SOUTH COAST AIR QUALITY MANAGEMENT DISTRICT

DRAFT

Technology Assessment: Commercial Harbor Craft








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EXECUTIVE SUMMARY

This executive summary presents the South Coast Air Quality Management District (SCAQMD) and the California Air Resources Board (ARB) staff's *Technology Assessment for Commercial Harbor Craft*.

Because of its geographical location and major ports and railways, California is a global gateway for goods movement. Some of the largest ports in the world are located in California, and with increases in trade and general goods movement, activity in the ports stands to grow over the next two decades. Commercial harbor craft are a significant source of emissions of diesel PM and NOx in California. Also, harbor craft operations are often located near densely populated areas exposing residents to unhealthy levels of pollutants. Commercial harbor craft such as ferries and water taxis carry passengers at commercial marine ports.

As part of a larger effort to assess the state of technology to further reduce emissions from goods movement related sources, presented below is an overview which briefly describes the commercial harbor craft sector, the technology assessed, and the proposed next steps. It should be noted that this summary provides only a brief discussion on these topics. The reader is directed to subsequent chapters in the main body of the report for more detailed information.

The South Coast Air Quality Management District staff conducted a technology assessment for commercial harbor craft to identify technology options that are either commercialized or can be commercialized to help meet air quality standards and, in the longer term, climate change goals.

Types of commercial harbor craft

Commercial harbor craft includes a wide range of vessels, barges, and dredges that are regulated by the ARB under the Commercial Harbor Craft Regulations (ARB, 2011). Pleasure craft, portable equipment used in harbors and ports, and dockside mobile equipment are not regulated through the ARB Commercial Harbor Craft Regulations and are not included in this assessment. Harbor craft included in this assessment include barges, fishing vessels, crew/supply vessels, dredges, ferries, excursion vessels, pilot and other government vessels, tow/push boats for barges, tug boats for assisting ocean going vessels, and work boats for harbor construction and maintenance activities.

ARB staff estimates (ARB, 2014) that in 2015 there will be about 3,800 commercial harbor craft vessels operating in California harbors and coastal waters. It is estimated that these vessels are equipped with approximately 7,800 propulsion and auxiliary engines; the auxiliary engines are primarily generators, for ship-board utility power.

Locations of commercial harbor craft

Commercial harbor craft are used throughout California harbors, bays, and other coast waters but are heavily concentrated at the principal California commercial ports of Long Beach, Los Angeles, Oakland, and San Francisco which collectively are home to 53% of California-based commercial harbor craft. It is expected that these commercial harbor craft will remain concentrated at these ports in the future.

Commercial harbor craft technologies assessed

This assessment includes the state of engine technology in the current commercial harbor craft fleet and developments in engine technology, alternative fuels, engine retrofit technologies, fuel cells, batteries, renewable energy sources, hybrid systems combining multiple technologies, and vessel efficiency improvements.

Additional work or information needed to refine and improve the assessment

Cost information was particularly difficult to obtain because technologies other than conventional diesel engines are not widely used. Where advanced technologies are used, the project costs are either not reported or, in the case of demonstration projects, costs are typically subsidized and are not representative of commercialized price levels because typical economies of scale have not been realized.

Main challenges to reducing emissions from commercial harbor craft

Commercial harbor craft are very different in terms of vocation, usage, engine horsepower and emission certification. This provides a challenge to technology providers because each vessel has individual characteristics affecting design and installation. In addition, commercial harbor craft engines have long service lives and only a few hundred may be replaced statewide each year.

Next steps and technologies to be developed and deployed

There are three principal factors leading to deployment of low emission technologies: compliance with the Commercial Harbor Craft regulation, incentive funding for surplus emission reductions, and reduction in fuel cost. The Commercial Harbor Craft regulation will result in average fleet emissions equivalent at least to Tier 2 by 2023 through the deployment of current technology engines. To the extent that advanced technologies provide fuel cost savings either through hybridization or fuel replacement, market forces will encourage their adoption.

Near term emission reductions are most likely to be provided by replacement of marine Tier 1 and older engines with lower emission marine Tier 3 or Tier 4 engines. Most replacements will be driven by regulation but incentives can accelerate replacement prior to the scheduled date in the regulation. Additional near term emission reductions can be provided by hybridization of existing or new vessels. Demonstration of fuel cells and battery electric propulsion systems should be encouraged and lower emission standards for marine engines should be considered and, when appropriate, adopted.

Longer term emission reductions can be obtained from lower emission standards, fuel cell, and battery electric systems for selected vessel categories. Combustion engines are expected to remain the principal technology for harbor craft through 2025. Fuel cell and battery electric systems should be demonstrated as the technologies mature.

Future activities

This assessment will provide input for development of sustainable freight strategies, the State Implementation Plan, research/demonstration projects, ARB's mobile source control program, and incentive programs to facilitate deployment of lower emission commercial harbor craft.

Recommendations

The following steps are recommended to encourage low emission technology deployment:

- Develop technology mechanisms to send market signals to technology developers/providers to commercialize their technologies as early as possible to meet air quality standards and climate change goals.
- Continue and expand Carl Moyer Program funding for engines and technologies certified/verified to low emission standards.
- Continue to conduct and expand demonstrations to bring to market more low emission technologies.
- As technologies mature, adopt more stringent regulations and standards.
- Conduct outreach on the advantages of advanced technologies including payback from fuel cost savings.
- Provide infrastructure funding for alternative fuels (e.g., natural gas and hydrogen) in harbors.

I. INTRODUCTION AND PURPOSE OF ASSESSMENT

The technology assessments evaluate the current state and projected development of mobile source technologies and fuels. For each technology, the assessment will include a description of the technology, its suitability in different applications, current and anticipated costs at widespread deployment (where available), and emissions levels.

These technology and fuels assessments support ARB planning and regulatory efforts, including:

- California's integrated freight planning,
- State Implementation Plan (SIP) development,
- Funding Plans
- Governor's ZEV Action Plan
- Governor's Petroleum reduction goals

II. OVERVIEW OF COMMERCIAL HARBOR CRAFT SECTOR

A. Types of Equipment and Uses

Commercial harbor craft include a variety of vessel types including ferries, excursion vessels, tugboats, towboats, crew vessels, work boats, commercial and charter fishing boats, and other types of harbor craft. These vessel types are described in Table II-1 below.

Table II-1: Categories of Commercial Harbor Craft

Vessel Type	Description
Commercial Fishing	Vessels used in the search and collection of fish for the purpose of sale at market.
Charter Fishing	Vessels available for hire by the general public and used for the search and collection of fish for the purpose of personal consumption.
Crew and Supply	Vessels used for carrying personnel and supplies to and from offshore and in-harbor locations, including vessels at anchorage, construction sites, and off-shore platforms.
Ferry/Excursion	Vessels used for public use in the transportation of persons or property as a part of the public transport systems and commercial vessels used for sightseeing, whale watching, and dinner cruising, etc.
Pilot Vessel	Vessels used to carry pilots to and from ships to provide pilot service into and out of a port or harbor.
Towboat/Pushboat	Vessels used to push barges and pontoons. Towboats are characterized by a square bow with steel knees for pushing, a shallow draft, and powerful engines. They are most often seen on inland waterways since their hull designs (like little freeboard) would make open ocean operations dangerous.
Tug Boat	Vessels primarily used to assist other vessels maneuvering in harbors, over the open sea or through rivers and canals by pushing and towing. They are also used to tow barges, or other floating structures.
Work boat	Vessels used to perform duties such as fire/rescue, law enforcement, hydrographic surveys, spill/response research, training, and construction.
Other	Vessels used in various commercial operations that do not fit into any other category such as vessels used to dispose of cremated remains.

ARB staff estimates (ARB, 2014) that in 2015 there will be about 3,800 harbor craft vessels and 7,800 harbor craft engines in use in California. Of these, there are nearly 600 ferries, excursion vessels, tugboats, and towboats equipped with about 1,900 propulsion and auxiliary engines directly involved in goods movement and passenger transportation. An additional 2,600 fishing vessels with 3,300 engines are located mostly along the California coastline, with some on inland waterways. This inventory covers commercial harbor craft that operate within California coastal waters and inland waterways, and have a home port located in California. Due to limited information currently available about the number of U.S. Navy and/or U.S. Coast Guard (USCG) vessels, vessel characteristics, and vessel activity, emissions from these vessel types are not included in this inventory. Essentially all commercial harbor craft are powered by diesel engines. In 2015, commercial harbor craft are estimated to emit approximately 1.9 tpd of diesel PM and 48 tpd of NOx statewide. The estimated number of vessels, engines, and emissions in 2015 for each vessel type in 2015 is provided in Table II-2 .

Table II-2: Commercial Harbor Craft Vessels and Emissions in 2015 (ARB, 2014a)

Vessel Category	Number of		2015 Pollutant Emissions, Tons/Day				
	Vessels	Engines	PM	NOx	HC	CO	CO2
Barges and Dredges	257	404	0.06	1.53	0.08	0.50	22.10
Commercial Fishing	2,002	3,162	0.57	12.92	0.79	3.58	82.18
Charter Fishing	602	1,517	0.47	10.70	0.72	3.82	96.30
Ferries and Excursion	447	1,448	0.45	12.56	1.06	7.79	190.61
Tugboats	128	450	0.20	6.22	0.53	4.34	99.40
Towboats	40	132	0.04	1.33	0.12	1.00	22.99
Crew and Supply	66	236	0.04	1.16	0.12	0.74	17.51
Pilot	27	52	0.01	0.33	0.02	0.12	3.16
Workboats	97	173	0.01	0.30	0.02	0.13	2.89
Other	151	238	0.06	1.34	0.09	0.45	11.37
Total	3,816	7,812	1.93	48.39	3.55	22.47	548.45

Table II-3 shows the estimated number of vessels, engines, and emissions by vessel type in 2030. Overall, the commercial harbor craft population is estimated to increase about 2% although the number of commercial fishing boats is forecast to decrease. Emissions of NOx and PM decrease with decreasing standards, while other pollutants increase slightly due to activity and vessel count.

Table II-3 - Commercial Harbor Craft Vessels and Emissions in 2030 (ARB, 2014a)

Vessel Category	Number of		2030 Pollutant Emissions, Tons/Day				
	Vessels	Engines	PM	NOx	HC	CO	CO2
Barges and Dredges	249	384	0.01	0.06	0.02	0.30	0.02
Commercial Fishing	1,938	3,062	0.43	9.80	0.67	3.51	76.56
Charter Fishing	629	1,585	0.25	6.89	0.64	4.60	101.58
Ferries and Excursion	503	1,628	0.26	10.26	1.11	10.64	214.77
Tugboats	128	449	0.16	5.53	0.54	4.96	100.37
Towboats	47	156	0.03	1.33	0.14	1.30	26.80
Crew and Supply	66	236	0.02	0.94	0.12	0.85	17.51
Pilot	28	54	0.01	0.19	0.02	0.14	3.11
Workboats	110	197	0.01	0.20	0.02	0.16	3.48
Other	176	277	0.04	0.99	0.08	0.59	13.65
Total	3,874	8,028	1.24	36.21	3.37	27.05	557.85

Commercial Fishing Boats

Commercial fishing boats are the most common type of commercial harbor craft representing 52% (2,000) of California vessels. Commercial fishing vessels are based in all major ports as well as many minor ports along the coast. The commercial fishing fleet has been decreasing due to competition and decline of local fisheries but is still expected to represent at least 50% of the vessel population over the next several decades.

Commercial fishing vessels come in a range of sizes and shapes based on function, e.g. trawlers, crab/lobster boats, etc. Most have a single propulsion engine; although some have two propulsion engines. There are approximately 3,100 propulsion engines with an average of 230 hp. There are also approximately 1,250 auxiliary engines with an average of 71 hp. Fishing vessels are based at a home port and make 1-3 day fishing trips.

<u>Charter Fishing Boats</u>

Charter fishing boats are for hire to individuals and organizations to go out for day trips for sport fishing. Charter fishing boats can be small for a few guests or large enough to carry a large group. Most have dual propulsion engines averaging 380 hp and one auxiliary engine averaging 50 hp. There are approximately 600 charter fishing boats with 1000 propulsion engines and 420 auxiliary engines.

<u>Crew and Supply Boats</u>

Crew and supply boats operate between harbors and off-shore oil platforms, ships at anchor, and coastal islands. They carry personnel, construction materials and operating supplies. The vessels are designed for high speed operation in order to minimize transit times between pickup and drop off locations. There are approximately 70 crew and supply vessels with 163 propulsion engines averaging 500 hp and 73 auxiliary engines averaging 110 hp.

<u>Ferries and Excursion Vessels</u>

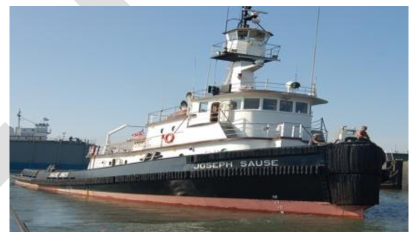
Ferries and excursion vessels are designed primarily for passenger transport and were combined in the ARB inventory. Ferries operate primarily in the San Francisco Bay area and between the Channel Islands and mainland in Southern California. Excursion vessels operate throughout California's coastal waters and include whale watching, dinner cruises, recreational diving, harbor tours, and other similar activities. Ferries operate on fixed routes and are designed to make each transit at the highest practical speed consistent with weather/sea conditions and fuel efficiency. Excursion vessels operate on more flexible routes and may include low speed or idling as part of the excursion. Ferries may also be used for excursion trips during off-peak hours. There are 416 ferry and excursion vessels with 836 propulsion engines averaging 733 HP and 512 auxiliary engines averaging 94 horsepower.

Tow/Push Boats

Tow boats and push boats are used to move and position barges in harbors and inland water ways. There are 35 tow or push boats in California with 74 propulsion engines averaging 500 hp and 41 auxiliary engines averaging 79 hp.

Tug Boats

Tug boats move and position vessels during entry into harbors and during arrival and departure from berths. There are 128 tug boats with 246 propulsion engines averaging 1,275 hp and 204 auxiliary engines averaging 111 hp.



Work Boats

Work boats assist with construction and maintenance of harbor facilities, research, and government functions including law enforcement and fire protection. Boats may be equipped with welders, air compressors, pumps, cranes, and other specialized equipment. There are 89 work boats with 130 propulsion engines averaging 239 hp and 28 auxiliary engines averaging 101 hp.

Pilot Vessels

Pilot vessels carry pilots to and from ocean going vessels as they approach or depart ports. Pilot vessels are small but highly maneuverable. There are 27 pilot vessels at commercial ports in California with 46 propulsion engines averaging 408 hp and 3 auxiliary engines averaging 30 hp.

Barges

Cargo barges carry liquid, bulk, and containerized cargo within and between harbors. Work barges may carry construction materials or equipment. Barges are moved and positioned by tug or push boats. Four propulsion engines were inventoried in barges averaging 251 hp along with 314 auxiliary engines averaging 346 hp. Auxiliary engines are used to power generators, pumps, air compressors, and cranes on the barges.

Dredges

Dredges are special purpose barges used to construct and maintain channels, berths, docks, breakwaters and other facilities in harbors and ports. Dredges may use a suction hose, continuous bucket, or clam shell bucket. A few dredges have propulsion engines but most are positioned and moved by a tug or push boat. There are 18 dredges with 6 propulsion engines averaging 2,708 hp and 77 auxiliary engines averaging 812 hp. Auxiliary engines are used to power generators, pumps, air compressors, and dredge machinery.

Other Vessels

Vessels include commercial vessels that don't fit into other categories. There are 136 vessels with 151 propulsion engines averaging 281 horsepower and 63 auxiliary engines averaging 56 horsepower.

B. Regulatory Requirements

1. New Engine Standards

The United States Environmental Protection Agency (U.S. EPA) regulates Category 1 and Category 2 marine diesel engines up to 3700 kw (4962 hp) which includes nearly all commercial harbor craft. Marine engine standards apply to propulsion engines and auxiliary engines designed for use on marine vessels including commercial harbor craft. Table 4 shows the marine engine standards and their earliest effective date. The standards were phased in over several years based on engine design and rated power and will be fully implemented by 2018, including Tier 4 standards.

Auxiliary engines used in gen-sets, cranes, winches, and pumps may also be certified under off-road engine regulations. These standards are more stringent than marine standards. Off-road Tier 4 standards generally require diesel particulate filters and selective catalytic reduction systems which may not be required to comply with marine Tier 4 standards. Off-road standards, shown in Table II-5, illustrate that lower marine standards are technically feasible.

Table II-4
U.S. EPA Marine Engine Standards for Category 1 and Category 2 Engines Used in Commercial Harbor Craft

Category	Tier	Starting Dates	PM (g/bhp-hr)	NOx (g/bhp-hr)
1	1	2004	---	7.3 - 12.7
	2	2004 - 2007	0.15 - 0.3	5.4 - 5.6
	3	2009 - 2014	0.08 - 0.22	3.5 - 5.6
	4	2014 - 2017	0.03 - 0.09	1.3
2	1	2004	---	7.3 - 12.7
	2	2007	0.2 - 0.37	5.8 - 0.82
	3	2013	0.1	4.6
	4	2014 - 2017	0.03 - 0.19	1.3

Notes:
1) Starting date and emission standard vary by engine horsepower category and cylinder displacement.
2) Tier 1 and Tier 2 standards are codified in 40 CFR Part 94.
3) Tier 3 and Tier 4 standards are codified in 40 CFR Part 1042.
4) Tier 1 NOx standard is 33.57 x $rpm^{-0.2}$.
5) Tier 2 and Tier 3 NOx standards are for NOx +Total HC.
6) Tier 4 standards do not apply to engines with maximum power < 800hp (600 kW).

2. Commercial Harbor Craft Regulation

On November 15, 2007, the California Air Resources Board (ARB) adopted the Commercial Harbor Craft Regulation to reduce emissions from diesel engines on commercial harbor craft vessels. The regulation is expected to reduce diesel particulate matter (PM) by 75% and oxides of nitrogen (NOx) emissions by 60% from harbor craft engines. The regulation, effective November 19, 2008, includes requirements for both new and in-use diesel engines used on commercial harbor craft operating in Regulated California Waters including internal, estuarine, and coastal waters.

All commercial harbor craft owner/operators are required to keep records for each vessel, and install (if not already installed) a non-resettable hour meter on each engine, and use low sulfur CARB diesel to fuel their engines All owner/operators were required to submit an initial report to the ARB in 2009. Vessel owner/operators are required to keep a copy of their initial report and subsequent yearly records on the vessel or in a central dockside location to be made available upon request of ARB staff.

Table II-5
U.S. EPA Off-Road Engine Standards for Auxiliary Engines Used in Commercial Harbor Craft

Tier	Starting Dates	PM (g/bhp-hr)	NOx (g/bhp-hr)
1	1996 - 2000	0.4 - 0.6	6.9 - 7.1
2	2001 - 2005	0.15 - 0.6	4.8 - 5.6
3	2006 - 2008	0.15 - 0.30	3.0 - 3.5
4 Interim	2008 - 2012	0.01 - 0.22	3.0 - 5.6
4 Final	2013 - 2015	0.01 - 0.03	0.3 - 3.5

Notes:
1) Starting date and emission standard vary by engine horsepower category ($\geq$25 hp)
2) Standards are codified in California Code of Regulations Title 13, Section 2423.
3) Tier 1 NOx standards below 50hp are for NOx + NMHC.
4) Tier 2 and Tier 3 NOx standards are for NOx + NMHC.
5) Tier 4 Interim standards below 750hp are for NOx + NMHC.
6) Tier 4 Final standards below 75hp are for NOx + NMHC

The engines on all newly built commercial harbor craft vessels will be required to meet the U.S. EPA marine engine emission standards in effect at the time the vessel is acquired. Newly acquired engines for all in-use harbor craft will be required to meet the Tier 2 or Tier 3 standards (or Tier 4 in certain cases) in effect at the time the vessel owner/operator acquires the engine. This provision ensures that as older engines on in-use vessels are retired, they will be replaced with the cleanest available engines.

Propulsion engines on newly built ferries will be required to be even cleaner than the Tier 2 and Tier 3 standards. All newly built ferries acquired after January 1, 2009, with capacity for 75 or more passengers, will be required to install on the propulsion engines the best available control technology (BACT) in addition to having engines that meet the applicable Tier 2 or Tier 3 standards in effect at the time of acquisition. Alternatively, ferry vessels may comply with the regulation by installing propulsion engines that meet the Tier 4 standards.

The regulation requires existing Tier 1 and earlier auxiliary and propulsion engines on in-use ferries, excursion vessels, tugboats, towboats, crew and supply vessels, barges, and dredges to meet U.S. EPA Tier 2 or Tier 3 standards in effect at the time the engine is brought into compliance with the regulation. There are two regulation compliance schedules: one for vessels with their home ports outside of the South Coast Air Quality

Management District (SCAQMD), and an accelerated schedule for vessels with their home ports in the SCAQMD. Both schedules are based on the engine model year and hours of operation and are designed to replace the oldest, highest use engines first. The vessel owner/operators are required to submit a report about how they plan to comply with these requirements and then an additional report when they have completed compliance.

By 2025, harbor craft diesel PM emissions will be reduced about 75 percent and NOx emissions about 60 percent compared to the 2004 baseline. These reductions will result in a decrease of over 60 percent for the population impacted by a cancer risk of 10 in a million and avoid approximately 310 premature non-cancer deaths statewide by 2025, as well as prevent numerous other non-cancer health effects.

The total cost of regulatory compliance for affected businesses is estimated to be approximately $140 million over the life of the regulation. The cost-effectiveness is estimated to be about $29 per pound of diesel PM reduced, if all costs are attributed to reducing diesel PM. If the costs are split evenly between reducing PM and NOx, the cost effectiveness is estimated at $14 per pound of PM and $1,800 per ton of NOx. Health cost savings due to reduced mortality and reduced incidences of non-cancer illnesses are estimated at a total valuation of $1.3 billion to $2 billion, calculated using U.S. EPA methodology.

3. International Standards and Practice

The International Maritime Organization (IMO) is a specialized agency of the United Nations with the responsibility to develop and maintain a comprehensive regulatory framework for worldwide shipping. The result is a comprehensive body of international conventions, supported by hundreds of recommendations governing every facet of shipping including safety, environmental concerns, legal matters, technical co-operation, maritime security and the efficiency of shipping. The IMO's International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI, which came into force in May 2005, set international NOx emission limits on marine engines above 130 kw (175 hp and higher) installed on new ocean going vessels. In October 2008, the IMO adopted an amendment which placed a global limit on marine fuel sulfur content of 0.1 percent by 2015 for specific areas known as Emission Control Areas (ECA). The ECA extends 200 nautical miles from the U.S. coast. In addition, the 2008 IMO amendment required that new ships built after January 1, 2016 entering an ECA must meet a Tier III NOx emission standard which is 80 percent lower than the Tier I emission standard. The IMO NOx standards were superseded by standards adopted by the U.S. EPA for commercial harbor craft engines up to 3,700 kW (5000 hp) but remain in force on U.S. built marine engines >3,700 kw. No other criteria pollutants are directly regulated by IMO by emission rate although specific operational or fuel sulfur requirements apply to SOx, VOCs on tankers, and ozone depleting gases.

European regulations do not specifically address harbor craft but rather address inland water ways. As in the U.S., there is a substantial difference between emission standards for marine engine emissions and truck engine emissions. The result is concern that the significant amount of goods movement by inland waterway compared to truck transport is impacting emission reduction goals. As a result, an amendment to the current European Union (EU) Commercial Craft Directive 97/68/EC (EU Stage IIIA) is being proposed to reduce emissions. In addition, incentive programs such as the Norwegian NOx Fund (Hoibye, 2012) encourage accelerated NOx emission reductions..

C. Commercial Harbor Craft Inventory

Table II-6 presents the harbor craft vessel and engine inventory forecast for 2015 calculated using the ARB harbor craft models (ARB, 2014a). These inventories are calculated using population counts, growth rates, and equipment turn-over rates based on surveys conducted in 2004, with updates for crew and supply vessels, barges, and dredges conducted in 2009.

Table II-6: Commercial Harbor Craft by Vessel and Engine Type in 2015

Vessel Category	Number of Vessels	Propulsion Engines		Auxiliary Engines		Total Engines
		Number	Ave. HP	Number	Ave. HP	
Barges / Dredges	257	8	1,725	396	437	404
Commercial Fishing	2,002	2,242	230	921	71	3,163
Charter Fishing	602	1,065	381	451	50	1,516
Ferries / Excursion	447	898	733	550	94	1,448
Tugboats	128	246	1,274	204	111	450
Towboats	40	85	500	47	79	132
Crew/ Supply	66	163	500	73	110	236
Pilot	27	48	408	4	30	52
Workboats	97	142	239	31	101	173
Other	151	168	281	70	56	238
Total	3,816	5,065	---	2747	---	7,812

Table II-7 presents the emission inventory forecast for 2015 for propulsion and auxiliary engines. Except for barges and dredges, which generally do not have propulsion engines, approximately 90% of NOx and PM commercial harbor craft emissions come from propulsion engines.

Tables II-8 and II-9 respectively show vessel and emission inventories for 2030. Compared to 2015, the population of vessels is forecast to decrease due mainly to fewer ferries and commercial fishing vessels. The engine population, however, is forecast to increase due to more dual engine vessels. Emissions of NOx and PM are expected to be reduced approximately 24% and 35%, respectively, due to fleet turnover to cleaner diesel engines.

Table II-7: Emission Inventory by Vessel and Engine Type in 2015

Vessel Category	2015 Emissions (Tons/Year)				Propulsion Engine % of Total	
	Propulsion Engines		Auxiliary Engines			
	PM	NOx	PM	NOx	PM	NOx
Barges / Dredges	1.2	47	21.6	513	5.3%	8.4%
Commercial Fishing	170.2	4,002	39.1	713	81.3%	84.9%
Charter Fishing	160.4	3,708	12.7	197	92.6%	94.9%
Ferries / Excursion	157.6	4,418	7.0	168	95.7%	96.3%
Tugboats	70.1	2,184	3.3	86	95.5%	96.2%
Towboats	12.5	449	1.6	36	88.5%	92.5%
Crew/ Supply	13.9	393	1.2	30	92.3%	92.9%
Pilot	5.3	121	0.0	0	99.5%	99.7%
Workboats	3.8	92	0.7	17	83.7%	84.5%
Other	21.0	475	0.8	13	96.5%	97.3%
Total	616.0	15,889	88.1	1,774	87.5%	90.0%

These estimates include benefits from new engine standards, turnover of Tier 0 and Tier 1 engines to comply with the Commercial Harbor Craft Regulation, and benefits from voluntary efforts undertaken at California's ports to reduce emissions from commercial harbor craft. Reductions of diesel PM in particular can be attributed to fleet turnover to newer, cleaner engines and introduction of ultra low sulfur (15 ppm) diesel fuel.

Figures II-1 and II-2 show the distribution of NOx and PM emissions by vessel category. Nearly 90% of statewide NOx and PM commercial harbor craft emissions are emitted by commercial fishing vessels, charter fishing vessels, ferries, and tugboats.

Table II-8: Commercial Harbor Craft by Vessel and Engine Type in 2030

Vessel Category	Number of Vessels	Propulsion Engines		Auxiliary Engines		Total Engines
		Number	Ave. HP	Number	Ave. HP	
Barges / Dredges	249	8	1,725	384	437	384
Commercial Fishing	1,938	2,164	230	898	70	3,062
Charter Fishing	269	1,115	381	470	50	1,585
Ferries / Excursion	503	1,010	733	618	94	1,628
Tugboats	128	243	1,274	203	111	449
Towboats	47	100	500	56	79	156
Crew/ Supply	66	163	500	73	110	236
Pilot	28	50	408	4	30	54
Workboats	110	161	239	35	101	197
Other	176	196	281	81	56	277
Total	3,514	5,210	---	2822	---	8,028

Table II-9: Emission Inventory by Vessel and Engine Type in 2030

Vessel Category	2030 Emissions (Tons/Year)				Propulsion Engine % of Total	
	Propulsion Engines		Auxiliary Engines			
	PM	NOx	PM	NOx	PM	NOx
Barges / Dredges	0.9	35	4.1	188	17.4%	15.8%
Commercial Fishing	130.3	3042	27.8	534	82.5%	85.1%
Charter Fishing	84.0	2373	7.0	142	92.3%	94.4%
Ferries / Excursion	89.4	3476	5.8	170	93.6%	95.5%
Tugboats	58.0	1936	3.0	83	96.6%	95.8%
Towboats	10.2	445	1.6	40	86.4%	91.6%
Crew/ Supply	8.0	315	1.0	29	88.9%	91.2%
Pilot	2.4	71	0.0	0.3	96.0%	99.4%
Workboats	2.3	67	0.2	8	90.4%	89.7%
Other	14.2	359	0.1	11	95.9%	97.2%
Total	399.7	12119	50.6	1,205	89.4%	91.7%

Figure II-1: Commercial Harbor Craft NOx Emission Distribution

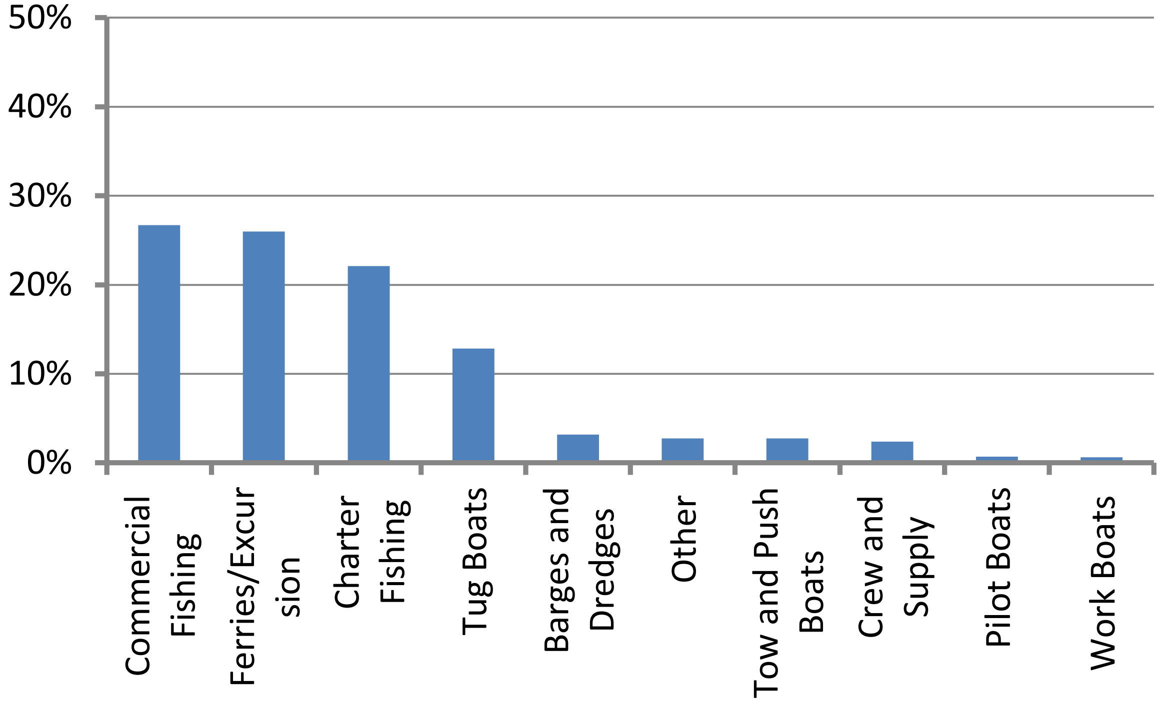
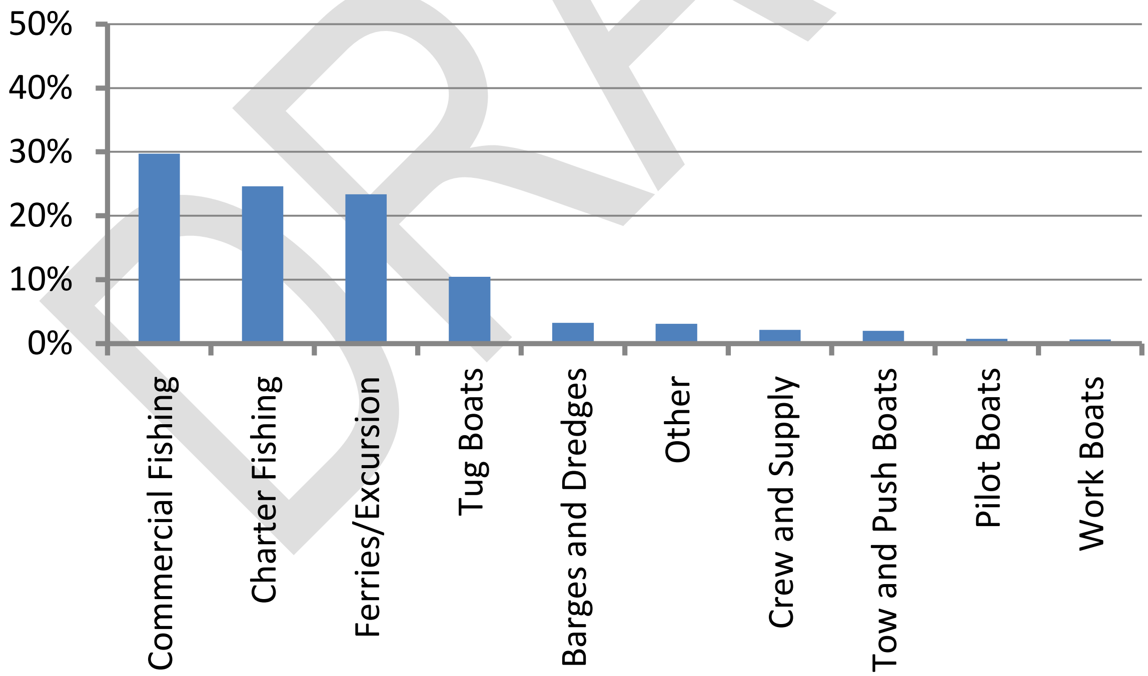


Figure II-2: Commercial Harbor Craft PM Emission Distribution



III. ASSESSMENT OF POTENTIAL TECHNOLOGIES

A. Current State of Engine Development for Commercial Harbor Craft

1. Diesel Engines

Diesel engines meeting marine Tier 3 emission standards are currently certified and available for sale in all horsepower categories. Most of these engines utilize electronic fuel injection, turbochargers, and charge air cooling. Turbocharger design is becoming more sophisticated, evolving from fixed geometry designs to turbochargers with waste gates, to variable geometry. Tables III-1 and III-2, respectively, list certified propulsion and auxiliary engines from the U.S. EPA certification data base

Table III-1: Tier 3 Marine Propulsion Engines Certified in 2014

Manufacturer	Tier 3 Propulsion Engines			
	Category	Number	Max HP	Technologies
AB Volvo - Penta	1	4	322-739	EDI ,TC-W, CAC
Anglo-Belgian Corp.	2	1	4023	EM, MDI, TC, CAC
Caterpillar	1	3	803-2675	EM, EDI, TC, CAC
Cummins	1	7	300-2548	EM, EDI, TC, TC-W, TC-V, CAC
Electro-Motive Diesel	2	1	5499	EM, EDI, TC, CAC
FPT Industrial S.p.A.	1	1	493	EDI ,TC-W, CAC
John Deere	1	3	280-750	EDI, EGR, TC-W, CAC
MAN	1	2	720-1627	EM, EDI, TC, CAC
Marinediesel Sweden	1	1	493	EM, EDI, TC-V, CAC
Mitsubishi	1	2	543-1261	EM, MDI, TC, CAC
MTU America Inc.	1	1	2681	EDI, CM, TC, CAC
Scania CV AB	1	1	571	EDI, TC, CAC
Yanmar	1	3	13-345	EM, MDI / EDI,TC,CAC

Abbreviations:

CAC - charge air cooling, CM - common rail fuel system, EDI - electronic diesel injection, EGR - exhaust gas recirculation, EM - engine modifications, MDI - mechanical diesel injection, TC - turbocharger, W - wastegate, V- variable geometry

Table III-2: Tier 3 Marine Auxiliary Engines Certified in 2014

Manufacturer	Tier 3 Auxiliary Engines			
	Category	Number	Max HP	Technologies
AB Volvo - Penta	1	1	536	EDI ,T-W, CAC
Caterpillar	1	4	536-2675	EM, EDI, TC, CAC
Cummins	1	4	282-2548	EM, EDI, TC, TC-W, TC-V, CAC
IHI Shibaura	1	6	6.8-44.7	IDI, NA, TC-W
John Deere	1	4	143-614	EDI, EGR, TC-W, CAC
Kohler, Inc.	1	1	20	EM, IDI, NA
Kubota Corporation	1	2	39-48	EM, IDI. NA
MTU America Inc.	1	1	2681	EDI, CM, TC, CAC
Northern Lights	1	2	39-184	IDI, NA / EDI, TC, CAC
Perkins	1	2	190-323	EDI, TC, CAC

Abbreviations:

CAC - charge air cooling, CM - common rail fuel system, EDI - electronic diesel injection, EGR - exhaust gas recirculation, EM - engine modifications, IDI - indirect diesel injection - IDI, MDI - mechanical diesel injection, NA - naturally aspirated, TC - turbocharger, W - wastegate, V- variable geometry

Marine Tier 4 diesel engines have not been certified at this time. Marine Tier 4 engines are expected to use similar technologies to those currently used in on-road and Tier 4 off-road engines. In the marine certification data base, there are six manufacturers currently producing engines between 800 and 5000 kW. The technologies used by these companies in non-marine off-road engines include: electronic direct injection (EDI), cooled exhaust gas recirculation (EGR), higher fuel injection pressure, diesel oxidation catalysts (DOC), and selective catalytic reduction (SCR). Some manufacturers may use EGR, EDI, and high injection pressures to meet NOx and PM emissions standards. Other may choose not to use EGR and instead use SCR to reduce NOx. Both technologies are capable of reaching 1.3 g/bhp-hr NOx and 0.03 g/bhp-hr PM since they are already meeting lower stationary engine standards.

Marine Tier 4 standards only apply to engines above 600 kW (800 hp) which for harbor craft are generally propulsion engines in ferries and tugboats.

2. Natural Gas

Natural gas has been commercialized for OGVs particularly LNG tankers which can use the normal boil-off gas from the storage tanks as fuel. A few large natural gas fueled harbor craft have been built but are not used in the U.S. The U.S. EPA certification data base (EPA, 2014) shows two natural gas marine engines suitable for commercial harbor craft. These engines have been used in a few oil platform supply vessels operating primarily in the Baltic Sea and North Sea.

Three natural gas engine technologies have been developed and commercialized, although not necessarily applied to marine applications. The first is pure natural gas engines using spark ignition engines. This technology is used in most on-road engines and operates at a stoichiometric air/fuel ratio with three-way catalyst systems to achieve low NOx and PM emissions. Larger stationary natural gas engines have also been designed as lean burn engines without after treatment where low NOx was not a constraint. The second technology is natural gas with diesel pilot ignition. The engine runs under load on natural gas but is started and idles using a small amount of diesel fuel. That fuel serves as the ignition source for the natural gas. This technology has been used in on-road truck engines and a few large stationary engines. The third technology, dual fuel, provides for starting on diesel and operation under load on a combination of natural gas and diesel fuel. Some designs allow operation at rated power on either pure diesel or a blend of diesel and natural gas.

Use of natural gas over diesel is attractive due to lower fuel cost, near zero mass emissions of PM, low emissions of NOx if after-treatment is used, and lower CO_2 emissions. Challenges to natural gas as an alternative fuel include increased methane emissions from the engine, potential methane emissions from upstream extraction, processing, and delivery of natural gas fuel, especially LNG, and lack of dockside natural gas refueling infrastructure.

3. Biodiesel

Use of biodiesel blends in ultra-low sulfur diesel, up to 20% biodiesel, is accepted by most engine manufacturers as not affecting engine operational or durability. However, there is no information on actual use of biodiesel fuels in California harbor craft. ARB sponsored a study (UCR, 2009) that compared emissions of 20% and 50% soy-based biodiesel blends in ULSD in a ferry with Tier 2 engines. The study showed that PM mass emissions were reduced 16% with a 20% biodiesel blend and 25% with a 50% biodiesel blend. NOx emissions increased 6% with the 50% blend and <0.5% with the 20% blend.

The alternative diesel fuels regulation will be considered for adoption by the Air Resources in 2015, including the use of biodiesel (ARB, 2014b). If adopted, these regulations will specify a process by which alternative diesel fuels are approved for sale in California and their use is regulated so as to prevent any negative environmental impact. A large comprehensive test program (Karavalakis, 2014) demonstrated that soy-based biodiesel blends as low as 5% caused measurable increases in NOx emissions.

Benefits of using biodiesel would be reduced PM emissions, lower greenhouse gas emissions, and conventional diesel engines would not require modification. Challenges to use are increased NOx emissions and minimal reductions of other criteria pollutants.

4. Other Alternative Fuels

Several other fuels are also alternatives to ultra low sulfur diesel: renewable diesel, liquefied petroleum gas (LPG) including propane, dimethyl ether (DME), and hydrogen. Renewable diesel is produced from a number of organic materials and is formulated to have physical and combustion properties similar to petroleum diesel. As such it may be used interchangeably with petroleum-based diesel.

LPG is used with indoor operation of equipment such as forklifts. In addition, there are a number of LPG spark ignited engines in the U.S. EPA certification data base for light/medium duty trucks and off-road equipment. LPG has not been adopted in new marine engines, although aftermarket kits converting a diesel engine to dual fuel are available.

DME is a gas at room temperature and can be liquefied at higher temperatures and lower pressures than natural gas. DME has similar storage and handling properties as LPG and is suitable for use in diesel engines with modifications to the fuel storage and injection systems. Mack and Volvo began trials of DME powered trucks in 2013. It can be produced from natural gas, coal gas, biogas, and other renewable sources. If produced from natural gas, it has equivalent greenhouse gas emissions to diesel. If produced from renewable sources, greenhouse gas emissions are much lower than diesel. It is considered by some as a better mobile source fuel than LNG because it is less energy intensive to produce from natural gas and store and has lower greenhouse gas emissions than natural gas (D. Kittelson, 2010). DME has not been used in marine engines.

Hydrogen has been demonstrated as a combustion fuel in a number of vehicle and on-road engine tests but has not been used in marine engines. The preferred usage of hydrogen is in fuel cells which are discussed separately below.

B. Lower Emission Marine Diesel Engines

The majority of harbor craft emissions come from the following four vessel categories:

- commercial fishing boats
- charter fishing boats
- ferries and excursion vessels
- tugboats

Except for tugboats, these vessel categories have average engine power below 800 hp and the most stringent currently adopted emission standards are Tier 3 (approximately 4 g/bhp-hr NOx+HC and 0.1g/bhp-hr PM). Technologies that could substantially reduce emissions from marine engines are currently used in similar on-road and off-road engines meeting emissions standards of 0.2 gm/bhp-hr NOx and 0.01 g/bhp-hr PM. These include high pressure fuel injection, variable geometry or 2 stage turbochargers, cooled EGR, charge air cooling, and after-treatment such as SCR and diesel particulate filters (DPFs). These technologies will also be utilized in marine engines >800 hp meeting Tier 4 marine standards of 1.3 g/bhp-hr NOx+HC and 0.03 g/bhp-hr PM although after-treatment is not expected to be needed. Approximately 70% emission reductions of NOx and PM could be achieved for marine engines <800 hp by applying Tier 4 marine standards to engines <800 hp.

Vessels categories with average power >800 hp include dredges and tugboats. In addition some ferries have engines > 800 hp. New vessels or engines delivered after Tier 4 standards take effect will have engines meeting Tier 4 standards of 1.3 g/bhp-hr NO+HC and 0.03 g/bhp-hr PM. On-road emission standards of 0.2 g/bhp-hr NOx have been in place since 2010. These standards were met with improved electronic fuel injection, SCR, cooled EGR, variable geometry turbochargers, and thermal management techniques for rapid catalyst warm-up and maintenance of catalyst temperatures during low load operation. Similar technologies could be applied to marine diesel engines in order to achieve additional emission reductions of at least 50% NOx. Additional reductions of PM emissions may not be possible without DPFs.

Lower emission diesel engines could be deployed with little or no change to fueling infrastructure or vessel operation. The additional complexity of the engine may increase maintenance requirements but any effect should be minor as has been seen with low emission technologies adopted in on-road and land-based off-road engines.

C. Retrofit After-Treatment Technologies

Several European manufacturers (e.g., Hug Engineering AG, Haldor-Topsoe, and Yarwil) provide retrofit SCR systems for marine engines. Over 500 harbor craft, river craft and ocean going vessels, primarily in Europe, and with varying propulsion and auxiliary engine sizes, have been retrofitted with SCR systems (IACCSEA, 2012). These retrofits include new builds and in-use vessels for regional tax reduction incentives such as the Norway NOx Fund (Hoibye, 2012). In addition, a number of U.S. based companies also provide SCR systems for stationary engine applications and could supply systems for commercial harbor-craft. Two retrofit systems have been tested in California on Tier 2 vessels: 1) an SCR system on ferries and 2) an SCR/DPF system on a tugboat.

Four newly built San Francisco Bay ferries with twin propulsion engines were retrofitted with SCR systems from Engine Emissions and Fuel Engineering, Inc. (MECA,, 2014) to satisfy a BACT requirement for new ferries. Three of the four newly built ferries were emission tested using portable emission measurement equipment. Rated horsepower of the engines on the ferries ranged from 670 to 2700 hp. Emissions were measured in normal passenger service over a range of operating modes. The goal was to achieve at least 85% reduction compared to Tier 2 standards which would be below Tier 4 standards. The emission reduction targets were met as shown in Table III-3 below for cruise above 85% load.

Table III-3: Demonstrations of Marine Retrofit Technologies

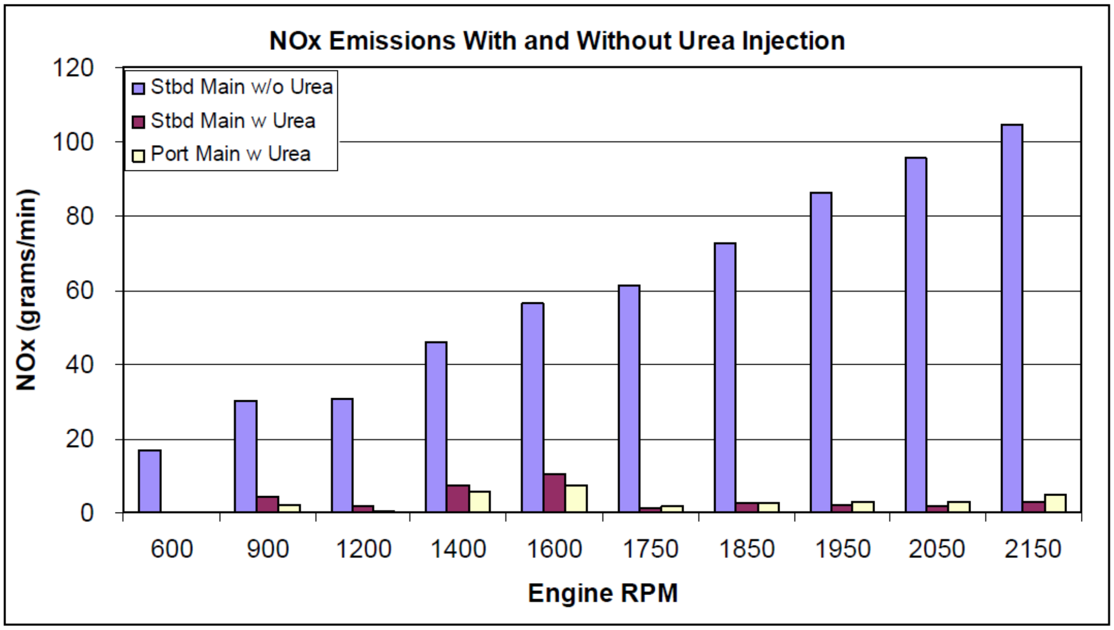
Parameter	Ferry[1]	Tugboat[2]
Engine Type	4 Cycle	2 Cycle
Engine Tier	Tier 2	Tier 2*
Engine Power (hp)	1410	365
Retrofit Technology	SCR	SCR/DPF
Emission Test Cycle	Cruise	E-3 cycle
Tier 4 Emission standards	1.3/0.03	1.3/0.03
Emissions Level (g/bhp-hr)		
NOx	0.20	0.48
PM	0.03	0.01
Emission Reduction (%)		
NOx	97%	92%
PM	60%	96%

[1]MECA,2014
[2]Jacobs,2014
*Tier 0 with Tier 2 ARB-verified rebuild kit

Figure III-1 shows the SCR inlet and outlet emission rate of NOx in grams per minute versus engine RPM for one of the ferries. Engine rpm is proportional to engine load and exhaust temperature which affects SCR catalyst efficiency. The figure demonstrates that SCR control efficiency remains >85% through most of the operating range of the engine.

One tugboat with its home port in the Port of Long Beach was equipped with an SCR/DPF retrofit system by Hug Filtersystems for a demonstration (Jacobs, 2014) in support of ARB verification. The demonstration was partially funded through an ARB Air Quality Improvement Program (AQIP) technology demonstration grant. Testing was conducted using the ISO8178 E3 marine engine test cycle for variable speed engines. Test results after approximately 200 hours of operation are shown in Table III-3. The emission levels for both retrofit systems met Tier 4 emission limits for NOx and PM.

Figure III-1: EF&EE SCR NOx Emission Rates Versus Engine RPM (Load)



Retrofit systems offer the benefit of significant emission reductions from existing vessel engines without repowering the vessel and, depending on the specific vessel configuration, the installed cost of retrofit systems may be less than new engines. The commercial harbor craft regulation includes provisions for using a non-verified retrofit system subject to providing test data to support the emission claim.

Additional monitoring and maintenance to ensure continued emission reduction effectiveness are required. In addition, the condition of the retrofitted engine can affect the effectiveness and durability of the retrofit system. Not all vessels may be candidates for retrofit due to duty cycle and usage, engine compartment space limitations, and condition of the engine.

D. Diesel Electric Hybrids

Diesel electric hybrid systems consist of multiple diesel engines, multiple propulsion and auxiliary motors, engine and motor controls, and may include batteries and battery management systems. Figure III-2 shows a generic diesel electric hybrid system. A prime example of marine diesel electric hybrids is submarines which have used this type of integrated propulsion system for over 100 years. These systems have many variants including DC or AC motors, series or parallel engine/motor combinations, and with or without battery storage. The illustration is for a series combination with battery storage.

A number of diesel electric hybrid vessels have been built. Foss Maritime designed and built a new diesel electric tugboat and retrofitted an existing tugboat with diesel electric hybrid systems (McKenna, 2013). Both systems utilized two large diesel generators and two smaller auxiliary diesel generators of different size. The generators provide electrical power to two propulsion motors, a battery bank, and for ship utility power. The four generators operate automatically beginning with the smallest to match electrical load and provide power as needed to recharge the batteries. Tug engines operate mainly at idling when waiting or low cruising loads when transiting to or from a job site. Short periods of full power are needed when assisting OGVs in arriving or departing the harbor or docks. These duty cycles are ideal for engines designed to provide less than full propulsion power but with batteries available to make up the difference when full propulsion power is needed. The Foss hybrid system was tested and verified to reduce NOx 25%, PM 30% and CO2 and fuel consumption 30% compared to a conventional tug.

The benefits of diesel electric hybrids are reduced criteria and GHG gases, reduced fuel consumption, and faster throttle response than is possible with diesel engines. Disadvantages are high capital cost and complex engine/motor controls, and space required by gensets, motors, batteries, and engine/motor controls (McKenna, 2013).

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Figure III-2: Illustration of Typical Diesel Electric Hybrid System

Source: www.stadt.no

E. Fuel Cells

Fuel cells are being demonstrated in a number of mobile source applications but have not been commercialized on a large scale. There are a number of fuel cell technologies (FuelCellToday, 2014):

- Proton Exchange Membrane or Polymer Electrolyte Membrane (PEMFC) - PEMFCs are most commonly used in automobile and truck applications. They operate at low (80-100C) temperature, start up relatively quickly and can follow load changes but require hydrogen fuel. Hydrogen is reacted with oxygen in air to form water.

- Direct Methanol Fuel Cell (DMFC) - DMFCs are similar to PEMFCs but are fueled with methanol which is reacted directly with oxygen in air in the fuel cell to CO_2, and water without needing a reformer to produce hydrogen. They operate at somewhat higher temperature (60-130C) and are well suited for moderate steady loads. DMFC have been used in mobile applications such as forklifts to replace battery powered forklifts due to the quick refueling time compared to battery recharging.

- Solid Oxide Fuel Cell (SOFC) - SOFCs use solid ceramic oxide electrolyte instead of fluids or membranes. They operate at high temperatures (~1000C) and can internally process hydrocarbon fuels into hydrogen and CO which, when reacted with oxygen in air, produce water and CO_2. SOFCs are used commercially for stationary power generation and have been used in demonstrations on-board OGVs to produce base-load auxiliary power.

- Alkaline Fuel Cells (AFC) - AFCs are not widely used commercially because they use an alkaline liquid electrolyte such as potassium hydroxide. Hydrogen is reacted with oxygen forming water. AFCs operate at low temperature (70C); however, the need for pure oxygen makes the cells more complex, expensive to operate, and not commercially competitive.

- Molten Carbonate Fuel Cell (MCFC) - MCFCs use a molten carbonate salt (potassium, sodium, or lithium) suspended in a porous ceramic as the electrolyte. MCFCs operate at high temperature (650C) and can process hydrocarbon fuels internally into hydrogen and carbon monoxide which are then reacted with oxygen in air to water and carbon dioxide. MCFCs are commercialized for megawatt scale stationary power plants.

- Phosphoric Acid Fuel Cells (PAFC) - PAFCs use phosphoric acid electrolyte suspended in a porous ceramic. Hydrogen is reacted with oxygen in air to produce water. PAFCs operate at moderately elevated temperatures (180-200C) and are used mainly in small stationary power plants in the 100-400 kW.

PEMFC systems have been used in harbor craft demonstrations because they are commercially available in standard power packs which can be combined to attain typical harbor craft power demands. Figure III-3 shows a photo of the *Hornblower Hybrid* (Hornblower, 2014a), a dinner cruise excursion vessel operating in New York harbor. The *Hornblower Hybrid* incorporates Tier 2 diesel gensets, electric propulsion, wind turbines and a 32kw PEMFC.

SOFC, MCFC, and PAFC systems have been demonstrated in or planned for OGVs for shipboard and auxiliary power in combination with diesel-electric hybrid. Figure III-4 shows a Scandinavian supply ship with a combined low emission design including LNG fueled gensets, electric propulsion, and a molten carbonate fuel cell.

Benefits of fuel cells are high fuel to electrical efficiency particularly with waste heat recovery (60-80%), reduced GHGs, and no NOx or PM emissions compared to combustion engines. Using fuel reformers, any hydrocarbon fuel could be used with any of the fuel cell technologies. LNG is likely to become available at major ports and could become a candidate fuel for fuel cells. Challenges are higher capital cost per kW than combustion engines and the potential need for special fuels (hydrogen, methanol).

Figure III-3: Diesel Electric - PEM Fuel Cell - Battery Hybrid Ferry

Hornblower Hybrid Source: Hornblower, 2014

Figure III-4: Supply Ship with LNG Engine - Molten Carbonate Fuel Cell Hybrid

Viking Lady Source: FuelCellToday, 2012

F. Battery Electric

Plug-in battery electric technology using lithium ion batteries has been commercialized for passenger cars (e.g., Nissan Leaf and Tesla) for several years. Similar technology has been developed for recreational harbor craft such as small harbor or river excursion boats as shown in Figure III-5.

Figure III-5: Battery Powered Harbor Excursion Boat

Source: Duffy Electric Boat Company (www.duffyboats.com)

Dedicated battery electric systems are being developed for larger ships but have not been adopted for commercial harbor craft. Scandinavian and European companies are leading the development of this technology due to the Baltic Sea Environmental Control Area (ECA) and Norwegian carbon tax penalties on diesel and marine fuels. Figure III-6 shows an illustration of a fully battery-powered car ferry developed by Norwegian shipyard Fjellstrand and Siemens, AG (Siemens, 2013). The battery weighs 10 metric tons and can provide continuous 400 kW and 800 kW peak power to twin propulsion motors and provide all shipboard auxiliary power. The ferry's battery is recharged at each stop from on-shore batteries because the local power grids cannot provide sufficient peak power. The on-shore batteries are recharged gradually between ferry visits from the local grid. Norway has over 100 ferries in inter island service and designers believe that any ferry trip of 30 minutes or less can be serviced by battery-powered ferries. The ferry is under construction and scheduled to enter service in 2015.

Benefits of battery electric propulsion are zero emissions from the vessel and potentially reduced maintenance cost. Challenges are high cost per kilowatt-hour compared to traditional combustion engines, limited range, and need for charging infrastructure.

G. Renewable Energy

Renewables considered for harbor craft are wind and solar energy. Other renewable energy sources such as wave energy were considered by staff as providing inadequate power when installed on individual vessels and better suited to port or harbor sites and converted to electrical grid power.

1. Solar Energy

Solar cells convert sunlight to electrical power which can be stored in batteries. Several demonstration projects with commercial harbor craft have included solar power to supplement the main energy sources, usually diesel engines.

Figure III-6: Battery-Powered 120-Vehicle Ferry

Source: Siemens, 2013

Hornblower Cruises developed two hybrid vessels which included solar cells, wind turbines, batteries, and diesel gensets for power sources coupled with electric propulsion motors. The *Hornblower Hybrid* is a dinner cruise excursion vessel (shown previously in Figure III-4) and is described in (Hornblower, 2014a). Hornblower also built a second ferry/excursion vessel, *Hornblower Hybrid Alcatraz* (see Figure III-7) which is described in (Hornblower, 2014b). The 1.2 kW solar cells were mounted on the metal awning covering the upper passenger deck.

2. Wind Energy

Wind energy is not steady in force or direction. To the extent wind energy is used in commercial harbor craft, it will be a supplemental energy source. Four technologies to utilize wind energy were evaluated

- Sails
- Wind wings
- Wind turbines
- Wind kites

Figure III-7: Diesel-Electric Hybrid Ferry with Solar Cells and Wind Turbines

Hornblower Hybrid Alcatraz Source: Hornblower, 2014b

Sails

Sails are the traditional marine technology for extracting wind energy. Sails are commonly used in recreational vessels but have essentially disappeared from commercial vessels other than excursion sailing vessels and are unlikely to be used in the future.

Wind wings

Wind wings are airfoil structures that take advantage of lift provided by airflow over a curved surface. For vessels, wind wings are mounted vertically as shown in Figure III-8 and wind flowing over the wing provides the forward thrust to move the vessel through the water.

Figure III-8: Wind Wing Demonstration in San Francisco Bay

Source: http://www.windwingtech.com/projects.html

ARB sponsored a demonstration of wind wing technology for San Francisco Bay ferries (Lipman, 2014). The demonstration used the 42 foot trimaran shown in Figure III-9 on typical ferry routes. The test vessel was equipped with a diesel engine and the study was conducted by operating at a steady cruising speed with engine power replaced by wind wing power. The study demonstrated that the wind wing could replace 26-44% of the engine power (measured as percent reduction in fuel flow rate) depending on wind speed and direction relative to the vessel's direction of travel. Wind wings are rigid composite structures that rotate to follow changing wind direction. Maximum fuel savings were obtained with wind coming at an 80-90 degree angle to the direction of travel. Wind wings are being developed for larger vessels including cargo vessels and passenger ferries.

Wind Turbines

Wind turbines convert wind energy to electrical energy. Vertical turbines rated at 1.2 kW were used on the *Hornblower Hybrid Alcatraz* (see Figure III-8) for auxiliary power. The amount of electrical energy extracted depends on the swept area of the turbine. Horizontal wind turbines generally have more swept area than vertical turbines although the vertical turbines are more aesthetically pleasing. Solar cell and wind turbine systems can be combined with batteries in a hybrid power system as described above. The wind turbine technology has not been adopted on harbor craft but could provide supplemental power for essentially all commercial harbor craft categories.

Wind Kites

Wind kites are a relatively new concept in which a sail is deployed above and in front of the vessel. As developed by SkySails GmbH for (SkySails, 2014) OGVs, the kite harvests energy at 400m where the wind velocity is greater and more consistent than at sea level (Figure III-9). Under favorable conditions, the 400m^2 kite delivers a towing force equal to 2,000kW of propulsion power. The SkySail is probably not suitable for commercial harbor craft due to their smaller size and short trips compared to OGVs.

Figure III-9: Wind Kite Renewable Propulsion System

Source: www.skysails.info

Benefits of renewable energy are zero emissions and reduced fuel consumption for the energy replaced by renewables. Challenges are reliability of energy supply, high initial cost, and relatively small energy contribution compared to overall vessel demand.

H. Vessel Efficiency Improvements

A number of efficiency improvements can be made to existing vessels or incorporated into new vessels which improve the efficiency of converting engine power into movement of the vessel through water. The improvements lead to reduced fuel consumption which is presumed to proportionally reduce criteria and GHG emissions. Energy reaching the propeller is allocated approximately as follows (OceanSMART, 2010):

- 35% to turn the propeller
- 27% to overcome wave resistance
- 18% to overcome skin friction
- 17% to overcome resistance from the wake and propeller wash against the hull
- 3% to overcome air resistance.

Improvements that reduce these losses are discussed in (OceanSMART, 2010) as they specifically relate to fishing vessels and can be categorized as:

- Hull maintenance to reduce skin friction

- Hull shape to reduce wave and wake resistance
- Propeller design to improve thrust per unit of power
- Operational changes to reduce engine operation

While OceanSMART was written primarily for commercial fishing vessel operators, the comments can apply to all commercial harbor craft.

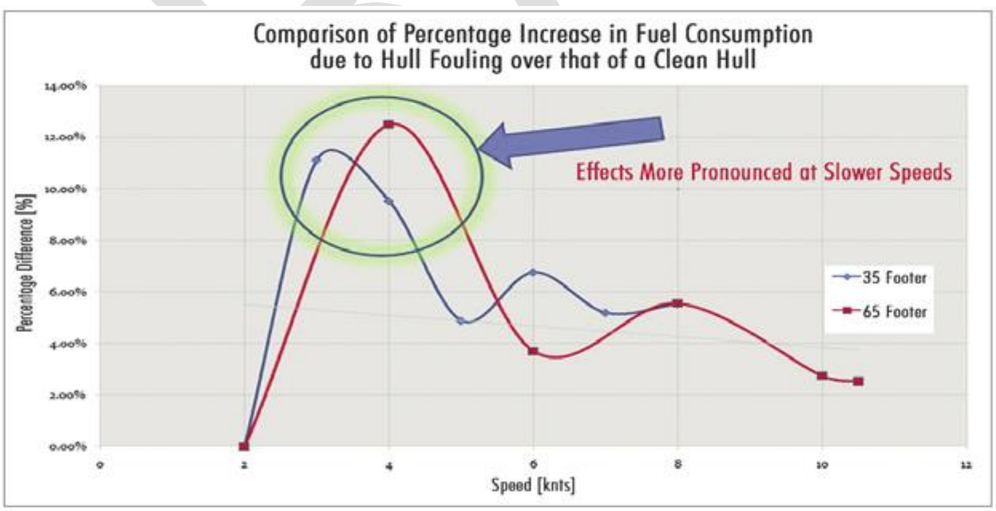
Hull Maintenance

Drag or resistance to movement through the water is increased as the surface roughness of the hull increases. Fouling is marine growth, such as barnacles and weeds, adhering to hulls. This roughens the hull and increases drag. Figure III-10 shows that a hull fouled with marine growth increases fuel consumption up to 14%. Fouling increases in warm water and with vessels that operate intermittently or at low speed Hull cleaning is recommended at least annually. Hull roughness also increases with vessel age due to corrosion or damage to steel hulls. Anti-corrosion and anti-fouling paints are recommended when hulls are repainted. (OceanSMART, 2010)

Hull Shape

The inclusion of improved hull efficiency elements (i.e. a bulbous nose or stern flaps) in the design of a new vessel or implementing hull efficiency elements as a retrofit strategy is a proven method of increasing fuel efficiency. Hull shape affects drag by altering water flow around the hull thereby reducing the energy lost to turbulence or pressure waves.

Figure III-10: Hull Fouling Increases Fuel Consumption



Source: OceanSMART, 2010

Bulbous bows are a protrusion designed or added to the bow (front) of a vessel that increases the efficiency of water flow over and around the hull. A bulbous bow added to the vessel bow below the water line causes a leading bow wave which counteracts the primary bow wave which decreases the resistance. Fuel savings up to 15% have been reported (OceanSMART, 2010).

Stern flaps are small extensions of the hull-bottom surface aft of the transom; they modify the stern wave system and the flow under the hull, thus reducing required propulsion power. (Zoccola, 2001) Stern flaps lengthen the bottom surface of the hull increasing the efficiency of water flow over the hull. Since 1998 the U.S. Navy and Coast Guard have identified and retrofitted vessels with stern flaps to improve vessel fuel efficiency approximately 5% and increase top speed approximately 1 knot. The U.S. Navy identified 71 vessels to be retrofit with stern flaps, and the U.S. Coast Guard identified 49 Island Class patrol boats to be retrofitted with stern flaps. As vessels are designed for the U.S. Navy and Coast Guard stern flaps will be part of the original design. (CRS, 2006, Cave III, unknown date)

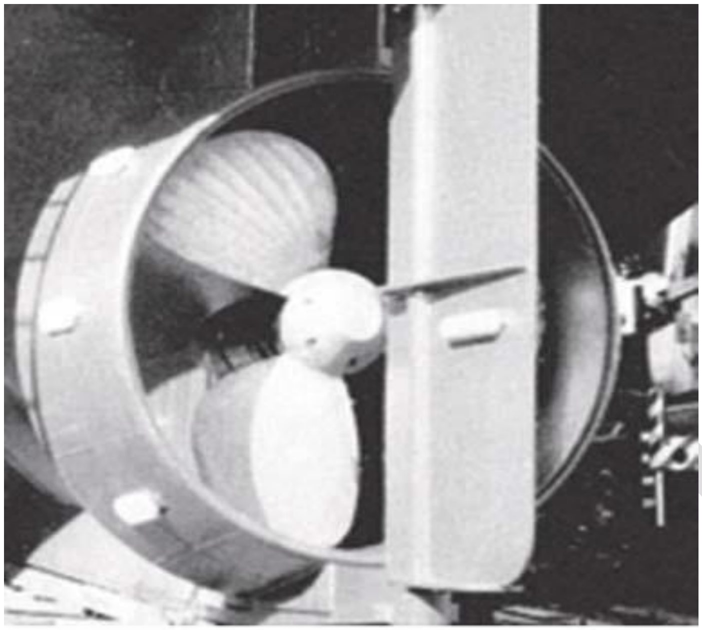
Vessels with larger length to beam ratios are inherently more efficient because the hydrodynamic efficiency and general stability increases which leads to reduced wave resistance. For new vessels, this can be considered during design. While it is generally not feasible to reduce the breadth of a finished vessel, the bow can be lengthened. The purpose of lengthening the bow is to reduce the approach angle of the bow which reduces wave resistance. A reduction in bow half angle from 30 degrees to 10 degrees can reduce fuel consumption 10%. (OceanSMART, 2010).

Propeller Design

Propeller design and specifications have a direct influence on vessel fuel efficiency. The most important single factor is propeller diameter. In general, a larger diameter propeller turning slowly is more efficient than a small diameter propeller turning rapidly. Therefore, the propeller diameter should be as large as hull clearance and engine power allows so that as much water as possible passes through the propeller. Maximum propeller speed should be limited to a speed below that at which cavitation occurs while cruising. Cavitation is caused when the leading edge of the propeller blade reduces the water pressure enough for it to boil forming small bubbles. Cavitation reduces propeller efficiency and can cause pitting of the blade. Other factors of propeller design affecting efficiency include blade pitch, number of blades and blade area. For maximum efficiency the propeller design must take into consideration the use of the vessel including need for thrust at low vessel speed (towing and maneuvering), the desired cruising speed, and engine power curve.

Also considered in propeller design is shrouding or nozzles (Figure III-11) which improve rearward thrust by preventing side slip and back flow of water. This improves overall efficiency of the propeller and can also improve maneuverability by directing more water past the rudder. Adopting all improvement measures related to propellers and matching propellers to engine capability can increase efficiency as measured by fuel consumption up to 15% (OceanSMART, 2010).

Figure III-11: Propeller with Nozzle



Source: OceanSmart, 2010

Operational Changes

Speed reduction is a method of improving fuel efficiency since power demand is roughly a function of the square of vessel speed. Table III-4 shows the fuel consumption during a 20 nautical mile trip conducted at various speeds. For example, a 22% reduction in speed (9 to 7 knots) increased the trip time 32% (2.2 to 2.9 hours) and reduced fuel consumed during the trip 43% (41.1 to 23.5 gallons) and fuel consumption rate nearly 57% (18.7 to 8.1 gallons per hour (OceanSMART, 2010). Speed reduction can provide cost saving but must be offset by crew cost for the extra hours and potential impact on passengers or customers for longer schedules.

Table III-4: Efficiency Improvement from Speed Reduction

Estimates in Fuel savings for a 20 nautical mile trip (one day)						
Speed	Time taken	Consumption gallons per day	Total fuel used	Fuel Cost	Total Savings	Savings (per hour/knot)
9	2.2	41.1	41	$ 186.50	$ 0	$ -
8	2.5	31.7	32	$ 143.96	$ 42.54	$153.14
7	2.9	23.5	24	$ 106.87	$ 79.62	$125.40
6	3.3	16.6	17	$ 75.24	$ 111.25	$100.13
5	4.0	10.8	11	$ 49.07	$ 137.43	$ 77.31

Source: OceanSMART, 2010

Trip reduction is another method of improving vessel efficiency. On-road delivery services use trip routing programs to optimize vehicle operations. Similar planning tools are available for vessel management. Updated electronic charts, fish finding sonar, and improved Global Positioning System (GPS) software are examples of currently available electronic technologies that CHC vessel owner/operators can install to help improve the fuel efficiency of their operations. Updated electronic charts help owner/operators chart the most direct course and avoid potential hazards. Fish-finding sonar allows commercial fishermen to locate potential target species more quickly. Updated GPS allows CHC vessel owner/operators to maintain an improved record of the most fuel efficient course and resource locations. All of those factors can result in improved CHC vessel fuel efficiency by up to 10 percent (Hollin and Windh, 1984).

One final electrical upgrade is the replacement of incandescent lighting with light emitting diodes (LED) which use less energy and should last longer. The associated fuel savings are based on the number and wattage of incandescent lights replaced which can vary depending on vessel size and type.

Benefits of efficiency improvements are reduced emissions, fuel consumption, and potential increased maximum vessel speed. Challenges are increased maintenance, operational changes, and potentially higher cost than fuel cost saving depending on the vessel category and its operation.

IV. SUMMARY OF TECHNOLOGY ASSESSMENT AND NEXT STEPS TO DEPLOYING ADVANCED TECHNOLOGIES

A range of technologies for reducing emissions from commercial harbor craft have been assessed. These technologies are similar to those found in other emission source sectors but their development for commercial harbor craft generally lags due to the relatively small size and specialized nature of the commercial harbor craft market compared to other source sectors such as passenger cars, trucks and off-road equipment.

<u>Commercialized Technologies</u>

Commercialized technologies are developed, certified if required for sale, and available for sale in the commercial harbor craft market. Marine Tier 3 diesel engines are currently required under the Commercial Harbor Craft regulation. In addition to Marine Tier 3 diesel engines, these technologies have been demonstrated to reduce emissions of one or more criteria and/or GHG emissions. The cost of some technologies may be off-set by reduced cost of operations by improved efficiency:

- Marine Tier 3 diesel engines
- SCR/DPF retrofit systems for Tier 2 and older engines
- Biodiesel/renewable diesel
- Vessel efficiency improvements

<u>Demonstrated Technologies</u>

Demonstrated technologies have been installed and evaluated for durability and performance in at least one commercial harbor craft vessel. The technologies may be fully commercialized in other emission sectors, i.e. passenger cars, trucks, off-road equipment. These technologies may require government certification as well as demonstrations to fine-tune performance to meet end-user expectations (durability, reliability, and cost):

- Marine Tier 4 diesel engines
- Natural gas engines
- Diesel-electric propulsion systems
- Hybrid diesel-electric systems with battery storage

<u>Technologies Needing Further Development</u>

These technologies may be developed beyond a research stage but need further development to obtain performance, range, reliability, and cost competitive with commercialized or demonstrated harbor craft technologies:

- Diesel engines cleaner than Tier 4

- Fuel cells
- Battery electric
- Solar energy
- Wind energy

Challenges to Deployment

The commercial harbor craft sector has unique challenges to deployment of low emission technologies including:

- Long useful life of engines (20 years).
- Wide range of engine sizes and duty cycles.
- Small number of vessels and engines (4000 vessels statewide).
- Variety of vessel vocations
- Numerous vessel/engine combinations
- Propulsion engine duty cycles vary by vessel vocation
- Weight and space constraints
- Lack of dockside alternative fuel infrastructure

These challenges mean that there will be a small number of potential low emission technology sales in any one year. If average engine life is 20 years, there is 5% turnover each year and approximately 200 vessels will be repowered or replaced. The Commercial Harbor Craft regulation slightly accelerates this schedule by requiring turnover of most marine Tier 1 and older engines to marine Tier 2 or cleaner engines after 15 years. The final required engine turnovers are in 2022.

Other challenges relate to vessel specific space and configuration limitations that may require specific designs for individual vessels. Design, modification, and installation costs may equal or exceed the technology cost. To minimize design and installation costs, many in-use harbor craft will be upgraded with lower emission diesel engines or by retrofit technologies. Newly built vessels can be readily designed to use any power source or combination of sources.

Table IV-1 lists recommended technologies and the vessel vocation considered most appropriate based on duty cycle and attributes of the technologies. All of the listed technologies have been developed in at least one source sector, usually passenger cars or trucks. A demonstrated technology has had at least one harbor craft system successfully demonstrated. Commercialized technologies are currently available for sale in the harbor craft market. Relative benefit is based on reported emission reductions.

Table IV-1: Technology Assessment Summary

Technology	Development Status	Relative Benefit	Most Suitable Vessels
Tier 3 Diesel	Commercialized	Moderate	All
Tier 4 Diesel	Developing	High	All
Cleaner Diesel	Developing	High	All
Retrofit Aftertreatment	Commercialized	High	Ferry, Towboat, Dredge, Crew/Supply(1)
Biodiesel	Commercialized	Low	All
Natural Gas	Commercialized	High	Ferry(2)
Engine/Electric Hybrid	Demonstrated	Moderate	Tug, Excursion, Fishing, Crew/Supply(3)
Fuel Cell	Demonstrated	High	All
Battery Electric	Developing	High	Barges, Excursion(4)
Efficiency Improvements	Commercialized	Moderate	Ferries, Fishing, Towboat, Crew/Supply(5)
Renewables	Commercialized	Low	All (6)

Notes:

(1) Engines cruise at high power which maintains high catalyst efficiency. Not all vessels can fit retrofit systems into engine rooms.
(2) Vessels operate on relatively short, fixed routes facilitating refueling.
(3) Engines have lower average load factor and variable duty cycle with periods of low and high power demand.
(4) Barges with navigation lights and small harbor excursion vessels.
(5) Vessels operate at higher average speeds where efficiency improvements have greater impact.
(6) Vessels with area to mount renewable power sources and with higher auxiliary power demand.

<u>Next Steps for Deployment</u>

There are three principal factors driving fleets to use low emission technologies: 1) compliance with rules or regulations (e.g., the Commercial Harbor Craft regulation, CEQA, etc); 2) incentive funding (e.g., Carl Moyer Program) for surplus emission reductions; and 3) reduction in operating cost (fuel, supplies, labor) . The Commercial Harbor Craft regulation will result in average fleet emissions equivalent to at least Tier 2 by 2023. Achieving lower emissions will require advanced lower emission technologies. To the extent that advanced technologies provide fuel cost savings either through hybridization or fuel replacement, market forces will encourage their adoption. Incentive funding also encourages lower emission technologies that go beyond current emission standards or provide implementation earlier than otherwise required by regulations. Finally, continued development of advanced technologies so that the market and incentive programs have more technology choices will ensure better penetration of these technologies.

The following steps are recommended to encourage low emission technology deployment:

- Develop technology mechanisms to send market signals to technology developers/providers to commercialize their technologies as early as possible to meet air quality standards and climate change goals.
- Continue and expand Carl Moyer Program funding for engines and technologies certified/verified to low emission standards.
- Continue to conduct and expand demonstrations to bring to market more low emission technologies.
- Develop stringent emission standards.
- Conduct outreach on the advantages of advanced technologies including payback from fuel cost savings.
- Provide infrastructure funding for alternative fuels (e.g., natural gas and hydrogen) in harbors.

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