Towards true zero-emission vehicles in a single step: Air pollution and greenhouse gas reductions through hydrogen fueled ships with carbon management

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***Abstract*-In this paper, we show that one of the easiest routes to true zero emission transport may be in the marine transportation system (MTS), demonstrated by comparing the opportunities and barriers to entry for H_2/CM systems across all modes. Relying on contemporary theories of technological innovation and diffusion, we identify initial niche markets for H_2/CM fuel systems and hydrogen-fueled vehicles. We identify marine shipping as an important sector for several reasons. First, recent revelations of the important environmental impact of ship emissions have created significant impetus for the first large-scale pollution reductions in the sector. Second, the design and performance tradeoffs of hydrogen storage and propulsion are less challenging for ships than for on-road vehicles. Third, centralized fuel production and distribution is already standard for ships, minimizing the costs of both H_2 infrastructure and CM. Marine propulsion innovation in the shipping industry offers significant potential to achieve both air-quality improvements and greenhouse-gas reductions through a single technology step.**

I. Introduction

Oceangoing ships and inland river vessels have long been considered to have less air pollution impact than other transportation sources. While that may be true under certain metrics, recent research has shown that the impacts of ship emissions on the environment are more significant than previously thought [1-4]. Policymakers now recognize that ships contribute traditional air pollutants that degrade local and regional air quality [5, 6], and are a source of carbon dioxide and other trace gases that influence climate change [4, 7, 8].

These impacts are compounded by two facts. First, globalization and growth in international trade is projected to continue at an average 4% per year, with proportional growth in fleet size and fuel consumption [9, 10]. International shipping uses approximately 2% of the world's fossil fuel, and about 5% of world petroleum [1]. As a result, ships produce about 2% of the world's CO_2 emissions from anthropogenic activity. In terms of traditional pollutants, oceangoing ships account for 14% of global nitrogen emissions and 5% of sulfur emissions from all fossil fuels. Nearly 70% of these pollutants are emitted by ships within 400 km of land, where they can impact air quality in populated coastal regions. Therefore, environmental impacts from these emissions are local, regional and global [11, 12]. Historically, growth in fleet fuel consumption (and related emissions) has averaged about 2% annually [9].

Second, despite recent regulations designed to reduce ship emissions for the first time ever [5, 7, 13], other modes of transportation have long been regulated and continue to become cleaner largely as a result of strict environmental regulation. Moreover, ships perform a substantial amount of the cargo movement on both international and domestic scales. Some 35,000 oceangoing ships annually move cargo more than 12 trillion tonne-km internationally [9, 10], and the tonne-km of waterborne commerce in U.S. waters is nearly equal to that of trucks and rail [14, 15]. This implies that more pressure can be expected to reduce ship emissions even further. Accomplishing these reductions will require advanced control technologies and propulsion modernization in the shipping industry.

Meeting these challenges presents an opportunity for maritime nations and corporations. For example, the U.S. commercial shipbuilding industry, with its technology-driven expertise in Naval ship design is a leader in new technologies. Moreover, the U.S. commercial fleet needs modernization; more than half the oceangoing ships registered under the U.S. flag are steam powered and the average age of vessels in the U.S. fleet is more than 23 years [16]. These environmental requirements present opportunity for industry.

II. Basics of Carbon Management

A. Background

Although transportation has major energy and environmental policy implications, not all sectors are treated equally, and ships are often overlooked. However, shipping in U.S. and international waters is a significant source of air pollution and account for a non-trivial portion of U.S. petroleum demand. The U.S. EPA has proposed moderate emissions standards for new marine engines (more stringent, but harmonizing with standards proposed by the International Maritime Organization), but these will take well over a decade to become effective once they are enacted, and include no energy-policy provisions for ships. Nonetheless, ships may offer cost-effective options for reductions of traditional pollution emissions through the use of alternative fuels and propulsion systems.

The primary focus of research and regulatory action aimed at reducing airborne emissions from transportation is motivated by conventional air quality concerns, not climate. Thus, technological innovation and vehicle design reflect an effort to reduce emissions of pollutants like NO_X, not CO_2. This focus, until recently primarily addressing automobiles, has resulted in a series of cleaner engines, cleaner gasolines, exhaust gas treatment devices, and recently new prime movers (e.g., advanced diesels and fuel cells) and new electric drive trains (e.g. battery or hybrid vehicles). Some efforts have been made to introduce non-petroleum transportation fuels, but these have been relatively ineffective in terms of increasing the percent of alternative fuel, although they have increased the number and quality of alternative fueled vehicles in major cities. In any case climate is not the

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motivating factor here either. We may, arguably, characterize the current policy environment as driven by three maxims: (i) focus on the biggest pollution sources first, (ii) focus solely on conventional emissions, and (ii) focus on engine and drive train improvements first while providing only modest incentives for the introduction of new vehicle fuels.

Although the current focus is elsewhere, we expect that climate concerns will increasingly influence public debate in the near future and judge that serious regulatory action to limit U.S. CO_2 emissions is likely within the next two decades. The deep reductions in CO_2 emissions needed to mitigate anthropogenic climate change will require that all sectors participate in emissions control, including transportation. Achieving large reductions in CO_2 emissions from transportation will likely require the introduction of new transportation fuels that result in little or no emissions of fossil-derived CO_2. There is considerable uncertainty about how to do so cost-effectively, however. Here we examine the possibility of introducing of new fuels: hydrogen and natural gas (NG).

B. Industrial Carbon Management

In simplistic terms, one way to mitigate effects of human activity on the climate is to reduce CO_2 emissions from human activity. Although this effort can take several forms, the one we focus on here, termed Industrial Carbon Management (ICM), attempts to achieve the same energy output with less CO_2 emitted. We define ICM as the linked processes of capturing the carbon content of fossil fuels while generating carbon-free energy products such as electricity and hydrogen, and sequestering the resulting carbon dioxide.

Fig. 1 illustrates the ICM concept using a fossil fuel source. Here, a hydrocarbon fuel such as petroleum is reformed to decouple the carbon from the hydrogen. The long-term use of fossil energy without emissions of CO_2 may be the most cost-effective approach for some time [17]. Note that H_2 *must* be used as a fuel in order to allow CO_2 capture and sequestration. To achieve ICM, onboard reforming is not possible unless CO_2 emissions are also captured onboard – which we judge to be infeasible. We call such hydrogen H_2/ICM. Although many of the component technologies are well known, the idea that ICM could play a central role in our energy future is a radical break with recent thinking about energy system responses to climate change.

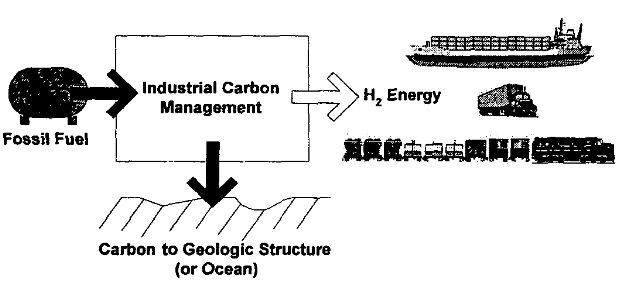

Fig. 1. Conceptual Framework for ICM in Transportation.

Other alternative fuels (particularly natural gas) can be transitional energy sources to traditional hydrocarbon fuels (such as gasoline, diesel, and residual heavy fuel oil). These alternative fuels with smaller carbon:hydrogen ratios can reduce CO_2 emissions without significant reformulation, and some alternative fuel and engine combinations reduce NOx, PM emissions without significant aftertreatment. Most importantly perhaps, liquefied gaseous fuel (LNG) could serve as a transition fuel, although LNG is not a carbon-free fuel.

C. Other Carbon Management Approaches

For completeness, two other carbon management approaches exist in addition to ICM. One is termed biological carbon management, and is aimed at increasing sinks for CO_2 removal. This includes efforts to manage forestation and depletion processes. This paper will not address this method.

The other approach is to increase energy efficiency through efforts such as conservation and power train improvement [18]. In this way carbon emissions are reduced by fuel economy improvements, similar to those accomplished following the energy crises of the 1970s. Since the conversion from sail to marine engines (steam-turbine, gas-turbine, and diesel), the commercial shipping industry led the transportation sector by developing large, slow-speed diesels. Marine diesel engines demonstrate the lowest fuel consumption per brake horsepower of all transportation combustion engines. (The high combustion temperatures and pressures associated with this fuel economy and the heavy residual fuels account for the significant emissions of NOx and SO_2.) Motivation for this was primarily economic; fuel costs can account for as much as 60% of ship operating costs [19]. There is little room for fuel-economy improvement on a per tonne-km basis, especially compared to that of other transportation modes, particularly trucks.

III. Carbon Management Role for Transportation

Transportation accounts for about 500 million tonnes of CO_2, or 1/3 of national CO_2 emissions [20]. This implies that any serious effort to reduce U.S. emissions of CO_2 as part of a climate change mitigation policy will need to include the transportation sector.

In general, there are five systemic challenges for reducing CO_2 emissions from the transportation sector:

1) *Synergistic reduction of CO_2 and conventional pollutants*. ICM is easiest to implement in the sectors with the greatest potential for joint reductions – which are those facing the largest pollution reductions in the future. Here our maxim is simple: Look at transportation systems that have not yet been regulated for conventional pollutants.

2) *Network effects and economies of scale*. The high cost of providing new vehicle fuels at multiple refueling sites poses a significant barrier to the introduction of new fuels. Transportation systems vary greatly in the number and typical size of existing refueling sites (Table I), and this variation strongly influences the choice of where to introduce new carbon-free gaseous transportation fuels. Put simply, centralized fueling helps.

3) *Power plant technology and efficiency gains*. Improved energy efficiencies cannot meet the challenge of deep reductions in transportation CO_2 emissions we take as our motivation. Moreover, since ICM delinks fossil fuel use and

CO_2 emissions entirely, energy efficiency becomes irrelevant compared to economic efficiency. Thus, when considering the deployment of new low emission vehicle/fuels systems then we should focus on improved energy efficiency only to the extent that it improves the economics of such deployment.

4) *Fuel storage.* Current hydrogen storage systems achieve lower energy densities than liquid fuels. Compare, for example, conventional gasoline storage in automobiles with hydrogen storage as high-pressure gas; including tankage, the volumetric energy densities of gasoline and hydrogen are (approximately) 30 and 3 MJ/L and mass densities are 40 and 10 MJ/kg. Liquefied gas storage is somewhat less disadvantageous, but presents other challenges. The major implication of lower densities for gaseous fuels is that for a given platform and trip profile, available space goes down. The best vehicles for the application of gaseous fuels are those with fewer space constraints and less need for rapid acceleration: Here, size does matter.

5) *User considerations.* Climate concerns will require the introduction of new fuels and vehicle that are very different from current technologies. For several reasons, consumer applications are probably the worst place to do this. First, the introduction of new risks is more easily accomplished in the workplace than in consumer products. Second, fuels delivered as highly compressed gases or cryogenic liquids are simply more difficult to handle than liquid fuels, so special training or insurance may be needed. Third, in many commercial applications, there is in-house engineering capability that may further ease the introduction of new technologies.

TABLE I
SYSTEMIC FACTORS

	Emissions (g/kg fuel)[2]		Carbon intensity[3]	Fraction of CO_2	Size of fueling stations	No. of fueling stations
	NO_x	CO	($/tC)	(%)	(power)	
Marine	71	16	950	6	175 MW	28-40[4]
Autos[1]	14	130	2300	56	2.7 MW	180,000
Aircraft	3	17	2100	8.7	240 MW	72[5]
Heavy trucks	30	17	2800	16	20 MW	5,500
Rail	76	9	3500	2.3		

All figures for the United States. All figures rounded to two significant digits. (1) Includes both automobiles and light trucks. (2) Computed using estimated actual emissions and fuel use. (3) End user expenditures divided by carbon emissions. (4) Total of companies in the large U.S. ports providing international marine fuels (@ 4-10 per port). (5) Large hub airports.

TABLE II
1999 REGIONAL BUNKER DEMAND (MILLION TONNES)

Region or Major Port	Number of Bunker Providers	Average Load to Ship (tonnes)	Annual Bunker Demand (10^6 tonnes)	
East Coast				5.9
Port of NY/NJ	5	1040	1.7	
Philiadelphia	NA	1020	1.2	
Gulf Coast				6.1
Port of Houston	7	860	2.4	
New Orleans	NA	770	1.9	
West Coast				6.4
Port of LA/LB	7	1340	2.7	
SF Bay	NA	944	1.3	
Seattle/Tacoma	NA	NA	1.1	
Totals			12.3	18.4

In summary, there are two fundamental problems in addressing CO_2 emissions in transportation sector: Cost and Cost. First, alternative fuels can cost more to produce than petroleum. Second, handling of these fuels is more difficult and therefore more costly at all stages.

IV. WHY CONSIDER SHIPS?

Ships are the most feasible transportation mode for ICM in terms of the five systemic challenges listed above. Shipping accounts for 6% of energy use in the transportation sector, but it is the most carbon-intensive mode. This means that shipping would be most affected by CO_2 reduction policies like a carbon tax. Moreover, marine engine emissions are the least – but increasingly – regulated in terms of traditional air pollutants (NOx, PM, SOx). This means that the benefits of ICM efforts to reduce CO2 will be leveraged significantly by associated reductions in air pollution.

A. *Intermodal Comparisons*

Tables I, II, and III present a comparison of system and end use factors influencing the introduction of new vehicle fuels such as H_2 or NG. In analyzing the economic factors we have used the size and number of fueling stations as an indicator of the importance of centralization. Large marine vessels are probably the easiest case as large ports have only a handful of suppliers. Automobiles are the most challenging due to the extreme dispersion of fueling stations. For example, approximately 400 gasoline stations would have to be converted to capture as much energy infrastructure as converting 2 marine fuel terminals in the major port on each of the three coasts. This would capture only 0.2% of the automobile market, but could account for some 5-7% of the U.S. marine bunker market. In other words, greater fuel centralization offers major economies of scale that favor introduction of ICM into a niche transportation mode like maritime transportation.

TABLE III
END USE FACTORS

Mode	Space, Weight Impacts	Institutional capacity to manage new technology
Marine	low	Dedicated engineer onboard. Experience with hazardous cargo.
Autos	high	Consumers are end users. Factors such as range and ease-of-use likely overwhelm minor differences in operating cost.
Aircraft	very high	Highly trained and well equipped engineering support and institutional familiarity with management of new technologies.
Heavy trucks	moderate	Licensed operators. Heavy truck fueling often separated from automotive fueling. NG now being introduced in some regions.
Rail	low	Dedicated engineering, and experience with hazardous cargo

The carbon intensity figures in Table I indicate which sectors would be most sensitive to any cost imposed for emitting carbon; a uniform charge would affect marine shipping most. The main argument in favor of a Carbon tax is that, while it may not produce immediate reductions in CO2, it will stimulate *technological innovation.* As an example a $100 per ton Carbon tax would raise marine shipping costs by over 10% but trucking costs by less than 4%. Further, since marine shipping is substantially cheaper than other modes and is hard to substitute for, there would be little leakage to other modes. These factors tend to make the economic incentive for the development and deployment of carbon-free fuels strongest and most robust in the marine sector.

B. Marine Propulsion Technologies and Fuel Storage

In principle, an H_2-fueled ship could use a fuel cell (FC) coupled to an electric drive train. As with megawatt-scale land-based electric generation—but unlike automotive applications—high temperatures and long startup times would not be problematic so the favored fuel cell technology might be solid oxide or molten carbonate. In addition, as with land-based generation, both high-temperature fuel cells and IC engines permit the use of a thermal bottoming cycle to boost efficiency. A significant research effort into marine fuel cells now exists, however, the focus is on high reliability auxiliary power rather than propulsion [21].

The possible introduction of fuel-cell-powered cars is currently attracting substantial attention and private investments. The proposed cars would use H_2 directly or would reform methanol or gasoline on-board. Only the direct use of H_2 offers the possibility of dramatic reduction in CO_2 emissions. Fuel cells can achieve very high efficiencies and near-zero emissions, however, the capital costs are still prohibitively expensive and thus fuel cell vehicle technology has yet to move beyond the demonstration of prototypes. The trade-offs between fuel cells and internal combustion (IC) engine technology is strongly dependent on power plant size. The efficiency of IC engines increases strongly with size, while typical fuel cell technologies have efficiencies that are roughly independent of size. At the largest sizes (tens of MW) IC engines have efficiencies roughly equal to that provided by fuel cells at a capital cost that is at least an order-of-magnitude smaller (see Table IV). Moreover, these large IC engines can easily run on NG, H_2 or conventional fuels.

Therefore, it seems highly implausible that fuel cells could be economically competitive for marine propulsion at least in the near term. The trade-offs between FC and IC power plants for ships are very different from those for personal automobiles, basically because the much smaller IC engines in cars are much less efficient (about 25% thermal efficiency) than the very large marine engines. For automobiles it is argued that the efficiency of hydrogen fueled FC power plants could be 50 to 100% higher than the efficiency of current engines, and that this efficiency advantage could outweigh the capital cost penalty. For ships however, the efficiency of IC engines is roughly equal to the projected efficiency of FC systems and the costs of IC engines are substantially smaller.

However, IC propulsion engines powered by liquefied gaseous fuels may be feasible, and may also promote the use of fuel cells as auxiliary power sources. Table V summarizes typical energy requirements for several marine applications, and the mass and volume of fuel required. Two general classes of vessel application are shown: Oceangoing cargo service, and regional ferry service. Calculations are based on data for hydrogen reformers that produce liquefied hydrogen (LHY) fuel [22].

Potential fuel storage requirements can be evaluated by considering the infrastructure needed to meet the energy of each application in Table V. The first oceangoing case illustrates a 12.5-day voyage for a large containership; this would be equivalent to a Los Angeles (LA) to Hong Kong route with refueling at each end of voyage, or to a New York (NY) to Rotterdam route refueled only in NY. For these scenarios, a medium-sized reformer (with a capacity of 27 tonnes per day) could meet this demand if the LHY-powered ship visited the fueling port once a month. The second oceangoing case represents a 6-day transit from NY to Rotterdam with LHY provided at each end. In this case, installing one large natural gas-to-hydrogen reformer (with a capacity of 270 tonnes per day) at each port could meet the demand of 10 large containerships arriving in port every three days.

TABLE IV
IC ENGINE COSTS PER POWER FOR RESIDUAL (HFO) FUEL AND GAS/DIESEL ENGINE SYSTEMS

Cost ($/W)			Power Range (kW)		Capital Costs ($k)	
	Wartsila Engines		Lower Bound	Upper Bound	Engine Only	Compression System
$0.15	18V46	Diesel (HFO)	16,290	17,550	$2,565	
$0.20	18V46	Gas Diesel	15,638	16,848	$2,718	$560
$0.11	18V32	Diesel (HFO)	6,660	6,750	$724	
$0.21	18V32	Gas Diesel	6,394	6,480	$896	$460
	Sulzer Engines					
$0.19	7RTA84	Diesel (HFO)	28,350	28,350	$5,300	

TABLE V
MARINE FUEL DEMAND AND ONBOARD STORAGE REQUIREMENTS

Marine Application	Energy (GJ)	Base-Case Fuel Demand	LNG[1] Fuel Demand	LHY Fuel Demand
Large Containership[2]; LA-Hong Kong one way or NY-Rotterdam round trip	110,000	2800 t 18 kbbl	1900 t 29 kbbl	790 t 69 kbbl
Large Containership[2]; NY-Rotterdam one way	54,000	1400 t 9 kbbl	920 t 14 kbbl	380 t 33 kbbl
Small ferry[3]; daily service	49	4.2 t 8 bbl	0.84 t 13 bbl	0.34 t 35 bbl
Large ferry[3]; daily service	230	5.9 t 38 bbl	4 t 60 bbl	1.6 t 170 bbl
Boston Ferry System[3]; system-wide daily service	650	17 t 110 bbl	11 t 170 bbl	4.6 t 470 bbl
Proposed SF Ferry System[3]; system-wide daily service	29,000	730 t 4.7 kbbl	490 t 7.4 kbbl	200 t 21 kbbl

(1) LNG calculations are based on methane properties; (2) Base-case fuel is residual oil; (3) Base-case fuel is diesel oil. All figures rounded to two significant digits.

For regional ferry service, we calculate the daily energy requirements for several scenarios. Based on the energy required to operate one small ferry vessel (based on a 49-passenger ferry) or one large ferry (based on a 149-passenger ferry), one medium reformer could supply as many as 78 small ferries or 17 small ferries.

This suggests that a regional ferry system could convert to LHY with currently available technology. Taking the last two scenarios in Table V, we estimate that one medium reformer loaded at less than 20% could fuel the entire Boston Ferry System daily. Similarly, the proposed ferry expansion in the San Francisco Bay Area could be fueled by 8 medium LHY reformers. (Note that in all cases, fuel consumption depends on route, speed, and hours of operation.)

An important additional insight in Table V is that the mass and volume trade-off that currently informs the design of petroleum-fueled ships is very different for liquefied gaseous fuels. The different densities between fuel oil (residual and diesel) and liquefied gaseous fuels (LNG and LHY) may enable innovations in shipboard fuel-storage design. Losses in payload volume occur under both LNG and LHY, but these larger volumes have much less mass than traditional fuel oil. Comparing the base-case and LHY fuels for the large containership, the 3.8-times volume "penalty" of LHY is nearly offset by a 3.5-times mass "savings". This may enable ship designers to reconfigure cargo storage so that heavier-packed cargoes may offset the volume losses.

C. *Economic Analysis*

We provide a first-order economic analysis to compare the cost of mitigating emissions through ICM in maritime transportation. The cost of mitigation (COM) may be computed as follows:

$$COM = \frac{E_b - E}{c_f + c_c - c_b} \qquad (1)$$

Where E is the emissions (NO_x or CO_2) and c is the cost per unit delivered energy. The subscript b denotes the base case value, f denotes fuel cost and c denotes capital cost, as defined by equations (2) and (3). The additional capital cost and the lifetime output are computed assuming a 20 year life and a discount rate of 5%. The input assumptions and computed COM is presented in Table VI. The fuel costs and the capital costs for a FC power plant are the most uncertain.

$$c_f = \frac{\text{Fuel price}}{\text{Engine Efficiency}} \qquad (2)$$

$$c_c = \frac{\text{Additional capital cost}}{\text{Lifetime output energy}} \qquad (3)$$

The additional capital cost and the lifetime output are computed assuming a 20 year life and a discount rate of 5%. The input assumptions and computed COM is presented in Table VI. The fuel costs and the capital costs for a FC power plant are the most uncertain.

V. Opportunities for Research and Innovation

Based on these results, the maritime sector should pursue several research efforts in support of marine ICM applications. First, the analyses presented here could be extended to other types of vessels to determine whether they also show promise. In particular, combined pollution and carbon emissions reduction may be feasible for some research vessels. Moreover, developing ICM tools for oceanographic research vessels may demonstrate the potential for these technologies in other marine applications, even if research ships that may operate at sea for extended periods (e.g., months) are not be the most feasible platform for this concept. This concept should be put on the research agenda, at least for federally supported academy training ships and perhaps for general oceanographic research vessels.

Despite the current advantages of LHY-fueled IC engines over fuel cell technologies for propulsion applications, marine fuel-cell development should continue. This technology has clear potential for clean auxiliary power that may complement ICM for main propulsion. This research could build on current Navy research into fuel cells. The true-zero emission ship of the future may be a hybrid vessel fueled by LHY, with propulsion using IC main engines, and with auxiliary power employing both IC engines and fuel cells, as appropriate.

TABLE VI
ECONOMIC ANALYSIS OF H_2/ICM IN MARINE FREIGHT TRANSPORTATION

	Residual fuel (base case)	Natural Gas	Hydrogen	Hydrogen fuel cell
Fuel price ($/GJ)	3	5	7	7
Engine efficiency (%)	50	50	50	55
Additional capital cost ($/GJ-output)	0	0.5	0.5	4
NO_x emissions (kg/GJ-output)	4	2	0.5	0
CO_2 emissions (kgC/GJ-output)	39	27	0	0
Cost of NO_x mitigation ($/t$NO_x$)		2250	2429	2682
Cost of CO_2 mitigation ($/tC)		375	218	275

Acknowledgment

This work was supported by NSF grant SBR9521914, the Carnegie Mellon University Green Design Initiative, and by academic funds of the Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA. We also thank Jamie Winebrake for his valuable comments on earlier drafts.

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