation, this is precisely the compromise that the strawman makes (Figure 4.9(c)). This arrangement would still place a comparatively onerous burden on fast growers. To partially correct this, the strawman adds a further embellishment: the reduction in offset obligations offered very fast growing airlines. Figure 4.9(f) shows the effect that this adjustment has: fast growers offset a smaller proportion of their emissions initially, but this rises steeply in later years – for reasons discussed above – until, by 2035, such airlines are responsible for offsetting a much larger proportion of their emissions than are slower-growing rivals. This form of compensation is an explicit subsidy from slow-growing airlines to fast-growing ones. The reserve is created by tightening the cap to below 2020 levels for the entire sector. It may be that, assuming that most of the airlines that are eligible for such compensation are from (and serve) the developing world, this compensation is a way for ICAO to implement some form of the principle of common but differentiated responsibilities, while also adhering to the principle of non-discrimination by not explicitly making the subsidy available to only airlines from the developing world.

We end this section with a discussion of the *de minimis* exemption of the strawman. Its provisions are described in detail in Section 4.2.1. Because of the way the exemption is worded, exempting flights in and out of the lowest-emitting states with cumulative emissions of X% of the total would exempt X% of global emissions.

The list of exempt states would be updated every five years, which would ensure that this would remain the case. Figure 4.10 is drawn by applying the *de minimis* exemption rules to 2012 data, and this limits its validity to the discussion of ICAO's market-based mechanism.

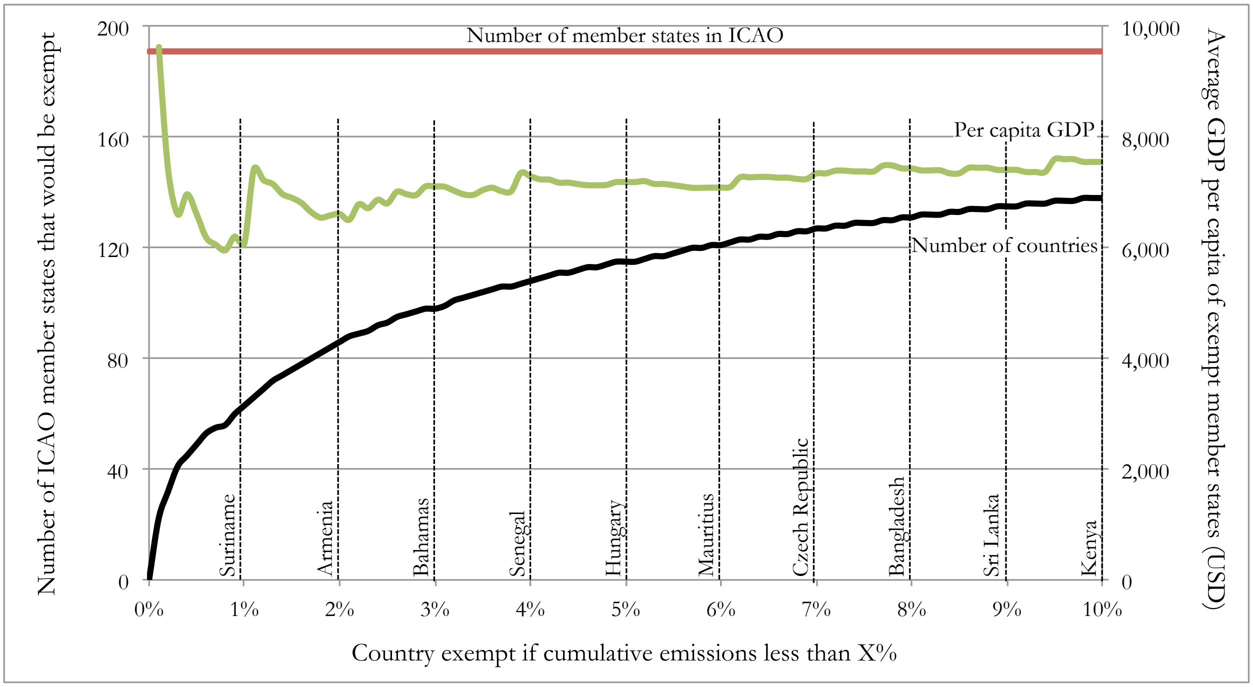

Figure 4.10: If the threshold for *de minimis* exemption were set at more than 4%, over half the member states of ICAO would be exempt from participation in the scheme. The "marginal" member – the member state with the highest emissions that still received an exemption - would be Senegal. For X>0.5%, the average GDP per capita of exempt states would be over US$8,000.

It shows that setting X at greater than 4% would exempt traffic in and out of over half the ICAO's 191 member states. The figure shows the "marginal" state that would be exempt at different levels. Even a 2% threshold would exempt Armenia, a European country; a 5% threshold would exempt Hungary, a member of the European Union. It is also clear that, while some of the countries that would be exempt are poor (e.g., Afghanistan), making exemptions in this way does not exclusively relieve poor countries. For X>0.5%, the average per capita GDP of an exempt state exceeds $8,000 per year. A cumulative threshold of 0.5% would exclude EU countries such as Slovenia and the Slovak Republic. A 2% threshold would exclude flights in and out of Luxembourg. As such, while having a *de minimis* threshold that is agnostic to which state is being exempted is compatible with ICAO's non-discrimination principle, this form of relief is not particularly well targeted.

The exempted emissions are calculated on the basis of the first year of *application,* which is assumed to be 2020. The strawman also says, "exempted emissions are not included in the reference year and in the current year." How this is interpreted has a significant bearing on whether or not the strawman emissions are actually capped at 2020 levels, at some other level, or not capped at all. To see why, consider that the strawman says, "The baseline for determining quantities to be offset is computed first by using an average of three-year of emissions from 2018 to 2020…this average will be taken as the reference." This leads to the following question: is this initial reference then lowered to account for the *de minimis* exemption, and are the reference emissions for individual airlines also proportionally reduced? Does the reference – for the sector and for airlines – change every time the size of the *de minimis* exemption changes?[73] Consider also that that the size of the reserve used to "compensate" early movers and fast growers is set by calculating "the difference between the reference and the actual global emissions in 2020, or 3% of the actual global emissions in 2020, whichever is the highest." Does the reference level used to calculate the reserve account for *de minimis* exemptions calculated in 2020? Are the actual emissions for 2020 adjusted to exclude *de minimis* exemptions?[74] Depending on the answers to these questions, a number of scenarios can be constructed, as shown in Table 4.3.

The figures presented in this table assume that the sector grows at a uniform rate of 4% per year, and assumes that the threshold for exemption is set at 3% of total global emissions in 2020. In this case, in the most adverse interpretation of the strawman, net emissions would exceed 2020 levels by over 5% in 2035. The overshoot would be greater if the industry growth rate were higher. Net

[73] Recall that the *de minimis* exemption is recalculated every five years. While the exemption is set to exclude the lowest emitting states whose cumulative emissions are the same proportion of the sector's total emissions, that total will likely grow, as will the absolute magnitude of the *de minimis* exemption.

[74] If the first year of application is not 2020 and the actual emissions for 2020 are to be adjusted to account for the *de minimis* exemptions, that raises the question: by how much should the 2020 emissions be adjusted?

emissions would be capped at 2020 levels if the value for the initial reference year emissions for both individual airlines and the sector – which is the basis for calculating offsets for the collective and individual parts of the airlines' offset obligations, respectively – were adjusted for the *de minimis* exemption, and if these values were updated every time the absolute value of the *de minimis* exemption were adjusted. In addition, it is important that a consistent approach is adopted in calculating the size of the reserve: either both, the reference and 2020 emissions, must be corrected for the *de minimis* exemption, or neither. To be clear, if both these things were done, the mechanism would tighten the cap for countries that do not receive the *de minimis* exemption by the total volume of the exemption. These emissions would still be offset, but indirectly. Failure to adjust the reference emissions to account for the *de minimis* exemption would mean a *de minimis* threshold of 3% would cause net emissions in 2035 to overshoot the 2020 level by 5%.

Table 4.3: Depending on how the text of the strawman is interpreted, even emissions that are not part of the technical exemption could exceed 2020 levels by 5% or more. This table assumes sectorial growth of 4% per year throughout the period of the scheme, and assumes that the threshold for exemption is set at 3% of total global emissions in 2020. If this were higher, the overshoot would be even higher than 5%. In this table, internally contradictory scenarios – that is, ones in which the reference level in the first year ignored the *de minimis* exemption, but those in future years took account of it – are ignored and marked as "NA"

Is the initial reference for airlines and the sector adjusted?	Is this adjusted reference used for calculating the reserve?	Are 2020 emissions adjusted to account of the de minimis exemption when calculating the reserve?	Is the reference adjusted every time the de minimis exemption changes?	Emissions in 2035 (Index, 2020 = 100)
Yes	Yes	Yes	Yes	100.0
Yes	Yes	Yes	No	102.4
Yes	Yes	No	Yes	103.0
Yes	Yes	No	No	105.4
Yes	No	Yes	Yes	99.1
Yes	No	Yes	No	101.5
Yes	No	No	Yes	100.0
Yes	No	No	No	102.4
No	No	No	No	105.4
No	Yes	Yes	Yes	NA
No	Yes	Yes	No	105.4
No	Yes	No	Yes	NA
No	Yes	No	No	104.6
No	No	Yes	Yes	NA
No	No	Yes	No	104.5
No	No	No	Yes	NA
No	No	No	No	104.6

4.4 Discussion

4.4.1 Comparison with the EU-ETS

The strawman draws several elements from the European Union (EU) directive that was meant to integrate aviation into the EU's Emissions Trading System (ETS). For example, the EU-ETS set aside a reserve for fast growing airlines (also set at 3% of the emissions of a reference year), as well as *de minimis* exemptions for small aircraft and airlines. (The European Parliament and Council 2008)

The EU mechanism – which is dormant for non-European airlines, but still on the statute books – is designed to base offset requirements entirely on growth, with reductions offered to fast growers. That is, it resembles Figure 4.9(e). This is instructive: the complexity of the strawman's provisions is easier to understand if we assume that the EU-ETS served as a template and, as a consequence, Figure 4.9(e) was a starting point for its design rather than Figure 4.9(a). One could speculate that the designers of the strawman started with the mechanism represented by Figure 4.9(e), and sought to make it less harsh on fast growers.[75] At the same time, two useful features of the EU ETS are not – but ought to be – included in the strawman. One, the EU ETS includes a disincentive for airlines to split off their fast-growing operations as subsidiaries by restricting access to fast-growers' compensation to activities "not in whole or in part a continuation of an aviation activity previously performed by another aircraft operator." (Article 3f of Directive 2008/101/EC of The European Parliament and Council 2008) For the purpose of calculating the exemptions for fast growers, the EU ETS is defines growth in terms of air transport service provided rather than emissions. An operator whose tonne-miles grow by 18% per year would qualify for a reduction even if its emissions grew by only 16%. This creates an incentive for even fast growers to reduce emissions as much as possible.

[75] Under the EU ETS, an airline would have to meet a much higher bar – an annual growth rate of 18% – to qualify as a fast grower.

The EU ETS also took a more nuanced approach in granting *de minimis* exemptions, saying that the functioning of the directive "should consider the structural dependence on aviation of countries which do not have adequate and comparable alternative modes of transport and which are therefore highly dependent on air transport and in which the tourism sector provides a high contribution to those countries' gross domestic product." Taking such a deliberative approach is clearly easier in the context of a mechanism that the EU designed "unilaterally" and would impose, than in the context of a multi-lateral forum such as ICAO. Nonetheless, as shown in Figure 4.10 and discussed in Section 4.3, the ICAO's blunt approach produces some counter-intuitive outcomes. Possible alternatives are considered in Section 4.4.2.

4.4.2 Alternatives

Economists have discussed the merits of introducing a carbon tax on aviation and using the revenues to compensate states that are hardest hit by such a tax, as well as by climate change in general. (AGF 2010a) Even if the legal objections (see Footnote 72) to such a scheme could be overcome, and in the highly unlikely event that objections from the industry could be overcome,[76] such a mechanism would raise the impossible question of whom the resulting revenues belong to, and how they ought to be spent.

Section 4.4.1 speculates that the strawman might have started with the EU-ETS, and sought to tweak that mechanism so as to be less burdensome for fast-growing airlines. The designers ought to consider the sort of mechanism outlined in Figure 4.9(a), whereby an airline's offset obligations are calculated as the product of its sectorial emissions share and the growth of the market since the reference year. Assuming that airlines have access to a large and uniformly priced pool of offsets,

[76] The International Air Transport Association (IATA), which represents the industry in these negotiations, has said (IATA 2013) that a market-based mechanism "should not be designed or used to raise general revenues," and is likely to remain implacably opposed to a revenue-generating scheme.

such an approach ensures that they all face the same average cost per tonne of emissions reductions. This approach does away with the gyrations the strawman goes through to get to a mechanism that is not overly burdensome on new or fast-growing airlines and to ensure that most airlines (including those whose emissions are flat or falling) are brought under the scheme. As the ongoing discussion demonstrates, the current proposal is complex enough that the text of the strawman is unequal to the task of describing it precisely and fully. Numerous assumptions are needed to work out what impact it would actually have on airlines (See footnotes 58-61 and Table 4.3). The mechanism could be made simpler, and therefore less contentious and possibly fairer.

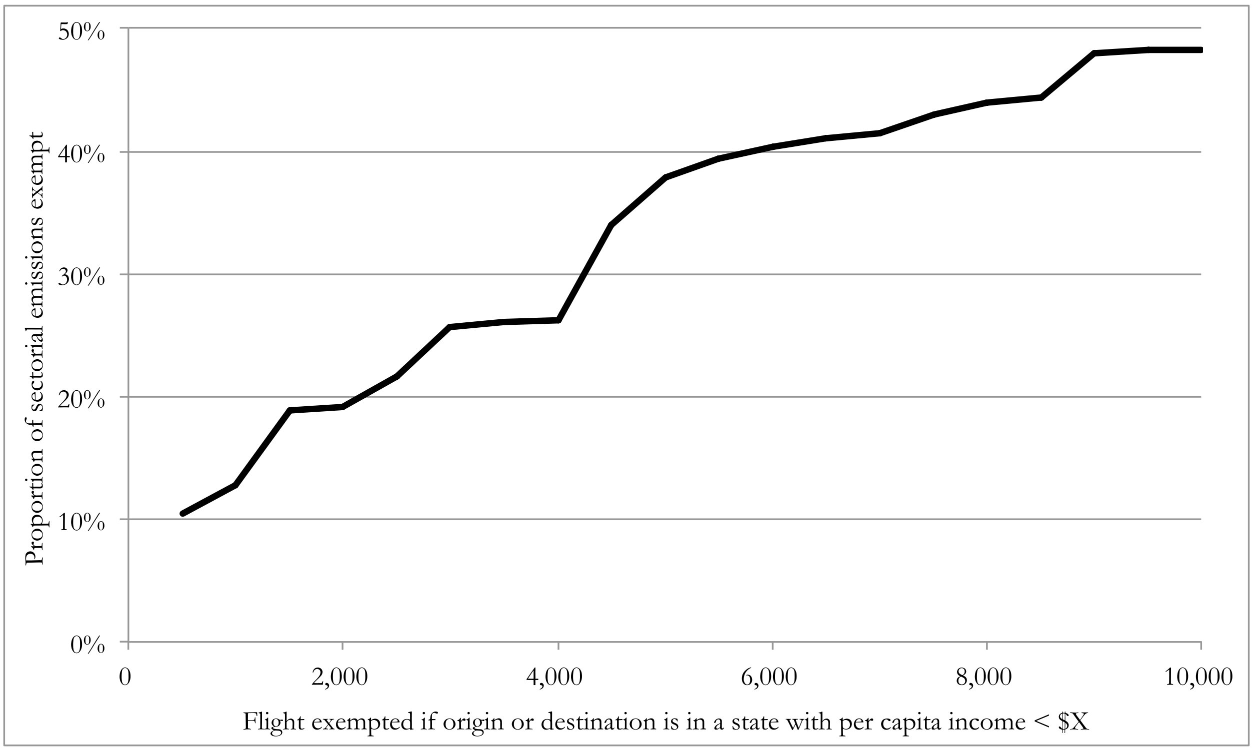

Figure 4.11: Proportion of emissions from international aviation that would be exempt if flights in and out of countries with different levels of GDP per capita were exempt. The GDP per capita data are from the World Bank's 2013 statistics, or the latest year available. They are in 2013 US$, calculated at market exchange rates.

The current proposal for de minimis exemptions would exclude counties with an average GDP per capita of $8,000 per year for a wide range of exemption thresholds (see Figure 4.10). If flights going in and out of countries with an income of less than $8,000 were excluded, that would translate to 44% of global emissions.

The strawman's provisions could also be improved by targeting the *de minimis* exemption more precisely towards poorer countries. One way of doing this without adopting the EU's approach – which would make exemptions on a case-by-case basis – would be to apply an income threshold below which traffic in and out of a country would become exempt. The advantage of such a scheme is that – so long as the threshold was held constant in, say real 2020 US dollars - countries would automatically become ineligible as they grew richer. Over time, the scheme would cover an increasing proportion of the emissions from international aviation. The impact of this form of *de-minimis* exemption is shown in Figure 4.11. It is interesting to contrast Figure 4.11 with Figure 4.10, which shows that the average income of the countries that are exempt would be around $8,000 per capita per year. Recall that the approach set out in the strawman produces surprising outcomes: at a 2% threshold, flights in and out of Luxembourg would be exempt, whereas flights to and from Ethiopia would not. Figure 4.11 shows that if traffic flying in and out of *all* countries with this level of income or lower were made exempt, over 40% of the sector's emissions would be affected. If the threshold for exemption were held at $500 per year per capita, 10% of global emissions would qualify.

Table 4.4: Proportion of sectorial emissions that would be included if routes where either origin or destination were in countries with per capita income less than certain thresholds, and which were served by fewer than a certain number of airlines. Only two routes – Singapore-Jakarta and Hong Kong-Bangkok – are served by 12 airlines; none is served by 11.

If served by X or	Annual per capita income less than									
fewer airlines	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000
X = 1	2%	3%	5%	6%	7%	8%	8%	8%	11%	12%
2	5%	7%	10%	11%	12%	14%	15%	15%	20%	23%
3	7%	9%	14%	14%	16%	19%	19%	19%	26%	29%
4	8%	10%	15%	16%	17%	21%	21%	21%	29%	32%
5	9%	11%	16%	17%	19%	23%	23%	23%	31%	34%
6	9%	12%	18%	18%	20%	24%	24%	25%	32%	36%
7	10%	12%	18%	18%	21%	25%	25%	25%	33%	36%
8	10%	12%	19%	19%	21%	25%	25%	26%	33%	37%
9	10%	13%	19%	19%	21%	25%	26%	26%	34%	37%
10	10%	13%	19%	19%	21%	25%	26%	26%	34%	37%
12	10%	13%	19%	19%	22%	26%	26%	26%	34%	38%

Perhaps an even more refined approach might be to consider not only how poor a country is, but also how well it is served by airlines. This is especially relevant because 2012 data indicate that, of 13200 routes, nearly 8900 – or well over half – are served by only one airline. If only routes that went either to or from countries with per capita income less than $500 per year and that were served by only one airline were exempt, the total size of the exemption would be 2% of total global emissions (see Table 4.4). This approach makes it possible to target exemptions at individual routes, rather than at entire countries. This might encourage airlines to expand to hitherto underserved routes in poor countries. On the other hand – if the prices of offsets were high enough – it might also spawn a commercially sub-optimal route-structure. On eligible routes served by two airlines, it might encourage predatory behavior, where one player seeks to drive the other out of the market and thus have its own emissions on that route be made exempt.

This section has argued for a system that is based on relatively simple metrics that are tied directly to something that can be easily measured: for example, we argue that an airline's offset obligations should be tied directly to its emissions, and that the *de minimis* exemption – if it must exist at all, and assuming it is designed to spare poor, underserved countries – ought to be tied directly to income levels and level of service.

4.4.3 An organizational theory perspective on the strawman

Austin (1996) provides a compelling account of why such simplicity is not merely a matter of aesthetics, and is in fact crucial to avoiding dysfunction. Most policies, including the one being studied in this chapter, have multiple objectives and a finite set of resources to achieve those objectives. Given this budget constraint, policymakers must strike a balance between different objectives: doing better on one comes at the expense of poor performance on another. There is also an optimal balance, where the policymaker would not accept any deterioration in the attainment of one objective in order to make gains on another. Sometimes, it is difficult to know – or there is disagreement about – where this optimal lies. It may also be difficult to tell when the optimum has been attained. This is especially true when performance on one or more of the objectives is much easier to measure than on the others. Austin's argument is that, in such cases, organizations create incentives to maximize performance on whatever objective is easiest to measure even if this is to the detriment of the overall performance. This argument is illustrated in Figure 4.12.

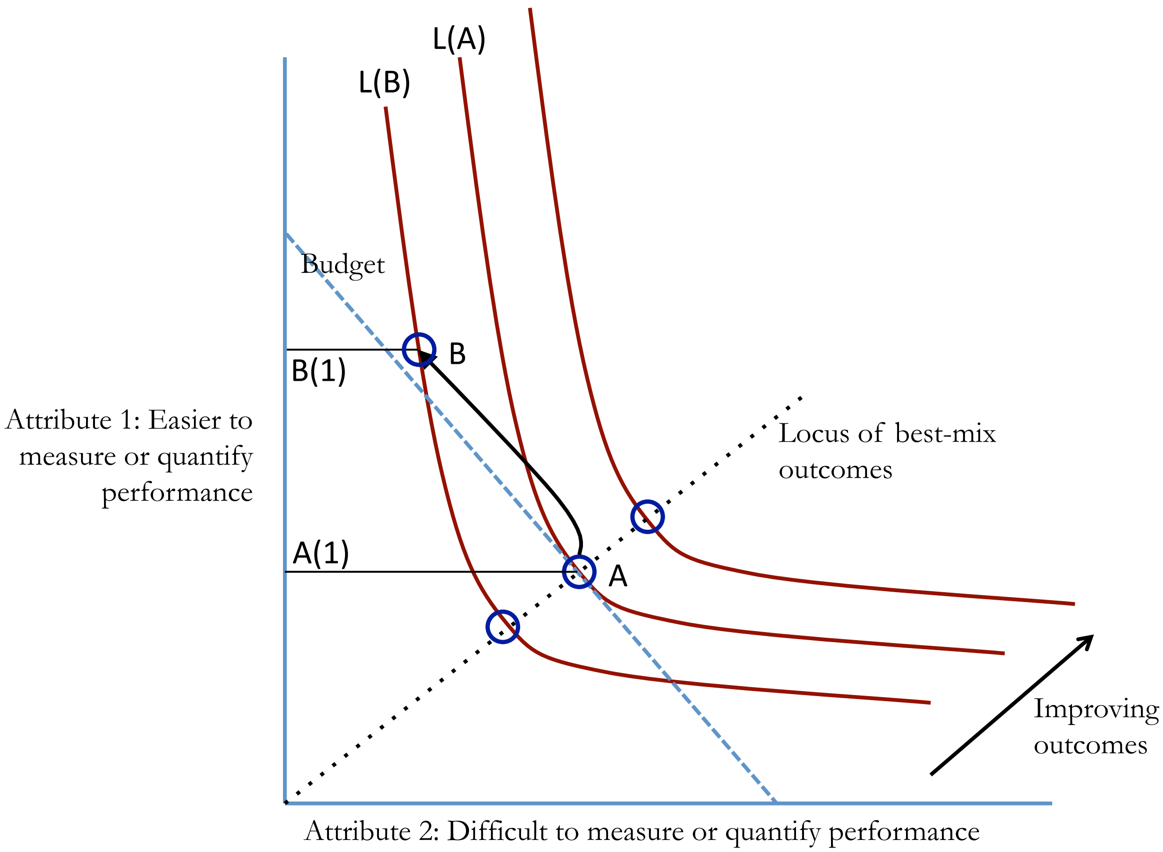

Figure 4.12: This figure plots trade-offs between two attributes, (1) and (2). The policymaker is indifferent between attaining any combination of these attributes so long as they are on the same curve. As we move away from the origin, each successive curve represents higher performance. The policymaker would like the actor to get as far away from the origin as possible, but his attainment is constrained by his budget, shown by the dashed inclined line. Given this constraint, optimal performance occurs at Point A. Now, the policymaker decides to put in place incentives to improve performance. Ideally, he would like the actor to move further away from the origin along the dotted line. However, both attributes (1) and (2) are somewhat abstract, and it is hard to measure performance on them. Of the two, performance is more easily measured on Attribute (1). This causes the policymaker to design a policy that emphasizes performance on Attribute (1). Even if he does not, the actor has an incentive to over-deliver on Attribute (1) because such performance is easy to measure (and therefore demonstrate) and might be accepted by the policymaker as proof of overall high performance. Due to the incentives provided, the actor might even work harder than he otherwise would have – that is, exceed his original budget – in trying to attain as a high a performance as possible on Attribute (1). The resultant outcome (Point B) is, however, worse than it would have been if the actor had simply stayed at A, or even slacked and slipped to a lower level of performance along the dotted line.

The strawman evidently tries to balance a number of different objectives, at least two of which are penalizing gross contribution to pollution (represented by an airline's share of sectorial emissions) and offsetting the growth in emissions since 2020. It is not clear that there has been any deliberation about the relative importance of these objectives: for most airlines, the strawman simply assigns equal weight to both. A number of the other details of the strawman – *de minimis* exemptions, reserves for fast growth and for early movers, and special provisions for new entrants – are presumably an effort to attain some degree of performance on other objectives such as not stifling the growth of nascent airlines, or providing relief to small states whose economies might be disproportionately reliant on aviation. These objectives are pursued at the expense of simplicity and clarity. It is unclear that the strawman attains any of these individual objectives. It is also unclear whether the balance it strikes between these objectives makes it anywhere closer to the optimal than if it had picked one, clear, measurable objective and set out to achieve it in the simplest possible manner. Of course, it is possible that the strawman was not framed with the objective of being optimal: its authors might have started with the EU ETS (See Section 4.4.1) and simply tweaked it, making it an example of "coherent arbitrariness," a phenomenon in which people begin at an arbitrary starting point, but make quite rational adjustments to it depending on whatever new information they receive. (Ariely, Loewenstein, and Prelec 2003)

Austin's model of organizational dysfunction also suggests that great care will be needed to ensure that the emission reductions units, or offsets, that the mechanism requires airlines to acquire fulfill its objectives. These reduction units must perform to a high standard on a number of potentially conflicting objectives. They must have high integrity; that is, they must represent reductions in CO_2 emissions that are permanent, quantifiable, and additional to what would have happened in the absence of whatever activity generated the credit. There must also be a relatively large, broad supply of credits that is accessible to all airlines, ideally at prices that are economically well behaved (e.g., with low volatility). At the same time, prices should be high enough to provide an incentive for airlines to be as efficient as possible. The risk is that policymakers give in to airlines' demand for access to emissions reductions that perform very well on one, easily observable, attribute (e.g., ubiquity) at the expense of another attribute (e.g., environmental integrity) that is crucial, but less easily observed.

4.5 Conclusions and recommendations

The strawman describes a complex mechanism, which it fails to adequately specify. We recommend that it be replaced with a much simpler mechanism, and we have made suggestions about the contours of such a mechanism in the previous section.

It is also clear that the *de minimis* exemptions for small states are poorly targeted if their aim is – as it should be – to provide relief to poor states that can ill-afford an increase in the cost of their air links to the rest of the world. We recommend that any exemptions be based on national income and level of service on specific routes.

The current text also is not explicit in saying that reference emissions will be updated to take into account any growth in the volume of emissions that fall under the *de minimis* exemption, and that emissions by new entrants will be included when calculating sectorial emissions for each year. Both these measures are needed to ensure that emissions do, in fact, stay capped at 2020 levels.

Growth, when determining eligibility for the fast growers allowance, should be calculated based on service provided (revenue tonne kilometers) rather than emissions. The strawman should also make it clear than new entrants and fast growers cannot simply replace activities that were previously performed by another operator.

Finally, the strawman does not even attempt to address several crucial questions. How should the use of alternative fuels be accounted for? How should an airline's fuel burn (and therefore emissions) be calculated: is an airline required to accurately measure and report its fuel use, or will fuel use be estimated by models based on, for example, radar or satellite data on flight paths? Our preference is for the former approach as the latter removes any incentive for airlines to do better than the model. The strawman would regulate operating entities; that is, airlines. However, the relationship between airlines and the economic entities that own them, whose shareholders would have to pay for offsets, and who might well make strategic decisions that determine the long-term trajectory of the airline's emissions, is extremely complex. The strawman is also aimed at achieving IATA's short-term goal of carbon-neutral growth by 2020. It does not, however, even hint at how the industry might go about achieving its much more challenging long-term goal of a 50% reduction in net emissions relative to a 2005 baseline by 2050.

These questions are all ripe for further research.

Chapter 5: The Benefits and Costs of Using Shore Power for Vessels Calling at US Ports

Abstract

Ships in port are a significant contributor to poor local and regional air quality. While some jurisdictions – most notably California – require that some ships use electricity supplied from shore when berthed, the practice is not common because of the upfront costs to both ship owners and port operators. We used mixed-integer linear programming to identify optimal combinations of vessels and berths that could be switched to using and supplying shore power to produce the largest gains for society. We used two integrated air quality models to quantify the benefits of reducing the emissions of NO_X, SO_X, and $PM_{2.5}$ that would obtain from the use of shore power: the Air Pollution Emission Experiments and Policy analysis (APEEP) based on the Climatological Regional Dispersion Model (CRDM), and the Estimating Air pollution Social Impact Using Regression (EASIUR) method applied to the Comprehensive Air Quality Model with Extensions (CAMx). Our results indicate that, at current fuel prices – depending on the social costs of pollution assumed – an air quality benefit of $70-150 million per year could be produced by retrofitting between a quarter and two-thirds of all vessels that call at US ports. Such a benefit could be produced at no net cost to society (environmental benefits would be balanced by the cost of ship and port retrofit), but would require that a large number of ships equip themselves to receive shore power even if doing so would result in a private loss for the operator. This suggests that regulators could produce a net societal gain by putting in place a combination of incentives and mandates to encourage a shift towards shore power. While our study is restricted to the US, using shore power would likely produce even bigger benefits in other parts of the world, where population densities are higher and where ships may be allowed to burn fuel with 35 times as much sulfur as is permitted in US and European ports.

5.1 Introduction

Cold ironing is the use of electricity from the shore to power a ship's systems when it is in port. When it is cruising, a ship's main engines drive an auxiliary power generator. As the ship begins maneuvering to enter a port, the main engines slow down, and no longer drive the generator. An auxiliary generator is then switched on, and starts to supply electricity. Once the ship is docked, the main engines are switched off, and the auxiliary generator continues to power the vessel (Doves 2006). The electricity needed by a vessel in port is called the hotelling load. Hotelling loads can range from a few hundred kilowatts to several megawatts, depending on the size and purpose of the vessel. (Environ 2004)

While there is an ongoing move towards the use of cleaner, low-sulfur, fuels by ships in port, hotelling emissions continue to be a significant contributor to poor local air quality. For instance, in 2012, hotelling emissions were 72% of all the SO_x emissions from the Ports of Los Angeles and Long Beach and 11% of $PM_{2.5}$ and diesel PM (DPM) emissions. Hotelling accounted for 18% of all SO_x emissions in Los Angeles County, where both ports are located, and about 1% of the County's $PM_{2.5}$ and DPM emissions (Starcrest Consulting Group LLC 2013a, Starcrest Consulting Group LLC 2013b, California Air Resources Board 2013a).

In fact, the California Air Resources Board (CARB, 2013b) already requires that, starting in 2014

- At least 50 percent of a fleet's visits to a port must satisfy the following limit on engine operation: for each visit, the auxiliary engines on the vessel cannot operate for more than three hours during the entire time the vessel is at-berth (e.g., a shore power visit); and
- The fleet's total onboard auxiliary engine power generation must be reduced by at least 50 percent from the fleet's baseline power generation.

CARB requires that 70% of all port calls meet this requirement starting in 2017, and 80% starting in 2020. CARB's regulations apply to container vessels, passenger vessels, and refrigerated cargo vessels (California Air Resources Board 2007). This regulation is controversial,[77] and our analysis will contribute to determining whether the benefits it produces do, in fact, exceed the costs of implementing it.

5.2 Prior work

The most comprehensive study preceding the 2007 regulation was conducted for the Port of Long Beach (PoLB, Environ 2004). This study assumed that the equipment needed to enable cold ironing would have to be retrofitted to existing port infrastructure and existing ships. It also measured cost effectiveness in terms of the annualized cost per ton of emissions[78] avoided, and concluded that cold ironing was marginally cost-effective at best.

Another key conclusion was that fuel cost savings accrued due to switching from the residual or distillate fuel to electricity would not pay for the private cost of retrofitting a vessel, let alone the cost of expanding the power distribution system and retrofitting port facilities.

The Port of Rotterdam conducted an analysis (Doves 2006) to decide whether to equip its new Euromax terminal at Maasvlakte with cold-ironing facilities. It found that "Although the levels of air pollution reduction found close to the terminal are significant, the effects on the air quality on nearby urban areas will be minimal, at high design and annual costs." In this, Rotterdam differs significantly from the ports in California: Maasvlakte 2 is over 30 miles away from the center of Rotterdam, whereas the ports of Los Angeles and Long Beach are *in* the densely populated San Pedro and Long Beach neighborhoods of Los Angeles County, and – for much of the year – upwind from Orange County. (LA Times 2014)

[77] See, for example: http://shipandbunker.com/news/am/219260-concerns-raised-ahead-of-new-california-shore-power-regulation

[78] This was the sum total of the mass of the emissions of volatile organic compounds, carbon monoxide, NO_x, PM_{10}, and SO_x

A study of the economics of shore power at the Port of Goteborg (Wilske 2009) in Sweden concluded that – at the prices prevailing in 2009 – shore power was not economical.

Goteborg itself has been providing shore power to ferries and roll-on-roll-off vessels. Like the new Bayport terminal in the Port of Houston (EPRI 2008), all new quays in the port of Goteborg are being built with the canalization necessary to extend power to the berth and therefore make it cheaper to retrofit the facility for cold ironing. A survey of 53 ports conducted by Goteborg found that 17 provided some form of onshore power for ships, while only six provided the high-voltage supply needed for ocean-going ships. In the US, apart from ports in California[79], the port of Juneau is equipped to supply shore power to vessels operated by Princess Cruises.

More recently, Korn, Martin, and Wallace (2011) outline the engineering required to retrofit both vessels and berths. They also make a cursory attempt to estimate the reductions in emissions associated with cold ironing.

There are several shortcomings associated with the studies of cold ironing done so far. First, petroleum prices have changed significantly since these studies were done. The 2004 study assumed that ten out of the 12 ships it analyzed would use heavy fuel oil – priced at less than $200 per tonne in 2004 - when in port. Two vessels were assumed to use marine gas oil, which was assumed to cost $300 per tonne. IMO regulations now force ships to use only low-sulfur marine gas or diesel oil, which costs twice as much as marine gas oil was assumed to cost in 2004.[80]

Second, the California regulation was driven by a desire to reduce emissions of NO_x and diesel particulate matter. The cost-effectiveness calculations in the Port of Long Beach's 2004 study were done by simply dividing the annualized cost of implementing cold ironing by the total mass of hydrocarbons, carbon monoxide, NO_x, PM_{10} and SO_x emissions that would have been avoided as a

[79] Los Angeles, Long Beach, Oakland, Hueneme, San Diego, San Francisco
[80] See Bunkerworld: http://www.bunkerworld.com/prices/port/us/hou/

consequence. The cost, in dollars per ton, thus obtained was then compared to the $13,600[81] per ton of NO_x emissions reduced, which is the most that California's Carl Moyer program would have paid in 2002 to retrofit diesel engines to reduce their NO_x emissions. Retrofits were considered acceptable for those combinations of vessels and berths where the annualized cost could have been kept below approximately $13,600 per weighted ton of emissions avoided.

However, diesel exhaust is composed of $PM_{2.5}$ (US Department of Health and Human Services 2011), which is more detrimental to human health than PM_{10} (World Health Organization 2013). Sulfur dioxide – in addition to being harmful to human health in and of itself – contributes to the formation of secondary particulate matter (AQEG 2005), and its effect on human health in this form needs to be accounted for in the analysis. On the other hand, it is the case that ships are now required to burn fuel with a much lower sulfur content than was permitted in 2004, reducing the total amount of sulfur dioxide emitted. Considerably better tools than were used in the 2004 study are now available to quantify the complex impact of these pollutants.

Third, the US studies have been limited to California ports. This was driven by the chronically high ozone concentrations, which are related *inter alia* to NO_x emissions, in southern California's cities. However, the health risk stemming from particulate matter and sulfur dioxide emissions is a global phenomenon: Winebrake et al. (2009) estimate that, even after the IMO's standard of limiting the sulfur content of the fuel used in Emission Control Areas (ECAs, which include both US coasts) to 0.1% on a mass basis is reached in 2015, it is estimated that emissions from oceangoing vessels will continue to cause between 20,000 and 70,000 premature deaths every year. While there are regional variations in the level of premature mortality, there is likely to be a sizeable impact along most coastlines with ports, including the eastern and western seaboards of the United States.

[81] This was the figure in 2002. By 2004, the threshold was $14,300 per weighted ton (California Air Resources Board 2014)

The current study addresses these shortcomings, and extends the 2004 study to include other US ports, as well as every one of the 3,200 vessels that have called at US ports in the 18 months between July 2013 and December 2014. The study seeks to find out whether and how to deploy shore power in a way that properly accounts for the benefits it confers and costs it imposes on society.

5.3 METHODS & DATA

5.3.1 Vessel call history

This analysis is underpinned by a large dataset of vessel port calls purchased from Fleetmon, a German firm that collects and archives data on ship locations using land-based base stations that receive transmissions from the automatic identification system (AIS) used on ships. We sent Fleetmon a list of the twenty largest international ports in the United States, and obtained a list of all the vessels that had departed at least once from those ports in the 18 months from July 2013 to Dec 2014. For each of these vessels, we obtained a list of every call that it had made – at any port in the world – during that time. Each vessel call record consisted of the following information: the identity of the vessel, the name of the port, the time at which the vessel arrived at the port, and the time at which it departed.[82] Finally, Fleetmon provided us – pro bono – with key vessel information. This includes the Maritime Mobile Service Identity (MMSI), a "unique and official"[83] 9-digit number associated with the AIS station carried by the ship, the ship's International Maritime Organization (IMO) registration number, as well as some information about vessel dimensions (length, width, and capacity in deadweight tonnes, DWT). We were also given information about the category (e.g.,

[82] Time stamps were precise, and included the date and time in hours, minutes and seconds. Feeltmon defined the arrival time of a vessel as the time at which it "a vessel enters a port zone and then truly stops moving (0,0 knots, no speed over ground)" and the departure time as when the vessel starts moving again.

[83] For more information on AIS and MMSI, see the US Coastguard Navigation Center at: http://www.navcen.uscg.gov/?pageName=AISFAQ

fishing, cargo, pleasure vessel) and type (container ship, oil tanker, bulk cargo vessel) that each ship fell into.[84] The raw dataset consisted of 7,600 vessels and 870,000 port calls.

These data were an unfiltered archive of what a series of AIS base stations had recorded, and were therefore somewhat noisy. To prepare them for analysis, they had to be cleaned. First, we filtered out the records for calls to US ports. Only records in which the vessel had arrived in port after June 2013 were retained. Records where the call duration (the difference between arrival and departure times) was zero were discarded. A number of vessel types (e.g., tugs, yachts, pleasure boats, coast guard, law enforcement vessels etc.) that are not relevant to this analysis were removed. The California regulation requiring the use of shore power applies only to vessels with a capacity of greater than 10,000 dead weight tons (DWT) and longer than 400 feet.[85] (California Air Resources Board 2007) As such, in this analysis only vessels larger than this threshold were retained. We also identified and discarded duplicate records.

We also discarded vessel calls of less than five hours' duration for two reasons. First, we believed that a call of this duration might not be one in which a vessel actually pulls into port to discharge cargo.[86] Second, even if such a record represented a "genuine" port call, it would be too short for it to be economical for the vessel to be connected and disconnected to shore power.[87] At this point,

[84] We were also provided with details of each vessel's engines. However, these data were provided in the form of a free text field, were not in a uniform format, and were not available for all vessels. As such, they have not been used in the analysis.

[85] The California regulation only applies to container, refrigerated cargo, and passenger vessels; however, we do not apply that restriction here. Also, a capacity threshold of 10,000 DWT excludes virtually all passenger vessels, including cruise liners. In our analysis, cruise liners are analyzed separately, as they are unlikely to share shore power infrastructure with cargo vessels.

[86] In addition to the Fleetmon data, we obtained vessel call histories from the ports of Pascagoula, Houston, and Seattle. About 1% of the vessel calls (66/4,760 at Houston, 12/1,131 at Seattle, and none at Pascagoula) were of less than five hours' duration. As such, our assumption was largely validated by independent data.

[87] Environ (2004, 28) suggests that connecting a vessel to shore power would take between 20 minutes and two hours, and disconnecting it would take similarly long.

the dataset consisted of about 46,000 unique calls by 3,300 unique ships to 187 unique US ports.[88] It was found that certain port calls, especially for tankers and liquefied gas carriers were extraordinarily long (>1000 hours). This may be due to errors in the raw data, or due to the fact that some tankers might have been used as floating storage for substantial periods of time (see, for example, Raval 2015). Similarly, ongoing industrial action at US west coast ports might have prolonged the stay of some other types of vessels. (Khouri 2015) It is unlikely that such vessels would be able to use shore power even if it were available, as they might have been anchored in or near the port area but not at a berth.[89] To prevent such outliers from distorting our analysis, we calculated the 90th percentile value of call durations for each type of ship (Table 5.1). For calls that lasted longer than the 90th percentile value of calls for that vessel type, we replaced the call duration with the 90th percentile value.

Environ (2004) discussed the ways in which electricity could be delivered to vessels. Vessels that did not require the use of a gantry crane to load and unload cargo could be supplied by means of a gantry tower constructed on the shore. Cables could then be lowered on to the ship from such a tower (Figure 5.2). On the other hand, vessels that required the use of gantry cranes for loading and unloading could not be supplied in such a way. This is because such a structure would interfere with the movement of gantry cranes, which are designed to move along the full length of the wharf. As such, such vessels would need to be supplied using a work barge, which would be deployed when the vessel was in port (Figure 5.1). Note that these two types of vessels (those that require cranes, and those that do not) are likely to use different parts of the port; i.e., dock at different terminals and berths.

[88] Note that we purchased data on *all* vessel calls for only the twenty busiest ports in the United States. We have data for *some* vessel calls at a large number of US ports because many of the vessels in the dataset called at these smaller ports also.

[89] AIS transmissions can be reliably received for 10-20 nautical miles., and the range may be up to 50 nautical miles. (Smith et al. 2014, 38)

Table 5.1: For most vessel types, there is a small tail of very long port calls. These port calls, while few in number, could dominate the analysis if it were assumed that the vessel could be switched to shore power over this entire duration. To prevent this, call durations are replaced by the shorter of the actual call duration and the 90th quantile value of call durations for vessels of a particular type.

Vessel type	Unique vessels	Calls	Total hours	Call durations (in hours)				
				q99	q90	q50	q10	q1
Bulk carrier	638	5,300	460,000	540	190	48	7	5
Oil tanker	512	8,400	610,000	780	140	33	7	5
Liquefied gas carrier	57	400	65,000	1,700	360	65	18	6
Container ship	1084	18,200	650,000	230	69	21	10	6
General cargo vessel	159	1,300	100,000	610	150	47	11	5
Chemical carrier	174	2,300	130,000	550	110	28	8	5
Vehicle carrier	255	3,400	140,000	410	43	17	8	5
Oil Products Tanker	285	3,600	190,000	460	100	30	8	5
RoRo ship	44	800	26,000	200	64	20	8	5
Tanker	50	800	60,000	690	130	36	9	5
Heavy Lift Vessel	10	100	16,000	1,900	230	42	16	9
Forest-product carrier	22	200	15,000	430	170	50	9	6

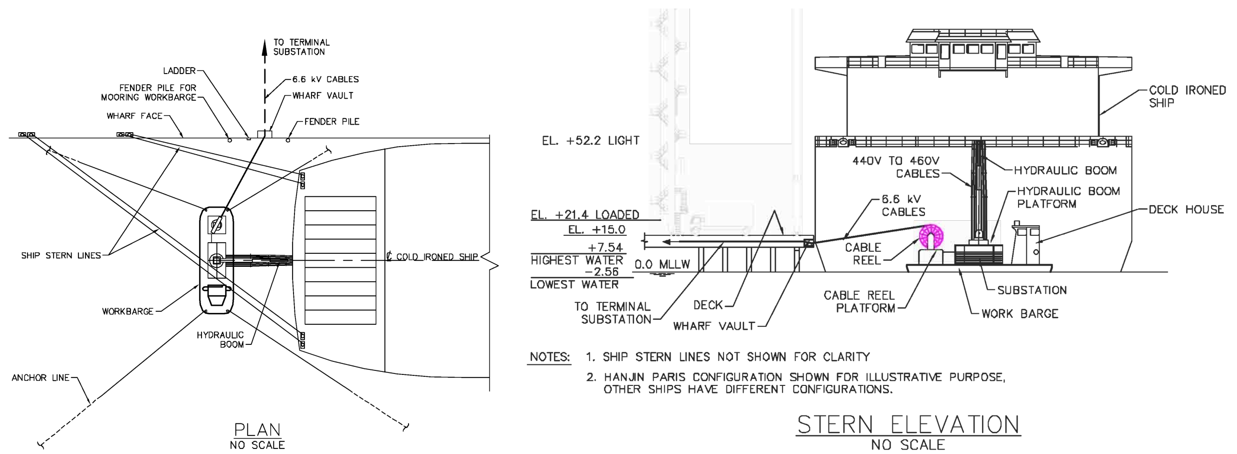

Figure 5.1: Plan and elevation views that illustrate how a work barge could be used to supply electricity from the shore to a container ship. The silhouette of a part of a gantry crane, which would complicate the use of a gantry tower, is shown in the elevation view. From Environ 2004 (71: engineering drawing by Han–Padron Associates)

In recognition of this fact, we further split our data into two sets. Vessels types – including container, general cargo and bulk cargo - that are likely to be supplied by barge were placed in one set, whereas those – including tankers and vehicle carriers of various types – were in another. We treated these two sets as completely independent: they were analyzed separately from one another. There were 1,910 vessels that would need to be supplied by barge, and 1,373 vessels that could be supplied using a gantry tower.

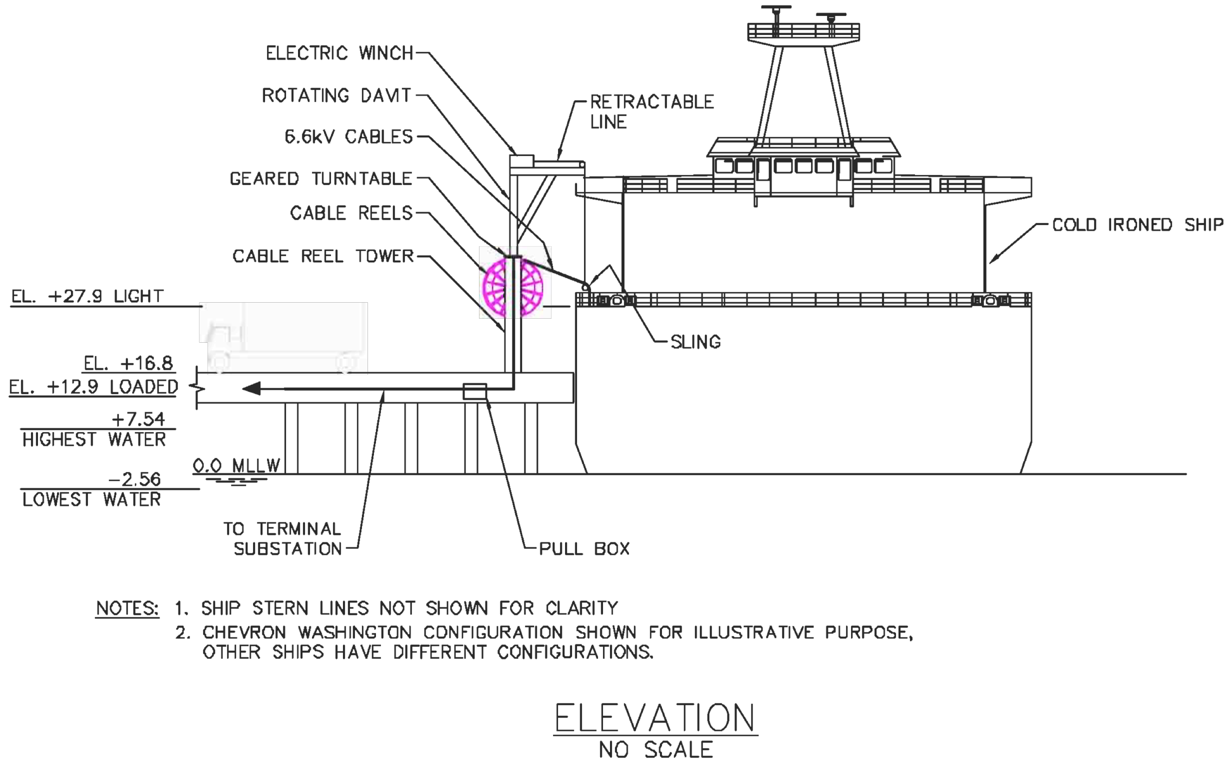

Figure 5.2: Illustration of an oil tanker being supplied with electricity from the shore. Since there is no gantry crane, a tower can be used to lower cables into the vessel. From Environ (2004, 83: engineering drawing by Han–Padron Associates)

Table 5.2 provides a summary of the vessel call data for four key, geographically dispersed ports. The average power used when the vessel is in port is obtained from Starcrest Consulting Group, LLC (2013). Our vessel data did not tell us the capacity of container ships in terms of their capacity in twenty-foot equivalent units (TEUs). However, this information was manually obtained for 270 vessels and regressed using ordinary least squares against the ship's capacity in deadweight tonnes (DWT).

Table 5.2: Summary statistics for cargo vessel calls included in the analysis. The busiest ports are in Southern California and the Gulf of Mexico. The former are dominated by vessels that require gantry cranes to unload, and would therefore require a work barge to supply with electricity from the shore (primarily, container ships). The latter are dominated by vessels that could be supplied from a tower erected on shore (primarily, tankers).

Vessel type	Average power at berth	Number of ships	Los Angeles	Houston	Newark	Seattle	Los Angeles	Houston	Newark	Seattle	Los Angeles	Houston	Newark	Seattle
	kW		number of visits				average duration of calls (hours)				total energy use (MWh)			
Container - 1000	720	10	33	25	9	0	45	51	13	-	1,068	925	85	-
Container - 2000	1,039	78	184	160	103	59	33	47	18	25	6,359	7,876	1,881	1,541
Container - 3000	641	79	188	174	29	21	30	28	18	25	3,565	3,102	334	340
Container - 4000	1,136	150	288	255	281	63	41	29	26	24	13,430	8,379	8,441	1,731
Container - 5000	1,128	201	511	208	846	75	35	24	21	32	19,988	5,730	20,036	2,700
Container - 6000	804	261	473	226	529	212	34	25	25	27	12,761	4,533	10,789	4,645
Container - 7000	845	65	176	78	56	41	65	28	27	20	9,620	1,856	1,293	688
Container - 7000	845	28	175	6	111	17	60	30	22	30	8,901	150	2,036	430
Container - 8000	1,008	18	37	0	5	14	68	-	48	41	2,529	-	241	574
Container - 9000	1,030	118	267	2	109	153	65	32	42	43	17,941	65	4,664	6,840
Container - 10000	1,075	50	200	0	37	28	68	-	39	25	14,526	-	1,563	748
Container - 11000	1,500	12	62	0	0	6	69	-	-	23	6,406	-	-	211
Container - 12000	2,000	11	36	0	0	0	66	-	-	-	4,749	-	-	-
Container - 13000	1,700	3	4	0	0	0	69	-	-	-	470	-	-	-
Bulk carrier	208	638	237	600	80	55	60	82	100	124	2,936	10,252	1,660	1,419
Heavy Lift Vessel	467	10	5	17	5	1	67	71	33	21	157	564	76	10
Cargo ship	575	25	28	35	7	0	61	81	91	-	977	1,635	367	-
General cargo vessel	575	159	41	334	8	32	59	87	29	31	1,396	16,618	132	562
Forest-product carrier	208	22	14	16	1	4	57	61	82	116	167	202	17	96
Dry cargo	575	2	0	6	0	0	-	77	-	-	-	264	-	-
"Barge" vessels		**1,940**	**2,959**	**2,142**	**2,216**	**781**	**47**	**55**	**27**	**38**	**127,945**	**62,151**	**53,615**	**22,536**
Oil tanker	605	512	743	1,014	38	11	43	53	25	77	19,370	32,671	572	514
Tanker	605	50	74	205	18	6	49	59	72	79	2,200	7,374	785	286
Chemical carrier	738	173	22	773	51	1	48	49	28	17	781	27,711	1,051	13
Oil Products Tanker	605	285	140	896	45	1	41	48	26	44	3,502	25,889	708	27
Liquefied gas carrier	2,520	57	2	278	1	0	38	105	22	-	190	73,518	56	-
RoRo ship	229	44	0	46	72	1	-	49	13	9	-	515	220	2
Vehicle carrier	1,284	255	130	93	331	2	18	22	16	14	3,008	2,627	6,971	36
Ore-bulk-oil carrier	605	4	4	7	0	0	17	45	-	-	41	192	-	-
"Tower" vessels		**1,380**	**1,115**	**3,312**	**556**	**22**	**40**	**54**	**20**	**65**	**29,093**	**170,497**	**10,363**	**878**

The relationship between capacity in DWT and number of TEUs was found to be linear and highly significant ($R^2 = 0.96$, $p \sim 0$), and was used to deduce the capacity in terms of TEUs for the remaining 800 container ships in the dataset.

Table 5.3 shows the total energy use while the ship is in port. We also calculated the total energy use that would be displaced by shore power by assuming that a ship would be connected to shore power for 2.5 hours less than the total time it spent in port, as it would take some time to physically connect the necessary cables as well as to transfer the electrical load from on-board generators to the shore supply.

5.3.2 Port information

The data were also used to deduce the number of berths at each port for each of the two sets of vessels. Because we knew the arrival and departure times for each vessel at each port, we could count the number of vessels from each set that were in port on each of the approximately 500 days for which we have data. We assumed that the 90th percentile value of this distribution represented the actual number of berths available to the types of vessels belonging to that set. We also calculated the average utilization of berths at each port by dividing the total duration (adjusted, as described above for extreme values) for which the ships were in port by the product of the total number of berths available and the total number of hours that had passed between the earliest arrival date and the latest departure date for vessels at that port.[90] Alternatively, these numbers can be thought of simply as the maximum number of ships that is likely to be in the port at any given time. If one shore power supply point were built to cater to each such vessel, then the rate of utilization

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[90] This number was needed to ensure that, when we calculated the number of berths that ought to be retrofit at each port, we could account for the that the total number of hours for which ships could expect to obtain shore power was limited by the availability of a berth that was equipped to supply it. Due to gaps in scheduling (i.e., it would be unreasonable to assume that each vessel would arrive at a berth immediately after the previous one had left) we would expect the actual availability of a berth to be less than 100%. We assume that the current average levels of utilization are a good first approximation of this availability. We will test this assumption when we present results.

represents the percentage of time that each supply point would be used on average. Table 5.3 summarizes the information extracted from the data. Note that the relatively low level of utilization is a conservative assumption. We assume that there is something about the way vessels are scheduled to arrive and depart from a port that prevents utilization from being higher. If, in fact, utilization is low simply because some ports have spare capacity, then berths equipped to supply shore power could be used more efficiently. As a consequence, fewer berths would need to be retrofitted, which in turn would lower costs and make shore power more attractive. Based on data that we obtained directly from the ports, it is the case that some berths are used more efficiently than others: the rates of utilization of some berths at the Barbour's Cut terminal in the port of Houston are well over 75%.

Table 5.3: Number of berths available for vessels in each of our sets, as well as the average rate of utilization of the berths. Alternatively, these can be thought of simply as the maximum number of ships that is likely to be in the port at any given time. If shore power infrastructure were built to cater to all such vessels, then the rate of utilization represents the percentage of time that the shore power infrastructure would be used on average. These ports were selected because a preliminary analysis indicated that they would have the highest energy use (and were therefore likely benefit the most from a shift to shore power).

Port	**"Barge" vessels**		**"Tower" vessels**	
	Number of berths	Average berth utilization	Number of berths	Average berth utilization
Los Angeles	20	47%	11	31%
Houston	21	38%	40	34%
Long Beach	13	34%	15	30%
Tacoma	8	38%	4	12%
Port of Miami	4	20%	2	5%
Oakland	8	28%	3	16%
Galveston	6	16%	37	17%
Everglades	3	17%	8	13%
Port of Baltimore	6	30%	9	29%
Newark	9	31%	5	17%
Richmond, CA	2	16%	6	36%
Seattle	6	29%	2	5%
Port Angeles, WA	1	1%	5	21%
Corpus Christi	4	19%	11	19%
Yerbabuena Island	4	12%	5	15%
New Orleans	11	27%	5	16%
New York	3	20%	6	20%

5.3.3 Cruise vessel data

The data discussed in Sections 5.3.1 and 5.3.2 dealt with cargo vessels. Since cruise vessels often call on a different set of ports (e.g., Port Canaveral), these data capture only a small portion of the cruise vessel activity in US ports. To analyze cruise vessel activity, we obtained a nearly complete record of cruise vessel arrivals and departures that was maintained by the US Army Corps of Engineers' Navigation Data Center until 2012, which is therefore the last year for which we have data. The data only had date information: they told us on what day vessels arrived and departed, but not at what time. We selected the 17 busiest ports in the continental United States[91]and the 132 cruise vessels that visited them in 2012 for analysis.

Table 5.4: The 17 ports analyzed to determine the benefits and costs of using shore power for cruise vessels. Utilization and annual energy use are calculated assuming that each visit lasts 10 hours and that the vessel draws 5,400kW of power on average when in port.

Name	Number of calls	Number of berths	Utilization	Total energy use (GWh)
Miami	726	7	12%	40
Port Canaveral	692	5	16%	38
Port Everglades	627	8	9%	34
New York	332	5	8%	18
Key West	331	5	8%	18
Tampa	210	3	8%	11
Seattle	198	4	6%	11
New Orleans	181	3	7%	10
Galveston	175	3	7%	10
Long Beach	160	2	9%	9
Boston	117	3	4%	6
Baltimore	108	2	6%	6
Los Angeles	102	3	4%	6
San Diego	90	4	3%	5
Charleston	84	1	10%	5
Bar Harbor	83	3	3%	5
Jacksonville	80	1	9%	4

[91] The integrated air quality models that we use to quantify the benefits of a shift to shore power do not extend to Hawaii, Alaska, or US overseas territories such as the Virgin Islands, all of which see significant cruise activity.

We deduced the number of berths at each port by assuming that each berth could handle only one departure per day: as such, the maximum number of departures on a single day was used as a proxy for the number of berths at each port. Analysis of the data showed that the overwhelming majority of vessel calls (>6,000 out of 7,500) lasted less than one day. As such, in our analysis we assumed that all cruise vessels stay in port for 10 hours on each visit.[92] We also assumed that cruise vessels use, on average, 5400kW of power when in port (Starcrest Consulting Group, LLC 2013b, 33). Our data are summarized in Table 5.4.

5.3.4 Problem definition

With this basic data in place, we could explore the benefits and costs of retrofitting different ships and berths for shore power. We consider two kinds of benefits. The first is the monetary benefit that accrues to the ship owner because at current fuel prices,[93] it is cheaper to buy a kWh of useful electrical energy off the grid than to produce it using the vessel's diesel-fired auxiliary generator. The second benefit is environmental: grid electricity is generally cleaner than electricity produced by burning marine diesel oil. This benefit accrues to society, mostly in the form of an improvement in air quality and corresponding improvements in health. The calculation of these benefits is described in detail below.

[92] This number is based on Table 2-1 on p27 of Moffatt & Nichol (2013), which suggests that cruise vessels typically stay an average of 12 hours in the Port of Charleston. Cruise operators are under pressure to bring this number down in the interests of efficiency and lower costs, as well as for environmental reasons. As such, assuming that vessels stay in port for 10 hours is a conservative assumption: longer stays would make shore power more attractive.

[93] We assumed that, by default, vessels would use marine diesel oil or marine gas oil with 0.1%S in deference to Regulation 14 of the IMO (see http://tinyurl.com/IMOReg14), and that engines would conform to the IMO's Tier 2 standards. This second assumption is conservative: engines may not conform to the Tier 2 NO_X standard (see http://tinyurl.com/IMOReg13), which only applies to vessels constructed after January 2011. For dirtier engines, the environmental benefit of switching to shore power would be even greater than what we show here. In our analysis, we assumed that such fuel was priced at $680 per tonne. Clearly, this price is subject to fluctuations, and we performed a sensitivity analysis to assess the impact of such fluctuations.

We also consider two kinds of costs. The first is the cost to the ship owner of retrofitting the vessel so that it may accept shore power. The second is the cost to the port of extending or expanding the power distribution network, as well as of putting in place the electrical equipment (transformers, cables etc.) required. In addition, the port would have to acquire, maintain, and operate a work barge for each berth that was already equipped with gantry cranes and catered to vessels that required these to load and unload, and a gantry tower for other berths.

With these costs and benefits in mind, a decision maker might have one of the following objectives in mind.

(i) Maximizing the benefit (the sum of the private saving to ship owners or operators and the environmental benefit), subject to the condition that the total net benefit be greater than or equal to zero.

(ii) Maximizing the total net benefit (the sum of environmental and private benefit less the cost of retrofitting the vessels and the berths).

The benefits and costs discussed above are defined mathematically as follows.

$$ben\_pvt_{i,j} = \left(m - e_j\right) \times ener_{i,j} \times o_{i,j} \qquad \textbf{Equation 5.1}$$

where

$ben\_pvt_{i,j}$ is the private benefit, expressed in dollars per year, that would accrue to the vessel operator if vessel i were to use shore power at port j

m is the cost of electric power generated from marine fuel on board the vessel, expressed in $ per kWh. This is calculated based on the price of marine fuel, and takes into account the efficiency of the diesel generator

e_j is the average price of electricity for industrial use in the state in which port j is located. This number is obtained from the Energy Information Administration (EIA 2015a).

$ener_{i,j}$ is the amount of energy, expressed in kWh, that would go from being generated on board to being provided from shore. Note that this is not the total quantity of energy that the vessel would use while in port: the vessel would generate its own power while it was being connected to and disconnected from shore power (see Section 5.3.1) For cruise vessels, this would be given by the number of visits by vessel i to port j, multiplied by 10 hours per visit, multiplied by 5400kW.

$o_{i,j}$ is a binary decision variable. It is a dummy, which takes the value of one (1) if vessel i uses shore power at port j; and is zero (0) if it does not.[94]

$$ben\_env_{i,j} = ener_{i,j} \times o_{i,j} \times \sum_{q} \left(eim_q - \frac{eie_{q,j}}{1-t} \right) \times sc_{q,j} \times 10^{-6} \qquad \textbf{Equation 5.2}$$

where

$ben\_env_{i,j}$ is the net annual environmental benefit that would accrue from switching vessel i at port j to shore power

$ener_{i,j}$ and $o_{i,j}$ are defined as in Equation 5.1

eim_q is the emission index expressed in grams per kWh for pollutant k for marine diesel or gas oil. k = {NO_X, SO_X, $PM_{2.5}$, CO_2}. For NO_X, CO_2, and $PM_{2.5}$, we use the numbers given in Starcrest Consulting Group, LLC (2013, 33) for marine diesel or gas oil with 0.3% sulfur content, burned in IMO Tier 2 engines. For SO_X - recognizing that Regulation 14 requires that only fuels with a maximum sulfur content of 0.1% be used in Emissions Control Areas (ECAs), including both US coasts – we use one third of the value given in (Starcrest Consulting Group, LLC 2013b, 33).

$eie_{q,j}$ is the emission index expressed in grams per kWh for pollutant k for the electricity that would be consumed in port j. This number is obtained by dividing the total emissions from fuel combustion from electric generation of each pollutant given in the National Emissions

[94] $o_{i,j}$ helps determine the number of berths that must be retrofit at a port, j. The optimization problems below are written so that a new berth would have to be retrofit (and the cost of retrofit incurred) if accommodating an additional vessel at a port would cause the total annual number of hours that shore power is used at that port to exceed $k_j' \times \mu_j \times 8760$, where k'_j is the number of retrofitted berths at port j before the new vessel is accommodated, and μ_j is the average rate of utilization of berths at port j (see Equation 5.6 below). Some vessels – even if they were equipped to use shore power – might not generate a large enough benefit from plugging in *at a particular port* to justify the retrofit of an additional berth (e.g., if they did not spend much time there). Since μ_j is an *average* rate, in practice, it is possible that a vessel (i) that is equipped to use shore power (r_i =1) pulls into port and finds a retrofitted berth free, even if – when determining how many berths to retrofit – the decision maker had concluded that it was optimal to assume that that vessel (i) would not use shore power at port j ($o_{i,j}$ = 0). If such a vessel were able to use shore power at port j, this would not be accounted for in the benefits calculated in Equation 5.1 and Equation 5.2. That is, the benefits would be underestimated. We estimated the maximum possible size of this gap by analyzing the solutions to each of the problems defined below to work out how much energy is consumed by vessels (i) that are equipped to use shore power (r_i=1), pull into a port (j) that has at least one retrofitted berth ($k_j \geq 1$), but for which $o_{i,j}$=0. We found that, for the busiest ports, this number was zero: any ship that was equipped to use shore power at Los Angeles or Houston would, in the optimal solution, use it. Across all 17 ports, this number was ~5%, which is therefore the upper limit of the amount of benefit that we are "leaving on the table" by making a decision based on an average. (See Appendix 5.6.3 for port-by-port data).

Inventory (EPA 2013) for the state in which port j is located and dividing it by the net power generated in that state.[95]

t is the transmission and distribution loss, expressed as a percentage, and assumed to have a value of 10% We include this term to take into account the fact that more electricity would have to be generated than is used by the ship.

$sc_{q,j}$ is the value, in dollars per ton, of emitting pollutant k at port j. For NO_X, SO_X, and $PM_{2.5}$ we obtain this value from two models: Air Pollution Emission Experiments and Policy analysis (APEEP, Muller and Mendelsohn 2008) and the Estimating Air Pollution Impacts Using Regression (EASIUR, Heo 2015) method applied to the Comprehensive Air Quality Model with extensions (CAMx, Environ 2015). APEEP provides the mean, as well as 5th and 95th percentile values of the social cost of emitting one ton of a particular pollutant in each county in the continental United States. We will conduct the analysis and report results assuming social costs obtained from both models. For CO_2, we assume a social cost of $40 per ton.

$$cst\_ship_i = r_i \times p_i \qquad \textbf{Equation 5.3}$$

where

cst_ship_i is the annualized cost of retrofitting a ship to accept shore power.

r_i is a decision variable that takes the value of one (1) if a vessel is retrofit, and zero (0) if it is not

p_i is the annualized cost of retrofitting a ship for shore power. For this analysis, we assume that such a retrofit would cost $500,000 for all ships. The number is a first order approximation of the average cost of retrofit of the twelve vessels studied in Environ (2004, 75). This cost is amortized over 20 years, assuming a discount rate of 5%.[96]

$$cst\_port_j = c \times k_j \qquad \textbf{Equation 5.4}$$

where

cst_port_j is the annualized cost of retrofitting a port to provide shore power to all the ships that require it.

c is the sum of the annualized cost of retrofitting a single berth to provide shore power and the annual cost of operating and maintaining the required equipment. When the analysis was done for the set of vessels that do not require a barge (including cruise vessels), we assumed (again, based on the numbers provided in Environ 2004, 76, Table 5–8) that putting in an electrical

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[95] Available with the Energy Information Administration: http://www.eia.gov/electricity/data/state/

[96] Clearly, this is a simplifying assumption: retrofit cost is likely to vary substantially from vessel to vessel. Due to the very large number of vessels considered in this analysis (>3,000), it is not practical to work out the cost of retrofitting each vessel. Nonetheless, an obvious way of improving on the present approach is to derive a formula or heuristic to estimate retrofit costs based on vessel size, type, and vintage.

distribution network costs $1,000,000 and that a terminal substation costs $500,000. These capital costs are amortized over 20 years at a discount rate of 5%. We assume that terminal operating and maintenance (O&M) costs are $100,000 per year. For the set of vessels for which a barge is required, an additional capital expense (amortized over 20 years and at 5%) of $2,000,000 is assumed, as well as an additional O&M cost of $350,000 per year. These costs assume that a complete retrofit of existing port facilities would be needed, and are therefore conservative. The incremental cost of building new berths that are equipped for shore power would be smaller, as would the cost of retrofitting berths that were designed with future shore power implementation in mind (e.g., if the canalization is already in place.)

k_j is decision variable that takes the value of the number of berths that must be retrofit at port j. k_j is a positive integer.

Objectives (i) and (ii) must both be achieved subject to the following physical constraints.

The number of berths retrofitted at each port cannot exceed the total number of berths available for that set of vessels (i.e., "barge" or "tower" vessels), as shown in Table 5.3.

$$\forall j: k_j \leq n_j$$ **Equation 5.5**

where

n_j is the number of berths available for a particular set of vessels at port j, and k_j is as in Equation 5.4.

The total number of hours for which vessels occupied berths at a port could not exceed the number of hours for which the berth would be available.

$$\forall j: \sum_i o_{i,j} \times h_{i,j} \leq k_j \times u_j \times 8760$$ **Equation 5.6**

where

$o_{i,j}$ and k_j are defined as in Equation 5.1 and Equation 5.4, respectively

$h_{i,j}$ is the number of hours that vessel i spent in port j in a year. Note that this is the total number of hours for which the vessel occupied the berth, and as such is greater than the number of hours for which the vessel uses shore power. For cruise vessels, $h_{i,j}$ would be calculated by multiplying the visits made by vessel i to port j by 10 hours per visit.

u_j is the average rate of utilization of berths for a particular set of vessels at port j

Finally, a ship must be retrofit for it to be able to use shore power anywhere.

$$\forall i,j: o_{i,j} \leq r_i$$ **Equation 5.7**

where $o_{i,j}$ and r_i are as defined in Equation 5.1 and Equation 5.3, respectively.

With these quantities and constraints rigorously defined, we can define two distinct optimization problems as shown in Table 5.5. The optimization problems in Table 5.5 were solved for six cases. We solved separate problems for the set of cargo vessels that require work barges, the set of cargo vessels that do not, and for cruise vessels. For each of these three sets, the calculations were performed using the social cost of pollutants derived from APEEP and from EASIUR.

These problems are mixed integer linear problems and were written in the General Algebraic Modeling System (GAMS) and solved using the Gurobi solver. The advantage of formulating the problems as shown in Table 5.5 is that such an approach allows for the quick exploration of the entire solution space.

Table 5.5: A decision maker might seek to solve one of these two optimization problems in deciding which ships to retrofit, and how many berths to retrofit at each port.

Problem	**(i)**	**(ii)**
Direction	Maximize	Maximize
Objective function	$\sum_{i,j} ben\_pvt_{i,j} + \sum_{i,j} ben\_env_{i,j}$	$\sum_{i,j} ben\_pvt_{i,j} + \sum_{i,j} ben\_env_{i,j} - \sum_{i} cst\_ship_i - \sum_{j} cst\_port_j$
Constraints	Equation 5.5 Equation 5.6 Equation 5.7	Equation 5.5 Equation 5.6 Equation 5.7
	$\left(\sum_{i,j} ben\_pvt_{i,j} + \sum_{i,j} ben\_env_{i,j} - \sum_{i} cst\_ship_i - \sum_{j} cst\_port_j\right) \geq 0$	

For cargo vessels, we considered three cases additional cases of "blunt" or command and control regulation. In the first, we assess the California shore power regulation by evaluating the distribution of benefits and costs if all container vessels calling at major California ports were required to use shore power. In the second case, we consider the case in which all vessels calling at major California ports are required to use shore power. Finally, we consider a regulation that simply mandates that all vessels use shore power in the 17 US ports listed in Table 5.3. RESULTS

5.3.5 Shore power for cruise vessels

There have already been moves towards the use of shore power for cruise vessels in a number of places,[97] starting with ecologically sensitive environments such as Alaska and the Puget Sound. Due to the large power consumption of cruise vessels (>5MW per vessel on average), there is already a strong incentive for cruise operators to use the cheapest possible source of energy. At current fuel prices, grid electricity in the continental United States is cheaper per kWh than power produced by the diesel-fired generators on board the vessel. Indeed, an analysis of our raw data, which included 42 ports and 138 vessels, showed that – at the current cost of marine diesel or gas oil of around $700 per tonne, and assuming that they did not have to pay to retrofit shore facilities to supply electricity – it would make economic sense for around 85 (or 60%) of the vessels in our dataset to equip themselves for shore power purely because doing so would save their operators money. The evidence supports this conclusion. We believe that at least 25 of the vessels in our dataset are likely to be equipped to accept shore power.[98] Our model suggests that, of these, 22 would save their owners money by switching to electricity when calling at any of the 42 ports we considered.[99]

Annual fuel cost savings associated with the retrofit would be $18 million, whereas the annualized cost of vessel retrofit would be $5 million.

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[97] See for example, Princess Cruises at: http://www.princess.com/news/backgrounders_and_fact_sheets/factsheet/Princess-Ships-Clear-the-Air-with-Shore-Power-Connections.html#.VRg19Fwk_AM

[98] Data on which ships might already be equipped for shore power were collected by Prof James J. Corbett, who kindly them made available for this analysis.

[99] The fact that we conclude that three vessels that are likely equipped for shore power would not produce fuel savings in excess of the cost of retrofit is a limitation of our dataset. One, MS Amsterdam, sails around Alaska in the summer and makes voyages around the world when it is winter in the northern hemisphere. The other two are often active around the US Virgin Islands. We do not have ports from either the Virgin Islands or Alaska in our dataset.

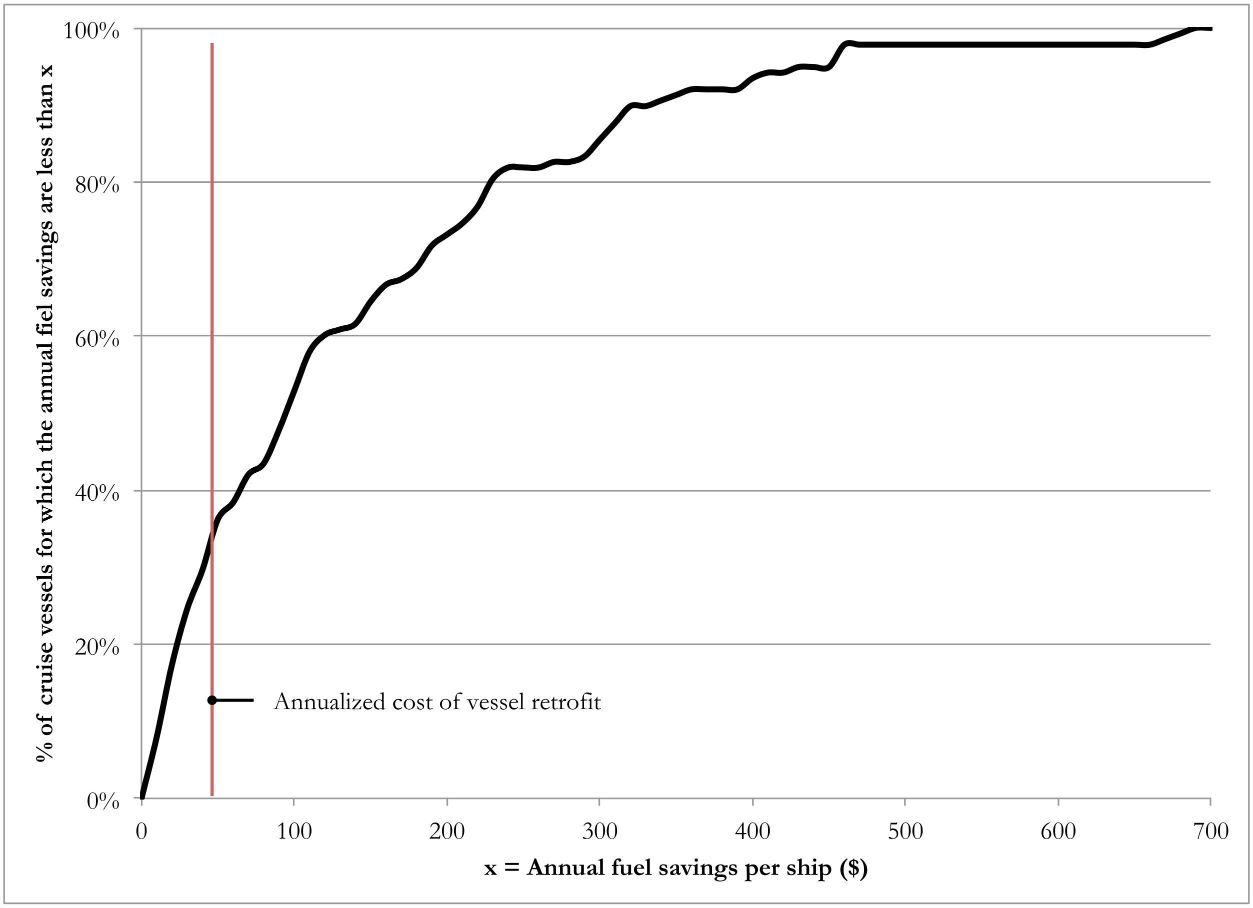
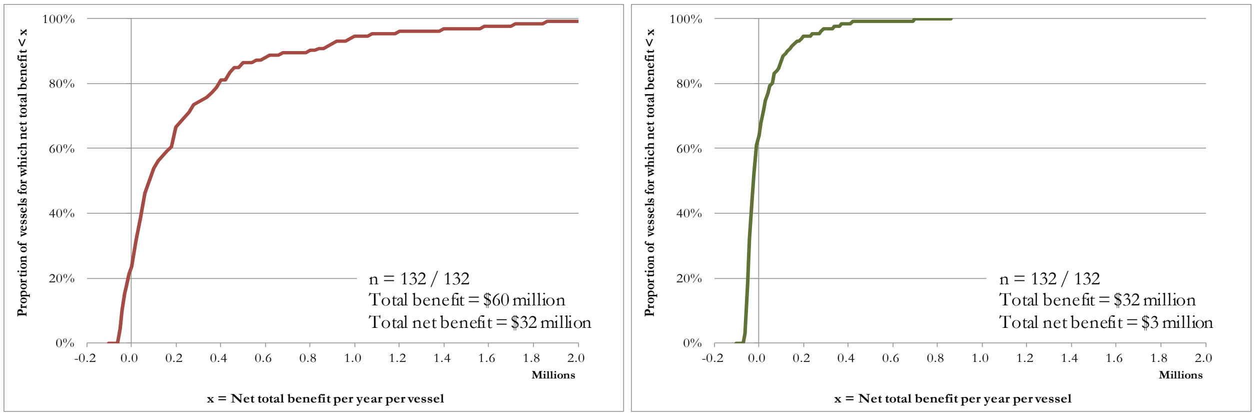


Figure 5.3: Based on our dataset, 60% of the vessels analyzed would achieve fuel costs savings that would fully pay for the cost of retrofit.

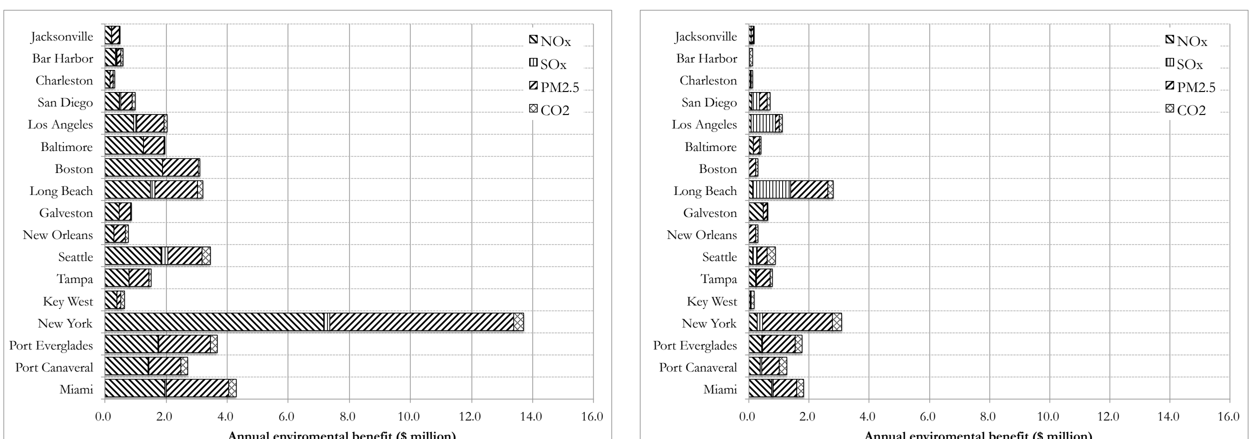
The analysis presented so far ignores the environmental benefits, as well as the cost to the port of retrofitting the berths. A policy maker might be more interested in the problems outlined in Table 5.5, which account for environmental benefits and the cost of additional shore infrastructure.

Figure 5.4 shows the results of solving Problem (i) for cruise vessels: regardless of air quality model used, the corner solution is optimal. A decision maker who wants to maximize benefits subject to the condition that net total benefit is at least zero would switch all vessels and berths to shore power. Based on EASIUR, doing so would generate an annual environmental benefit of $45 million, and a fuel saving of $16 million. This would be partially offset by $8 million in annualized vessel retrofit costs, and $20 million in berth retrofit costs. Based on APEEP, the total environmental benefit would be 16 million per year: all other costs and benefits would be the same as those with EASIUR.



(a) (b)

Figure 5.4: Distribution of the net total benefit from shore power based on social cost of pollution derived from (a) EASIUR and (b) APEEP. Regardless of the air quality model used, the corner solution to Problem (i) is optimal in the case of cruise vessels: all vessels and berths ought to switch to shore power.



(a) (b)

Figure 5.5: The distribution by port of environmental benefits assuming the social cost of pollution given in (a) EASIUR and (b) APEEP if the optimal solution to Problem (i) were implemented. Note that in Boston, Galveston, and Baltimore, the switch to shore power produces a very small increase in the emissions of SO_X. This is not shown in the charts above, because it is much smaller than the benefits produced by the reduction in emissions of other pollutants.

Figure 5.5 demonstrates vividly that these benefits are much smaller if the social costs of pollution from APEEP are assumed, and the distribution of benefits – both geographically and in the proportion of benefits produced by different pollutants - is quite different under the two models.

The solution to Problem (i) is an illustration of why a policy intervention might be needed to produce a public benefit that a profit-maximizing firm might be unwilling to provide. Figure 5.3 shows that, left to themselves, about 60% of all cruise vessels would shift to shore power. Figure 5.4 shows that such an outcome would leave considerable environmental benefits "on the table" and that such benefits could be obtained at no net cost to society by requiring that *all* cruise vessels use shore power. The individual vessels for whom the shift is uneconomical could be compensated by society: the benefit in terms of improved air quality would more than make up for this cost. Alternatively, it could be argued that – so far – cruise vessels operators have been allowed to impose an externality on society. Requiring them to retrofit the vessels (or even pay all or part of the cost of berth retrofit) simply internalizes this externality.

Problem (i) asks what a decision maker would do, if she wants to generate the largest possible benefit, while ensuring that costs do not exceed those benefits.

Another reasonable goal for a decision maker might be to simply ensure that the total net benefit – total benefits less total costs – be as large as possible. That is the goal of Problem (ii). The optimal solution to this problem for cruise vessels is shown in Figure 5.6. Depending on the air quality model used, between half (APEEP) and two-thirds (EASIUR) of all vessels ought to be retrofit. The total environmental benefit would be $40 million based on EASIUR and $13 million based on APEEP. Based on EASIUR, the benefits would be evenly split between reductions in NO_X emissions and $PM_{2.5}$ emissions. Based on APEEP, about half the benefit would come from reductions in $PM_{2.5}$, a quarter from a reduction in NO_X, a sixth from reductions in SO_2, and the rest from CO_2 emissions reductions (see Figure 5.7).

There has been significant progress both in the United States (e.g., California is phasing in a requirement that all cruse liners calling at its ports use shore power) and elsewhere (e.g., Wahlquist 2015) in moving cruise vessels to shore power. This is partially because each vessel represents a large and visible source of pollution, and partially because there is a commercial incentive for vessel operators to make the switch. Our results indicate that society might benefit from an even broader (perhaps universal) move towards shore power for cruise vessels.

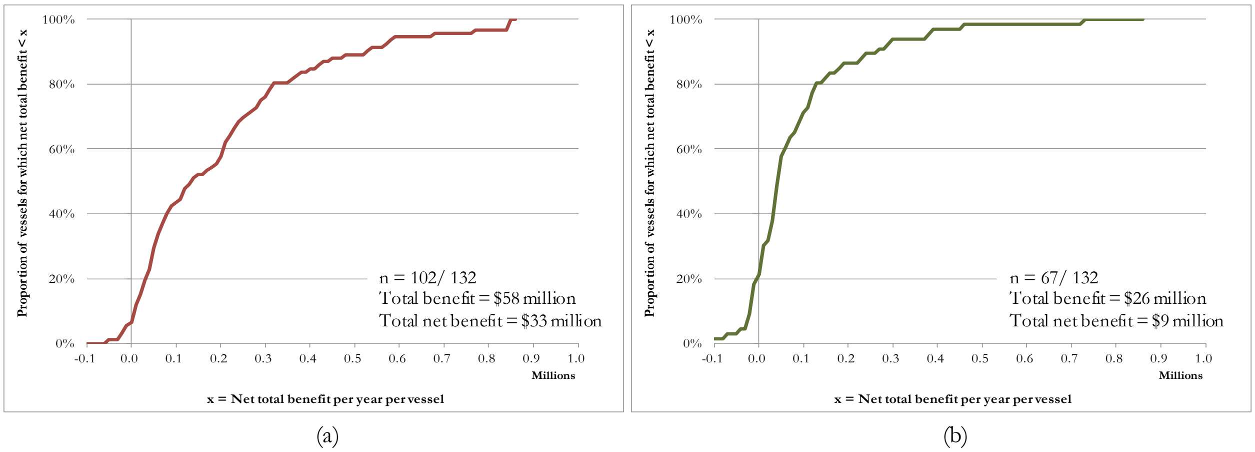
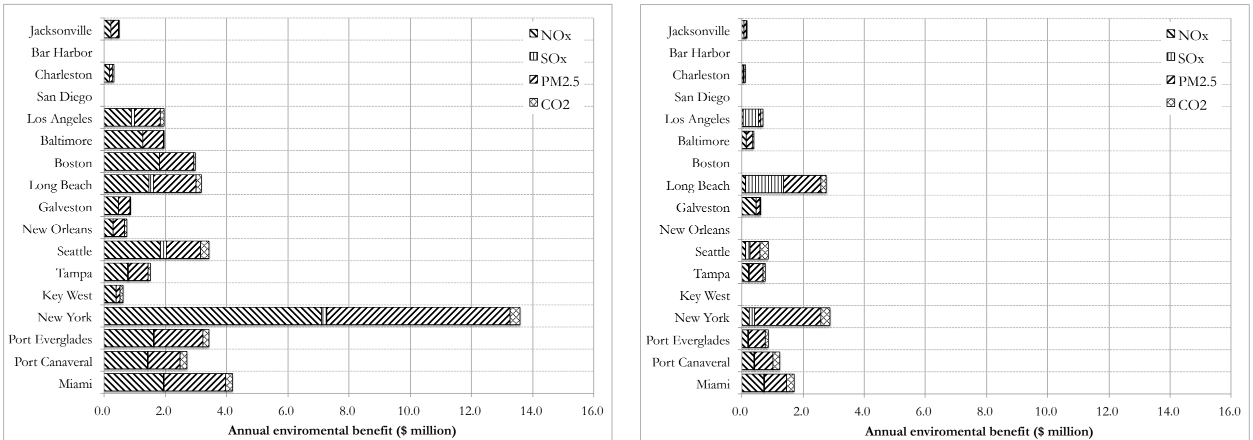


Figure 5.6: Distribution of the net total benefit from shore power based on social cost of pollution derived from (a) EASIUR and (b) APEEP. The two air quality models produce markedly different solutions to Problem (ii). Based on EASIUR, the decision maker would retrofit more than two thirds of all cruise vessels, whereas the optimal solution based on APEEP is to retrofit just over half of all cruise vessels.[100]

On the other hand, the use of shore power for cargo ships is still in its early stages, and once again, California is at the forefront of this move. We begin by analyzing California's shore power regulation.

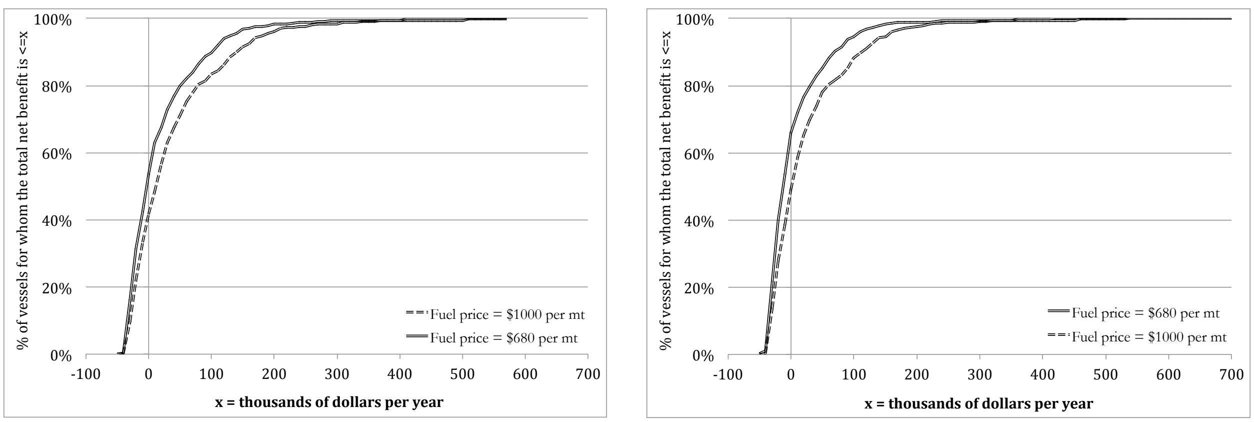
[100] Figure 5.6 suggests that, for some vessels, using shore power produces a net total loss. If this were the case, it would mean that the solution is not optimal: it could be improved by not retrofitting such vessels. However, this is an artifact of the way these figures are drawn. Displaying the results as shown in Figure 5.6 requires that the cost of retrofitting a berth be apportioned among different vessels. We did this by dividing the total annualized cost of berth retrofit by the total number of hours that all the vessels under consideration were in port each year to arrive at an "hourly cost of port retrofit." Each vessel's share of the cost of retrofit was calculated by multiplying this hourly cost by the number of hours that that vessel was in port. This approach is based on average costs. However, the optimization algorithm makes its decisions based on marginal costs, which is economically rational. For instance, a berth at a port may already be retrofitted to accommodate one vessel. If this berth were not fully utilized by that one vessel, a second vessel could use it at no additional cost and produce an environmental benefit. In fact, the benefit of supplying such a vessel with shore power would be positive so long as the total benefits exceeded the cost of retrofitting it. However, in the approach used to produce Figure 5.6, some part of the cost of retrofitting the berth would be allocated to the second vessel, resulting in an apparent – but not real – net loss. (See Appendix 5.6.2)



(a) (b)

Figure 5.7: The distribution by port of environmental benefits assuming the social cost of pollution given in (a) EASIUR and (b) APEEP if the optimal solution to Problem (ii) were implemented for cruise vessels.

5.3.6 Requiring all container ships calling at major California ports to use shore power



(a) (b)

Figure 5.8: Distribution of total net benefit of using shore power for all 525 container vessels that called at California ports using social costs of pollutants from (a) EASIUR and (b) APEEP. It is apparent that at current prices, for most ships, the total net benefit that obtains from making them use shore power is negative. Overall, EASIUR yields an estimate of the net benefit of $3 million per year, whereas APEEP estimates a loss of $4 million.

Figure 5.8 suggests that requiring all container ships calling at California ports to use shore power produces close to no net benefit (or loss) overall. At current fuel prices, for more than half the 525 container vessels, using shore power produces a net loss even after taking into account environmental benefits. The California regulation produces the kind of optimum described by Problem (i): benefits are maximized; subject to the condition that total *net* benefit is positive.

Given that, as it stands, the California rule achieves an outcome in which pollution is cut without a significant net loss (or net benefit) to society, we ask if it would be a good idea to expand this rule to cover other types of vessels.

5.3.7 Requiring all ships at California ports to use shore power

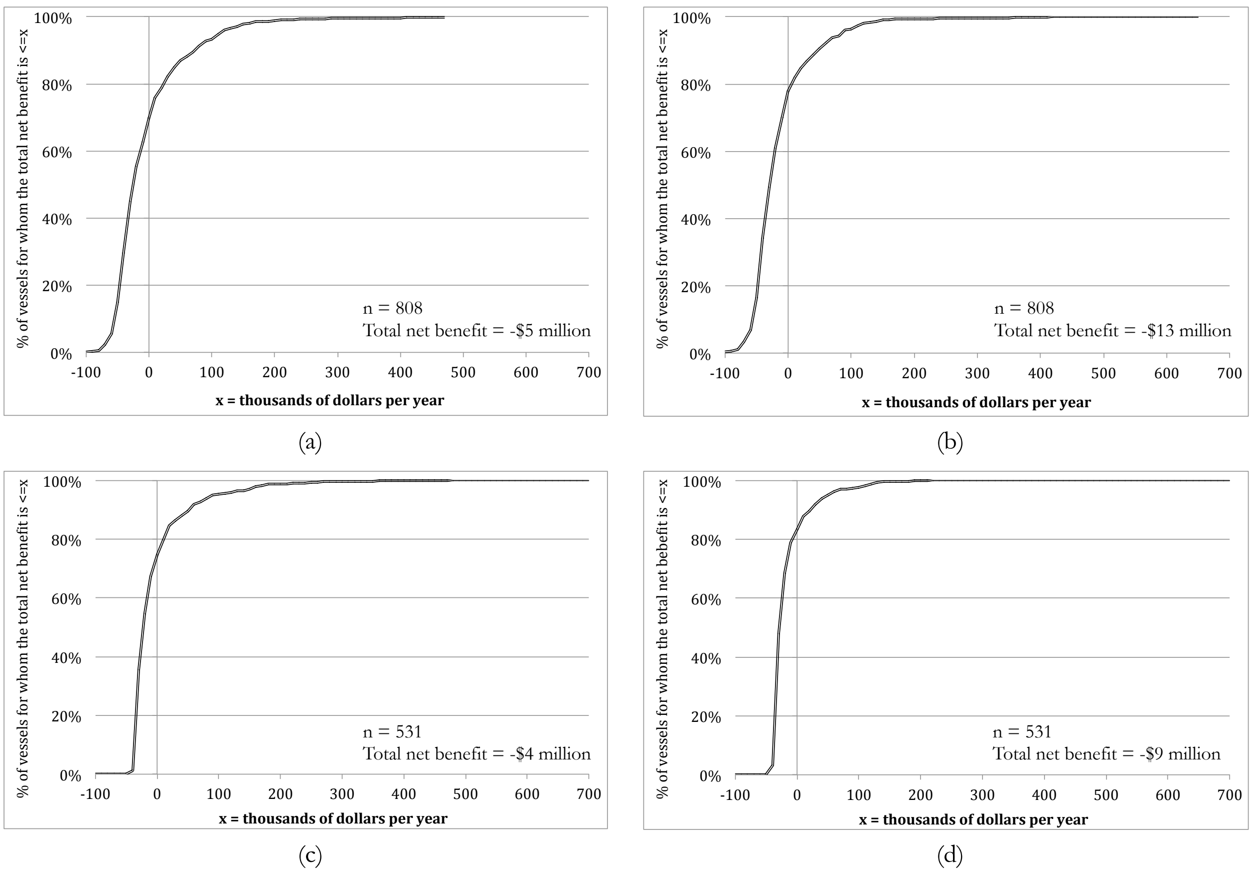


Figure 5.9: Distribution of the total net benefit from shore power at California ports for (a) container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) container and bulk cargo vessels assuming APEEP, (c) tankers and vehicle carriers assuming EASIUR, and (d) tankers and vehicle carriers assuming APEEP. Based on EASIUR, requiring the use of shore power at all major California ports would result in a net total loss of nearly $10 million per year. The loss would be $22 million per year if APEEP were used.

The total cost of requiring all vessels calling at California ports would significantly exceed the benefits, regardless of which integrated air quality model was used, as shown in Figure 5.9. In all cases, retrofitting close to 80% of the 1,339 vessels analyzed would result in a total net loss.

5.3.8 Requiring all ships calling at major US ports to use shore power

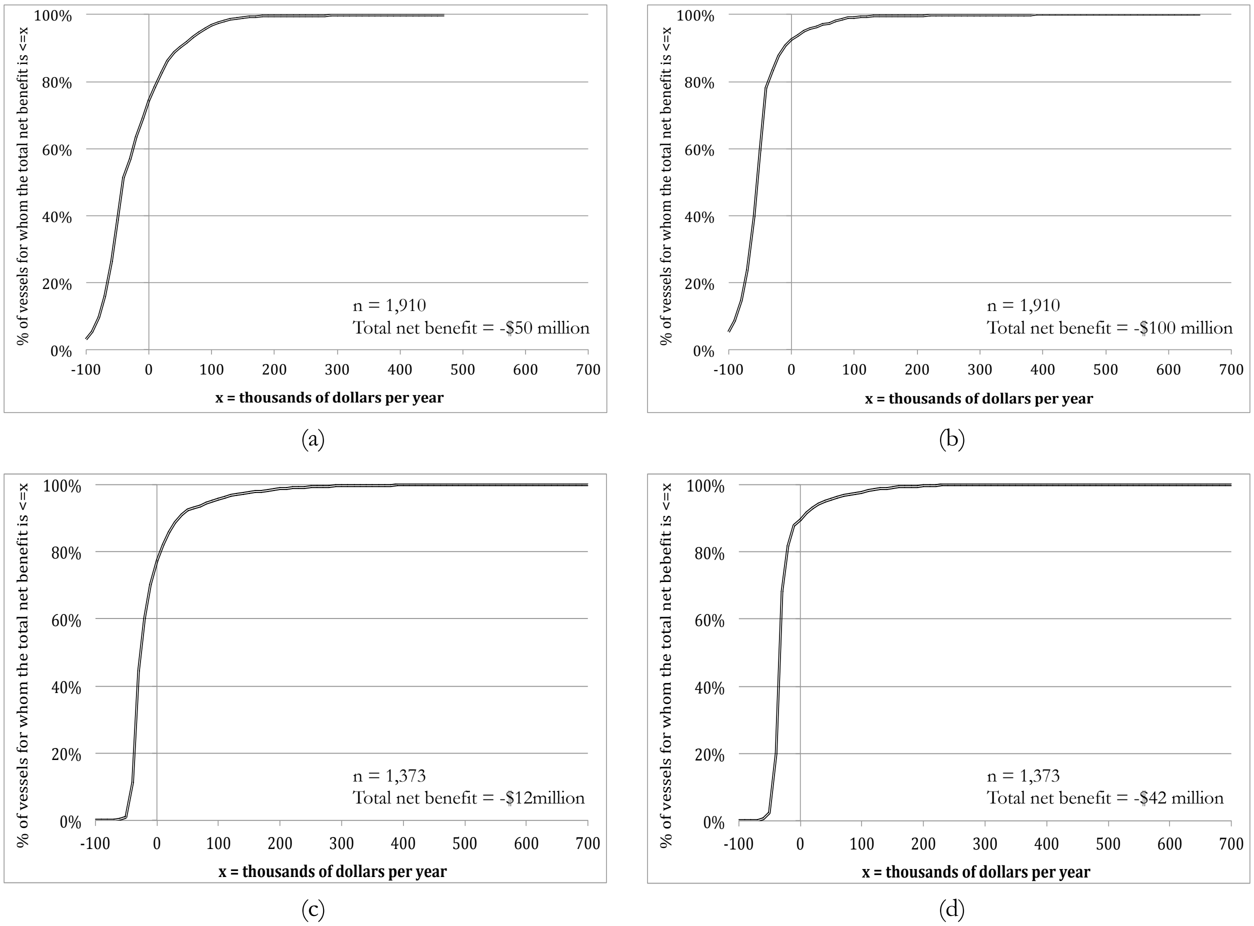


Figure 5.10: Distribution of the total net benefit from shore power at all major US ports for (a) container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) container and bulk cargo vessels assuming APEEP, (c) tankers and vehicle carriers assuming EASIUR, and (d) tankers and vehicle carriers assuming APEEP. Based on EASIUR, requiring the use of shore power at all major US ports would result in a net total loss of over $70 million per year. The loss would be $140 million per year if APEEP were used.

Figure 5.10 clearly demonstrates that mandating the use of shore power at all US ports and for all ships would result in a substantial net loss to society. Depending on which model was used to estimate the social cost of pollution, this loss would be between $70 and $140 million per year. APEEP generally produces a lower estimate for the environmental benefit of a switch to shore power. This is because – with the significant exception of the social cost of SO_X emissions in southern California and the Bay Area, where EASIUR's estimate is about an order of magnitude lower than that obtained from APEEP – EASIUR generally arrives at a higher social cost of emissions than APEEP.[101]

Table 5.6: A summary of the results discussed in Sections 5.3.6 - 5.3.8 suggests that - except for container ships in California - applying a blanket requirement that shore power be used is likely to produce a net societal loss

Objective	**Use shore power for all (EASIUR)**					**Use shore power for all (APEEP)**				
Applied to	Container ships Calling at California ports	Container and bulk cargo ships calling at California ports	Tankers and vessel carriers calling at California ports	All container andbulk cargo ships calling at major US ports	All tankers and vehicle carriers calling at major US ports	Container ships Calling at California ports	Container and bulk cargo ships calling at California ports	Tankers and vessel carriers calling at California ports	All container andbulk cargo ships calling at major US ports	All tankers and vehicle carriers calling at major US ports
Total number of vessels	525	808	531	1,910	1,373	525	808	531	1,910	1,373
Number of vessels retrofit	525	808	531	1,910	1,373				1,910	1,373
Container	*525*	*525*		*1,064*		*525*	*525*		*1,064*	
Other "barge" vessels		*283*		*846*			*283*		*846*	
Tankers			*397*		*1,077*			*397*		*1,077*
Of which liqified gas carriers					*57*					*57*
Ro-Ro and vehicle carriers			*134*		*296*			*134*		*296*
Other "tower" vessels										
Cost of vessel retrofit	$21	$32	$21	$77	$55	$21	$32	$21	$77	$55
Fuel savings	$4	$4	$2	$16	$20	$4	$4	$2	$16	$20
Net private benefit	-$17	-$28	-$19	-$61	-$36	-$17	-$28	-$19	-$61	-$36
Environmental benefit	$54	$57	$24	$108	$62	$47	$50	$19	$59	$32
NOx	*$27*	*$28*	*$12*	*$55*	*$33*	*$12*	*$12*	*$2*	*$16*	*$11*
SOx	*$3*	*$3*	*$10*	*$4*	*$27*	*$16*	*$17*	*$8*	*$17*	*$12*
PM2.5	*$22*	*$23*	*$1*	*$44*	*-$1*	*$17*	*$18*	*$8*	*$21*	*$6*
CO2	*$3*	*$3*	*$1*	*$5*	*$3*	*$3*	*$3*	*$1*	*$5*	*$3*
Number of berths retrofit	47	47	42	130	174	47	47	42	130	174
Los_Angeles	*20*	*20*	*10*	*20*	*11*	*20*	*20*	*10*	*20*	*11*
Houston	*0*	*0*		*21*	*40*	*0*	*0*		*21*	*40*
Long_Beach	*13*	*13*	*14*	*13*	*15*	*13*	*13*	*14*	*13*	*15*
Tacoma	*0*	*0*		*8*	*4*	*0*	*0*		*8*	*4*
Port_of_Miami	*0*	*0*		*4*	*2*	*0*	*0*		*4*	*2*
Oakland	*8*	*8*	*6*	*8*	*3*	*8*	*8*	*6*	*8*	*3*
Galveston	*0*	*0*		*6*	*37*	*0*	*0*		*6*	*37*
Port_Everglades	*0*	*0*		*3*	*8*	*0*	*0*		*3*	*8*
Port_of_Baltimore	*0*	*0*		*6*	*9*	*0*	*0*		*6*	*9*
Newark_(New_York)	*0*	*0*		*9*	*5*	*0*	*0*		*9*	*5*
Port_of_Richmond	*2*	*2*	*7*	*2*	*6*	*2*	*2*	*7*	*2*	*6*
Seattle	*0*	*0*		*6*	*2*	*0*	*0*		*6*	*2*
Port_Angeles	*0*	*0*		*2*	*5*	*0*	*0*		*2*	*5*
Corpus_Christi	*0*	*0*		*4*	*11*	*0*	*0*		*4*	*11*
Yerbabuena_Island	*4*	*4*	*5*	*4*	*5*	*4*	*4*	*5*	*4*	*5*
New_Orleans	*0*	*0*		*11*	*5*	*0*	*0*		*11*	*5*
New_York	*0*	*0*		*3*	*6*	*0*	*0*		*3*	*6*
Cost of berth retrofit	$34	$34	$9	$95	$39	$34	$34	$9	$95	$39
Net social benefit	$20	$23	$16	$13	$23	$13	$16	$10	-$36	-$7
Total net benefit	**$3**	**-$5**	**-$4**	**-$48**	**-$12**	**-$4**	**-$13**	**-$9**	**-$97**	**-$42**

The results so far (summarized in Table 5.6) demonstrate that – while the California shore power rule might come close to maximizing environmental benefits without resulting in a large total net loss – a command and control approach that requires all vessels to retrofit is unlikely to be

101 A detailed discussion of the differences between APEEP and EASIUR is beyond the scope of the current analysis, and is in fact the subject of ongoing research. For an early discussion of these differences and maps that illustrate them, see Heo (2015, 51, 106–165) and Section 5.5. Also see Appendix 5.6.1 to see the marginal social costs, derived from both models, of different pollutants at all the ports considered in this study.

economically efficient. Discretion needs to be exercised in deciding which vessels to retrofit and how many berths at which ports. We now discuss the solutions for cargo vessels to the problems laid out in Table 5.5, which suggest ways in which decision makers might exercise such discretion.

5.3.9 Maximizing total benefits while ensuring no net total loss – Problem (i) in Table 5.5

In this case, we seek a solution that would maximize the total benefit (the sum of fuel savings and air quality benefits) subject to the condition that total net benefit must be at least zero. That is, the costs of retrofitting the vessels and berths must not exceed the benefits that obtain from using shore power. If inputs from EASIUR are used, the optimal solution is to retrofit nearly two thirds of the fleet. Doing so would produce \$150 million in annual environmental benefits and \$30 million in fuel savings (Figure 5.11), which would be completely offset by \$80 million in vessel retrofit costs and \$100 million in berth retrofit costs. If the calculations were based on APEEP, the total benefit would be \$85 million per year of which \$15 million would come from fuel cost savings and the rest from improved air quality. Based on EASIUR, it would be optimal to retrofit nearly two thirds of the vessels considered and 250 of 300 berths. Based on APEEP, it would be optimal to retrofit about a quarter of the vessels and 120 of 300 berths.

In the EASIUR-derived solution, half the total environmental benefit stems from a reduction in NO_X and half from a reduction in $PM_{2.5}$ emissions. In the APEEP-based solution, about two fifths of the benefits come from reducing $PM_{2.5}$, and approximately a third each from SO_X and NO_X reduction.

As before, the geographical distribution of both benefits and optimal locations for berth retrofits varies considerably based on the air quality model used (Figure 5.12 and Figure 5.13). APEEP still produces a solution where proportionally more berths in California are retrofitted than in other parts of the country.

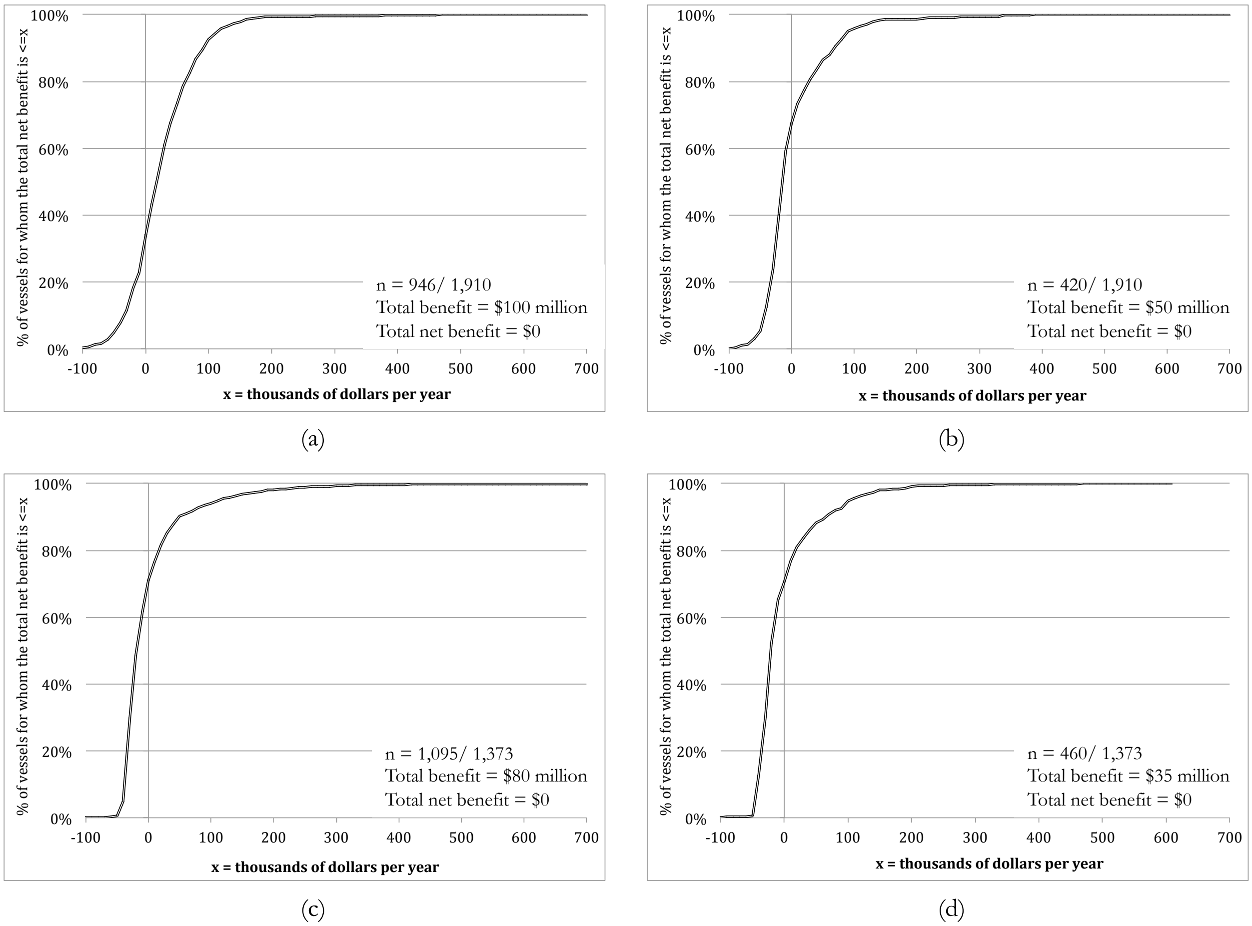


Figure 5.11: Distribution of the total net benefit from retrofitting vessels and berths in order to maximize the total benefit subject to the condition that total net benefit is positive for (a) container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) container and bulk cargo vessels assuming APEEP, (c) tankers and vehicle carriers assuming EASIUR, and (d) tankers and vehicle carriers assuming APEEP. The algebraic sum of the area under each of these curves is equal to zero. Based on EASIUR, this approach would result in a total benefit of $180 million per year, while applying APEEP would result in an annual benefit of $85 million. Using social costs from EASIUR produces an optimal solution in which more than 2,000 – or about two-thirds of the 3,200 vessels under consideration – ought to be retrofit, whereas APEEP suggests that 880 – or about one a quarter – be retrofit.

(a)

(b)

(c)

(d)

Figure 5.12: Geographical distribution of berths that it is optimal to retrofit in order to maximize the total net benefit for (a) container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) container and bulk cargo vessels assuming APEEP, (c) tankers and vehicle carriers assuming EASIUR, and (d) tankers and vehicle carriers assuming APEEP. For container vessels, the optimal solution based on APEEP is still to concentrate on California, whereas the optimal solution in EASIUR involves retrofitting ports in the Pacific Northwest as well as in the northeast United States and the Gulf of Mexico. For tankers and vehicle carriers, assuming the social costs in APEEP produces a solution in which ports on both coasts – as well as the Gulf of Mexico are retrofit, as does EASIUR.

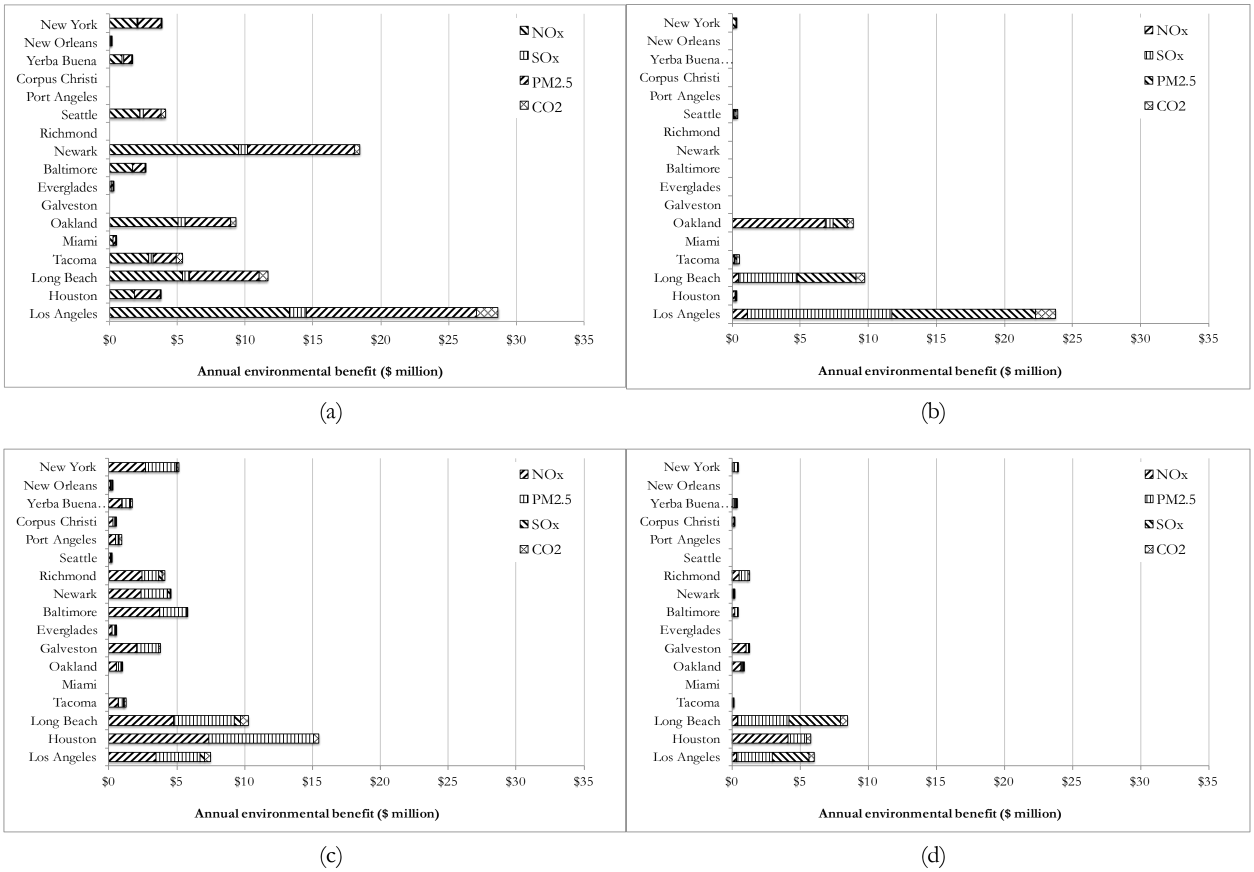


Figure 5.13: Environmental benefits if the optimal solution to Problem (i) were implemented, disaggregated by pollutant and port for (a) container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) container and bulk cargo vessels assuming APEEP, (c) tankers and vehicle carriers assuming EASIUR, and (d) tankers and vehicle carriers assuming APEEP. If estimates of social cost from APEEP were used, it would be optimal to only use shore power at California ports for container ships. A few berths at ports in the Gulf of Mexico would be retrofit to accommodate tankers; but even for these, most of the environmental benefit would come from California. If EASIUR were used, significant benefit would accrue from using shore power at northeast and Gulf of Mexico ports.

Figure 5.14 demonstrates the need for policy intervention. The solution to Problem (i) produces a large environmental benefit, while ensuring that society is no worse off when all costs are accounted for (i.e., total net benefits ≥ 0). This requires the retrofit of a large number of vessels, more than 80% of which would not be able to recover the cost of vessel retrofit from fuel savings. As such, left to themselves, the owners of these vessels would not switch to shore power. Society generates a large enough surplus from the reduced pollution for it to make economic sense to compensate these vessel owners for any net loss they incur. On the other hand, it could be argued that the vessel owners have hitherto been allowed to pollute without bearing the costs of the deterioration in air quality, and requiring them to retrofit the vessels – and perhaps even bear part of the cost of berth retrofit – ensures that they are no longer allowed to impose an externality on society.

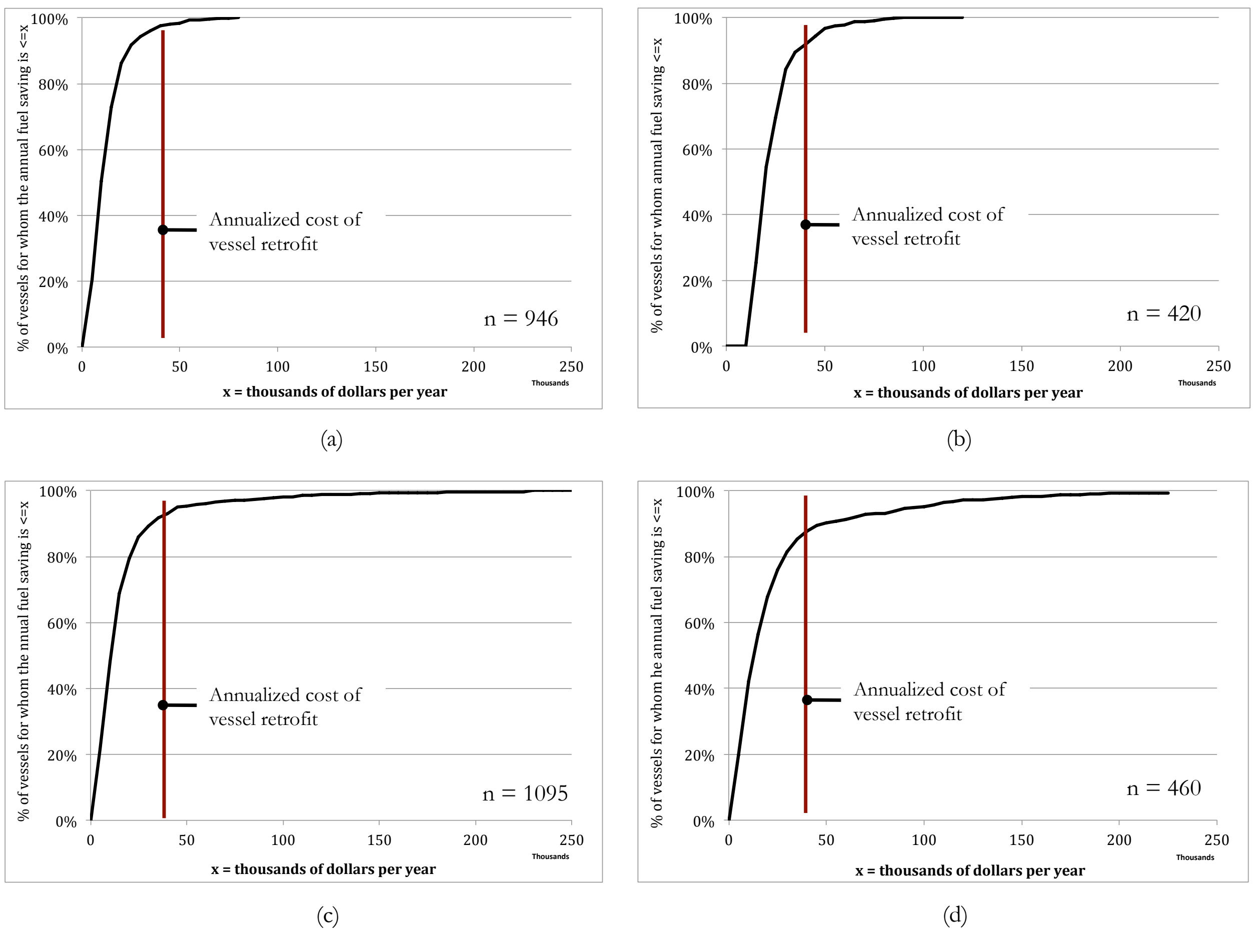
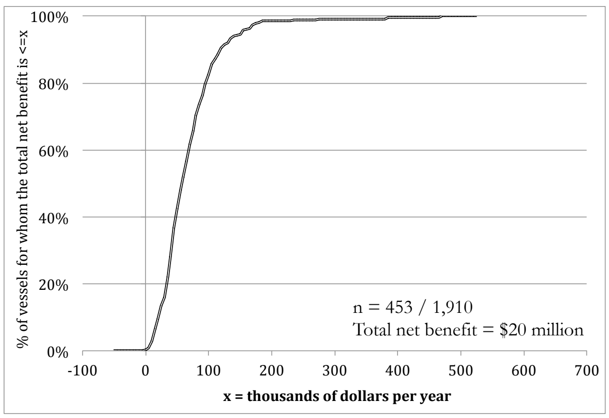


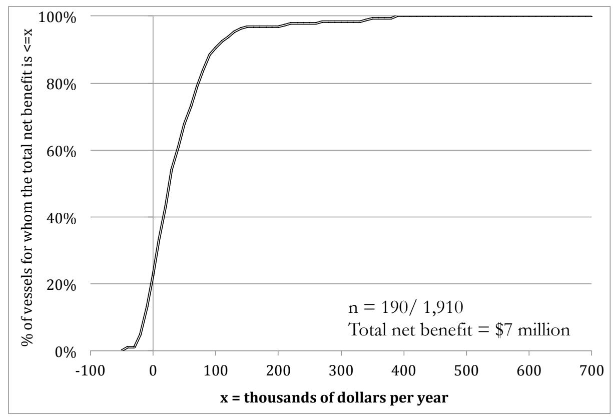
Figure 5.14: Distribution of annual fuel cost savings for all the vessels that the solution to Problem (i) suggests it is optimal to retrofit. Panel (a) is for container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) for container and bulk cargo vessels assuming APEEP, (c) for tankers and vehicle carriers assuming EASIUR, and (d) for tankers and vehicle carriers assuming APEEP. In all cases, the solution that maximizes total benefit subject to the condition that total *net* benefit is at least zero requires the retrofit of a large number of vessels whose operators will not be able to recover the cost of vessel retrofit from fuel savings.

5.3.10 Maximizing net total benefit: Problem (ii) in Table 5.5

In this problem, we assume that the decision maker seeks to *maximize* total net benefit. Implementing the optimal solution to this problem, as shown in Figure 5.15 would result in a significant total net benefit: $40 million per year assuming the social costs produced by EASIUR and $15 million assuming the social costs in APEEP.



(a)



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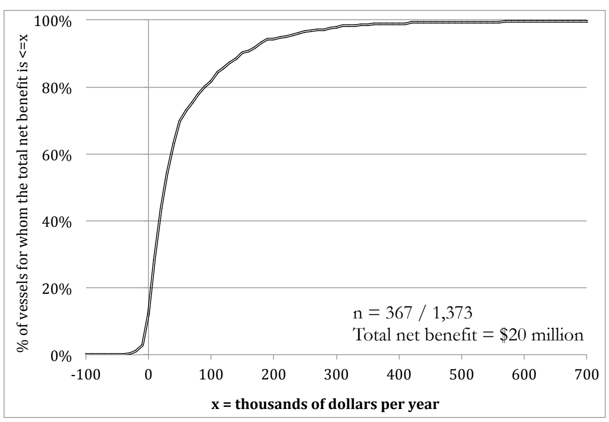

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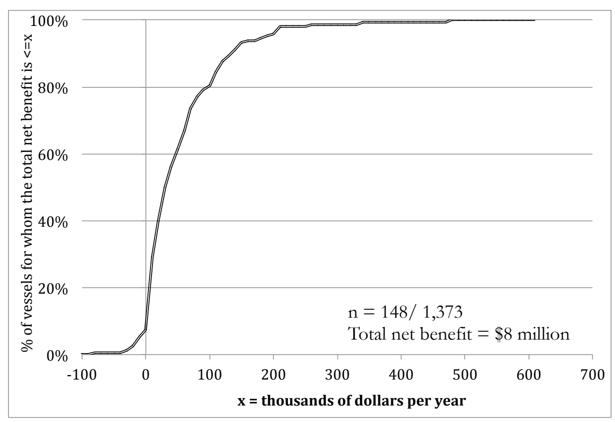


(d)

Figure 5.15: Distribution of the total net benefit from retrofitting vessels and berths in order to maximize the total net benefit for (a) container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) container and bulk cargo vessels assuming APEEP, (c) tankers and vehicle carriers assuming EASIUR, and (d) tankers and vehicle carriers assuming APEEP. Based on EASIUR, this approach would result in a net total benefit of $40 million per year, while applying APEEP would result in an annual net benefit of $15 million Using social costs from EASIUR produces an optimal solution in which 820 – or about a quarter of the 3,200 vessels under consideration – ought to be retrofit, whereas APEEP suggests that 338 – or about one in ten vessels – be retrofit.[102]

[102] See Footnote 100

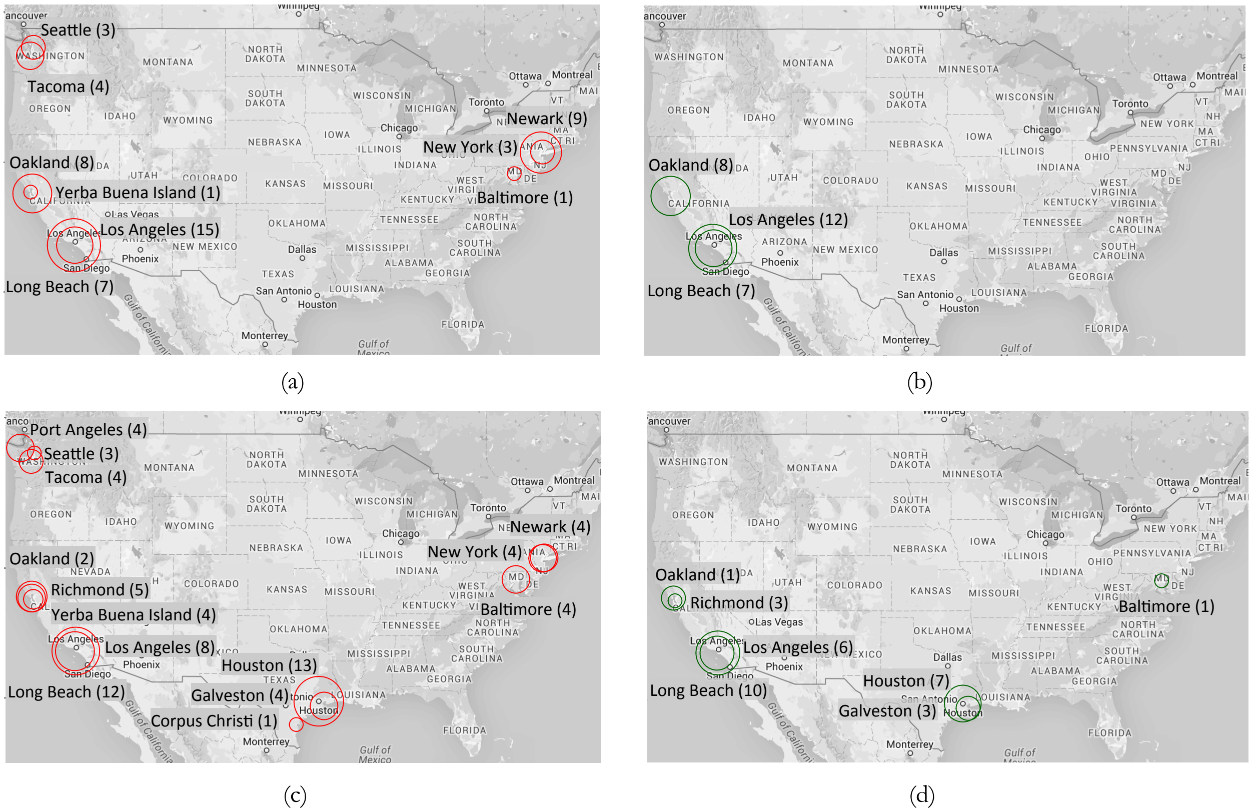
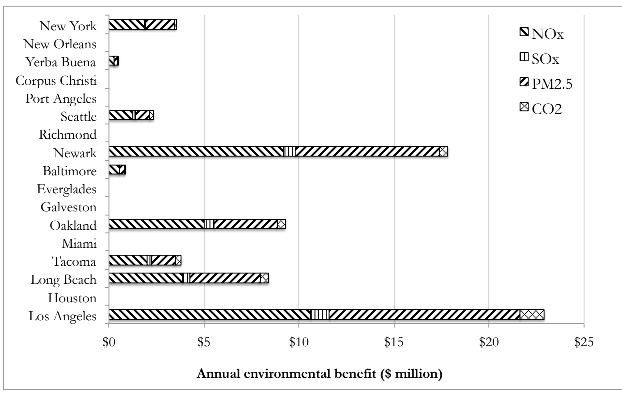
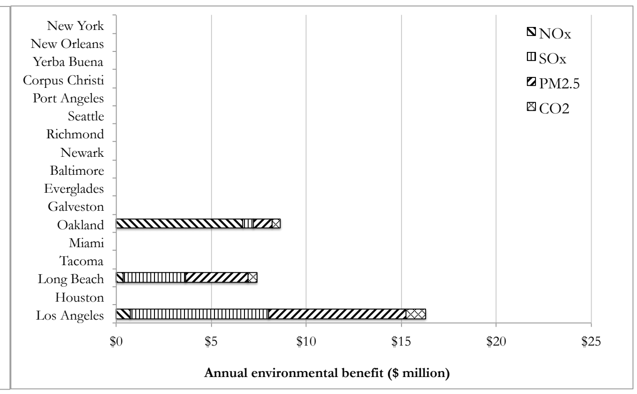


Figure 5.16: Geographical distribution of berths that it is optimal to retrofit in order to maximize the total net benefit for (a) container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) container and bulk cargo vessels assuming APEEP, (c) tankers and vehicle carriers assuming EASIUR, and (d) tankers and vehicle carriers assuming APEEP. The number in the bracket indicates the number of berths that ought to be retrofit in the optimal solution. For container vessels, the optimal solution based on APEEP is to simply concentrate on California, whereas the optimal solution in EASIUR involves retrofitting ports in the Pacific Northwest as well as in the northeast United States. For tankers and vehicle carriers, assuming the social costs in APEEP again produces a solution that is dominated by California ports, with some use of shore power in the Gulf of Mexico. Using EASIUR produces a solution in which a large number of ports across the country ought to be retrofit.

The total environmental benefit in the optimal solution based on EASIUR is \$110 million per year, which is split almost evenly between reduction in NO_X and $PM_{2.5}$. This benefit is offset by a net private loss of \$20 million to ship operators and a cost of port retrofit of \$50 million. Given that we are assuming that marine fuel with a sulfur content of 0.1% is used, the benefit from a reduction in SO_X emissions is small. Based on APEEP, the total environmental benefit would be about \$50 million annually, with approximately a third each coming from reductions in NO_X, SO_X, and $PM_{2.5}$ emissions. This is offset by a net private loss of \$5 million to vessel owners and an annualized port retrofit cost of \$25 million. Regardless of the air quality model employed, virtually all the "barge" vessels that it is optimal to retrofit are container vessels. Among the "tower" vessels, the optimal solution based on EASIUR is to retrofit tankers (the plurality of which are liquefied gas carriers) and many vehicle carriers and RoRo vessels. The optimal solution for "tower" vessels based on APEEP is to retrofit only tankers.



(a)



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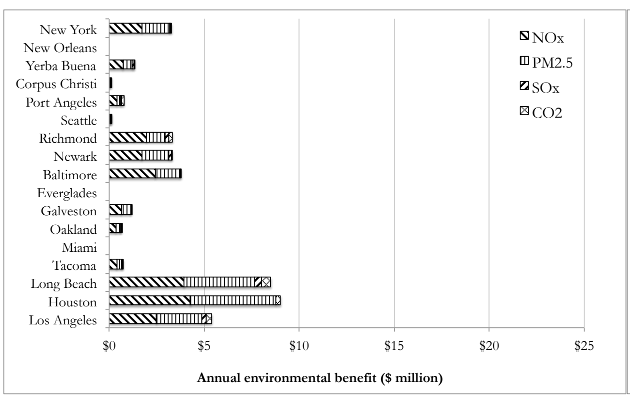

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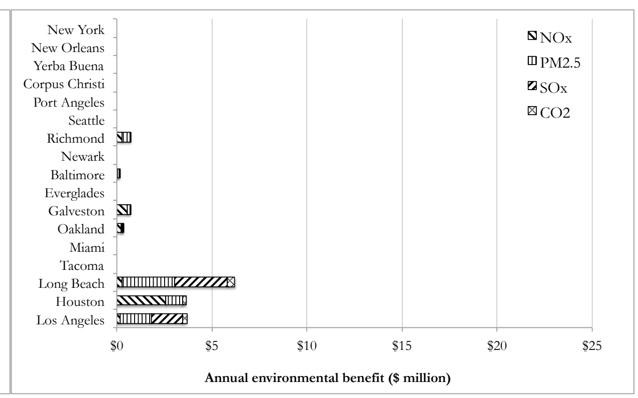

(d)

Figure 5.17: Environmental benefits if the optimal solution to Problem (ii) were implemented, disaggregated by pollutant and port for (a) container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) container and bulk cargo vessels assuming APEEP, (c) tankers and vehicle carriers assuming EASIUR, and (d) tankers and vehicle carriers assuming APEEP. If estimates of social cost from APEEP were used, it would be optimal to only use shore power at California ports for container ships. A few berths at ports in the Gulf of Mexico would be retrofit to accommodate tankers; but even for these, most of the environmental benefit would come from California. If EASIUR were used, significant benefit would accrue from using shore power at northeast and Gulf of Mexico ports.

Using each air quality model produces optimal solutions that have a different distribution of vessels, vessel types, costs, and benefits (Figure 5.16 and Figure 5.17). Additionally, the optimal solutions differ in terms of which ports ought to be retrofitted. As discussed above, APEEP produces a much higher estimate of the social cost of SO_X emissions in southern California and the

Bay Area than does EASIUR, while producing a somewhat lower estimate of all other pollutants virtually everywhere else. As such, the optimal solution based on APEEP is to mostly retrofit large numbers of berths in California, with only a handful of retrofits elsewhere. EASIUR's optimal solution would recommend retrofitting berths on both coasts. Because we are assuming that fuel with low sulfur content is used (as mandated by IMO regulations), APEEP also produces a lower estimate of environmental benefits and therefore generally recommends that fewer ships and berths be retrofit.

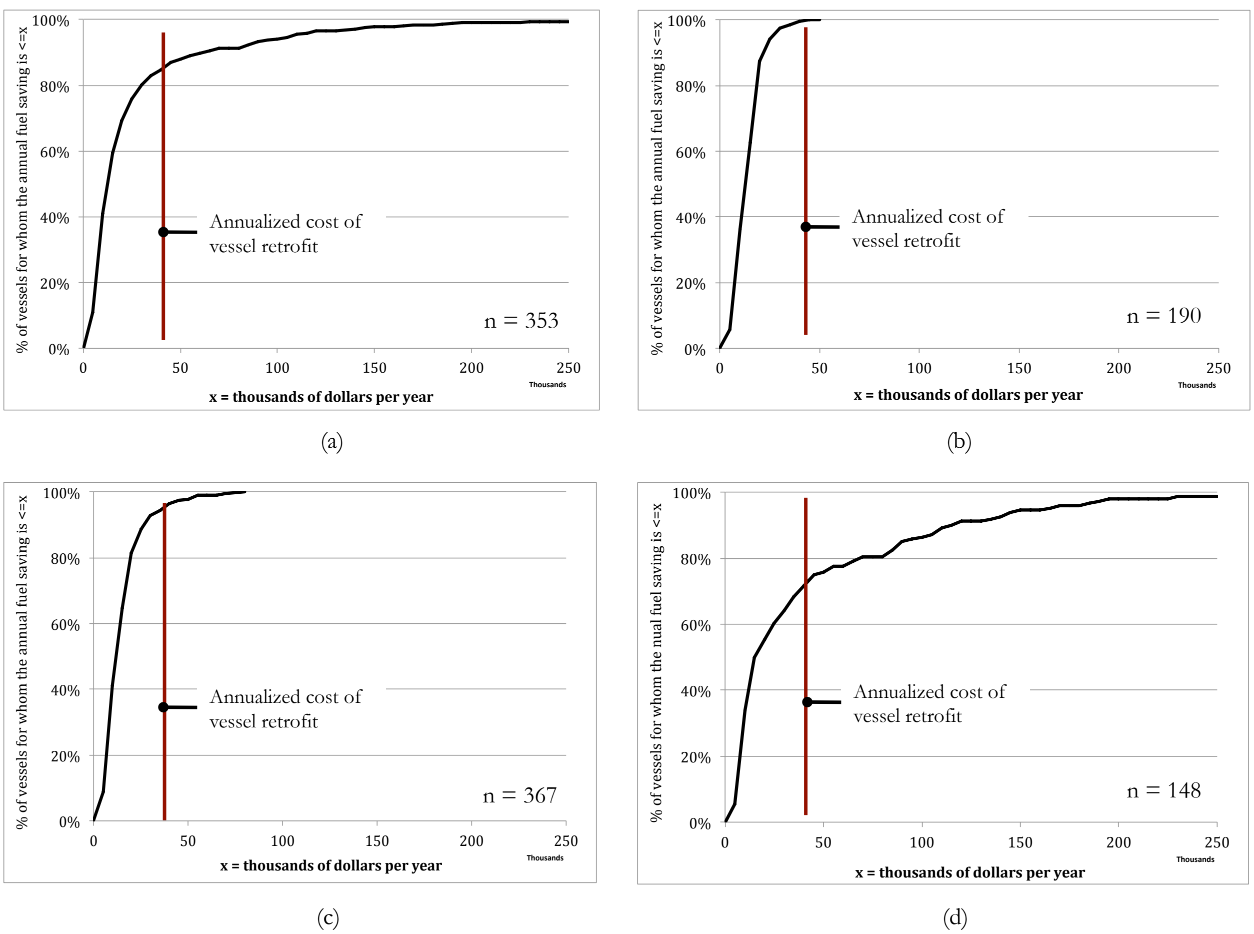

Figure 5.18: Distribution of annual fuel cost savings for all the vessels that the solution to Problem (ii) suggests it is optimal to retrofit. Panel (a) is for container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) for container and bulk cargo vessels assuming APEEP, (c) for tankers and vehicle carriers assuming EASIUR, and (d) for tankers and vehicle carriers assuming APEEP.

Like Figure 5.14, Figure 5.18 demonstrates that a decision maker who wants to maximize the total net benefit to society is unlikely to achieve her goal by simply leaving vessel owners to retrofit when it makes economic sense for them to do so (i.e., when their fuel savings exceed the cost of retrofit). As before, over 80% of the vessels that would be retrofit in the optimal solution to Problem (ii) would not save money by doing so. Once again, they could be compensated, or simply asked to compensate society for the damage that their pollution imposes on society.

Table 5.7 summarizes our findings. It suggests that a widespread (between a quarter and two-thirds of all vessels, depending on which air quality model is applied) switch to shore power can generate a significant environmental benefit, which would be offset by the cost of putting in place the necessary infrastructure on shore and on ships. A more limited deployment of shore power (between a tenth and quarter of vessels, depending on air quality model) would produce a significant societal benefit net of the costs of putting in place shore power equipment.

Comparing Table 5.6 to Table 5.7 is instructive. The former shows that mandating that all vessels that call at US ports produces an environmental benefit of $170 million per year based on EASIUR and $100 million per year based on APEEP. However, such a requirement would come at a cost of $230 million per year, resulting in a large net loss to society. Table 5.7 shows that by selecting vessels and ports judiciously an environmental benefit of between $70 million and $150 million can be generated in a way that produces no net loss to society. An annual environmental benefit of $50-110 million can be generated at a cost of $35-70 million each year, resulting in a significant net benefit to society.

Finally, Table 5.7 shows that in most cases, all the liquefied gas carriers in our dataset ought to be retrofitted. This is not surprising: they spend more time in port than any other vessel type (Table 5.1). These ships require specialized facilities to unload: they cannot share the same facilities as other tankers or vessel carriers. Any future analysis will treat them as a separate category (e.g., like cruise vessels).

Table 5.7: Summary of the optimal solutions to Problems (i) and (ii) in Table 5.5. Depending on which vessels and ports are selected for retrofit a large environmental benefit can be created that is fully offset by the costs to society of putting in place the required infrastructure. Selecting a smaller set of vessels and ports could create a significant benefit to society, net of the costs of retrofit. Compared to EASIUR, APEEP generally produces lower estimates of environmental benefits and results an optimal solutions that involve a more limited application of shore power. All monetary estimates are in millions of dollars.

	EASIUR				APEEP			
Objective	**Max. net total benefit**		**Max. total benefit, subject to no net total**		**Max. net total benefit**		**Max. total benefit, subject to no net total loss**	
Applied to	All container andbulk cargo ships calling at major US ports	All tankers and vehicle carriers calling at major US ports	All container andbulk cargo ships calling at major US ports	All tankers and vehicle carriers calling at major US ports	All container andbulk cargo ships calling at major US ports	All tankers and vehicle carriers calling at major US ports	All container andbulk cargo ships calling at major US ports	All tankers and vehicle carriers calling at major US ports
Total number of vessels	1,910	1,373	1,910	1,373	1,910	1,373	1,910	1,373
Number of vessels retrofit	453	367	946	1,151	190	148	420	516
Container	*450*		*834*		*190*		*414*	
Other "barge" vessels	*3*		*112*				*6*	
Tankers		*256*		*849*		*142*		*398*
Of which liqified gas carriers		*53*		*56*		*48*		*56*
Ro-Ro and vehicle carriers		*111*		*246*		*6*		*62*
Other "tower" vessels								
Cost of vessel retrofit	$18	$15	$38	$44	$8	$6	$17	$18
Fuel savings	$7	$10	$12	$18	$3	$6	$5	$11
Net private benefit	-$12	-$5	-$26	-$26	-$5	$0	-$12	-$7
Environmental benefit	$69	$41	$90	$61	$32	$15	$44	$24
NOx	*$35*	*$21*	*$45*	*$32*	*$8*	*$4*	*$9*	*$7*
SOx	*$3*	*$0*	*$3*	*$0*	*$11*	*$4*	*$16*	*$6*
PM2.5	*$29*	*$17*	*$38*	*$27*	*$12*	*$6*	*$16*	*$10*
CO2	*$3*	*$2*	*$4*	*$3*	*$2*	*$1*	*$3*	*$2*
Number of berths retrofit	51	69	87	161	27	31	44	77
Los_Angeles	*15*	*8*	*20*	*11*	*12*	*6*	*19*	*10*
Houston	*0*	*13*	*10*	*36*		*7*	*1*	*21*
Long_Beach	*7*	*12*	*11*	*15*	*7*	*10*	*10*	*14*
Tacoma	*4*	*3*	*6*	*4*		*0*	*3*	*2*
Port_of_Miami	*0*	*0*	*3*	*0*		*0*	*0*	*0*
Oakland	*8*	*2*	*8*	*3*	*8*	*1*	*8*	*3*
Galveston	*0*	*4*	*0*	*35*		*3*	*0*	*11*
Port_Everglades	*0*	*0*	*2*	*7*		*0*	*0*	*0*
Port_of_Baltimore	*1*	*4*	*4*	*8*		*1*	*0*	*2*
Newark_(New_York)	*9*	*4*	*9*	*5*		*0*	*0*	*2*
Port_of_Richmond	*0*	*5*	*0*	*6*		*3*	*0*	*5*
Seattle	*3*	*1*	*6*	*2*		*0*	*2*	*0*
Port_Angeles	*0*	*4*	*0*	*5*		*0*	*0*	*0*
Corpus_Christi	*0*	*1*	*0*	*9*		*0*	*0*	*2*
Yerbabuena_Island	*1*	*4*	*4*	*5*		*0*	*0*	*3*
New_Orleans	*0*	*0*	*1*	*4*		*0*	*0*	*0*
New_York	*3*	*4*	*3*	*6*		*0*	*1*	*2*
Cost of berth retrofit	$37	$15	$64	$35	$20	$7	$32	$17
Net social benefit	$32	$25	$26	$26	$13	$8	$12	$8
Total net benefit	**$20**	**$20**	**$0**	**$0**	**$7**	**$8**	**$0**	**$0**

5.3.11 Sensitivity analysis

We performed a sensitivity analysis on the results of Problems (ii). Figure 5.19 demonstrates that a two-fold increase in fuel prices results in a two-fold increase in net benefit in the solution based on EASIUR, but a three-fold increase in the solution based on APEEP. This is not surprising, as APEEP results in an optimal solution with smaller environmental benefits; as such, private benefits – which are highly sensitive to fuel price – play a greater role in it.

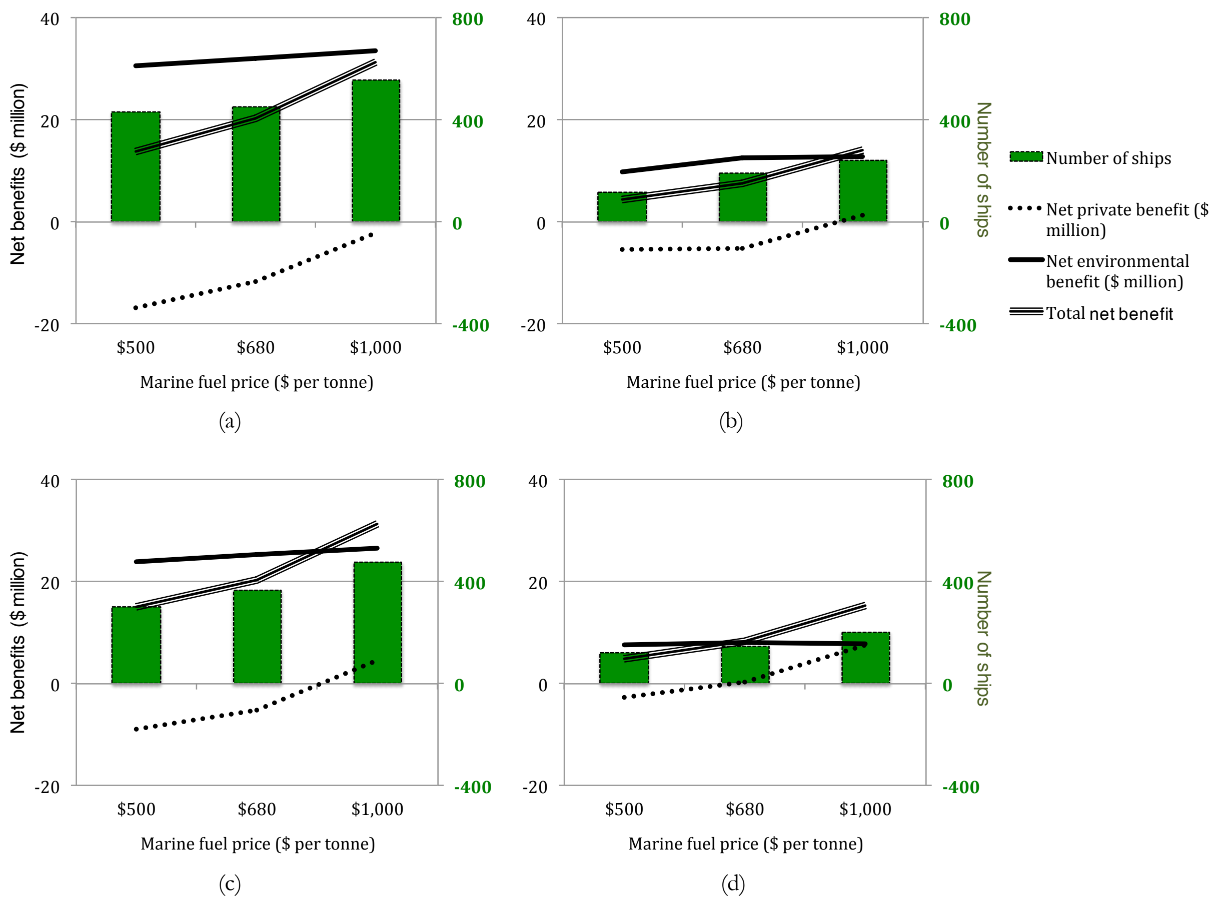

Figure 5.19: Sensitivity of the solution to Problem (ii) to changes in the price of marine fuel for (a) container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) container and bulk cargo vessels assuming APEEP, (c) tankers and vehicle carriers assuming EASIUR, and (d) tankers and vehicle carriers assuming APEEP. At low fuel prices, the benefits of shore power are dominated by environmental benefits, which – for any given vessel - do not diminish with rising fuel costs. However, due to falling private benefits, it may become uneconomical to retrofit a few vessels or a few ports for which the environmental benefits of shore power are not large (e.g., ports where grid electricity is dirtier than average). This would diminish the environmental benefits somewhat, but also result in a solution where fewer berths need to be retrofit. As such, the net environmental benefit falls somewhat less steeply than the net private benefit. On the other hand, a high fuel price creates an incentive for more ships to be retrofit. Both environmental and private net benefits rise – the former less steeply than the latter – to produce a non-linear increase in total net benefit.

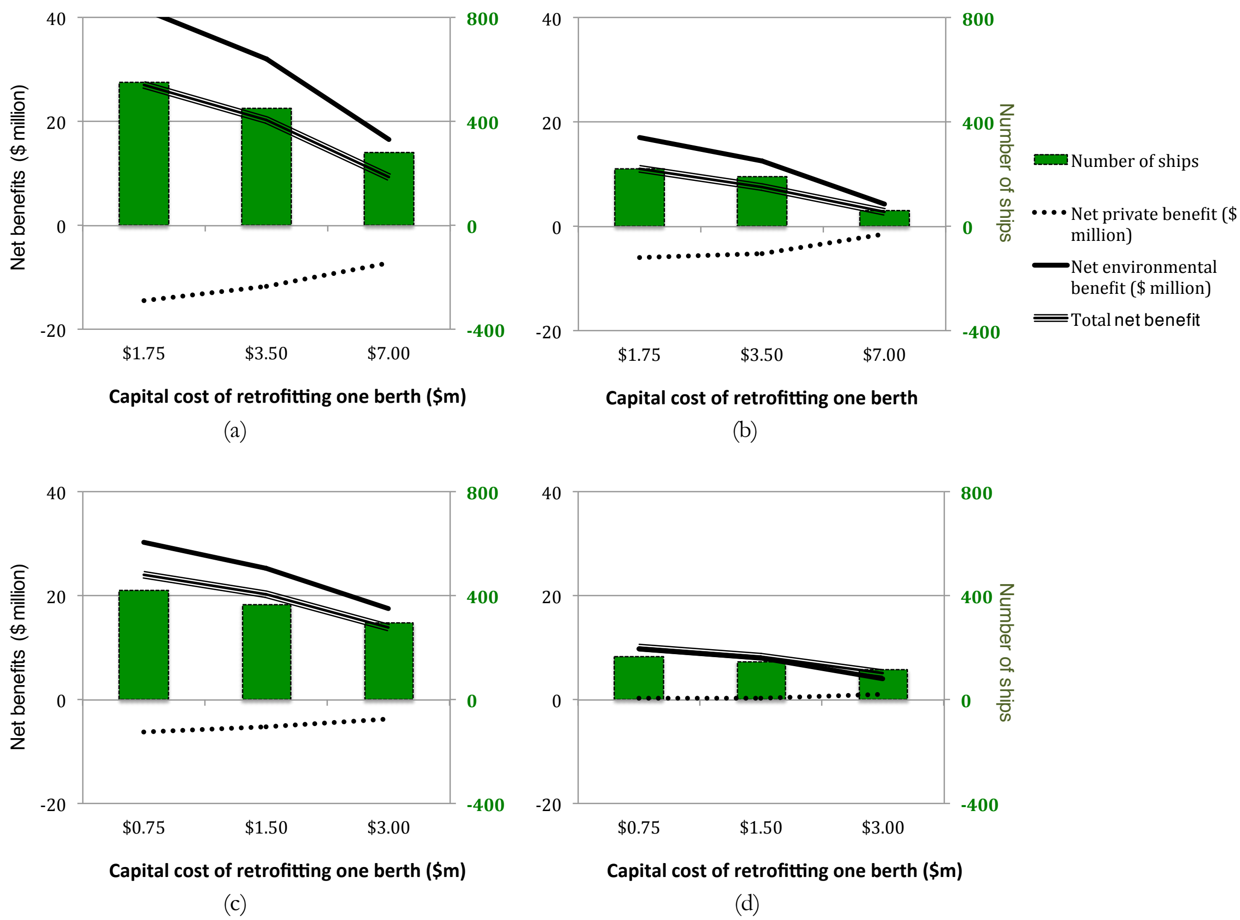

Figure 5.20: Sensitivity of the solution to Problem (ii) to changes in capital cost associated with retrofitting a single berth for (a) container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) container and bulk cargo vessels assuming APEEP, (c) tankers and vehicle carriers assuming EASIUR, and (d) tankers and vehicle carriers assuming APEEP. Results are somewhat less sensitive to the capital cost than they are to changes in the price of fuel: in both models, a four-fold increase in capital cost reduces net benefits to a third for contaier and bulk cargo ships, and to half for tankers and vehicle carriers. This is because, in both cases, operations and maintenance costs are as large, or larger than, the annualized cost of berth retrofit.

Figure 5.20 demonstrates that the response to changes in the capital cost of berth retrofit are non-linear, and greater for container and bulk cargo vessels – for which a work barge needs to be deployed at high capital cost – than for tankers or vehicle carriers. Because a work barge is required, supplying container and bulk cargo vessels is more capital-intensive. The benefits associated with retrofitting them and the berths they use are therefore more sensitive to changes in capital cost than tankers and vehicle carriers. In general, a quadrupling of capital costs causes benefits to fall to between one-third and half, depending on the type of vessel and air quality model.

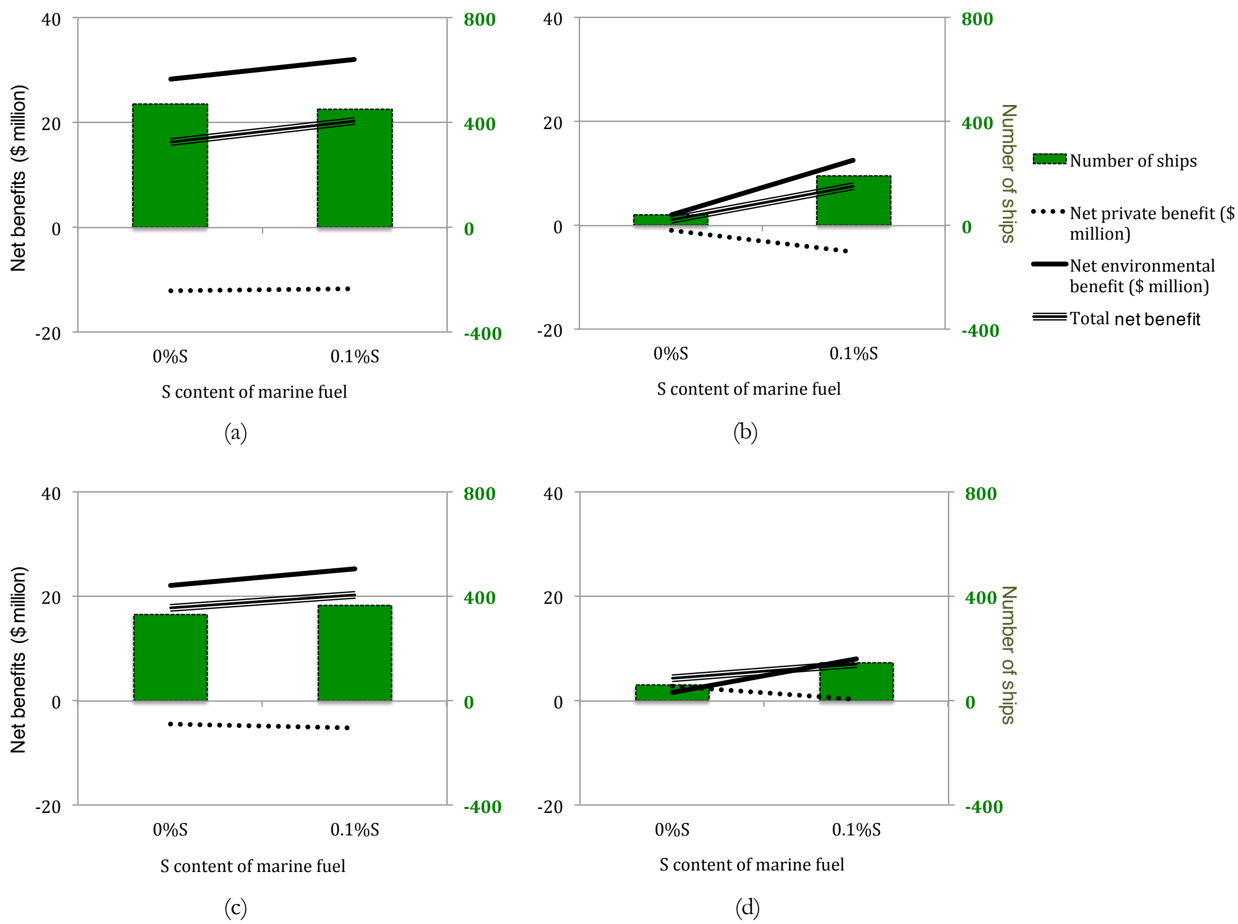

Figure 5.21: Sensitivity of the solution to Problem (ii) to changes in the sulfur content of the fuel that may be burnt off the US coast for (a) container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) container and bulk cargo vessels assuming APEEP, (c) tankers and vehicle carriers assuming EASIUR, and (d) tankers and vehicle carriers assuming APEEP. The optimal solution based on APEEP – which is dominated by the high social cost of SO_2 emissions in southern California – is far more sensitive to a change in the sulfur content of marine fuel than is the solution based on EASIUR.

IMO regulations have reduced the permitted sulfur content of marine fuels that are burnt off the US coast by a factor of 15 in the last five years. Nonetheless, the 0.1% sulfur content assumed in this analysis and which represents the most stringent IMO standard currently in place still translates to a sulfur content of 1000 parts per million (ppm), almost two orders of magnitude higher than what is permitted in road vehicles. Burning this fuel in or near ports has the potential to cause substantial harm to human health near port as well as hundreds of miles inland. In light of this observation, we consider the possibility that – in the future – IMO might mandate an even lower sulfur content. Figure 5.21 suggests that, if the decision were based on the APEEP air quality model, such a change would essentially destroy the case for shore power, whereas – if the EASIUR model were used – the optimal solution would be an only slightly less widespread adoption of shore power.

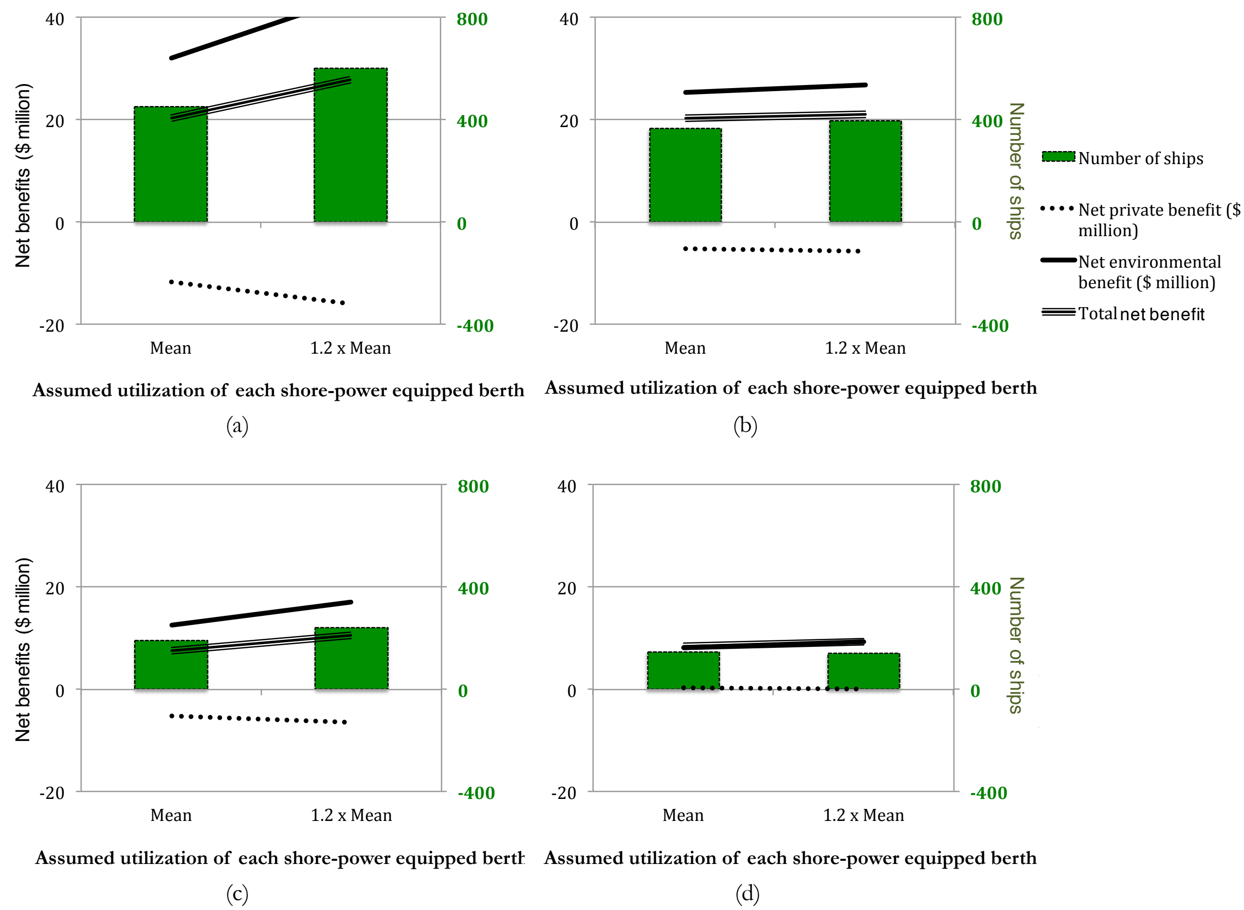

Figure 5.22: Sensitivity of the solution to Problem (ii) to an increase in the rate of utilization of retrofitted berths for (a) container and bulk cargo vessels assuming social costs of pollution derived from EASIUR, (b) container and bulk cargo vessels assuming APEEP, (c) tankers and vehicle carriers assuming EASIUR, and (d) tankers and vehicle carriers assuming APEEP. If retrofitted berths at each port were scheduled 20% more efficiently than the mean for that port, the result would be to increase the net benefit of retrofit, though this effect would be more prominent if the social costs were based on EASIUR than on APEEP.

This analysis has been premised on the assumption that ports are currently scheduled as efficiently as they can be; that is, every berth at port j can be occupied for only a total of (μ_j x 8760) hours each year. As discussed in Section 5.3.2, it is the case that some berths at some ports see much higher utilization than the average. Having invested in retrofitting a berth, it may be assumed that a port would schedule this valuable asset with great care and therefore extract a higher rate of utilization from it. Such a move would lower the cost of using shore power, make its adoption more widespread in the optimal solution. We tested the sensitivity of the optimal solution to the assumption of a higher rate of utilization for each berth (see Figure 5.22). The solution based on EASIUR is very sensitive to what we assume about the rate of utilization; the solution based on APEEP is not. In both cases, the direction of the sensitivity is as we would expect it to be: scheduling berths more efficiently increases the total net benefit.

Finally, we recognize that the social cost of pollution produced either by the EASIUR or APEEP models is itself uncertain. The APEEP model quantifies this uncertainty by reporting the 5^{th} and 95^{th} percentile values of the social cost of each pollutant, in addition to the mean. We analyze the impact of this uncertainty on the decision to retrofit in two ways. First, we re-run our optimization models assuming the 5^{th} and 95^{th} percentile. The results are shown in Figure 5.23: if the decision maker based her decision on the 5^{th} percentile values, she would decide not to retrofit a single ship or port. Based on the 95^{th} percentile value, the decision maker would retrofit nearly a quarter of all container and bulk cargo vessels, and nearly a third of all tankers and vehicle carriers (recall that when the mean value of social cost was assumed, the optimal solution based on APEEP was to retrofit 10% of all vessels).

Another, perhaps more realistic, way of looking at the problem is to say that a decision maker might decide on the basis of the average social cost but might want to understand what would happen if it turned out that the actual social cost was given by the 5^{th} or 95^{th} percentile values. Figure 5.24 shows that, if the actual social cost were given by the 5^{th} percentile values in APEEP, the loss associated with implementing an optimal solution based on the mean values would be about $30 million per year. If, on the other hand, the actual social costs were given by the 95^{th} percentile values in APEEP, the total benefit would be three to five times what the decision maker had anticipated, but about 25% lower than the benefits she could have obtained if she had based her optimization on the 95^{th} percentile values in the first place.

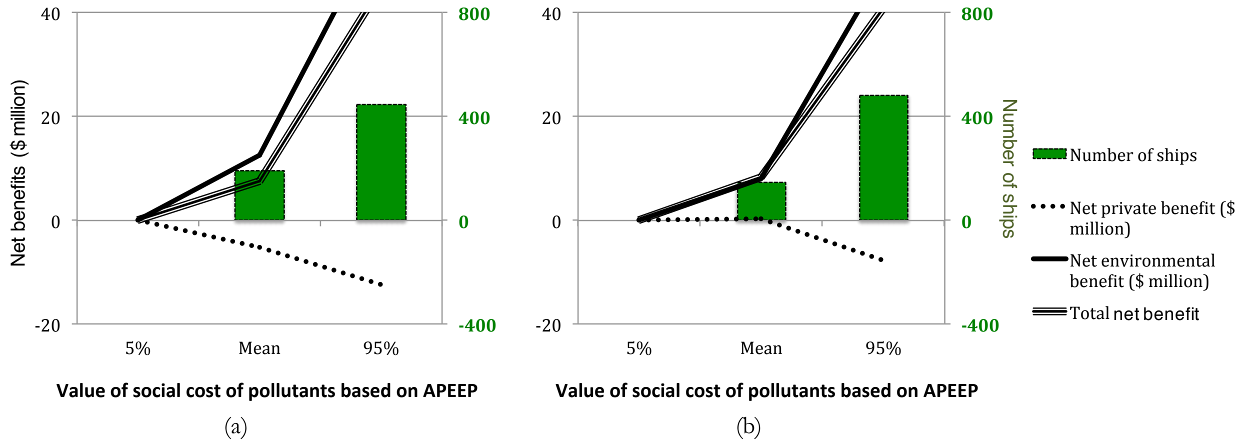

Figure 5.23: The optimal decision for (a) container and bulk cargo vessels and (b) tankers and vehicle carriers if the actual social costs of pollution were equal to the 5th, mean, or 95th percentile values in APEEP. An optimal decision based on the 5th percentile values would be to do nothing. If the true social cost was given by the 95th percentile value two to three times as many vessels would be retrofitted as in the case based on mean values, generating five to six times the total net benefit.

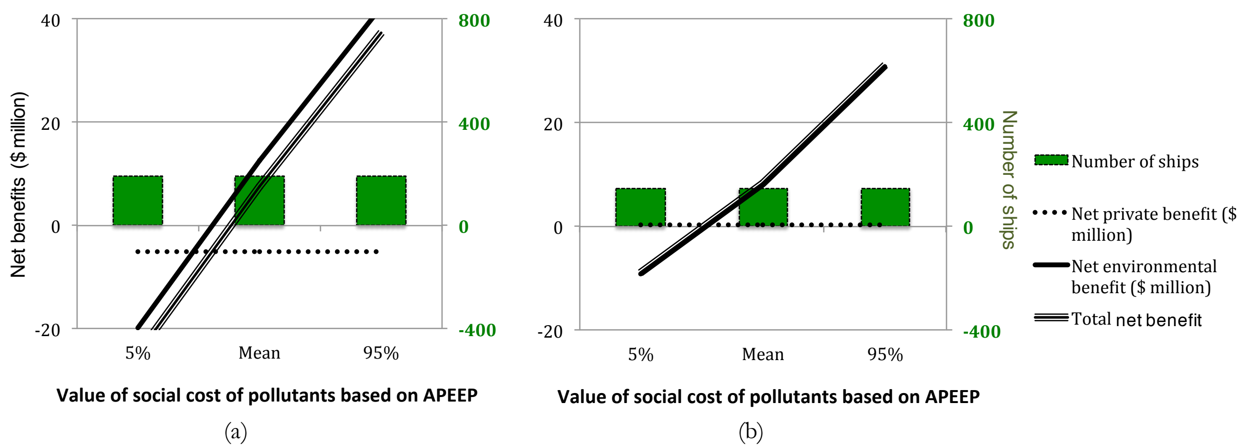

Figure 5.24: The optimal decision for (a) container and bulk cargo vessels and (b) tankers and vehicle carriers if the actual social costs of pollution were equal to the 5th, mean, or 95th percentile values in APEEP and the decision maker had implemented the optimal solution based on mean values. This would result in a loss of about $30 million per year if it turned out that the true social cost of pollution was given by the 5th percentile values. The net benefit would be three to five times larger if it turns out that the true social cost is given by the 95th percentile.

5.4 DISCUSSION

The analysis above demonstrates that shore power represents a case for policy intervention: requiring vessel operators to switch to shore power will produce a net benefit to society that they do not have an incentive to provide in the absence of such a requirement.

The analysis is performed from the point of view of a single decision maker, who wants to maximize the total benefit - in terms of reduced fuel cost and improved air quality - to society. The actual number of decision makers is large and the motivations of these decision makers are complex.

Ports in the United States are operated by local authorities, which must be persuaded to impose a requirement for shore power on vessel operators. Apart from the indirect economic benefits that localities derive from the presence of a port, local authorities might receive significant income from the fees that vessels pay to dock at ports. As such, they may be reluctant to mandate the use of shore power if they felt that doing so would cause vessel operators to prefer other ports with less stringent regulation. Furthermore, at many ports, a significant number of berths are controlled by private entities (e.g., refiners) and the ability of port authorities to persuade them to institute a new practice that is expensive to them might be limited.

This argues for a method of regulation that involves state or federal agencies that may either phase in a requirement for shore power or provide incentives (e.g., matching funds for port retrofit) for its uptake. The fact that California has made the use of shore power mandatory might help shift incentives: around a sixth of the vessels in our dataset are container ships that called at California ports. Once these vessels are already retrofitted to accept shore power, they would want to maximize their opportunities to reduce fuel costs by plugging into shore power as often as possible.

In the interest of exploring as much of the solution space as possible, several simplifying assumptions have been made. However, with more data collection, these can be relaxed quite easily and the model expanded. For example, ports could be replaced with individual berths and the decision variable k_j could be replaced with a binary variable to determine whether or not it is optimal to retrofit a particular berth. As discussed above, the retrofit costs for ships are treated as uniform, but could be updated to reflect the cost of retrofitting each particular vessel: we have assumed that all retrofit costs are amortized over 20 years, which is clearly not a sensible assumption make about a ship that is nearing the end of its life.

The analysis also demonstrates that shore power is an inefficient way of reducing CO_2 emissions. The solution to Problem (i) involves the most widespread deployment of shore power. Implementing this solution would reduce CO_2 emissions about 0.2 million tons per year. The cost of berth retrofit would be $100 million and the cost (net of fuel savings) of vessel retrofit would be $50 million. If the co-benefits in terms of improved air quality were ignored, this would translate to a cost of $750 per tonne of CO_2 emissions abated. Put differently, the solution would reduce fuel use by about 60,000 tonnes per year. Smith et al. (2014) estimate that, between 2007-12, vessels reduced their steaming speed by 12% and produced a 24% reduction in fuel use. This translates to a reduction in fuel use of 100 million tonnes per year.

Table 5.8: Comparing shore power (the solution to Problem (i) based on EASUR, applied to the Port of Long Beach) to the VSR program at that Port. The cost of shore power to the port is estimated to be the annualized cost of retrofitting and operating the required number of berths.

Pollutant	VSR (2008) at the Port of Long Beach	Shore power
	reduction in tons per year	
NOx	680	937
SOx	450	39
$PM_{2.5}$	60	26
CO_2	26,000	45,000
Cost	$1.6 million	$11 million

Shore power may also be compared to the voluntary speed reduction program (VSR) in which some ports in California offer a reduction in port fees to vessels that cut their speed to 12 knots within a 40 nautical mile zone around the port (Table 5.8). Note that the numbers for the VSR scheme are from 2008 (Faber et al. 2012, 27), when vessels were allowed to use fuel with a sulfur content 15 times higher than what is permitted now: shore power produces a much smaller benefit from SO_X emissions reduction because the fuel now contains much less sulfur. Table 5.8 shows that, even as a method of improving air quality, paying vessels to slow down is more cost effective than shore power. Clearly, there are limits to how much a vessel can be showed down and what benefits such a slowdown can produce. A selective deployment of shore power can ensure that benefits always exceed costs. The benefit cost ratio of the solution to Problem (i) is one (1) by design. The optimal solution to Problem (ii) produces a benefit cost ratio of between 2 (based on APEEP) and 3 (based on EASIUR). Gains from deploying shore power can therefore be additional to those made by the VSR program.

Our sensitivity analysis reveals that – while the results of the optimization are sensitive to fuel and capital costs – the biggest sensitivity is to the choice of air quality model. The social costs in APEEP are obtained by running a reduced-form air quality model called Climatological Regional Dispersion Model (CRDM), which was developed in 1996 (Heo 2015, 51). The model makes significant compromises to ensure that it is computationally tractable: for example, it uses "annual-average meteorological input and emissions." (Heo 2015, 52) It also does not account adequately for recent advances in the understanding of the atmospheric chemistry of key pollutants: for example, that organic particulate matter (PM) is composed primarily of secondary (rather than primary) PM. (Heo 2015, 52) (Miracolo et al. 2011) EASIUR is based on CAMx, a comprehensive air quality model that is developed and used for major regulatory impact analysis (e.g., US EPA 2011a, US EPA 2011b). CAMx is "state-of-the-science" (Heo 2015, 53) and can operate at a much higher spatial and temporal resolution than does CRDM / APEEP: for example, it can "estimate the concentrations of key air pollutants and their precursors at a high temporal resolution typically of 15 minutes or less." (Heo 2015, 109) This fidelity comes at a high computational price: Heo (2015, 51) estimates that producing county by county estimates of the social costs of pollution (as APEEP does) using CAMx would take 6000 CPU-years. To address this, Heo (2015) imposed a 148 x 112 square grid on the continental United States and adjacent Mexico and Canada and took a stratified random sample of

100 36kmx36km cells.[103] He then ran a CAMx simulation for these cells to calculate the marginal social cost of emissions in those counties, and fitted a regression model with high goodness of fit (R^2>0.9) to it. While the air quality model was different from the one used in APEEP, everything else used to get from the change in the concentration of a pollutant to its social cost (e.g., dose-response functions, value of statistical life) was identical to it. This regression model was then used to estimate the social cost of pollution at the other cells in the grid. It is these estimates that have been used in all the EASIUR-based solutions discussed above. As such, EASIUR is a close approximation of an air quality model with higher fidelity than the one APEEP is based on. However, the higher fidelity does not automatically mean that CAMx / EASIUR is a closer approximation of reality than CRDM / APEEP, and a systematic comparison of the two models is the subject of a proposal that is currently before the National Science Foundation.[104] Until such a comparison sheds more light on which of the two models is closer to reality, the choice of air quality model – and therefore the extent to which a decision maker feels that shore power ought to be deployed – may be informed by two considerations. If she wants to base her decision on a model that is a close approximation of a model that the EPA uses in its regulatory analysis, then the results based on EASIUR are more relevant to her. Using social costs from APEEP usually results in an optimal solution that involves retrofitting a subset of the vessels and ports that it is optimal to retrofit based on EASIUR. A decision maker looking for a no-regrets option might therefore choose to use social costs from APEEP.

Finally, the current analysis is limited to ports in the continental United States, partly because we did not have good integrated air quality models to help us calculate the social cost of pollution in

[103] This is a higher resolution - especially in the western United States - than is available in CRDM, which operates at the resolution of individual counties. For example, Los Angeles County is about 100km across and 150km from north to south. CRDM / APEEP treat it as a homogenous block; CAMx / EASIUR does not.

[104] Peter Adams, personal communication, March 17, 2015

non-US ports. It would be useful if estimates of these costs could be generated, especially for ports in Asia, where ships are permitted to use fuel with a significantly higher sulfur content when in port and where – it is likely – quite large populations are exposed to pollution from vessels in port.

5.5 CONCLUSIONS AND IMPLICATIONS FOR POLICYMAKERS

Our results demonstrate that private incentives (i.e., fuel cost savings) might come close to producing a socially optimal outcome by persuading most cruise ships operating in the United States to shift to shore power. Nevertheless, the process could be supported and expedited by phasing in a requirement to use shore power. Private incentives fluctuate with fuel prices, whereas environmental benefits do not. Regulation would prevent backsliding if fuel prices fall enough to alter cruise ship operators' incentives.

The California shore power rule comes close to maximizing environmental benefits, while imposing no net cost on society. While the expansion of this rule to include all other vessels that call at California ports would likely produce a net loss to society, a selective expansion would be beneficial.

The same conclusion applies to many other ports in the United States. Port authorities, state environment or air quality boards, federal agencies - or perhaps interested NGOs – could produce a large environmental benefit by working with vessel operators and ports to selectively expand shore power. The analysis presented above identifies the vessels and ports for which this would be most beneficial to do. The methodology used can be adapted quite easily for a more detailed study.

Finally, shore power could produce even greater benefits in other parts of the world where a bigger population is exposed to emissions from less stringently controlled fuel.

5.6 APPENDICES

5.6.1 Social costs of various pollutants

Figure 5.25 and Figure 5.26 show the mean social cost of NO_x, SO_X, and $PM_{2.5}$ produced by APEEP and EASIUR. For APEEP, we also display the 5th and 95th percentile values as error bars.

5.6.2 Average and marginal costs

As discussed in Footnote 100, the Figure 5.6 and Figure 5.15 appear to suggest that some ships are retrofit for shore power even if doing so produces a total net loss. This is an artifact produced because these figures are drawn on the basis of average costs, whereas the decision as to whether or not to retrofit a vessel is taken on the basis of the marginal cost of doing so. The latter is the economically rational approach.

Consider the situation described by Figure 5.27 in which the numbers are fictitious. Imagine that we have only one port (say, j). Each of its berths is available for 50 hours a year. The cost of retrofitting each berth for shore power is 10 units. Two vessels (A and B) call at port j, spending a total time of 50 hours. As such, the cost of retrofitting a berth at port j is 0.2 units per vessel-hour.

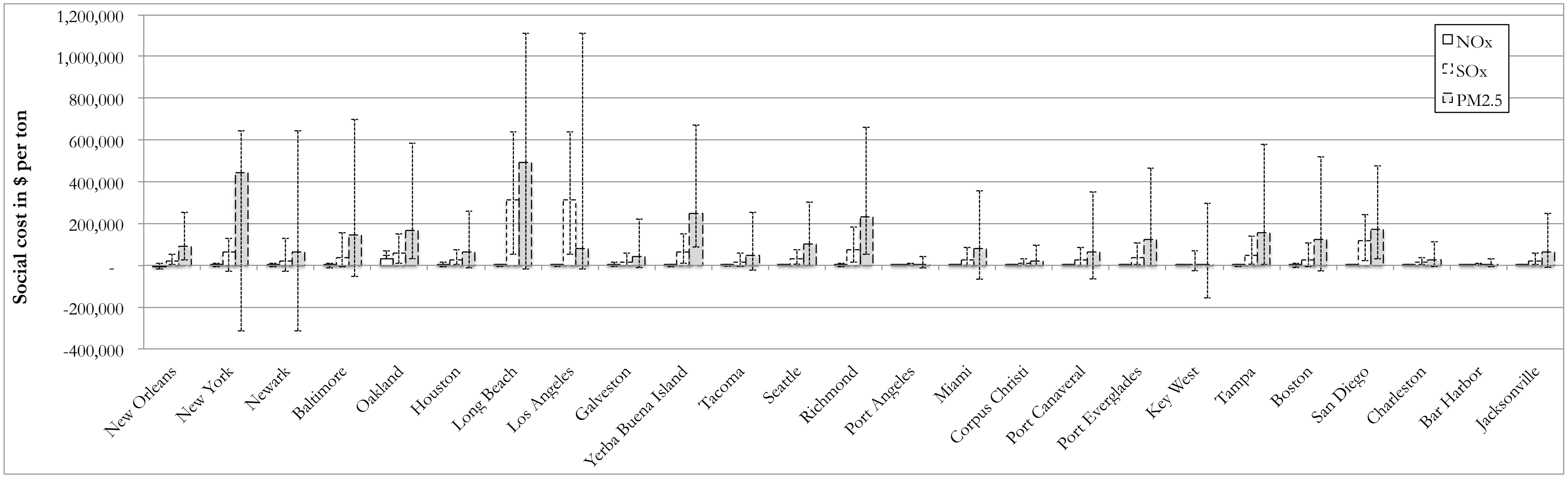

Figure 5.25: Mean social cost in $ per ton of NOx, SOx, and PM2.5 based on APEEP. The error bars represent the 5th and 95th percentile values.

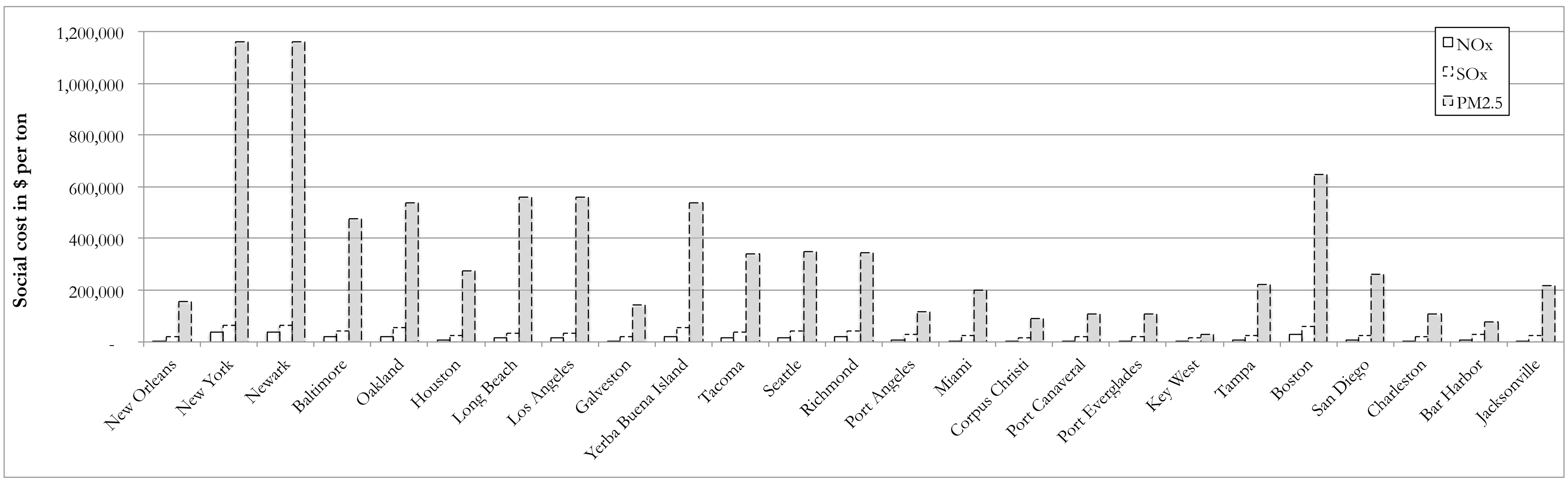

Figure 5.26: Mean social cost in $ per ton of NOx, SOx, and PM2.5 based on EASIUR

Max hours per berth	50
Cost per berth	10
Total number of berths needed	1
Total cost of berths	10
Total vessel-hours	50
Average cost of berth per vessel hour	0.20

Ship	Hours in Port	Benefit of the ship using shore power at that port	Cost of retrofitting berth based on average vessel hours	Net benefit based on average cost	Marginal cost of providing a berth for the vessel to plug into	Net benefit based on marginal cost
A	30	9	6	3	10	- 1
B	20	3	4	-1	-	3

Figure 5.27: An example of how using average and marginal costs can produce contradictory results

Vessel A spends 30 hours a year in port, and the sum of the environmental benefit and fuel savings associated with vessel A using shore power is 9 units, net of the cost of retrofitting the vessel itself. Vessel B spends 20 hours in port and the sum of the environmental benefit and fuel savings associated with vessel B using shore power is 3 units (perhaps because the vessel uses less power than vessel A when it is in port), net of the cost of retrofitting the vessel itself.

Based on average costs, we would allocate the cost of berth retrofit as follows:

- 30 hours x 0.2 units per vessel-hour = 6 units to Vessel A, and
- 20 hours x 0.2 units per vessel-hour = 4 units to Vessel B

This would result in a total net benefit of 3 units for vessel A and (-1) units for vessel B. This is the type of calculation that was done when drawing Figure 5.6 and Figure 5.15.

This, however, is not an economically rational way to decide whether or not to retrofit the berth, and whether or not it would economical for a ship to use that berth. The total benefit from accommodating both vessels is 12 units, which exceeds the cost of retrofitting the berths at 10 units. As such, we would decide to retrofit the berth. Once we decide to retrofit the berth to accommodate either vessel, the marginal cost of accommodating the second vessel is zero. As such, we should assume that both vessels use it (i.e., $o_{A,j} = o_{B,j} = 1$). This logic cannot be used to draw Figure 5.6 and Figure 5.15 because drawing them requires some mechanism to explicitly allocate berth retrofit costs between the vessels. The difference between the "average" and "marginal" approaches is shown graphically in Figure 5.28.

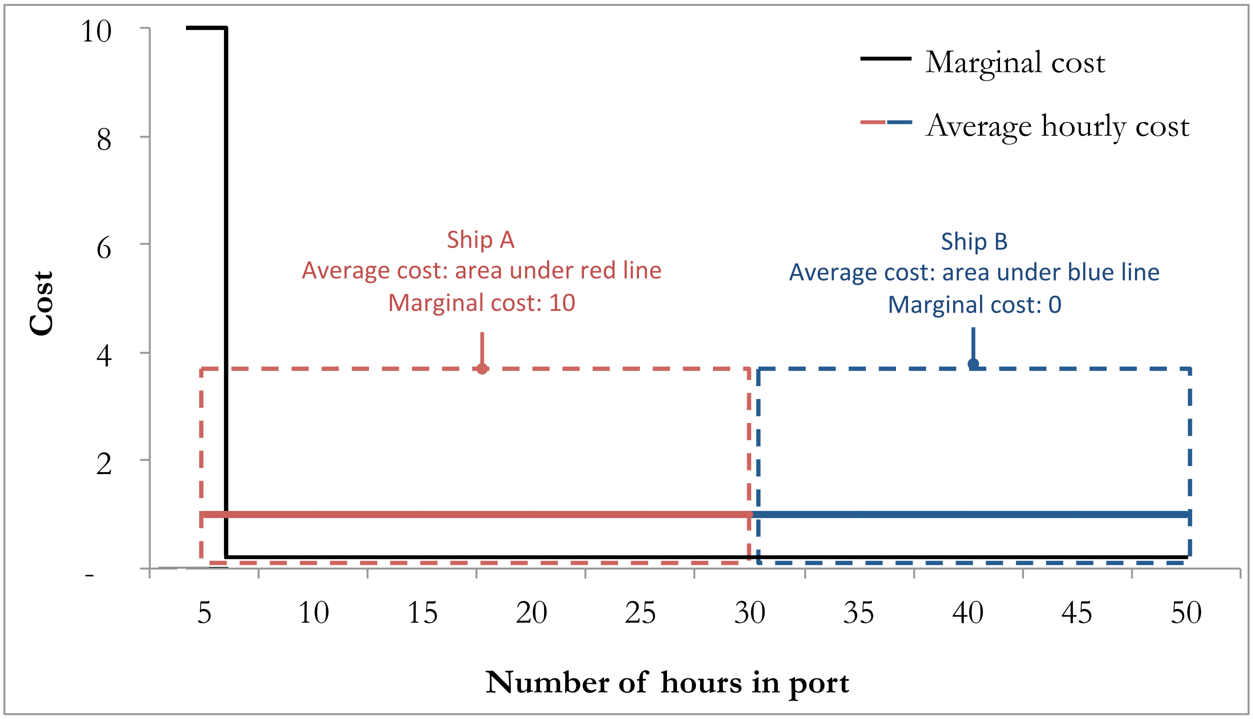

Figure 5.28: Illustration of the differences in allocating costs based on average hourly cost of berth retrofit versus deciding whether or not to retrofit accommodate a ship at a berth based on marginal costs. Note that we could swap the positions Ship A and Ship B occupy on this diagram. Doing so would not change the decision, but would change the marginal costs of accommodating each vessel.

5.6.3 Setting an upper bound on the potential underestimate of benefits

As discussed in Footnote 94, this problem is written so that the optimal solution sometimes requires the assumption that a vessel (i) will not use shore power at a port (j) even if it is equipped to do so (r_i=1) and the port has at least one berth retrofit to provide shore power (k_j≥1). This is to ensure that, over the course of the year, the number of hours for which berths equipped to supply shore power are available is always greater than the number of hours that vessels will use shore power at that port (Equation 5.6). In practice such a vessel (for which $o_{i,j}$=0, but r_i=1) might pull into port and find that a retrofitted berth available and presumably use it. The resulting benefits would not be accounted for in Equation 5.1 and Equation 5.2. In Table 5.9 we give a port-by-port estimate of the upper limit of this underestimate for the different problems discussed above.

In Table 5.9, "Actual kWh used" for each port, j, is given by

$$\sum_{i} (ener_{i,j} \times o_{i,j})$$ **Equation 5.8**

"Total kWh possible for retrofitted ships" is given by

$$\sum_{i} (ener_{i,j} \times r_i \times \min(k_j, 1))$$ **Equation 5.9**

where

$ener_{i,j}$ is the amount of energy, expressed in kWh, that would go from being generated on board to being provided from shore. Note that this not the total quantity of energy that the vessel would use while in port: the vessel would generate its own power while it was being connected to and disconnected from shore power (see Section 5.3.1)

r_i is a decision variable that takes the value of one (1) if a vessel is retrofit, and zero (0) if it is not

$o_{i,j}$ is a binary dummy variable, which takes the value of one (1) if vessel i uses shore power at port j; and is zero (0) if it does not. (See Footnote 94)

k_j is decision variable that takes the value of the number of berths that must be retrofit at port j. k_j is a positive integer.

"Maximum leakage" is the fractional difference between the two quantities in Equation 5.8 and Equation 5.9.

Table 5.9: Potential reduction in the quantity of electricity supplied by shore power by assuming that some vessels will not plug into shore power even if they are equipped to receive it and at least one berth is equipped to supply it

Problem (i) – Container and bulk cargo vessels - EASIUR

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	353,876,865	116,569,724	38,189,069	47,446,286	26,123,927	6,688,237	31,993,852	-	4,007,352	11,825,982	35,708,994	-	19,444,166	-	-	5,854,188	2,355,367	7,669,720
Total kWh possible for retrofited ships	374,353,112	116,628,464	38,662,498	47,446,286	26,745,663	6,688,237	45,618,146	-	5,029,324	12,143,127	37,407,625	-	19,444,166	-	-	6,749,444	3,007,803	8,782,330
Maximum "leakage"	-5%	0%	-1%	0%	-2%	0%	-30%	-	-20%	-3%	-5%	-	0%	-	-	-13%	-22%	-13%

Problem (i) – Tankers and vehicle carriers - EASIUR

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	404,917,609	30,367,351	154,896,178	41,749,391	6,019,839	-	3,367,178	62,351,237	7,375,429	26,191,258	8,899,344	18,399,010	876,488	9,622,298	13,940,188	5,801,866	4,861,263	10,199,289
Total kWh possible for retrofited ships	407,061,410	30,367,351	156,096,847	41,749,391	6,019,839	-	3,367,178	62,370,745	7,375,429	26,191,258	8,899,344	18,399,010	876,488	9,622,298	14,863,811	5,801,866	4,861,263	10,199,289
Maximum "leakage"	-1%	0%	-1%	0%	0%	-	0%	0%	0%	0%	0%	0%	0%	0%	-6%	0%	0%	0%

Problem (ii) – Container and bulk cargo vessels - EASIUR

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	235,558,369	93,093,278	-	34,205,824	18,479,327	-	31,805,469	-	-	3,774,134	34,497,635	-	11,051,537	-	-	1,649,526	-	7,001,638
Total kWh possible for retrofited ships	246,289,908	93,093,278	-	34,205,824	18,661,152	-	36,814,850	-	-	5,495,510	34,497,635	-	11,184,354	-	-	5,235,335	-	7,101,971
Maximum "leakage"	-4%	0%	-	0%	-1%	-	-14%	-	-	-31%	0%	-	-1%	-	-	-68%	-	-1%

Problem (ii) – Tankers and vehicle carriers - EASIUR

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	232,823,002	21,958,782	90,191,776	34,563,522	3,659,974	-	2,253,898	19,489,632	-	17,066,394	6,441,154	14,809,576	464,799	8,119,864	2,628,998	4,651,208	-	6,523,426
Total kWh possible for retrofited ships	239,280,381	22,029,817	90,427,810	34,563,522	3,659,974	-	2,253,898	24,896,460	-	17,071,707	6,441,154	14,809,576	639,227	8,407,860	2,904,742	4,651,208	-	6,523,426
Maximum "leakage"	-3%	0%	0%	0%	0%	-	0%	-22%	-	0%	0%	0%	-27%	-3%	-9%	0%	-	0%

Problem (i) – Container and bulk cargo vessels - APEEP

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	141,293,539	75,746,645	-	34,518,033	-	-	31,028,861	-	-	-	-	-	-	-	-	-	-	-
Total kWh possible for retrofited ships	141,599,630	75,746,645	-	34,518,033	-	-	31,334,952	-	-	-	-	-	-	-	-	-	-	-
Maximum "leakage"	0%	0%	-	0%	-	-	-1%	-	-	-	-	-	-	-	-	-	-	-

Problem (i) – Tankers and vehicle carriers – APEEP

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	147,400,518	17,118,546	71,593,667	28,921,980	-	-	1,130,720	16,392,101	-	3,010,873	-	9,232,631	-	-	-	-	-	-
Total kWh possible for retrofited ships	152,073,210	17,601,028	71,619,306	28,921,980	-	-	1,618,840	18,701,277	-	3,010,873	-	10,599,907	-	-	-	-	-	-
Maximum "leakage"	-3%	-3%	0%	0%	-	-	-30%	-12%	-	0%	-	-13%	-	-	-	-	-	-

Problem (ii) – Containers and bulk cargo vessels – APEEP

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	216,751,897	110,636,954	5,013,992	45,310,611	14,182,436	-	31,947,516	-	-	-	-	-	7,215,767	-	-	-	-	2,444,620
Total kWh possible for retrofited ships	230,359,104	110,636,954	5,083,826	45,310,611	16,247,800	-	42,030,954	-	-	-	-	-	8,604,339	-	-	-	-	2,444,620
Maximum "leakage"	-6%	0%	-1%	0%	-13%	-	-24%	-	-	-	-	-	-16%	-	-	-	-	0%

Problem (ii) – Tankers and vehicle carriers – APEEP

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	255,544,431	27,921,189	113,257,358	39,380,687	3,337,968	-	3,054,443	29,289,063	-	8,647,975	3,677,285	15,345,336	-	-	4,197,286	3,564,704	-	3,871,136
Total kWh possible for retrofited ships	268,113,633	27,921,189	113,823,933	39,380,687	3,337,968	-	3,054,443	36,167,792	-	10,368,701	3,732,129	16,185,157	-	-	4,879,746	5,091,326	-	4,170,562
Maximum "leakage"	-5%	0%	0%	0%	0%	-	0%	-19%	-	-17%	-1%	-5%	-	-	-14%	-30%	-	-7%

Chapter 6: CONCLUSION

6.1 Review of the interventions analyzed in Chapters 3 to 5

Although the methods of emissions reductions discussed in Chapters 3 to 5 are quite different from each other, Table 6.1 presents a summary of their costs and benefits.

For the two technological interventions – dispatch towing and shore power – CO_2 emissions reductions are small and dominated by the benefits of improved air quality. This is only partially due to the limited geographical scope of these interventions. For instance, global commercial aviation consumed 73 billion gallons of fuel in 2013 (IATA 2014b), of which 10 billion gallons were consumed by scheduled US airlines on domestic service (BTS 2015a): any measure that addresses US domestic aviation will address a substantial proportion of the overall problem.

As discussed in Chapter 2:, operational and technological measures will only be able to offset a fraction of the growth in greenhouse gas emissions that will likely occur in these sectors. The economics of these measures are very sensitive to fuel prices. The analysis in Chapter 3: was performed in 2012-13, when the price of jet fuel was about $3 per gallon. That price is currently (April 2015) $1.59 per gallon, and – as Figure 3.8 and Table 6.1 show – this 50% drop in prices is significant enough to reverse the economics of dispatch towing.

The evolution of the environmental goals of the Federal Aviation Administration's (FAA) Next Generation air transportation system program (NextGen) illustrates the difficulties associated with accurately forecasting fuel burn and emissions reductions through operational improvements. The 2011 implementation plan for NextGen said, "Our latest estimates, which are sensitive to traffic and fuel price forecasts, indicate that by 2018, NextGen will reduce total delays…by about 35 percent [generating] $23 billion in cumulative benefits…[saving] about 1.4 billion gallons of aviation fuel during this period, reducing carbon dioxide emissions by 14 million tons." (FAA 2011)

Table 6.1: A comparison of the costs and benefits of the approaches to emissions reductions discussed in Chapters 3 to 5. Where a range of values is reported, this reflects the differences in values obtained from using APEEP and EASIUR air quality models. For all estimates, APEEP produces the lower value.

Measure	Scope	CO_2 emissions reduction	Net cost of implemen-tation	Cost per tonne of emissions avoided	Air quality benefits
		million tonnes per year	$ million per year	$ per tonne	$ million per year
Use of tugs to tow large narrow-body aircraft from the gate to the edge of the runway at select airports	US domestic flights; 2013 fuel prices	0.5	-50	-100	150-200[105]
Use of tugs to tow large narrow-body aircraft from the gate to the edge of the runway at select airports	US domestic flights; current fuel prices	0.5	40	80	150-200
Use of shore power to maximize the total benefit to society, subject to the condition that net benefit is positive	Cargo and cruise vessels calling at major US ports	0.18-0.24	80-160	400-650	80-190
Capping emissions from international aviation at 2020 levels	All international flights	270[106]	Airlines would offset emissions using credits bought on the market		Unknown

A cumulative emissions reduction of 14 million tonnes of CO_2 over several years from a multi-billion dollar program is not very large, when compared, for example, to the 0.5 million tonnes per year that could be cut by the relatively low-tech practice of using tugs. The FAA seems to have backed away from even this modest claim. The current implementation plan states, simply, that NextGen "will, where feasible, save time and fuel while allowing the potential to limit overflight of

[105] The analysis in Chapter 1: did not include the benefits associated with a reduction in emissions of SO_2. This is because the sulfur content of jet fuel can vary widely: specifications permit a maximum of up to 3000ppm "although the worldwide average sulfur content in jet fuel appears to be between 500 and 1000 ppm." (Chevron Corporation 2006) Furthermore, experiments suggest that the fraction of the fuel's sulfur that is converted to SO_2 high for low-sulfur fuels and falls as sulfur content rises. (Miake-Lye et al. 1998) ICAO's engine database (International Civil Aviation Organisation 2010) does not publish an emission index for sulfur. Assuming a sulfur content of 600ppm, and assuming that 70% of this is emitted at SO_2, we calculated that reduced SO_X emissions would produce a benefit of $9 million per year, of which about half would be accrued in the New York City airports, Los Angeles, and San Francisco.

[106] Average of the total emissions that would be offset under the ICAO mechanism in 2021-25

environmentally sensitive areas." (FAA 2014) As it happens, fuel use in the US domestic aviation sector in 2014 was slightly lower than in 2011, and more than 20% or 3 billion gallons lower than in 2005. (BTS 2015a) However, these gains in efficiency – which were spurred by a rapid increase in fuel prices and underpinned by an increase in load factors – are unlikely to be sustained, because fuel prices have fallen and improvements in load factors have stalled. See Appendix 6.3 for a detailed discussion.

In the case of shipping, the sector's greenhouse gas emissions have remained more or less stable for the last five years by the practice of operating ships at speeds that are well below their design capacity. Shippers' willingness to sacrifice speed for better fuel economy is the serendipitous outcome of several factors: high fuel prices until the end of 2014, low interest rates that made it possible to put in place additional warehouse capacity, and a large oversupply of shipping capacity. All these factors are reversible – fuel prices are much lower than they were a year ago – and this represents "latent emission increases."[107] (Smith et al. 2014, 27)[108]

Such volatility also likely discourages investment. For example, while the introduction of dispatch towing for aircraft might have seemed attractive in 2012 or 2013, any early adopters would likely have seen their investment turn sour within a couple of years, long before their upfront costs would have been recovered. The decision not to invest is rational from the point of view of a private profit-maximizing investor. However, from a societal perspective, a large gain in terms of improved air quality is unrealized, even though total benefits would exceed costs even at current fuel prices.

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[107] Airliners also fly slower in response to higher fuel prices (The Associated Press 2008), but their ability to do so is limited. US airliners slowed down by an average of 1.1% between 2007-11. (Kemp 2014) A study concluded that speed optimization could reduce fuel burn by 2.4% compared to current practice. (Lovegren and Hansman 2011) This suggests that aircraft might well be flying at as close to the optimal speed as is practical. A step change in efficiency for short haul flights could be achieved by the more extensive use of turboprop aircraft (Åkerman 2005, *The Economist* 2012), but turboprops are perceived negatively by travellers.

[108] James J. Corbett, Personal communication, March 11, 2015

Measures such as the International Maritime Organization's Energy Efficiency Design Index (EEDI) for ships, though far from being ambitious, at least ensure that some efficiency gains take place and stay in place even as the financial attractiveness of higher efficiency fluctuates with the oil price.

The limitations of technological and operational measures serve to highlight the importance of the type of broad market-based mechanism that is analyzed in Chapter 4:. Giving the aviation and marine sectors access to potentially cheaper emissions reductions in other sectors may be the most (or even only) economically efficient way of ensuring that the net emissions from these sectors fall substantially until low-carbon alternative fuels become available. Clearly, the efficiency, effectiveness, and equity of any such mechanism depends on its design. An offset program will only be effective if the traded credits represent real reductions in emissions that are additional to what would have happened in the absence of the credit-generating mechanism. Both buyers and sellers have an incentive to subvert this process. A strong arbiter, who is capable of imposing costs on both sellers and buyers, and not merely in balancing their interests, is needed.

Another crucial ingredient for the success of a market-based mechanism is the availability of reliable, detailed, and transparent data on sectorial fuel use and emissions. Such data are currently not available. The authors of the IMO's second and third greenhouse gas reports go to great lengths to collate the best such data (although they are published at quite high levels of aggregation), and – upon finding large discrepancies – attempt to quantify the underlying uncertainties. No analogous effort to quantify and understand international aviation fuel use and emissions has been made, or at least its results have not been made publicly available. One reason why there is not much pressure to make such information available is that not much of consequence would be done with it. (See Victor 2011, 255–6) Decision makers at the ICAO and IMO should move to ensure that detailed, reliable information on emissions from aviation and international shipping becomes publicly available. Any mechanism to control greenhouse gas emissions will require that such a database exist, and the existence of such information will make it possible to design a rational mechanism with broad input.

Importantly, an offset mechanism for greenhouse gases does not guarantee that emissions of other harmful substances, such as particulate matter, will be reduced or even that these will not increase. Recall that particulate matter from aviation contributes to an estimated 10,000 premature deaths each year across the world (Barrett, Britter, and Waitz 2010), and it is estimated that shipping will cause 20,000-70,000 (Winebrake et al. 2009) premature deaths annually even after the most stringent IMO regulations on the sulfur content of marine fuels come into force.

Mandating that ships or airplanes use less fuel (or cleaner fuel) will address this harm, whereas a market-based mechanism that is only targeted at reducing greenhouse gas emissions may not. In fact, the IMO and ICAO have reasonable track records in addressing some forms of air pollution: NO_X, SO_X, particulate matter, and volatile organic compounds from tankers in the case of the IMO, and NO_X, carbon monoxide, and unburned fuel in the case of ICAO. It is important that efforts to further reduce emissions of these pollutants continue.

Conversely, there are a number of interventions (such as the use of shore power) that reduce greenhouse gas emissions, but do so at great cost. Such interventions are only cost-effective if the co-benefits they generate of reducing criteria pollutants (e.g., PM, SO_X, and NO_X), which are more stringently controlled, are accounted for. Other technologies, such as exhaust scrubbers, exist to help operators meet emissions standards for these pollutants. If and when these technologies become cost effective, operators will have a much-diminished incentive to lower fuel use or to switch to comparatively low-carbon energy sources such as electricity. Indeed, emissions of CO_2 might rise due to the parasitic load of the scrubbers.

When negotiated at global forums such as the ICAO, pollution control mechanisms can take a very long time to come into force. Recall that ICAO first mentioned a market-based mechanism to curb greenhouse gas emissions in 1998. The fledgling regulation will be implemented almost a generation later in 2021. This long gestation allows for the accumulation of a large number of often contradictory, and almost always poorly defined, requirements. An ICAO mechanism must pay heed both to the organization's non-discrimination principle and the UNFCCC's principle of common-but-differentiated responsibilities. Drafters of the market-based mechanism were urged to "recognize past and future achievements in aviation fuel efficiency," (ICAO 2010, I–74) and also to recognize that "different regions of the world are experiencing wide differences in absolute levels of aviation emissions and aviation emissions growth rates both internationally and domestically." (ICAO 2007, Appendix J) It may be that some of the contortions in the strawman discussed in Chapter 4: are the consequence of efforts to connect the rather arbitrary scattering of dots laid down by ICAO Assembly resolutions over the last two decades.

ICAO would do well to instead implement a simple mechanism, a straight line instead of a tangled web: for example, one that apportions offset obligations in any given year in proportion to each airline's carbon footprint in that year.

6.2 Towards long-term emissions reductions in aviation and shipping

Even if the ICAO market-based mechanism works precisely as intended, it will only cap greenhouse gas emissions from international aviation – which are only about two-thirds of total emissions from all commercial aviation – at 2020 levels. A more ambitious mechanism will be needed to achieve IATA's goal of a reduction of 50% relative to 2005 by 2050. The shipping industry should also start working on a plan that – in the long term – delivers significant cuts in emissions. Victor (2011, chap. 8) proposes an alternative to the current approach of seeking global, legally binding agreements to control greenhouse gas emissions. He argues that legally binding requirements are almost always negotiated so as to be easily attainable, and therefore lack in ambition. The relatively modest goals of the EEDI mechanism for international shipping certainly lend credence to this hypothesis.

Instead, Victor proposes a mechanism in which a small "club" of countries takes the initiative to work on an ambitious program of action, and not just on goals. For aviation, such a club could consist only of the United States and the European Union. Over 50% of all passenger miles are flown within, or in and out of the EU and the US, their refiners produce 50% of all jet fuel, their aircraft manufacturers supply about 90% of the commercial aircraft currently in service, and 90% of all aircraft currently on order. (IATA 2014b)(EIA 2015b) Both have made some progress in opening up their markets to each other (Official Journal of the European Union 2007) and on dealing with integrating their air navigation systems (U.S.-EU MOC Annex 1 – Coordination Committee 2014).

They are therefore well placed to work with each other, with their airlines, their airframe manufacturers, and their fuel producers to commit themselves to a detailed working plan for long-term emissions reductions. The United States and the global international airline industry (represented by the IATA) have, in fact, fairly ambitious goals for long-term reductions in emissions. The US plan envisages a world in which half the work of cutting emissions from their business-as-usual trajectory to 50% of their current levels would be done by operational and technological improvements, and the rest achieved by a shift to alternative fuels. (Maurice et al. 2009) The FAA has funded a center of excellence to study alternative jet fuels.

The negotiations would match these goals to specific actions. The EU Emissions Trading Scheme (ETS) already aims to reduce annual emissions during the 2013-2020 trading period to 5% below the average emissions from 2004-6. (European Commission 2013b) US airlines' fuel use (and, therefore, emissions) in 2014 were already 10% below their 2005 levels (BTS 2015a), and the EIA expects it to rise by 4% relative to 2014 by 2020. (EIA 2014a) A US-EU plan to dramatically cut emissions over a generation could therefore begin with a relatively gentle deviation from their current glide path. US airlines could perhaps offset any growth in emissions by participating in the regional carbon markets. As both parties prepare to make more drastic cuts, access to each other's carbon markets could help contribute to the vitality of those markets, and provide some mechanism to control the cost of greening aviation.

Finally, such a club could expand[109] by negotiating accession deals with third parties in which applicants make commitments to reduce their own emissions in exchange for the benefits of belonging to the club. A US-EU club would be in a position to offer strong incentives for countries to join: access to technology and operational know-how, and preferential treatment in future air transport agreements.

European and American companies operate five of the world's 10 largest container-shipping lines, including AP Moller-Maersk and the Mediterranean Shipping Company (MSC), which are by far the largest. (Cosco Pacific Limited 2010) Nonetheless, for shipping, the club must include China: 30% of the world's containers and 30% of the world's cargo by weight pass through Chinese ports, as opposed to 25% for the United States and Europe combined. (UNCTAD 2013)(UNCTAD 2015)

Growth in air transport and ocean shipping is an inevitable consequence of the expansion of the global economy and of global trade. Policymakers must not be resigned to a corresponding rise in the greenhouse gas and other air emissions from these sectors. While targeted measures by national

[109] A possible member for the aviation "club" could be Japan. Flights into, out of, and within Japan constituted 7% of all aviation activity in 2012. Furthermore, Japanese firms are deeply embedded in aviation supply chains and possess expertise in several technologies (e.g., the use of composite materials) that could play a crucial role in greening aviation. (Committee on Japan 1994) For shipping, the club could expand to include South Korea, which – after China – is the world's largest shipbuilding nation by gross tonnage. (Shipbuilders' Association of Japan 2013)

or local governments may go some way towards mitigating the worst harms that these modes of transport cause to air quality and therefore to human health, it seems unlikely that such interventions will make much of a dent in their contribution to climate change. Current global institutions, in which all the nations of the world either move in lockstep or not at all, may not deliver sufficiently deep cuts in emissions either. Policymakers must consider new approaches.

6.3 Appendix: Efficiency gains in US domestic aviation are unlikely to be sustained

The fuel efficiency (in gallons per passenger mile) of US domestic aviation has grown at about 3.5% per year from 2000 to 2013. This improvement was spurred by a fourfold increase in fuel prices, and was brought about by practices such as increasing the load factor on domestic flights (up 20% between 2002 and 2013). The efficiency of international flights operated by US carriers has grown by 1.7% per year between in 2002-13, aided by the increase in fuel prices as well as an 8% improvement in load factor. (BTS 2015a)(BTS 2015c)(BTS 2015b)

Both these factors – a dramatic increase in fuel prices and a sharp increase in load factor – are unlikely to repeat themselves.

Indeed, the load factor for US airlines' domestic operations has remained essentially constant, after rising from 69% in 2001 to 83% in 2010. The load factor for international operations peaked at 81% in 2010 from a low of 72% in 2001. Since then, it fell in 2011 and 2012, before returning to 81% in 2013. Flights are now as full as airlines can make them.

Jet fuel cost airlines $0.78-$0.86 per gallon in 2000. Prices peaked at $3.18 per gallon for domestic operations in 2012 and $3.23 in 2008 for international operations. Prices in 2013 were 5% lower than the peak for domestic operations, and 8% lower for international operations. (BTS 2015a) The Energy Information Administration's (EIA) most recent Energy Outlook forecasts that prices will stay essentially flat – at, or slightly below, current levels - until 2020. (EIA 2014b)

The pace of efficiency improvement will therefore likely be sluggish. The EIA forecasts efficiency improvements of only 0.5% per year for the aviation sector (including passenger and freight transport) between now and 2040. (EIA 2014a)

In the United States, domestic traffic is expected to grow at 2.3% per year in 2013-32, (Boeing 2014a) while international traffic on US airlines is likely to grow at about 4% per year in that period. (Federal Aviation Administration 2013) As such, traffic growth is likely to outstrip efficiency gains.

Chapter 7: REFERENCES

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