A Comparative Evaluation of Greenhouse Gas Emission Reduction Strategies for the Maritime Shipping and Aviation Sectors

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ABSTRACT

The transportation sector is one of the largest sectors contributing to Greenhouse Gas (GHG) emissions, the gases which cause anthropogenic climate change. The aviation and maritime shipping sectors are growing segments of transportation GHG emissions, yet mitigation strategies have largely avoided these sectors. There is a need for clearly defined strategies which can reduce GHG emissions of maritime and aviation operations and for an understanding of the potential magnitude and barriers to reduction. This research presents a framework for GHG emission reduction strategies and evaluates their reduction potential for maritime and aviation operations.

Key Words: Greenhouse Gas Emissions, Aviation, Maritime Shipping, Environmental

Impacts

Introduction

It is well known that the operation of transport vehicles is a major component of anthropogenic climate change – the warming of the Earth's temperatures due to human activities. The use of transportation fuels increases levels of greenhouse gases (GHG) (EPA, 2007). The transportation sector is responsible for 13 percent of global GHG emissions and 28 percent of United States domestic GHG emissions, making it the fifth and second largest contributor respectively (Pew Center on Global Climate Change, 2004). Of human produced GHG emissions in the US, Carbon Dioxide (CO_2) accounts for 85 percent of the radiative forcing, or perturbation to the earth-atmosphere energy system (EPA, 2006). The transportation sector is the largest sector contributing to US domestic CO_2 emissions, producing 30 percent. These figures are similar worldwide (International Energy Agency, 2004).

Attention to and regulation of transportation GHG emissions have largely focused on surface transportation, in particular road transport. This partly results from its high

share of GHG emissions. With US GHG emissions at 7,260.4 million metric tons (Mt) in 2005, 1,549.8 Mt (21.3 percent) were from passenger vehicles, light duty trucks, and heavy duty vehicles. In comparison, aviation accounted for 186.1 Mt (2.6 percent) (EPA, 2007). Globally, CO_2 emissions were 25,404.8 Mt in 2002, of which the transportation sector emitted 4990 Mt (19.6 percent). Comparatively, aviation contributed 354.4 Mt per year (1.4 percent) and maritime shipping contributed 463.0 Mt (1.8 percent) (International Energy Agency, 2004). More recent estimates of global shares put aviation at two to three percent; the figure reported for maritime sector is even higher (1.2 Billion tons CO_2), accounting for 4.5% of the global emissions, based on recent work accomplished by IPCC (Williams, 2007, EurActiv, 2008).

The discrepancy in GHG emission percentage between surface transportation and maritime shipping and aviation has resulted in policy following suit in the form of new vehicle emission standards and the incorporation of GHG emissions into the Clean Air Act (EPA, 2006; Supreme Court of the United States, 2006; Winston, et al., 1999). There is also abundant precedent and experience in regulating and otherwise reducing road vehicle emissions in order to attain air quality standards mandated by the Clean Air Act. On the contrary, much less attention has been given to the maritime shipping and aviation sectors, possibly due to the unique challenges they present.

The maritime shipping and aviation sectors offer challenges for policymakers because of their interregional character. While their GHG contributions are comparatively small, analysis of reduction opportunities is important for two reasons. First, following the model of the Kyoto Protocol, all sectors should be required to

reduce, or understand how to reduce, their share of GHG emissions. Next, growth patterns show that the maritime shipping and aviation sectors could contribute a large share of emissions in the future. To this end, this study presents a new framework for GHG emission reduction strategies for the maritime shipping and aviation sectors and analyzes their impact. This study seeks to identify the most promising strategies for reducing GHG emissions from these sectors and assess the reductions that could be achieved for pursuing such strategies.

Similarities between the Maritime Shipping and Aviation Sectors

The maritime shipping and aviation sectors are compared and examined in this study because they pose similar challenges to and opportunities for effective policy making to reduce GHG emissions. The GHG emissions of both sectors are overwhelmingly in the form of CO_2, with 98% in maritime and 99% in aviation sectors (U.N., 2005). These inputs manifest at a global rather than a local level. At the same time, they are presently small contributors that are sometimes overlooked. Beyond these superficialities, maritime and aviation activity share prospects for rapid growth, a global scale of operations and similar activity structures, as described below.

Rapid Growth

Maritime shipping and air transport have grown rapidly in recent decades, trends that are expected to continue in the future. Between 1960 and 1997, global air passenger and air cargo traffic have expanded at average annual rates of 9 percent and

11 percent respectively (Stevens, 1997). In the U.S., current plans for the National Airspace System (NAS) foresee a three-fold growth in system throughput by 2025, to be accommodated by a new infrastructure termed the Next Generation Air Transportation System (NextGen); similar plans exist for the European airspace system (Smirti and Hansen, 2007; Eurocontrol, 2006). Anticipated growth may increase aviation's global GHG emissions share of two to three percent to ten percent by 2050 (IPCC, 2001). For the maritime shipping sector, ton-kilometers and the carrying capacity of the world's merchant fleet nearly tripled from 1970 to 2005. This trend is expected to continue: seaborne trade is predicted to increase from 2004 at least 50 percent in terms of both tons and ton-miles by 2020 (Friedrich et al., 2007; Corbett and Wang, 2006). In the absence of reform, this growth will naturally lead to increased fuel use and GHG emissions.

Policy Constraints

Maritime shipping and air transport feature a challenging admixture of local, regional, national, and international operations, management, and policy. Private operators (airlines and shippers) operate on publicly managed airspace or unmanaged seas. The airspace is managed by an aviation service provider (such as the FAA in the United States, or the member states in the EU airspace). In the maritime shipping sector, ships do not report their routes and speeds and instead communicate with other ships. It is then up to a nation and a local region to regulate ships within a limited area close to the coast.

These management and policy challenges present a challenge to mitigating environmental externalities. Locally controlled ports and airports may seek to reduce emissions in the immediate port area (Port of LA, 2008, Port of Rotterdam, 2008), but are constrained by competitive pressures and limited jurisdiction. Likewise, many US states have adopted climate action plans (Arizona Climate Change Advisory Group, 2006; New Mexico Climate Change Advisory Group, 2006) that defer to the Federal Government on aviation and maritime shipping matters. National governments are also constrained by concerns about placing their own carriers at a competitive disadvantage. For these reasons, the United Nations Framework Convention on Climate Change (UNFCCC), an influential international treaty addressing climate change under the United Nations, has been trying to agree upon a methodology to assign responsibility for GHG emissions of international aviation and maritime shipping. In cooperation with the UNFCCC, the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO) have been instructed by Kyoto Protocol to analyze ways to reduce GHG emissions from fuel use (U.N., 1998; Per Kageson, 2001). Even under these circumstances, effective implementation of mitigation policies is progressing very slowly (Wit et al., 2004), mainly due to:

    1) the complexity of trans-boundary economic activities of transportation;

    2) the sector-specific perspective prevailing in ICAO and IMO;

    3) data availability and difficulties in finding accurate methods for quantifying GHG emissions from aviation and maritime shipping.

Despite difficulties, some initiatives are being introduced to varying degrees of

success. ICAO is currently investigating an open emission trading system for aviation and the European Commission (EC) has announced a legislative proposal for the inclusion of aviation in the European Union Emissions Trading Scheme (EU-ETS) (Wit et al., 2004; IATA, 2008; Scheelhaase et al., 2007). The IMO issued interim guidelines for voluntary trials with a CO_2 index for ships in 2005, but has not adopted policies or issued guidance on measures to reduce emissions based on the CO_2 index. The nascent measurement metrics impede regions interested in quantifying and mitigating GHG emissions from maritime shipping and aviation. For example, the European Union is having difficulty including maritime shipping into the EU-ETS, due to a number of factors such as geographical scope definition (Jasper et al., 2007).

Activity Structure

Aviation and maritime vehicle activities that consume fuel and therefore generate GHG emissions can be usefully divided into two sets: port related activities and en route activities.

Port related activities involve those that occur at the port, which for maritime shipping include the tugging process when ships are approaching/leaving the port area and hotelling at the berth. Corresponding activities in aviation take place in the taxi-in/-out phases between the runway and the airport gate and pre-departure operations at the gate (Midkiff, et. al., 2004). En route activities also include two phases. In the maritime shipping sector, these are acceleration/deceleration at the reduced speed zone (RSZ) and cruise phase in the open ocean. The approach phase and the take-off

phase of aircraft is analogous to what occurs at RSZ for ships, and the cruise phase in aviation is quite akin to that in maritime shipping, where vehicles operate at almost a constant cruise velocity. These activity sets are depicted in Figure 1.

In both modes vehicle activities occur on a hub-oriented network, where hub ports act as transfer points to move passengers/cargoes to their intended destinations to which there is no direct route from the origins. Hub ports are also places where large consolidation occurs, leading to substantial traffic. According to UNCTAD (2006), the world total container traffic in 2006 reached 336.9 million Twenty-Foot Equivalent Units (TEUs), in which the top 20 container terminals hold more than 54 percent. Aviation exhibits similar trends; for the U.S., the top 35 airports handle 70 percent of the traffic (FAA, 2007). Hubbing trends lead to congested terminals; congestion leads to inefficient network operations; this sequence leads to higher and unnecessary GHG emissions. As capacity constraints can lead to operational inefficiencies, increased delays at a concentrated port such as a hub can lead to increased GHG emissions.

Emission Distribution

Despite the discrepancy among different estimates, it appears that the maritime shipping and aviation sectors have a roughly equivalent distribution of GHG emissions due to activities. As can be seen in Tables 1 and 2, the majority of emissions from both sectors are through en route activities. Port related activities account for a comparatively small portion. Tables 1 and 2 describe the GHG emission

shares of maritime shipping and aviation GHG emissions compared with global, US, and transportation totals.

In sum, maritime shipping and air transport have many commonalities as sources of GHG emissions, including rapid growth in activity, a complex institutional environment, hub-oriented network structure, and differentiated port and terminal modes of operation. As will be elaborated below, GHG emission reduction strategies for these modes also have a similar taxonomy, to which we now turn.

Strategy Formulation and Definition

To compare and evaluate the maritime shipping and aviation sectors in terms of GHG reduction, we will define two criteria for strategy evaluation: operational and institutional. The operational reduction potential is derived from Climate Actions Plans in the US as well as the breakdown of reduction categories for aviation defined in Carlsson and Hammar (2002). The institutional framework will utilize the categories of political acceptability of new innovations outlined by Altshuler (1979). Identifying political acceptability and realizable reductions simultaneously will allow for identification of strategies which are both politically and technically feasible.

Taxonomy of Reduction Strategies

To compare and evaluate the maritime shipping and aviation sectors in terms of operational GHG reduction, we introduce a conceptual framework for identifying and classifying emissions reduction strategies. These strategies fall into two high level

categories: System and Component. System efficiency strategies represent a change in cargo or passenger flows to reduce GHG emissions on a system-wide level for aviation or maritime shipping. These strategies change activity levels, either system-wide or at a particular port. A decrease in activity on a route or at a port would reduce GHG emissions because of the simple elimination of operations or due to the decrease in congestion at a port. Component efficiency strategies include technological changes that allow for GHG emission reductions at constant activity levels. By enhancing technology, all or a subset of operations can have decreased GHG emissions without changing the structure and activity level of the system.

System Efficiency can be achieved by influencing an Origin/Destination (O/D) table or through network efficiency innovations. An O/D table specifies flows of passengers or cargo between origin and destination ports over a time period of interest. By changing an O/D table, vehicle activity levels are altered. For example, curtailing traffic between a particular origin and destination will reduce the number of vehicle movements between that O/D. Alternatively, shifting traffic from a highly congested port to a less congested one will reduce emissions through congestion mitigation. Network efficiency is changing the manner in which traffic in a particular O/D market is served. For example, this can be done by increasing the vehicle size, increasing load factors, or rescheduling operations to flatter demand periods. Network efficiency can also involve changing the network structure or eliminating intermediate ports between an origin and destination

Component efficiency strategies are those which reduce GHG emissions without

changing vehicle flows or capacity. Component efficiency strategies include vehicle efficiency, operational efficiency, and alternative fuels Vehicle efficiency includes innovations to current vehicle or engine design to use fuel more efficiently. Operational efficiency includes improvements at port and en route operations. Alternative energy includes the substitution of fuels other than fossil fuels for vehicle operations.

Institutional Potential

In Altshuler's (1979) seminal work he identifies transportation policy and operational innovations for their ability to diffuse cost and responsibility amongst different political actors and consumers. He asserts that "change strategies" fall along a continuum of political acceptability related to the institutional changes necessary. This continuum provides a framework through which GHG reduction strategies can be assessed for their political acceptability. The following will discuss the four categories of acceptability as they apply to aviation and maritime shipping.

Altshuler (1979) begins by describing the most viable, or "ideal" change strategy as a self-financing policy to bring about change that carriers or their customers will agree to voluntarily. Such a change must therefore lead to savings which are greater than the cost of the change. The second type of innovation is one that requires some compulsion. Such innovations overcome commonly regarded challenges at a low cost, which falls on carriers or their suppliers (ship/aircraft manufacturers), rather than individual customers, at the most acceptable level. The third type of innovation is one that entails significant public or private cost for the benefits it confers, yet in a manner

that permits diffusion over different actors and over time. The final and least acceptable type of innovation involves substantial costs and interference with established patterns of behavior; political responsibility, in this case, falls upon decision makers/public officials who adopt the innovations. The institutional framework for innovations provided by Altshuler (1979) provides a ranking methodology for the political acceptability of proposed GHG emission reduction strategies.

The following sections explore the potential of each GHG reduction strategies and related sub-strategy in the maritime shipping and aviation sectors individually. The reduction potential of each sub-strategy will be evaluated in the early part of each section, followed by an institutional discussion of each strategy.

Strategy Evaluation for Maritime Shipping

System Efficiency

Origin/Destination

The Origin/Destination strategy involves the manipulation of the shipping OD table, associated with GHG emissions corresponding to each element in the table, to reduce the emissions taking place during the maritime transportation process. It could be a wholesale cut (curtailing), or shift to other modes' OD tables, or decreasing some of the elements while increasing others or adding new elements in the table (O/D switching).

O/D Flow Curtailment

Curtailing O/D flows may not be an issue that can be addressed by the shipping sector alone, as more than 90 percent of global trade is currently served through maritime transportation (IMO, 2008). A pure curtailment of operations, however, could arouse considerable resistance from all the spheres related to trade, as the world economy relies heavily on global maritime logistics. This tight linkage between maritime shipping and the global economic activities, however, provides a unique opportunity to look at an O/D strategy; it suggests involvement of economic activities, from both trade and production process. This could be done through a macro-economic approach.

Macro-economic approaches, such as multi-region input-output models, have been intensively employed to study the environmental impact of either an entire economic system or a specific sector (Wiedmann, 2007). Applications to maritime shipping are limited. Strømman and Duchin (2006) developed a "World Trade Model with Bilateral Trade" which takes into account the geographically dependent freight transportation requirements for goods by means of four maritime modes (crude carriers, bulk carriers, container vessels, and LNG tankers). The merit of such I-O models lies in the consideration of the interaction between maritime shipping, transportation, and all other economic activities, with a focus on the latter. The promise of such models is embodied in their further extension to study policy changes in the maritime sector, whether technical or political, on trade flows. These models could capture the potential of policies to reduce emissions by applying GHG emissions factors to modeled trade flows before and after the change. It is for this reason that these models could be

enablers for GHG emission reduction policy.

Mode Shift

The second O/D strategy is shifting travel mode from marine to aviation for overseas transport or to rail and commercial vehicles for long-distance surface transport. A mode shift strategy in the maritime sector is logistically challenging and would require private sectors' participation. Furthermore, a mode shift from marine could also generate increased GHG emissions as maritime shipping is the most energy efficient method of transporting goods between countries and continents (European Commission, 2006). Therefore, a mode shift for trans-oceanic travel is not recommended. However, the potential for small vessels to replace overland in a mode shift exists. Initiatives such as short sea shipping have been given attention to promote mode shift from surface transportation modes to ships (Mulligan and Lombardo, 2006; GAO, 2005).

O/D Switching

O/D switching is concerned with using an alternative port instead of a major port because of two motivations: fleet selection programs and congestion. Environmental concerns have led ports to begin to apply fleet selection programs to cut port calls, which especially aim at preventing the entry of ships whose emissions go beyond the limits set by the port (Port of Seattle, 2007a). Facing the risk of being refused for entry, shipping companies may choose to unload cargoes at further gateway ports or nearby

secondary ports. In the presence of congestion, Shippers/carriers may choose to serve an alternative destination port instead of the main gateway port. Both cases lead to changes in cargo flows between origin and destination ports.

The potential of using alternative ports to reduce GHG emissions is unclear. An individual port authority's fleet selection program may add excess GHG emissions due to extra distance traveled by ships or the related surface modes if a vessel services an alternative port. For example, congestion at West Coast ports had some North American shippers considering rerouting traffic from China through the Suez Canal instead of crossing the Pacific; a method with ambiguous time and fuel savings on both the vessel and surface vehicles (Strauss, 2004). Shippers' and carriers' incentive to resort to alternative ports may not be consistent with the emission reduction objectives. First, shippers and carriers may prefer a gateway port in order to take advantage of economies of scale and avoid any capacity and equipment constraints, both at port and in terms of inland surface transportation infrastructure. Second, time savings related to the use of alternative ports do not necessarily equal fuel savings. In the case of congested seaports, delay at a warehouse or port yard would be much longer and more a concern of shippers'/carriers' than that occurring on ships.

Network Efficiency

Network efficiency strategies for maritime shipping involve an altering of vessel capacity or changing the network while cargo flows between origin and destination ports are held constant, discussed below.

<u>Alteration of Vessel Capacity</u>

Fleet selection programs, congestion, and the benefits of increasing returns to scale have contributed to shippers'/carriers' willingness to adopt higher capacity vessels (Table 3). As a specific example, in the four-year period of 2001 to 2005, the port of Los Angeles, California, the largest shipping port in terms of container traffic in the US, witnessed a 44 percent increase in container volume. At the same time, the port experienced a drop in containership calls from 1584 in 2001 to 1423 (Port of Los Angeles, 2007). This can be explained by increase in the TEU loading capacity per ship from 3,272 to 5,260 in this four-year period.

A decline in ship calls further leads to emission reductions in the port area. The Port of Los Angeles (2007) found that nitrogen oxide emissions, a local pollutant directly related to fuel burn, decreased six percent and sulfur oxides by four percent over the same period. This implies a reduction of total fuel burn, which is also related to GHG emissions. Major (2007) indicates that an increase of gross tonnage leads to a decrease in average fuel consumption per ton of goods given a fixed sailing distance. The extent depends upon the type of ship. For example, the emissions of a 5000-ton chemical tanker in terms of gCO_2/ton-mile, on average, is about three times that of a 20,000-ton chemical tanker; using the same metric, a 80,000-ton container ship emits only half the amount of a 40000-ton vessel of the same type. Given a certain demand, using larger ships thus would decreases overall GHG emissions. While shippers may be unaware of their contribution to GHG emission mitigation and are simply taking

advantage of economies of scale, the direct correlation exists.

Component Efficiency

Vehicle Efficiency

Vessel efficiency is achieved by upgrading vessels with either existing or innovative technology to make vessels more fuel efficient. Current technology includes hydrodynamic upgrades (hull and propeller) on both existing and new ships. A proper retrofit of propellers would lead to approximately one to three percent CO_2 reduction. Experience from MARINTEK as reported by IMO (2000) indicates a reduction of power on the order of 20 percent may still be achieved by relatively minor changes to the bow and/or stern on a vessel. Consequently, IMO concludes the average reduction in fuel consumption and CO_2 emissions from hull design is five to 20 percent. Likewise, taking into account constraints in propeller design such as dimension, cavitations and loading, the efforts in reducing CO_2 emission through choice of propeller for new ships is estimated to be between five to ten percent.

For existing ships, the impact of hull maintenance on GHG emissions is through the effect of hull roughness on ship resistance. Ship viscous (friction) resistance is positively correlated with hull roughness. Hull roughness can then be reduced to decrease fuel consumption. Fuel use and GHG emissions can be reduced by applying what IMO (2000) refers to as hull maintenance best practices. These include limiting port stays in warm water or long periods at port, use of antifouling paint, and frequently repainting the ship. By applying these practices, IMO (2000) estimates that fuel savings

can be achieved with three to five percent.

An additional means of improving vehicle efficiency is machinery plant concepts, including new propulsion configurations. Diesel-electric propulsion is one example. A typical diesel-electric propulsion system is different from traditional drive train where main engines connected to fixed propellers, as large main engines are substituted by many small diesel engines, each of them being connected to an electrical generator. This configuration enables the propulsion system to offer a great deal of flexibility and possibilities to run with optimal fuel consumption at different operational conditions rather than engaging all engines at all times. For example, pod propulsion has been demonstrated to reduce power requirement by approximately ten percent (ABB, 2008).

IMO (2000) estimated the technical potential for reducing CO_2 emissions from the world fleet, including new and old vessels. They found that this potential is 11.8 percent by 2010 and 19.7 percent by 2020, compared with a baseline fleet when no additional measures are applied. Michaelis et al. (1996) estimated the 2025 fleet average reduction potential at 25 to 35 percent over the 1990 baseline level. These two estimates are based on the assumption of unchanged performance. The US Department of Transportation (2000), by taking into account various factors including vessel efficiency and alternative fuels, gives a relatively optimistic view of aiming for a 40 percent reduction in GHG emissions by 2010, based on full life-cycle and fuel-cycle analysis under identical operating conditions.

Operational Efficiency

Operational efficiency refers to both marine vessel performance improvements for en route and port related operations.

En route

En route operational changes include optimizing speed choices and operational parameters for fuel savings, adjusting ship routes to avoid weather patterns that would affect ship performance, and reducing the length of port visits.

For a given ship condition, the fuel consumption and the GHG emissions will mainly be a function of the ship speed. Fuel consumption per distance traveled will approximately increase in proportion with the square of the speed (IMO, 2000). The selection of speed may not be an effective standalone GHG reduction method, due to limitations from required service levels or time constraints set by the cargo owner.

By applying routing techniques, ships can take advantage of varying weather and ocean current conditions to optimize their routes, through which fuel CO_2 emissions savings can be gained. A weather routing system can be implemented in a ship for assisting fleet in routing around weather. IMO (2000) estimated that the potential for reducing CO_2 emissions by effective weather routing is two to four percent. Ocean currents may also have significant impact on the fuel consumption. An early study conservatively estimates that exploiting currents in routing could reduce the annual fuel costs of the world commercial fleet on trans-Atlantic and trans-Pacific routes by USD 70 million (Lo et al., 1992). They also estimated averaged annual fuel savings were 0.8 to 2.2 percent and 1.1 to 1.3 percent for those two routes respectively, depending on

directions and speed of ships. As this study was conducted in 1992, the absolute cost and emissions savings would be much higher if applied to current demand level and soaring marine fuel price.

<u>Port Related</u>

For ships around the port area, reducing speed could reduce engine load and fuel consumption. In addition, time savings in port through promoting efficiency of cargo handling and mooring could be used to reduce cruise speed and save fuel consumption and CO_2 emissions en route. The extent of this potential reduction is one to five percent compared to normal practice (IMO, 2000). More efficient berthing and anchoring contribute to one to two percent reduction of GHG emissions occurring at port. The port initiatives, including requiring use of low-emission tugboats rather than having large ship engines running in port, may provide significant reduction potentials as well (IMO, 2000).

Alternative Energy

Alternative energy involves the substitution of alternative fuels in place of Heavy Fuel Oil (HFO). A replacement of HFO with lighter fuels could lead to reduced CO_2 emissions because alternative fuels have a lower carbon/hydrogen ratio, because of lower hydrocarbon chain length. IMO (2000) estimated the GHG emission reduction potential from the use of Marine Diesel Oil (MDO), an alternative to HFO which has a lower carbon/hydrogen ratio. The study assumed an annual marine fuel consumption of

approximately 225 Mt in year 2020, and a baseline situation of year 2000 fuel use, where 80 percent of fuel used was HFO. If a full replacement of HFO by MDO is implemented in 2020, CO_2 emissions are estimated to decrease by 36 Mt, or five percent (IMO, 2000).

Wind, a traditional ship energy source, also shows promise as an alternative source of energy when combined with innovative vessel design. The most recent alternative energy trial was reported in January 2008 by SkySails. SkySails launched a large cargo ship across the Atlantic with the help of wind. This method is expected to decrease fuel consumption by 10 to 15 percent. SkySails (2008) estimates that the potential savings could be up to 30 to 35 percent if larger kites are installed (SkySails, 2008).

Another alternative fuel, fuel cells, provides a quiet, fuel-efficient, and more importantly, zero operational emission propulsion concept for the future. More research now is concentrated on road transportation. Its application to ships is mainly constrained by power output requirement, volume, and costs. Nevertheless, it has attracted a significant amount of research and development on its application in ocean-going vessel. Other renewable energy technologies such as solar panels with conventional diesel engines or even diesel-electric systems are under investigation. A limited number of these hybrid vessels are currently being deployed (Solar Sailor, 2007; Wallenius Marine, 2007). Table 4 provides more details about the aforementioned alternative energy sources for ocean-going ships.

Shore-side electricity for docked ships is also a recent focus; ARB (2004) estimates that switching to electricity could reduce GHG emissions from in port activities by 66

percent. Facilities have been put into use in Juneau (Alaska), and the Port of Los Angeles; facilities are being constructed at the Port of Long Beach (Friedrich, A. et al, 2007; Kanter, 2008). To extend such implementations, international shore power standards need to be adopted; in addition, new ships must be built with shore-side electricity capacity.

Overall Political Acceptability Evaluation

Based on Altshuler's criteria, the GHG reduction sub-strategies are ranked for their political acceptability for implementation. Categorization of these is mainly based on estimated costs involved where possible, which subsequently influence the political acceptability level.

Altshuler Level Four

The least acceptable, or fourth category, of strategies includes fuel cell technologies. The maturity time frame in implementing fuel cell technologies in ships is very unlikely to be before 2020, suggesting a high economic infeasibility before that time (AEA Group, 2007). It is possible that an attempt to deploy fuel cells to power vessels would result in unacceptable production and supply costs. This interference with current established practices would entail a cost which would fall on ship operators, their customers, and vessel manufacturers.

Altshuler Level Three

The sub-strategies falling into the third group entail substantial public or private cost. Private cost could come from implementing a sail apparatus (wind) for vessel power or innovating ship equipment or parts (pod propulsion, propeller/hull design). Public cost could come in the form of a port authority investing in large-scale supply equipment (shore-side electricity). The costs of these sub-strategies could be offset by lower fuel consumption in the future and therefore would be diffused over time. In the case of shore-side electricity, lower environmental externalities for the ports overtime could assist in the temporal diffusion of costs. This high cost but also high diffusion of the benefits and costs over time is what leads these sub strategies to be categorized in level three.

Altshuler Level Two

Strategies such as the implementation of weather routing systems and improving propeller and hull maintenance would assist in overcoming the challenge of fuel savings with a low cost. These sub-strategies would require vessel manufacturers to innovate vessels and vessel equipment. Innovations would not require a behavior change on the part of the vessel operators or their customers, and costs falls on manufacturers rather than individual customers. Therefore, these sub-strategies fall in level two.

Altshuler Level One

Improving cargo handling efficiency would be motivated by a port authority's

desire to reduce operating costs and time and also entice new traffic. Such an improvement could also allow operations in a busy port to increase. As noted, improved cargo handling efficiency could allow for slower traveling speeds which would save fuel. Such a change which brings the benefit of fuel savings and faster time in port could be very welcome by both vessel operators and their customers. As this strategy would benefit many stakeholders and the cost falls on a small group it is a level one strategy.

Summary

These conclusions are reflected in Figure 3, where Altshuler's acceptability levels of different sub-strategies are plotted against their respective GHG reduction potentials based on existing literature, reported in CO_2 equivalents. The quantification of the emission reduction potential for system efficiency strategies is much less available than for component efficiency, mainly due to the lack of relative studies and complexity of evaluation. Also, in each Atshulerian group, each strategy's position does not mirror the relative ease of acceptance. In addition, such estimates are on a system-wide per year basis; therefore, emission reduction potential during a specific part of activities is thus converted to such a larger scope (e.g., short-side electricity).

By and large, this chart illustrates a negative relation between the political acceptability and reduction potentials of the strategies. Those strategies with high cost or political opposition are the ones with the greatest GHG reduction potential; the strategies with the lowest barriers to implementation are those with the least potential

for GHG reduction.

Strategy Evaluation for Aviation

System Efficiency

Origin/Destination

An O/D table of passenger flows between specific airports could be altered through the use of local airports to shift traffic from congested airports or through a mode shift. A system-wide change in GHG emissions for all O/D strategies to be discussed depends on the system response. Each strategy to be presented will curtail or shift operations from the aviation system. However, as noted by Hansen et al. (2001), schedule backfill will most likely occur when scheduled operations decrease. Backfill is the re-filling of the schedule with additional operations; this phenomenon is related to induced demand (Hansen, 1995). If schedule backfill occurs, system-wide GHG emissions will increase. Williams and Noland (2006) note that current studies examining certain O/D strategies assume that schedule backfill does not occur, and therefore may overestimate GHG emission reduction savings.

Use of Existing Local Airports

Pressure on hub airports can lead to inefficient operations, congestion, and therefore GHG emissions. The use of local airports to ease the congestion at major airports could reduce fuel burn (JPDO, 2007). Such an initiative is discussed in NASA's airspace modernization effort, the Virtual Airspace Modeling and Simulation project (VAMS) and also in NextGen (Smirti and Hansen, 2007; JPDO, 2007). Congestion can

cause airborne holding and inefficient use of fuel. By shifting demand to less congested airports this holding and associated fuel burn would not occur. However, this strategy would change the need for ground access to the local airport, for changes in airport runway and gate infrastructure, and for ground service vehicles at the airport, changes which must be incorporated in a complete GHG emission impact analysis of the use of local airports.

Mode Shift

Air travel between a city-pair could be replaced with another mode, such as rail, coach bus, or auto to decrease GHG emissions. A mode shift could be induced by government taxes or subsidies or, less likely, administrative controls on airline schedules. Research in this field shows that GHG emissions will decrease if certain aviation operations are replaced by other modes while other research points to the challenge of implementing such a strategy.

Williams and Noland (2006) show that rail GHG emissions emit less CO_2 per passenger-mile than air travel for route lengths up to 1240 miles (1995 km). In this report, Williams and Noland (2006) note that high speed rail emits 0.06 to 0.1 kg CO_2e per passenger mile (0.037 to 0.062 kg CO_2e per passenger km), compared with 0.17 to 0.24 kg CO_2e per passenger mile (0.106 to 0.149 kg CO_2e per passenger km) for aircraft used on short haul flights (Chester and Horvath, 2007). Horvath and Chester (2007) report similar findings for the 400 mile (643.6 km) corridor from San Francisco to Los Angeles in California. They find the kg CO_2e operational emissions per trip to be 30 for

rail, 12.8 for high speed rail, and 60 for aircraft.

Similar conclusions exist for short haul trips on modes beyond rail. For distances around 200 miles (321.8 km), a coach bus with 40 passengers (approximately 70% full) and an automobile with 1.56 passengers emit 4.3 and 36.6 kg per passenger of CO_2 respectively. Both figures are lower than a typical aircraft on this route, which would emit 63.9 kg to 44kg CO_2 per passenger for an aircraft with a load factor of 70 percent and 100 percent (Monbiot, 2007).

Jamin et al. (2004) note that the US government is planning ten high-speed rail corridors which exhibit redundancy with 220 airport pairs about 600 miles (965.4 km) apart. Under the assumption that rail would capture one-third of the aviation market by 2030, they calculate that overall CO_2 emissions would decrease by one million tons per year (Jamin et al., 2004) due to a mode shift. This assumption is potentially a large overestimation of the potential of mode shift: ICAO found that in Europe there is a maximum of 10 percent potential passenger shift from air to other modes, most rails (IPCC, 1999). Because the US has a limited rail infrastructure compared with Europe, this 10 percent could be considered an upper bound. Yet the previous assumption may still have its ground in that high speed rail is only at the beginning stage in the US, whereas such a system in Europe has decades' history. Furthermore, Jamin et al. (2004) find that the emissions of sulfur oxides (SO_X) increased by ten percent due to a mode shift to rail because of the use of coal for electricity. This underscores the challenge of implementing a mode shift strategy.

Network Efficiency

A network efficiency strategy would keep passenger flows between an origin and destination airport pair constant while decreasing the number of vehicle operations, bypassing congested transfer airports, or changing operation schedule times.

Emissions/Aircraft Size Match

An aircraft size match refers to allocating aircraft to certain routes based upon the most efficient use of that aircraft size over a certain stage length. Because fleets have different ranges, operating speeds, and fuel burn rates, matching fleet to routes could help minimize fuel burn. The European Environmental Agency (EEA) (2006) perform an emissions inventory of all aircraft operating in the EU, including the amount of fuel used and emissions per stage length. Using this fuel use data for different stage lengths, four categories of aircraft are compared for their fuel burn, normalized for the number of seats on each aircraft. The representative aircraft and seat numbers from each of the categories are as follows: turboprop (Saab 2000, 52 seats), regional jet (BAe146, 100 seats), narrow body (Boeing 737-400, 137 seats), and wide body (Boeing 747-400, 366 seats) (Boeing, 2008; Airliners, 2008).

Figure 4 shows the fuel burn per seat for each of these four aircraft for stage lengths from 232 to 1852 km. The regional jet and the wide body are consistently higher than the turboprop and the narrow body aircraft in terms of fuel burn per seat. For short stage lengths below 1000 km, turboprops have the fewest kilograms of fuel burned per seat. At 1100 km, the narrow body aircraft becomes the aircraft with the smallest amount of

fuel burn per seat. Not shown in Figure 4 but present in the EEA data is that beyond 1852 km (~1100 miles), the narrow body and wide body exhibit similar trends, and beyond 3704 km, the 747-400 is the only aircraft of the group for which there is data. Therefore the goal of reducing GHG emissions with an emissions/aircraft match strategy should focus on fleet substitutions over short stage lengths as there are fewer alternatives for long range operations.

Using these guidelines, the GHG reduction potential for an emissions/aircraft match strategy was evaluated. Data from the Department of Transportation Bureau of Transportation Statistics (BTS), T100 Schedule database for April 2008 was collected. This data captures aircraft types and the scheduled departures for each type for each stage length. Any flights flown less than 30 times in that month, or were solely for freight were eliminated, along with flights further than 1610 km (1000 miles). Any aircraft not in one of the four categories identified was eliminated from the dataset (under the assumption that they serve a specific purpose, as most were helicopters or Very Light Jets). The five fuel use per seat rates identified in Figure 4 were used as the representative fuel use rates for calculations; the aircraft operating on stage lengths equal to or less than the first point were ascribed the first fuel use per seat rate and so on.

Current fuel use was calculated for each stage length and aircraft pair. The fuel use per seat factor was multiplied to the number of seats flown for each pair and all observations in the month were summed. Next, the turboprop was substituted for all stage lengths under 1100 km and the narrow body was substituted for stage lengths between 1101 km and 1610 km and fuel use was estimated using the same method. The

difference in fuel use was converted into CO_2 emissions using the EPA value of 20.89 lbs CO_2 per gallon of aircraft fuel, Jet A (EPA, 2004). It was found that the CO_2 savings was 6.4 percent for the month of April. If this is generalized from one month to one year, and it is assumed that the entire range of stage lengths beyond 1610 km has this same potential, then the result is CO_2 savings of 6.4 percent system wide. However, if this estimation represents the maximum potential of this strategy, the savings is .04 percent.

These findings are further strengthened by those in Chester and Horvath (2007). Using the same data, they found that medium capacity aircraft have fewer GHG emissions per PMT than small aircraft, and fewer GHG emissions per PMT than larger aircraft. Therefore, a strategy focusing on efficiency over a given stage length is encouraged for GHG minimization.

Direct Routing

Airlines consolidate operations at one or several airports, termed hubs, to achieve economies of scale (Kanafani and Hansen, 1985). At these hubs, schedules are coordinated to allow for passenger transfers. Aircraft routes will include a stop at the hub airport between an origin and destination to allow for these transfers. A simple strategy to influence GHG emissions from aviation is to decrease hubbing activities and replace operations with non-stop flights between origin and destination pairs. This would decrease passenger miles traveled because the direct route will be shorter than the route with a stop. It also eliminates an additional Landing Take-Off (LTO) cycle and the associated emissions.

Morrell and Lu (2007) found that, for long-haul air travel, GHG emissions decreased when an air travel route with a transfer stop was replaced with non-stop service. They found that environmental social cost, which was a function of CO_2 emissions and noise, can be reduced by 25 percent and 71 percent per flight if hubbing is eliminated. The variation in reduction percentage depends on the location of the hub compared with the great circle route between the origin and destination airport. Jamin et al. (2004) tested the substitution of all connecting flights in the US National Airspace System (NAS) with direct, non-stop flights. Without changing fleet structure, this resulted in a ten percent decline in fuel burn and CO_2 emissions per year: four percent from decreased travel distances and six percent from fewer LTOs.

Rescheduling

A change in scheduled operation time from a congested period to a less congested period could ease congestion at busy airports, smoothing demand and eliminating excessive fuel burn due to delay. Such a strategy is related to previously discussed strategies which reduce congestion. This strategy presents challenges related to the multiple interrelated externalities of aviation. Many airports have operational restrictions in the off-peak to reduce community noise, presenting the tradeoff between noise mitigation and GHG emission reduction.

Component Efficiency

<u>Vehicle Efficiency</u>

Aircraft efficiency includes innovations to current airframe design and to the engine. As reported by the EPA (2006), fuel economy improvements in aircraft average one to two percent per year since the 1950s, and aviation fuel use per passenger-mile has been reduced by 60 percent in the last 35 years (Waitz, 2004). Despite these historical trends as well as recent innovations, it is unclear if more innovations are in the future or if innovations have reached their highest points.

Airframes can be innovated by reducing aircraft weight or minimizing air resistance by designing an aerodynamic aircraft. Using a lightweight composite, two manufactures have greatly improved fuel efficiency. Boeing has designed an aircraft, the Boeing 787, which uses 20 percent less fuel than an aircraft of similar size (Boeing, 2007). Airbus, an airframe manufacturer, developed the high capacity Airbus 380 which generates 50 percent less CO_2 per passenger kilometer traveled (PKT) when compared with a comparable long haul aircraft, the B747 (Airbus, 2007; Chester and Horvath, 2007). Interestingly, the A380 further demonstrates the constant struggle between aviation noise and environmental pollutants: the A380 fuel efficiency is reduced by one to two percent through changes necessitated after failed noise tests (Williams, 2007).

Operational Efficiency

Operational efficiency includes innovations in port related operations to reduce idling and taxiing and en route opportunities such as improved Air Traffic Management (ATM) techniques.

En route

En route efficiency can be broken into the open space and transition space segments as detailed in Figure 1. As noted in Table 2, over 90 percent of GHG emissions occur en route, while less than ten percent occur on the ground.

Open space operational efficiency measures include optimal en route trajectories as part of an innovative ATM system. Research for improving optimal en route trajectories to decrease fuel burn is currently a NextGen initiative (Joint Planning and Development Office, 2007). While the exact potential of this is unknown to the authors, the current US airspace is designed to allow near-optimal routings. McDonald and Zhao (2000) show that flying alternative routes to those currently flow for select routes in the US can save 1.56 to 2.7 minutes. This finding highlights the current efficiency of the US airspace system. This is not the case worldwide: the fragmented airspace in other regions, such as the European airspace, leads to increased travel distances and flying at inefficient altitudes, both of which lead to increased fuel burn (Williams, 2007). The current initiative to unite the European airspace, SESAR, is partially designed to correct this issue (Smirti and Hansen, 2007; Ky and Miaillier, 2006).

In the transition space, research has been performed on efficient approaches. One such operational improvement is termed Continuous Descent Approaches (CDA). CDAs introduce a continuous flight path during approach compared with the current stair-step descent (Clarke, et al., 2004). CDAs were found to have a 53.5 kg average reduction in Boeing 757 fuel burn per arrival and a 165.1 kg average reduction in

Boeing 767 fuel burn (Brooks, 2006). For a Boeing 757, which typically consumes 226.3 kg of fuel on approach, this is a 23.6% reduction; a Boeing 767 typically consumes 321.4 kg, and this is a saving of 50% (EEA, 2006) both compared with typical Boeing flights.

Port Related

Port related operational efficiency measures include decreased taxiing and idling time and strategies to reduce fuel consumption while those events are taking place. Aircraft tugging to the runway from the gate can reduce fuel burn, as an aircraft would taxi without the use of engines. Airlines are also having their aircraft taxiing on one engine when possible to reduce fuel consumption (Tedrow, 2008; Midkiff, et. al., 2004). However, the percentage of operations where innovative taxi procedures could take place is potentially marginal due to safety concerns. To reduce idling, a runway reservation system could be used, in which aircraft reserve a time to push back from the gate (Shiomi, 2001). A takeoff assignment could be given to each departing aircraft, so that instead of having aircraft taxi out and potentially idle on a departure queue, they could wait at the gate while the engines are not in use.

Alternative Energy

Alternative Energy for aviation could come in the form of the substitution or the partial use of fuels other than Jet A, the current commercial aviation fuel, for aviation operations or the use of alternative energy for the auxiliary power unit (APU). The APU

is used while the aircraft is at the gate, and Jet A is used while the aircraft is in motion.

Daggert (2007) notes that an aircraft fuel must have high energy content and a low weight, something that Jet A achieves. A short term alternative fuel solution must also be a drop-in fuel, in the sense that it does not require new aircraft or distribution infrastructure in the short run. Daggert (2007) also notes that most known alternative fuels have higher rates of CO_2 emissions in the lifecycle than does the current Jet A. He outlines eight current alternatives to Jet A, and notes that only two - Bio-Jet Fuel and Liquid Hydrogen from Water and Nuclear Power - decrease lifecycle CO_2 emissions. There is a potential to decrease lifecycle CO_2 emissions from bio-mass because the crops consume carbon as they are produced (Gaffney, 2008). These fuels are drop-in fuels and have higher energy content than fossil fuels.

There are currently many organizations investigating the potential of alternative fuels for aviation. The FAA has formed the Commercial Aviation Alternative Fuels Initiative (CAAFI), which is performing research and development on alternative fuels as well as analyzing the policy implications and certification potential for these fuels (FAA, 2007). The Boeing Company is investigating Jet A blends, including bio-mass from algae or soybeans (Daggert, 2007).

There are great challenges to the development and use of alternative fuels for aviation. Daggert (2007) reports that current bio-fuel blends have a higher freezing point than required, and Williams (2007) notes the potential energy cost and large land required for bio-mass production. While liquid hydrogen has the potential to reduce lifecycle emissions, it is not a drop in fuel and therefore presents a challenge to short

term implementation. Liquid hydrogen has a low energy density and therefore a large amount of fuel could be required to be present on the aircraft. This would also require development of a distribution infrastructure which would also have related emissions (Williams, 2007).

Another challenging fuel is ethanol, which is shown to decrease lifecycle CO_2 emissions by approximately 13 percent (Farrell et al., 2006). However, it presents challenges: it does not have the energy density needed for commercial aircraft and, depending on the source, its production can put pressure on farm land used to produce food supplies, making it unsustainable (Biello, 2007). It is not feasible that decreased lifecycle emissions will be the only decision variable in determining which alternative fuel to pursue, as noted in Biello (2007), which presents a large barrier to considering corn-based ethanol for aviation fuel.

These challenges have resulted in some organizations claiming that there is little potential for alternative fuels in aviation. The Royal Commission on Environmental Pollution (2002) concludes that Jet A will continue to be the source of fuel for aviation due to these and other challenges, as innovations in this field are extremely restrictive.

Electricity as an alternative fuel for aircraft operations at airport gates is both in operation at some airports and under review for others. Gate supplied electric power and pre-conditioned air provide an alternative to using the APU for lighting, temperature control, and other energy needs of a stationary aircraft. A reduction in CO_2 emissions from using the APU to using gate supplied electric power will involve both a loss of CO_2 emissions but at the same time an increase in CO_2 emissions because

electric power generation creates CO_2. CO_2 emissions savings are uncertain because electricity generation mixes vary from country to country and state to state. In the US states of Washington and California, electricity generation is largely from hydropower, which has a lower CO_2 emission coefficient than the burning of fossil fuel (EIA, 2002). This may not be the case for other countries or states. The Port of Seattle (2007b) is providing gate electrification and pre-conditioned air at gates to discourage the use of APUs while airlines are at the gate. They suggest that this could help reduce CO_2 emissions by 40,000 tons per year, or 0.78% of the 5.1 million tons of CO_2 per year generated at the port.

Overall Political Acceptability Evaluation

Similar to the discussion of maritime strategies, the sub-strategies outlined in the previous section can be categorized following Altshuler's criteria.

Altshuler Level Four

The introduction of high speed rail could incur a tremendous investment in infrastructure. Because of the cost to implement such a system it would most likely have to be compelled by a government body, which could lead this strategy to fall in the least acceptable bucket due to the inability for the "blame" of a failed system to be diffused. However, a mode shift strategy could also be viewed as highly acceptable if a system was already decided upon and developed. The funding of the system could be by a diffuse tax and the potential behavioral changes by consumers could be induced by

incentives, or "carrots," rather than "sticks." This strategy and its varied implementation methods fall across multiple buckets depending on implementation.

Altshuler Level Three

Deploying ethanol as a fuel substitute and using direct routing for airline operations both entail substantial costs which could be diffused either over time or over system users. The higher perceived cost of ethanol could be offset by rising Jet A prices. Similarly to a mode shift strategy, this strategy's location on the Altshuler continuum is also difficult to define: the potential for ethanol to compete with fuel sources could make it so that any government entity encouraging the use of ethanol would be open to blame. The costs from direct routing would be incurred due to operational procedure shifts by airlines and airports. These costs could be diffusible across the federal government, the airlines, and the airports. As a consequence, the two sub-strategies are categorized into the third group of acceptability.

Altshuler Level Two

Consistent with the definition of Altshuler's second category, an emissions/aircraft size match requires compulsion on the part of the airlines to adopt more fuel efficient aircraft or to change the way their current fleet is deployed. Airline business models and operational strategies would change as turboprops fly slower and provide a different number of seats per departure than more commonly used aircraft. However, such a strategy may not require large incentives to encourage airlines to adopt new fleet or to

alter their current fleet assignment methods, as fuel prices have leaped to levels constraining the airlines industry. Therefore, this strategy is a level two because it alleviates a widely perceived problem (fuel prices and GHG emissions), the resulting cost for airlines could be low, and it does not require substantial behavioral changes of individual travelers.

Altshuler Level One

Included in the first category are CDAs and ground power, because consumers and airlines would willingly use these innovations once in place. Ground power is a popular solution to fuel and emissions savings for aircraft that spend significant time at the gate. Costs are also diffusible across airport sand airlines, and also across time. CDAs, likewise, could save substantial amounts of fuel and therefore cost to airlines. The costs for CDAs are modest, especially when considering the ability to achieve and cite large fuel savings. Both strategies only entail procedural changes, and therefore no behavioral changes of individual travelers.

Summary

Figure 5 shows the potential of those categorized sub-strategies, based also on existing literature's estimates available. Interestingly, the chart exhibits the same trend as the maritime shipping figure (Figure 3): those sub-strategies which exhibit low Atshulerian acceptability present more reduction potential, whereas those with high acceptability seem to contribute to GHG reductions to a lesser degree.

Concluding Remarks

Based on the framework presented in this study, two seemingly disparate transportation sectors were shown to share commonalities in terms of transportation GHG emission producing activities. This study presents a unique strategic model for incorporating both system efficiency and component efficiency to examine the various potentials in reducing GHG emissions from the two sectors. It further ranks the political acceptability of these strategies, to facilitate an understanding of carrier responses and potential GHG reduction.

An interesting finding from this study is that strategies with high reduction potentials across modes are the least politically feasibility. This is consistent with incrementalism, or the idea that policies are made in small steps rather than with large changes. Lindblom (1959) discusses the policy making process involving small changes; this framework is applied to large scale transportation systems planning by Smirti and Hansen (2007).

As the various stakeholders in aviation and maritime shipping grapple with climate change and GHG reduction pressures, the smallest actions which involve the least amount of institutional change are being readily adopted. This practice of incremental adoption leads to modest gains in GHG reduction; however, it is an important albeit small step to large reduction gains. While the adoption of technologies and polices at the high GHG reduction potential and low politically acceptability end of the curve will occur, the sectors will have to wait until enough incremental changes have occurred so

that adoption of what seem like "radical" ideas at the present time seem radical no longer.

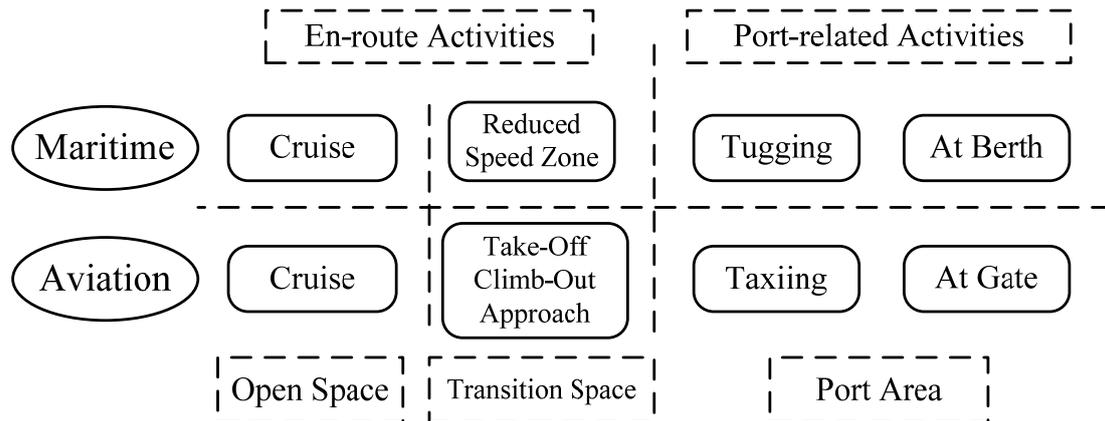**Acknowledgements**

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Figure 1 Activity Similarities Between Aviation and Maritime Shipping Sectors.
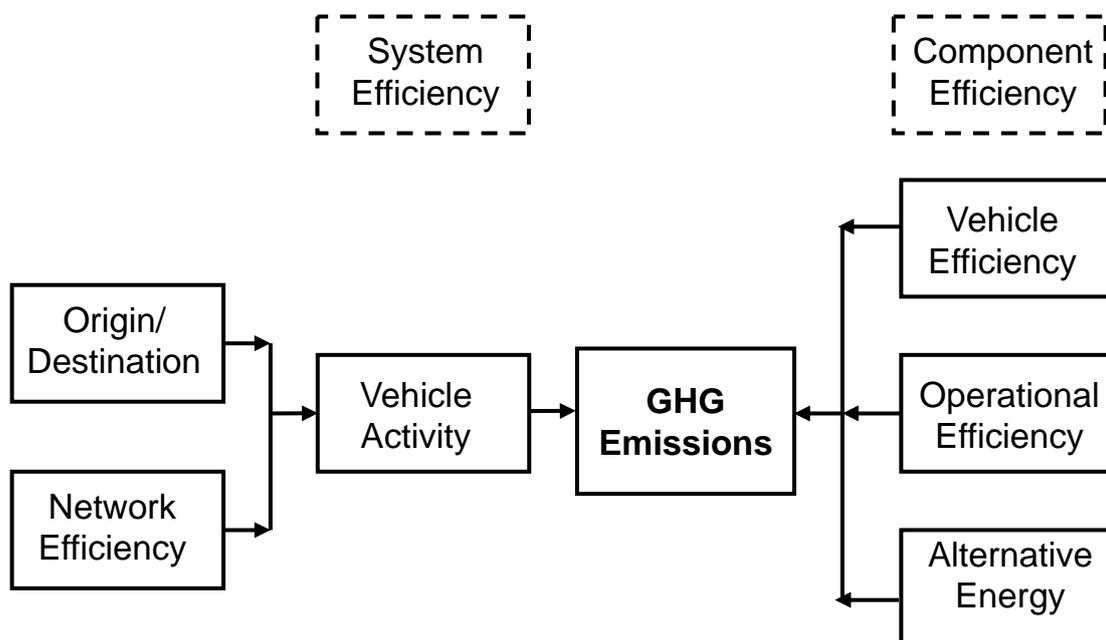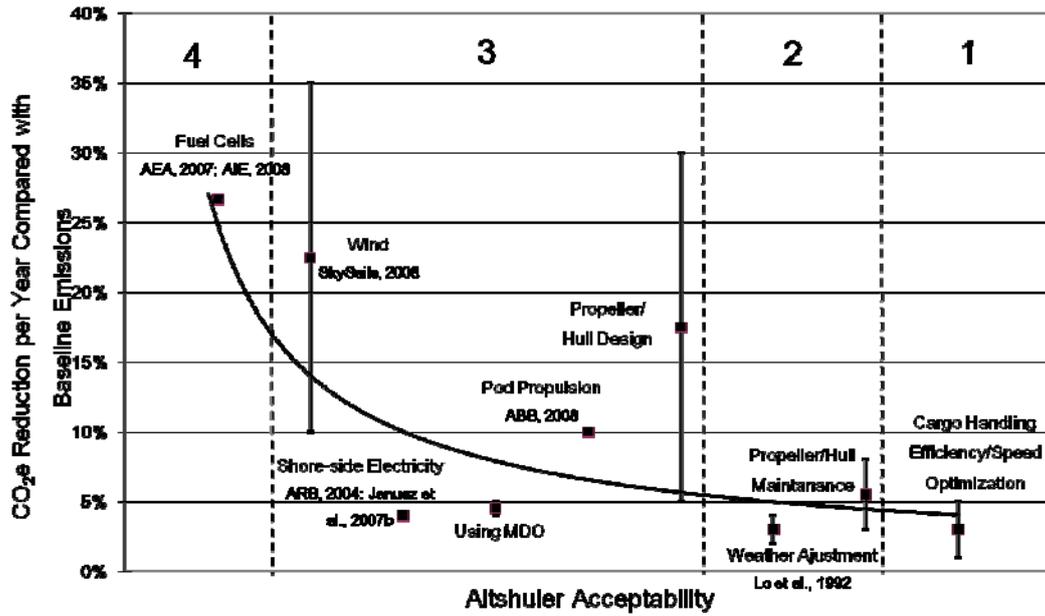

Figure 2 Conceptual Model of Aviation and Maritime Shipping Emissions.

Note: Estimates based on IMO, 2000 unless noted

Figure 3 GHG Reduction Potential and Acceptability
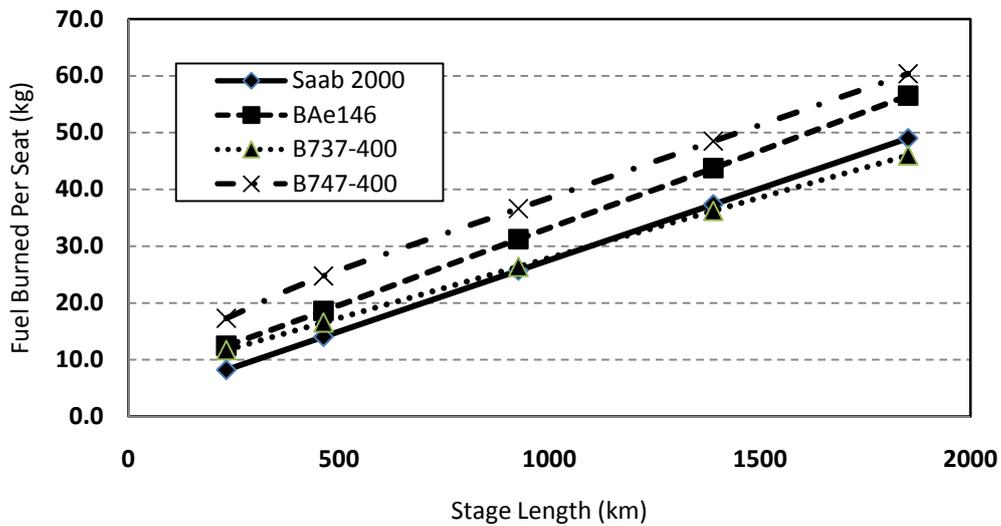of Strategies in the Maritime Sector.

Figure 4 Fuel Burn per Seat vs. Stage Length
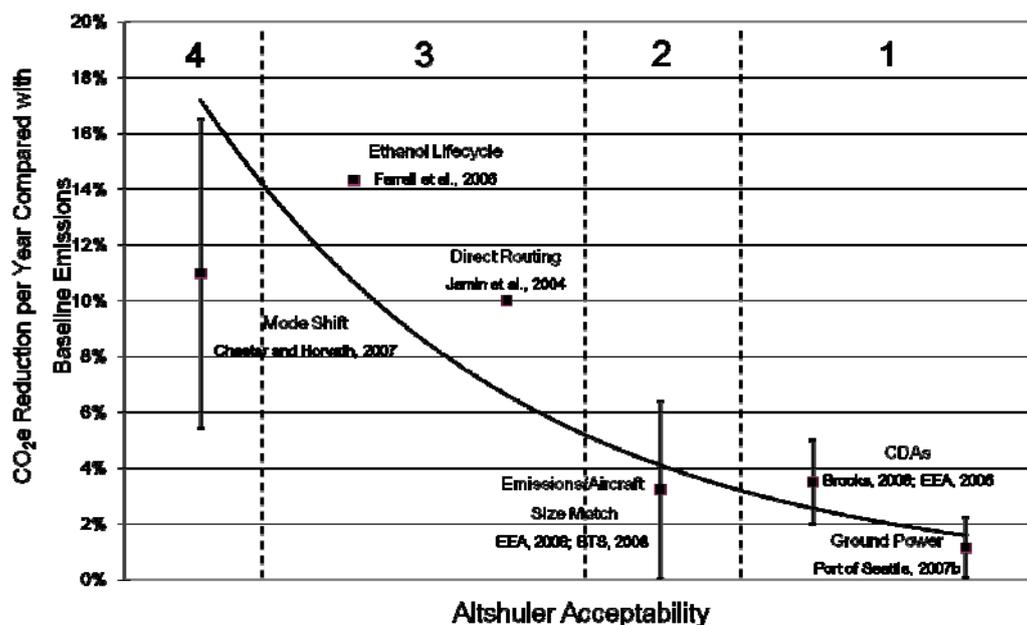for Four Representative Aircraft.

Figure 5 GHG Reduction Potential and Acceptability
of Strategies in the Aviation Sector.

Table 1 GHG Emission for the Maritime Shipping Sector.

GHG Emissions Estimates		Reference
Maritime Shipping GHG Emissions As a Percent of:		
Total Worldwide GHG Emissions	1.8%	Jasper F., 2007
	1.5-3.0%	Friedrich, A. et al., 2007
Port-Related and En-Route Operations GHG Emission Shares (for a standard vessel)		
Total Port-Related GHG Emissions		Calculated based on Janusz et al., 2007b
At Berth	6.3% for European Seas	
Tugging	0.6% for European Seas	
Total En-Route GHG Emissions		
Cruise and RSZ	93.1% for European Seas	
Physical Distribution of Maritime Shipping GHG Emission Shares		
12-nautical mile Territorial Water	10.7% for European Seas	Janusz et al., 2007a
200-nautical mile Exclusive Economic Zone	70% (within 250 miles, or 217 nautical miles of land)	Corbett, 1999
	74-83%	Oftedal, 1996
	79.0% for European Seas	Calculated based on Entec, 2005 and Janusz et al., 2007b

Table 2 GHG Emission for the Aviation Sector.

GHG Emissions Estimates		Reference
Aviation GHG Emissions As a Percent of:		
Total Worldwide GHG Emissions	2-3%	Intergovernmental Panel on Climate Change (IPCC), 1999
	3%	House of Lords, 2005
% of Transportation	13%	IPCC, 1999
Total US GHG Emissions	2.4%	EPA, 2006
% of Transportation	9%	
Port-Related and En-Route Operations GHG Emission Shares (for a Boeing 737)		
Total Port-Related GHG Emissions		Chester and Horvath, 2006
Auxiliary Power (at Gate)	0.7%	
Taxi Out	5.4%	
Take-off	1.5%	
Taxi In	2.0%	
Total En-Route GHG Emissions		
Cruise	83.7%	
Approach	2.7%	
Climb-out	4.0%	

Table 3 Scale Increases in Vessel Size: Evolution of the World Fleet 1991-2006.

	Jan 1991	Shares	Jan 1996	Shares	Jan 2001	Shares	Jan 2006	Shares
>5000 TEU	0	0.0%	30648	1.0%	621855	12.7%	2355033	30.0%
4000/4999 TEU	140032	7.5%	428429	14.4%	766048	15.6%	1339978	17.1%
3000/3999 TEU	325609	17.6%	612377	20.6%	814713	16.6%	892463	11.4%
2000/2999 TEU	538766	29.0%	673074	22.6%	1006006	20.5%	1391216	17.7%
1500/1999 TEU	238495	12.8%	367853	12.3%	604713	12.3%	719631	9.2%
1000/1499 TEU	329578	17.7%	480270	16.1%	567952	11,6%	596047	7.6%
500/999 TEU	191733	10.3%	269339	9.0%	393744	8.0%	438249	5.6%
100/499 TEU	92417	5.0%	117187	3.9%	132472	2.7%	114976	1.5%
TOTAL	1856927	100.0%	2979177	100.0%	4907503	100.0%	7847593	100.0%

Source: Notteboom, 2004

Table 4 Maritime Shipping Alternative Energy Research in Progress.

Energy	Marine Diesel Oil	Solar Panels	Sail	Hydrogen Fuel Cells
Main Ingredient	A blend of gasoil and HFO	Sun, wind, and wave	Wind	Hydrogen and Oxidant
Investigating Organization	N/A	Solar Sailor	SkySails	FCSHIP
Operational GHG Emissions Change from Heavy Fuel Oil	5% of total emissions compared with current marine fuel structure.	Theoretically zero emissions.	Annual average fuel costs can be lowered between 10-35% depending on wind conditions and achievable operational period.	Effectively no operational GHG emissions.
Lifecycle Emissions Change from Heavy Fuel Oil	At worst be CO_2 neutral; dependent upon assumptions, this would result in measurable net CO_2 reduction benefits.	Additional CO_2 emissions believed to be negligible as only solar panels and fins.	Consumption of CO_2 emissions during kite production is marginal.	99% of GHG emissions from fuel supply; 20% lower than marine gas oil/marine diesel oil in terms of lifecycle emissions' assuming equal emission factors of MDO and MGO (Entec, 2005)
Source	IMO, 2000	Intertanko, 2007	Skysail, 2008	AEA Group, 2007

Table 5 Aviation Alternative Energy Research in Progress.

Fuel	Ethanol Blends	Biofuel Blends	Liquid Hydrogen	Gate supplied electric power
Main Ingredient	Jet A mixes, with ethanol from corn	Jet A mixes, with algae, cellulose	Hydrogen	Electric power
Investigating Organization	None	CAAFI, Boeing Co., Virgin America, General Electric	None	Airports/Airlines
Operational Emissions Change from Jet A	Lower energy content would require more fuel; little change in CO_2 emissions from operation; also a drop-in	Little change in CO_2 emissions from operation; also a drop-in	Lower energy content would require more fuel; little change in CO_2 emissions from operation	CO_2 Emissions from power generation, varies between greatly decreased to little change
Lifecycle Emissions Change from Jet A	Decreased CO_2 emissions throughout the lifecycle (13%)	Decreased CO_2 emissions throughout the lifecycle	Lifecycle emissions would be virtually zero	CO_2 Emissions from power generation, varies between greatly decreased to little change
Source	Farrell et al., 2006	Gaffney, 2008	Williams, 2007	Chester and Horvath, 2007

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