United States Maritime Administration

DECISION FRAMEWORK FOR EMISSION CONTROL TECHNOLOGY SELECTION

Final Report

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EXECUTIVE SUMMARY

The marine transportation community has begun to consider technologies that reduce air emissions from marine engines.

The Maritime Administration (MARAD), in support of U.S. fleet technology development and modernization, wants to "accelerate the use of economical, low air emission marine power plants in the U.S. inland and coastal waters" (Voelker 2001). As the principal advocate within Government for U.S. maritime interests, MARAD has initiated a Maritime Energy and Clean Emissions Program. The Program seeks to:

- Investigate and demonstrate the potential for new technologies and fuels to improve marine power plant efficiency and to reduce air emissions.
- Provide guidance and information on maritime energy and emissions regulatory and policy issues.
- Protect the human and natural environment directly in contact with marine activity.

This document develops a decision framework applicable for considering emission control technologies on marine engines. The framework is informed by standard decision theory, and maintains an open structure so that it may be adapted by operators with specific vessel and technology attributes that may differ from those provided here. Attributes are chosen carefully to relate objectives important to choosing control technologies with specific alternatives that may meet several of the objectives differently. The framework is transparent, which enables multiple stakeholders to understand how different subjective judgments and varying attribute properties may result in different technology choices. The analysis uses standard scoring techniques to ensure that attributes are not biased by subjective scoring and that weights are the primary quantitative input where subjective preferences are exercised. An expected value decision structure is adopted that considers probabilities (likelihood) that a given alternative can meet its claims; alternative decision criteria are discussed. Capital and annual costs are combined using standard discounting techniques to compare costs for each alternative using a net present value (NPV) approach. An iterative approach is advocated that allows for screening and disqualifying alternatives that do not meet minimum conditions for acceptance, such as engine warranty or U.S. Coast Guard requirements. Lastly, the decision framework does not substitute for a decision maker in any way, but helps an operator structure the decision so that important attributes are considered explicitly and can be represented clearly to other stakeholders.

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1 INTRODUCTION

The marine transportation community has begun to consider technologies that reduce air emissions from marine engines. Reasons for this increased attention are several. Nonroad engines are generally less regulated for air pollution than onroad vehicles, such as cars that have been regulated for more than 30 years. Nonroad emissions have been recognized as an important contributor to air quality problems in major metropolitan regions. Among nonroad sources, marine engines are the least regulated and fastest growing sources of air pollution. Because of increased trade and transportation by ships and ferries, many regions project that marine vessel emissions will double over the next decade without increased emissions control. Some states have determined that their coastal communities cannot meet air quality objectives under the United States Clean Air Act unless the maritime sector is included in federally required State Implementation Plans (California Air Resources Board 1994; TNRCC 1999; California Air Resources Board 2003).

Current regulatory requirements are focused only on new engines, and some standards will not apply to engines installed before 2007. For some regions, these new-engine standards may be too weak to achieve the needed emissions reductions before 2010, and emerging technology for existing marine engines that meets or exceeds new engine standards is being demonstrated (mostly in Europe). With these facts in mind, port cities and regional air districts are increasingly pressuring vessel operators for help in meeting local air pollution mitigation goals.

The US Department of Transportation has established programs to assist these efforts, such as the Congestion Mitigation and Air Quality (CMAQ) program (DOT 1999), and has earmarked federal funds to help regions reduce emissions from marine engines to meet federal conformity requirements under the Clean Air Act (Federal Highway Administration 2000). The Maritime Administration (MARAD), in support of U.S. fleet technology development and modernization, wants to "accelerate the use of economical, low air emission marine power plants in the U.S. inland and coastal waters" (Voelker 2001). As the principal advocate within Government for U.S. maritime interests, MARAD has initiated a Maritime Energy and Clean Emissions Program. The Program seeks to:

- Investigate and demonstrate the potential for new technologies and fuels to improve marine power plant efficiency and to reduce air emissions;
- Provide guidance and information on maritime energy and emissions regulatory and policy issues; and
- Protect the human and natural environment directly in contact with marine activity.

This document outlines the key decision factors that need to be considered when evaluating emission reduction alternatives and place these decision elements in an integrated evaluation framework. The report develops a decision framework from a vessel operator perspective and applies methods of evaluating choices about retrofit, modernization, and operational options to reduce air emissions for specific applications.

Vessel operators, particularly operators of passenger ferries, are striving to improve the environmental performance of their power systems as expansion and modernization occurs in the

U.S. coastal and inland fleets. However, the choice of control strategies to reduce air pollution is complex and requires consideration of many factors. These include cost, performance, and compatibility with other ship systems. The study will assist ferry operators and other vessel managers to make more informed choices about ferry propulsion selection, retrofit, modernization, and operational options to reduce air pollution.

1.1 Environmental Motivation for Clean Engine Technologies

Marine diesel engines constitute a significant source of air pollution, as noted by the US Environmental Protection Agency (USEPA):

> "Diesel boats and ships range in size and application from small recreational runabouts to large ocean-going vessels. Combined, these diesel engines emit about 1 million tons of hydrocarbons plus nitrogen oxides (HC + NOx) and 30,000 tons of particulate matter (PM) each year across the United States. These emissions help form smog and contain toxic compounds such as benzene, so reducing them would benefit our health and environment." http://www.epa.gov/otaq/marine.htm

Public policy is providing an impetus for emissions reduction. For example, the San Francisco Bay area Water Transit Authority (WTA) has introduced ferry expansion legislation at the state level, where emissions mitigation has been a necessary requirement from the initial planning stages with the Perata bill requiring a plan for monitoring air emissions (Perata 1999). The draft Implementation and Operation Plan (IOP) was titled "A Strategy to Reduce Traffic Congestion and Improve Air Quality" (Water Transit Authority 2002); the final IOP was retitled "A Strategy to Improve Public Transit with an Environmentally Friendly Ferry System" (Water Transit Authority 2003). The goal is to expand the ferry fleet with the cleanest possible marine engine technologies. Related WTA studies have looked at technologies that may achieve these goals, setting a target to achieve greater than 85% reduction in emissions.

There are a number of efforts underway to reduce ferry emissions in support of related maritime projects. The New York New Jersey Port Authority has undertaken a demonstration project with the New York City Department of Transportation to retrofit a Staten Island ferryboat with new exhaust emission reduction devices.

> "The demonstration project grew out of discussions with the U.S. Army Corps of Engineers, the U.S. Environmental Protection Agency and environmental agencies in New Jersey, New York and New York City on air impacts associated with the upcoming project to deepen channels in New York harbor to 50 feet. These agencies recognized a need to offset the air emissions of tugs and dredging equipment involved in the historic channel-deepening program. Retrofitting the Staten Island Ferry exhaust system was identified as a potential solution. NYCDOT, recognizing the significance, offered the availability of one ferry to evaluate the feasibility of the emission reduction devices." http://www.panynj.gov/pr/pressrelease.php3?id=373

The US Army Corps of Engineers notes:

> "Government operated ferries; such as the Staten Island Ferry have several advantages as compared to the repowering of tugs or the retrofitting of private ferries. They are not subject to being idled (and therefore not producing emissions offsets) as a result of unfavorable business conditions, nor will they be taken outside of the nonattainment area to pursue better business opportunities. Moreover, they are sufficiently numerous to have the potential to offset all of the HDP construction emissions (the Staten Island Ferry fleet is the largest discrete unregulated source of marine emissions in the non-attainment area). Accordingly, they are accorded a preference in the USACE Headquarters memo. For these reasons, the Staten Island Ferries were prioritized, as a choice emission reduction source." (US Army Corps of Engineers 2003)

In another ferry emissions reduction effort, the Environmental Defense notes:

> Emissions from ferry boats are an ongoing concern throughout the ferry industry. What few ferry riders realize—and what may seem counterintuitive at first—is that ferry boats can have a greater impact on air quality than if passengers were in their own cars or on buses. The reason for higher ferry emissions is due to the lax standards on marine diesel engines (which most ferry boats use) currently in place. Though new EPA regulations will go into effect in 2007 many initiatives are meant to ensure that that emission criteria—or even emission controls beyond the EPA regulations—are enacted now to better improve air quality. An important program that was recently initiated intends to retrofit private ferries with innovative technology that will reduce particulate matter and NOx given off by marine diesel engines in our region. This program was initiated by a coalition of city, state and federal organizations as well as advocates in the environmental and educational communities. In September, the New York State Energy Research and Development Agency (NYSERDA) and Environmental Defense received $6.8 Million dollars for an eighteen to twenty-four month program that will retrofit over forty ferry boats in the NY/NJ region. The program, explained Environmental Defense's Living Cities Program Director Andy Darrell, consists of four phases, first NYSERDA and Environmental Defense will take an inventory of all the ferry boats in the NY Harbor then research the most appropriate technology for retrofitting the boats, test the technology on a sample of the ferry boats and finally retrofit the entire fleet. http://www.waterwire.net/News/fullstory.cfm?ContID=1446

Given the increasing commitment by vessel operators to improve environmental performance, and with public funds potentially available to assist technology demonstration projects, the question is not whether to reduce marine engine emissions but how.

1.2 U.S. Fleet Profile

A profile of the US ferry fleet was derived using a 2001 U.S. Army Corps of Engineeers data base (US Army Corps of Engineers 2001). There are 625 vessels in the data base, and not all vessels have data for all parameters. Ferries can be classified according to their regulatory status under federal regulations. Safety and environmental regulations for US-flagged vessels carrying passengers for hire are developed, promulgated, and enforced by the US Coast Guard and published in the Code of Federal Regulations (CFR), Title 46. Depending on the vessel size and passenger complement, such regulations are contained in 46 CFR Subchapter T, K, H, or C.

T-Boats are those passenger vessels regulated under 46 CFR Subchapter T, Parts 175-185. Such vessels have a gross tonnage (volume) of under 100 tons, carry no more than 150 passengers, and have accommodations for not more than 49 overnight passengers. If a vessel measures less than 100 gross tons but carries more than 150 passengers (or has accommodations for more than 49 overnight passengers), it then loses its "T-Boat" designation and becomes a Subchapter K vessel, subject to 46 CFR Subchapter K, Parts 114-122. If its tonnage is greater than 100, it then becomes a Subchapter H vessel, subject to 46 CFR Subchapter H, Parts 70-80. Subchapter C vessels include uninspected, special-case passenger vessels of over 100 tons, with 12 or fewer passengers (e.g., charter mega-yachts), or under 100 tons, with 6 or fewer passengers (e.g., charter fishing vessels, small charter sailboat or water taxi). For the latest regulation language, see Code of Federal Regulations (CFR), Main Page at http://www.gpoaccess.gov/cfr/index.html.

The ferry data base contains Subchapter T, K, and H vessels only. Sixty-one percent (320 of its 528 vessels with passenger capacity data) have 150 or fewer passengers; these are referred to as T-boats if their gross tonnage does not exceed 100 tons. Seventy-six percent (414 of its 548 vessels with tonnage data) measure less than 100 net tons. Of those 414 vessels, sixty-three percent have 150 or fewer passengers. Note that the data base includes net tonnage figures, not gross tonnage, on which the USCG regulations are based. As such, the correlation of net tonnage and passenger count is an approximation of vessel class, Subchapter T or K.

As shown in Figure 1, there is a large proportion of older vessels in the US ferry fleet. Almost three-quarters of the fleet (74%) is over ten years old, and over half of the fleet (51%) is over twenty years old. The tendency for operators to employ a "mature" fleet suggests that improvements in fleet engine technologies will likely be as a result of engine modifications and replacements as opposed to new vessel construction.

Figure 2 shows that approximately half of the fleet (52%) has under 1,000 installed horsepower, and about three-quarters of the fleet (76%) has under 2,000 installed horsepower. Note the single vessel above 15,000 Hp is "The Cat", operated in Maine by Bay Ferries Limited. The uniqueness of this vessel's design would suggest that the results of a technology decision analysis for this high-speed waterjet catamaran may differ from results for other vessels.

Figure 3 summarizes ferry vessel data from the U.S. Army Corps of Engineers (USACE) Navigational Data Center (US Army Corps of Engineers 2001). (The figure does not include USACE statistics for vessels with very lower power or for one vessel, "The Cat", which has ~38,000 installed power and 2497 net tons.) Approximately 76% of the passenger ferry fleet falls below 100 net tons, a correlated proxy for the percent of the fleet subject to regulation under Subchapters T or K of the passenger vessel rules of the U.S. Coast Guard. Approximately 76% of the fleet has installed power equal to or less than 2000 Hp. Of course, the statistical data includes gaps (some vessels' statistics do not include power) and possible inaccuracies (some vessels are listed with very low power, e.g., less than 50 Hp total); the data merely present an overall picture of installed power in the fleet.

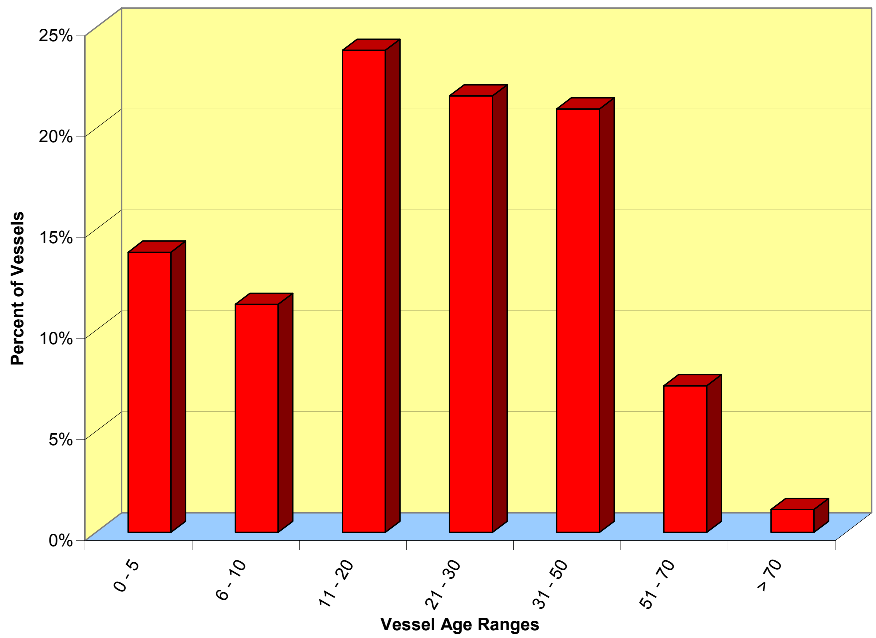

Figure 1. Age Distribution of U.S. Ferry Fleet in 2003.

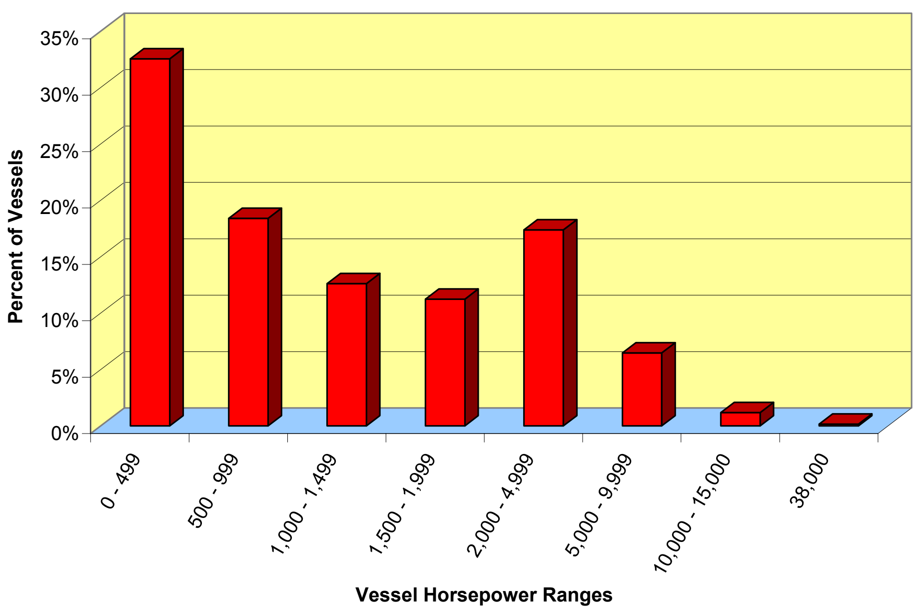

Figure 2. Power Distribution of U.S. Ferry Fleet in 2003.

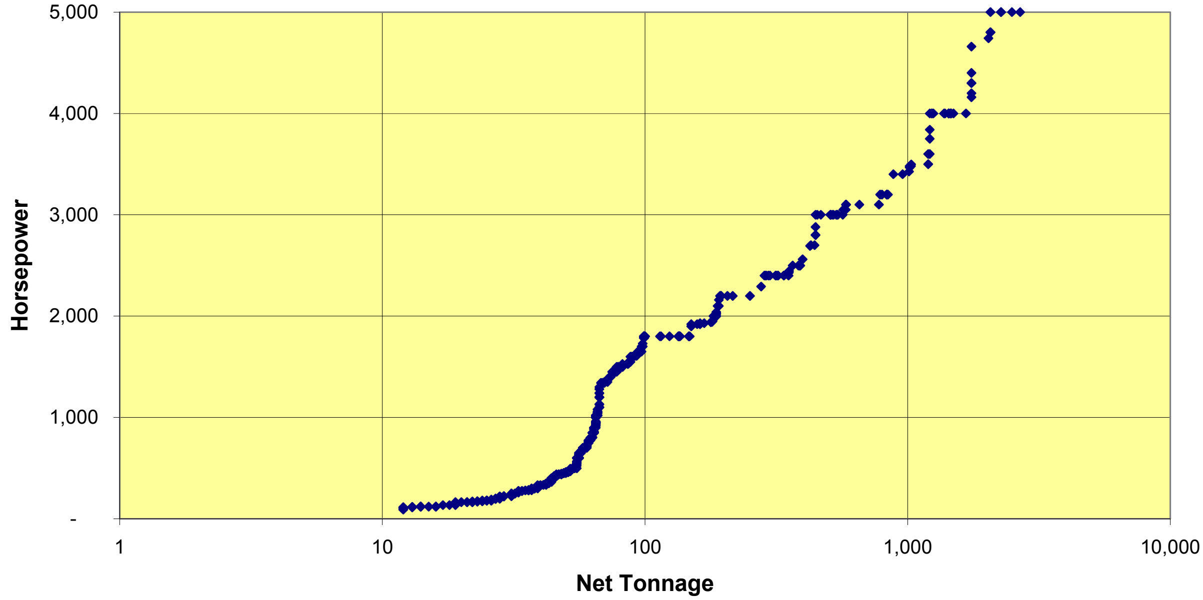

Figure 3. Relationship Between Net Tonnage and Power for U.S. Ferry Vessels.

2 A DECISION ANALYSIS FRAMEWORK FOR TECHNOLOGY CHOICE

The decision to adopt emission reduction technologies is not a simple one. There are many factors that an operator needs to consider before choosing a technology to improve environmental performance. Quoting the Diesel Technology Forum (Diesel Technology Forum 2003):

> "Creating a successful retrofit project begins with careful selection of engine candidates. Some engines and vehicle applications make much better retrofit candidates than others, and certain engines and vehicles may simply be inappropriate for investment in an upgrade. In other cases, retrofit may be technologically infeasible. Once appropriate candidates are identified, it is equally important to match those engines with the right enhancement technology. Proper technology matching helps en-sure that emissions performance meets a project's air quality improvement goals, and ensures that vehicle reliability is not negatively impacted."

In this section, we introduce some basic concepts of quantitative decision analysis. These are tools that are often used in engineering or economic studies. Quantitative decision tools offer operators the ability to structure alternatives and apply their own context to technology decisions in the process of achieving environmental performance goals.

2.1 Decision Analysis Overview

Decisions can be difficult for many reasons (Clemen and Reilly 2001). Perhaps the choices are simply complicated, with many factors that need to be considered; keeping different issues clear may be tough. Some of the important considerations may be uncertain; for example, the cost or performance of emission control technology may not be well understood in a certain type of vessel – or may be untested in the engine under consideration. Frequently the decision poses tradeoffs among desirable attributes or objectives; emissions reductions may be achieved but at some capital cost or with increased operating cost. Possibly the decision is influenced by different perspectives, each of which may prefer different choices; passengers and local residents may want reliable ferry transportation that is both clean and affordable, while operators may also be interested in meeting economic goals.

The use of decision frameworks and analytical tools can help make clear where objectives are shared, what are the key tradeoffs and uncertainties, and generally clarify the factors influencing a decision. By making the decision "transparent", issues that really matter to the decision makers and stakeholders can become the focus of discussion and participants can avoid polarizing debate on less related issues. Most importantly, better decisions may be possible.

Decision analysis does not replace individual judgment. Decision analysis ***requires*** personal judgments for good decisions. The methods provide a tool for decision makers to structure decisions so that good judgment can be applied to the relevant aspects of the choice. More to the point, tough decisions may not be made easy through decision analysis. In some cases, analysis clarifies the problem so that the toughest tradeoffs involved in a decision are made explicit – this doesn't make the choice easier than "muddling through" but it does allow the decision maker to appreciate better what may be at stake. By modeling the decision structure, one can ask “what if” questions, such as which conditions would affect most the recommended choice. These sensitive parameters may be worth investigating further, especially if they are uncertain. In some cases, this enables greater creativity in developing new options that better achieve fundamental objectives (Keeney 1992).

There are standard tools used in decision analysis. Often, a basic tool is simply a spreadsheet or sheet of ledger paper, used to define objectives, lay out basic alternatives, and consider the important attributes relating those alternatives to the objectives. This report does not discuss or apply many of the tools available to analysts, but rather provides one simple structure within the context of marine technology assessment for emission control. Many texts are available to help analysts understand and apply techniques (Keeney 1982; Saaty 1982; Yu 1985; Keeney 1992; Kleindorfer, Kunreuther et al. 1993; Clemen and Reilly 2001; Andrews 2002; Raiffa and Metcalfe 2002). Interested persons are directed to the large and active field of decision science for additional information.

2.1.1 Defining Objectives

One of the most important aspects of decision making is careful selection of the objectives. An objective is something that a decision maker wants to achieve (Keeney 1992). Many important decisions are made under the mistaken assumption that people clearly know what they want, that the objectives are clearly understood by all people affected. Sometimes a single objective can drive the decision; a ferry operator may want to decrease operating costs or maximize ridership revenue to maximize a profit objective. However, in many situations multiple objectives are present and may be in conflict. A vessel operator may want to maximize revenue but also may want to meet a minimum service schedule.

Specifying objectives is not as easy as it may appear. For example, maximizing profit over a near-term period (say, one or two years) may not achieve long-term profits. Similarly, setting clear environmental objectives for the next generation vessel may not achieve environmental goals in the near term. In fact, objectives that may appear similar can actually resulting in conflicting strategies. For example, expensive designs for cleaner replacement vessels may create incentives to continue operating existing vessels longer than originally planned, until an operator can justify the additional capital (or financing). Or, a decision to retrofit a vessel for a demonstration that will be removed in several months may select different technologies than a choice to permanently retrofit a vessel.

Many decision analysis texts distinguish between fundamental objectives and means objectives. Fundamental objectives are the basis for considering the decision at all (Keeney 1992); they most closely describe the decision makers’ values. Means objectives are more strategic and relate to the degree to which fundamental objectives can be met; they are goals that contribute to achieving the fundamental objective. This is somewhat context-dependent. Most importantly, objectives should be revisited iteratively during analysis to clarify them within the proper context.

Consider marine engine emissions as an example. One of the fundamental objectives motivating efforts to reduce emissions may be air quality goals (and related health benefits, or greater visibility, or reduced acid rain impacts, etc.). If air quality can be considered a fundamental objective, then reducing pollution emissions from various sources is a means objective to help achieve air quality standards. Additional objectives will be discussed in the next section as we develop criteria for considering emission control technologies.

2.1.2 Identifying Alternatives and Attributes

Once the objectives are defined (at least at the first iteration), one can begin to consider alternatives. Identifying alternatives is a natural and familiar step in any decision, but it is important to avoid narrowly identifying the obvious while ignoring creative solutions. Perhaps the first most important purpose in identifying alternatives early on is to define important attributes relating alternatives to objectives. Attributes may be considered the “criteria”, or performance measures used to judge preferences for one alternative versus another (Keeney 1992).

Natural attributes are ones commonly understood by all stakeholders (Keeney 1992). These include cost (measured in dollars) or physical properties (weight and volume). These attributes may appear obvious but choosing them can require judgment. For example, the absolute volume or weight of a new piece of equipment may be chosen if maintaining ship stability is one of the key objectives; on the other hand, determining whether new equipment impacts cargo or passenger capacity may require that the attribute be defined in terms of payload volume or weight.

If a natural attribute is not appropriate or available for the set of objectives, then one can choose to construct an attribute or select a proxy attribute. A constructed attribute may involve assigning value to descriptions of various properties. This is often done in market surveys, where stakeholders may associate a score with a perception. For example, reliability is an attribute that matters to an operator but may not be a natural attribute (commonly understood in the same terms) among operators. Perhaps a descriptive scale could be constructed that would enable operators to associate technology alternatives with objectives where reliability is important – such as on-time service for ferry departures. In this example, perhaps a lower score would be assigned to reliability problems where an equipment failure prevents the vessel from operating according to schedule; a higher score would be assigned to technologies that can be turned-off or bypassed without loss of vessel operations because on-time service reliability is not compromised. Here constructing a common attribute scale is important – one where operators can agree on the scale. Ideally, the scale should be objective (and clear) enough that different persons would assign the same attribute score; however, as long as scale is clear, the actual scoring of the attribute may be subjective. Examples of descriptive scales are provided in the next section.

Where natural attributes and constructed attributes are very difficult, an indirect measure or proxy may be chosen as the attribute (Keeney 1992). One example could be emissions from marine engines, as a proxy for meeting air quality goals. Note that a proxy attribute (emissions rate) may be a natural attribute for a means objective (controlling emissions) but a proxy attribute for a fundamental objective (clean air or better health of the public).

All types of attributes are more useful when they are measurable, operational, and understandable (Keeney 1992). In choosing the measurable scale, context matters; one way of measuring an attribute may be more appropriate to the objective than another. For example, looking for a least cost technology can be done in terms of capital and/or annual costs. For some operators, near-term costs may be more important than life-cycle costs; if so, then choosing a least-cost approach in terms of capital could be appropriate. In operational terms, a particular attribute score should describe one and only one condition; in this regard, assigning consequences and judgments to individual attributes are more operational than assigning these jointly to sets of attributes. For example, attributes that incorporate both capital and annual costs may relate better the set of alternatives with the objectives than if these costs are treated separately. In such a case, net present value may use a discount rate (interest rate) that appropriately relates the decision makers' preferences for the trade-off between capital costs today and annual costs in future years. Lastly, defining an attribute scale that is not ambiguous is important for understandability. Terms such as "slight increase" can be unnecessarily vague, since one operator may consider a 2% increase (in fuel consumption, for example) a slight increase while another would consider it more than "slight".

A special type of attribute that is often useful is the probability of the occurrence of an event. A simple example would be the NOx reduction performance of a technology. Perhaps a vendor claims her technology can achieve a 95% reduction in NOx, but some demonstration studies have shown NOx reductions ranging from 60% to 98%. What value should an operator use in considering this vendor's device among other alternatives? Of course, a detailed decision analysis might develop a probabilistic distribution that describes the range of possible NOx reduction values associated with the vendor's technology and distributes probabilities across this range. Application of probabilities will be applied in the examples to follow.

After using an initial set of alternatives to begin defining important attributes, as a first iteration, it is often useful to reconsider the set of alternatives. Perhaps with clear attributes defined, additional alternatives can be identified that were ignored before. For example, considering alternatives for emission control may include some combinations of initial options, such as combining new, cleaner engines with aftertreatment or alternative fuels. Or operational solutions may be considered if they achieve better scores among the attributes. The point is that these steps of choosing attributes that connect alternatives to carefully chosen objectives may benefit from additional iteration.

2.1.3 Analytical Tools: Net Present Value and Expected Value

In terms of technology assessment for reducing emissions from marine engines, two primary analytical tools are considered. First, the concept of net present value (NPV) is used to combine capital costs and annual costs – where costs occurring (or recurring) over time are combined to represent an equivalent total cost today. (Alternatively, one could convert all costs to equivalent annual costs over a given period; this is used to evaluate cost-effectiveness, discussed in Section 2.2. The same techniques are used but NPV will be demonstrated in this report.) Second, an "expected value" calculation is presented that allows one to combine possible consequences of choosing an alternative with the likelihood (probability) that the consequences will occur.

Net present value (NPV) is a tool for evaluating the tradeoff between spending (or receiving) dollars today or spending (or receiving) dollars in the future. The value of a dollar to a business or individual depends on when it is available to the decision maker (Clemen and Reilly 2001). Most people are familiar with this concept, since it is how we make purchases over time. In short, when we purchase on credit we pay more for a product (a home, a car, etc.) than its cash value today. We find the stream of payments over a period of time, at a given interest rate, to be preferable to paying the total amount up front.

In calculating the present value of a future cost (or future receipt), an illustration may help (Clemen and Reilly 2001). Consider an amount $\$x$ to be received at the end of n time periods, and let i represent the interest rate per time period in decimal form (e.g., an interest of 10% would be $i = 0.10$). The formula for calculating the present value (PV) is

$$PV(x,n,i) = \frac{x}{(1+i)^n}$$ **Equation 1**

Of course, current dollars represent a condition where $n = 0$, so the $\text{PV}(x, 0, i) = \$x$. The net present value (NPV) of a series of cash flows is the present value of positive cash flows (income) minus the present value of negative cash flows (costs). This is also known as discounting.

Expected value is a calculation that combines the value of an outcome with its likelihood. It is only one of many ways to choose among alternatives, but it has an advantage of favoring likely outcomes more than unlikely outcomes based on the rules of probability rather than desire for (or fear of) certain outcomes. This is calculated as the probability-weighted average of all outcomes related to a given alternative. Essentially, one multiplies the payoff (or consequence) of each given outcome by the probability of each outcome; then all possible outcomes that relate to a given choice are summed to arrive at an expected value for that choice. To present this concept, a simple lottery example from a widely used decision text may help (Clemen and Reilly 2001).

Consider that you have been automatically entered in Lottery 1, which will pay \$10 if you win. You have a 45% chance of winning – the likelihood or probability that you will win is $p = 0.45$. Your friend has a ticket for Lottery 2, which pays \$25 to the winner, but offers lower odds of 20% that his ticket will win – a probability $q = 0.20$. Your friend is willing to trade your ticket for his at the price of \$1. Would you agree to the trade or not?

This example represents a choice between two risky alternatives. Figure 4 illustrates the options available; note that the payoff if you play Lottery 2 is \$24 = \$25 winnings - \$1 trade. To make this choice using the given probabilities, begin by calculating the expected value of keeping the ticket for Lottery 1. The calculation is

$$EV(\text{Keep Ticket}) = 0.45 \cdot \$10 + 0.55 \cdot \$0 = \$4.50$$ **Equation 2**

Calculating the expected value for trading tickets, we get

$$EV(\text{Trade Ticket}) = 0.20 \cdot \$24 + 0.80 \cdot \$0 = \$4.00$$ **Equation 3**

Based on expected value results, it would be better to keep the ticket for Lottery 1. Expected value can be understood as the average value expected from making a decision many times. Of course the actual outcomes individually will never equal $4.50; one either wins $10 in Lottery 1 or wins nothing.

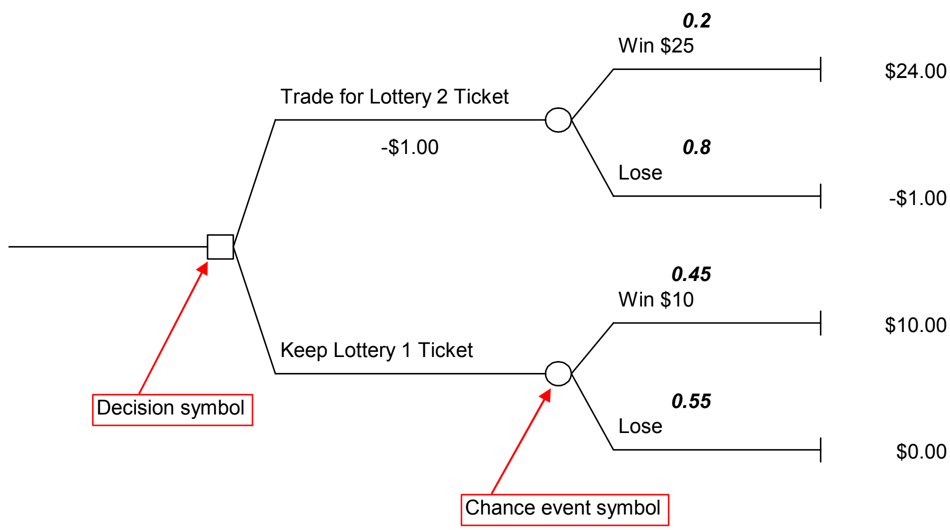

Figure 4a

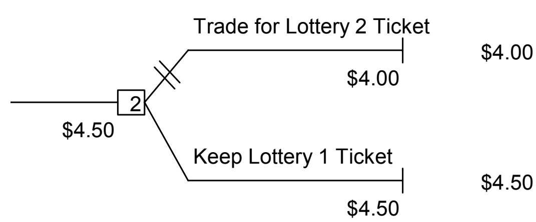

Figure 4b

Figure 4. Lottery example for calculating expected value (EV). Figure 4a presents the problem with chance events and decisions in symbol form; Figure 4b presents the same choices with chance events and payoffs replaced by their expected values.

Making a decision based on expected value is more "risk-neutral" than other criteria for choosing. Another scheme for choosing include a "Maxi-Max" strategy that simply looks for the best possible outcomes, ignores the likelihood of losing or winning, and chooses the alternative that maximizes the maximum preferred possible outcome. This strategy may be overly optimistic, given the odds of a preferred outcome. Similarly, a "Maxi-Min" approach considers only the worst outcomes for each choice and selects the alternative that maximizes the least preferred outcomes, again ignoring the probability of specific outcomes. This strategy may be overly pessimistic, given the chances for a undesirable outcome. In this report, an expected value framework will be employed.

2.1.4 ***Presentation Tools: Influence Diagrams and Decision Trees***

The previous expected value example used a decision tree to illustrate the decision choices, their uncertain outcomes, and the possible payoffs (Figure 4). This structure can be useful to assist in presenting and calculating quantitative results for decisions. The examples in this report were produced using Treeplan software, but other decision analysis software packages can be purchased that produce and solve decision trees. In Treeplan, squares represent decisions and circles represent chance events. However, software is optional; the calculations can be done without any software, or using simple spreadsheet formulations, as shown in the examples in the next section.

Another tool for presenting a decision context is an influence diagram. In an influence diagram, rectangles represent decisions, ovals represent chance events, and (if fully coded quantitatively) diamonds can represent final consequences or payoffs (Clemen and Reilly 2001). Software packages enable decision analysts to fully code relationships and use influence diagrams to solve for preferred choices. Alternatively, influence diagrams can be very useful at the early stages of a decision, when key relationships among factors that influence a decision may need clarification. That is how they are presented here.

For example, Figure 5 illustrates an influence diagram generated during the development of this report. Here, various attributes are depicted with five primary attributes affecting the technology selection decision. In this illustration, objectives for emission control technology may include goals related to achieving environmental performance, minimizing cost to the vessel, meeting vessel compatibility requirements, avoiding negative passenger or payload impacts, and matching a technology to the terminal infrastructure. These may closely represent the fundamental objectives described in Section 2.1.1.

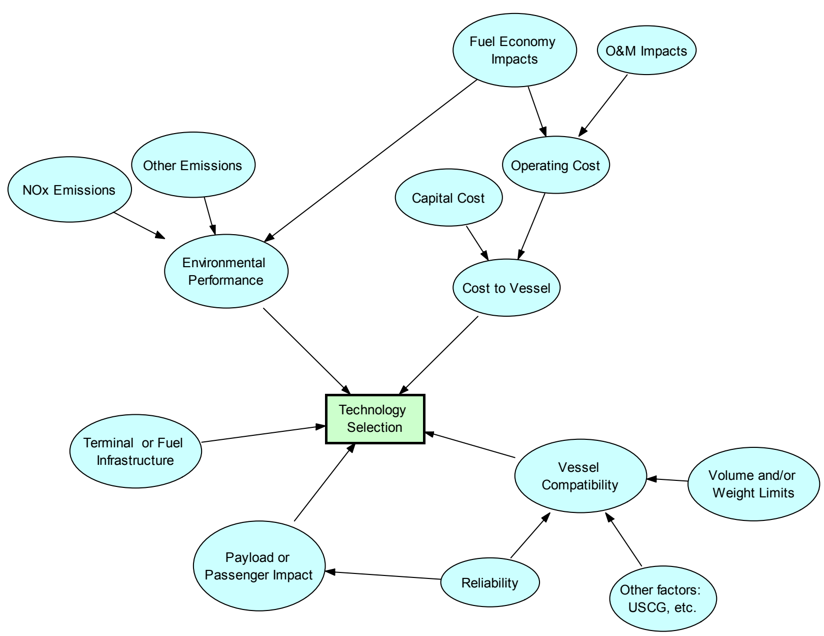

Figure 5. Example of an Influence Diagram illustrating factors that may be important to operators considering adoption of environmental control technologies.

2.1.5 Dealing with Multiple Objectives and Attributes

Consistent with the discussion above, ***objectives are the primary goals*** sought in a decision and ***attributes are the quantities relating alternative to objectives*** that are measured or assigned (the scores) for each alternative. Several authors describe essential criteria for choosing objectives and attributes (Keeney 1992; Clemen and Reilly 2001), and this summary condenses a discussion in one decision text (Clemen and Reilly 2001):

1. The set of objectives … should be complete; it should include all relevant aspects of a decision.
2. The set of objectives should be as small as possible. Too many objectives can be cumbersome. If all the alternatives are equivalent with regard to a particular objective, then that objective will not be of any help in making the decision.
3. The set of fundamental objectives should not be redundant (repeated or closely related). Redundant objectives treated as independent can unfairly bias the analysis.
4. Each objective in the set should be able to be considered without having to consider the others. (For example, we can usually consider the cost of a job and the time to complete a job according to separate attribute scores, even though both objectives – minimize time and cost – may be important. However, an operator may not really be able to consider separately an objective that "minimizes increased annual labor costs" from one that "minimizes increased equipment or fuel costs" related to a emissions control alternative; they may be combined as annual recurring costs.)
5. Means and fundamental objectives should be distinguished. It is important to remain clear why the decision matters in the first place as determined by fundamental objectives, even if attribute proxies are chosen according to means objectives.
6. Attributes must be operational, or relatively straightforward (easy) to apply.

One way to consider multiple attributes is to keep them separate and consider them on their own scales. An example of this is presented in Figure 6. By representing attributes orthogonally (on separate axes), we can consider the multi-dimensional problem in a way consistent with the multiple attributes. In Figure 6, for example, one can see quickly that alternatives that minimize both emissions (x-axis) and cost (y-axis) are preferred to ones that don't. This defines a "frontier" or boundary that maximizes emissions reductions at lowest NPV cost. As one would expect, the frontier shows that greater reductions in emissions cost more, although alternatives not on the boundary achieve less reductions at greater cost than the preferred alternatives.

Another item to note in Figure 6 is that ranges in performance and cost (shown by the bars on each alternative symbol) make the choice somewhat complicated. If only the average or "best guess" values are used (represented by the symbols), then water fuel emulsion would be preferred over repowering with a fuel-efficient engine at NOx reductions less than ~42%. However, if one could be assured of fuel savings with a repowering option, it may be less costly to achieve a 50% reduction through repowering than to achieve ~42% emissions control through emulsions. (Note that this commentary refers to the data developed for this report, based on technology literature; it may not represent a specific result that an operator may find when alternatives are considered for a particular vessel.)

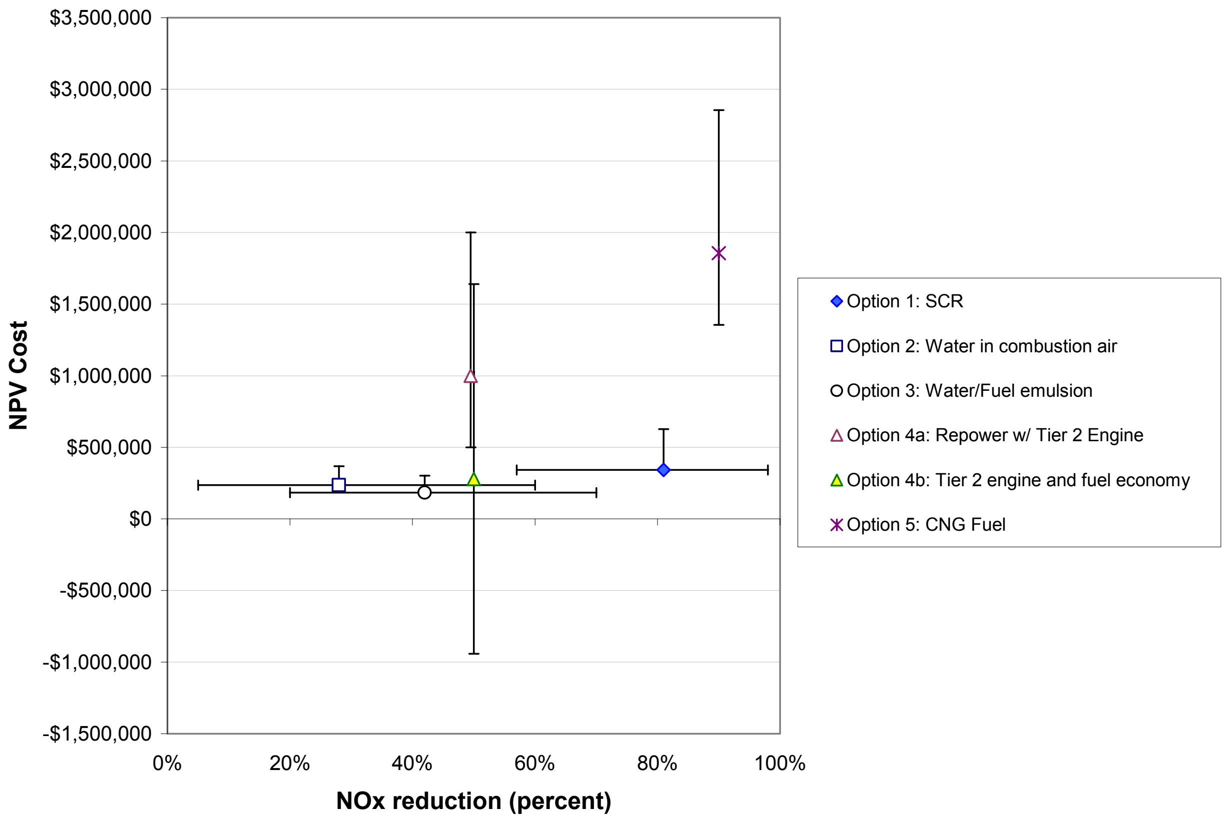

Figure 6. Graphical comparison of NOx reduction attributes with NPV cost attributes for various technologies, keeping the attributes separate (orthogonal on different axes). Bars represent uncertainty in emissions control (horizontal bars) or uncertainty in NPV cost (vertical bars). Note that improving fuel economy can greatly affect the NPV cost of repowering with an engine meeting EPA Tier 2 emissions standards (triangle symbols with and without fuel economy assumptions). Estimates presented here are consistent with the assumptions and data presented in Section 4.

2.1.6 Applying Constraints: Optimizing Versus Satisficing

A decision framework may either produce a clear recommendation of an optimal solution or present a set of "preferred" alternatives that generally satisfy objectives under a range of conditions. Using attributes to evaluate which alternatives meet objectives does not necessarily produce a single "best" solution.

In fact, optimization may not be the goal of a decision analysis – especially if the attributes for given alternatives are uncertain or likely to change over time. This is currently the case with many emission control technologies that are undergoing demonstration in the United States and Europe. For example, the cost of selective catalytic reduction technologies (SCR) used to be considered to be nearly $1 million per vessel, but market-ready demonstrations (mostly in Europe) show that current costs are much lower. In many situations, it is valuable to look for a set of choices that satisfy the objectives, and not optimize on a single alternative.

For a vessel operator, it is often more useful to identify what technologies are "contenders" – those that merit particular analysis for a given vessel – and what technologies do not require additional attention for the vessel class under consideration. This may be done by first considering "show-stopper" attributes – ones that would unilaterally disqualify a technology from consideration for a given vessel or class of vessels. An example might be violation of engine warranties, a condition that may be unacceptable to an operator regardless of the technology cost or performance. Then remaining attributes may be applied to look for those that may have similarities that are acceptable. Examples might be to identify alternatives that reduce NOx by at least 50% or those with NPV costs less than $500,000 (refer to Figure 6). Here iteration is again emphasized in the decision process. This is the way in which results will be presented in Section 4.

2.2 Previous Analyses of Emission Control Technologies

This section serves mainly as a presentation of examples for the operator, in that these prior studies evaluated emission control technologies for marine engines.

2.2.1 U.S. Navy Study: Marine Diesel Engine and Gas Turbine Exhaust Emissions

A 1994 study conducted by the Naval Sea Systems Command (NAVSEA) provided analysis "to support the decision process within the Navy regarding Navy marine engine exhaust emissions" (NAVSEA 1994). This study included a semi-quantitative analysis of eighteen technologies to reduce NOx emissions, using twelve attributes. An excerpt of the Navy's analysis is reproduced in Table 1, showing results for several of the technologies considered (we reproduce those technologies similar to technologies under consideration for demonstration in the commercial fleet). This example is provided only as an example of previous decision-based analyses of emission control technology.

The basic framework for this decision analysis essentially uses three steps. Step 1 can be called "attribute scoring", where each attribute is assigned a range of possible values defined to match the qualities of that attribute. The "Technology Code Key" defined in the NAVSEA study is how the Navy scored each of possible attribute values (see Table 1). While the possible values are specific to the technologies under consideration, the scores should be chosen without regard to a predetermined technology preference but only with regard to the attribute itself; this helps avoid inconsistent scoring. In this example, attributes could have between three and five specific values. Step 2 can be referred to as "attribute weighting," where the decision maker assigns a weight to each attribute relative to the other attributes. In the "Technology Code Key", the Navy study used a three-point weighting scale ranging from "very important" to "somewhat important."

This example has several limitations for today's commercial vessel operator. Most importantly, this excerpt is an older example of a decision framework for a unique decision maker, NAVSEA. Some of the judgments are specific to diesel-powered vessels in the U.S. Navy, and all of the data would have to be updated after nearly ten years. It is worth noting that NAVSEA placed greater weight on engine performance than cost (presumably for combat readiness); a commercial operator may assign different weights. Second, it may be preferable to assign the same number of possible attribute scores to each attribute to avoid unintentional weighting biases; giving one attribute five possible scores while assigning three to others introduces slightly different scales. Third, the definitions assigned to attribute scores should be clearly defined so that an objective (uninformed) observer can apply them. In this example, the terms "little effect", "somewhat important", and "some increase" cannot be assumed to mean the same thing to different decision makers; on the other hand, defining a decrease of "3% or more" or a cost range of "< $100,000" do meet the clarity standard. Lastly, there is no acknowledgement of uncertainty in the attribute values associated with each alternative, except for the vague definitions (such as "some increase"). This can mask uncertainties that may be important for the decision maker to consider. This is especially important where new technologies or market-prices are not still emerging; a "snapshot" today may not adequately inform an operator of the attributes that will be valid when a decision is implemented in the near future.

2.2.2 Water Transit Authority Study: New Technologies and Alternative Fuels

In a report commissioned by the San Francisco Bay Area Water Transit Authority (WTA), John J. McMullen and Associates, Inc. (JJMA) and Booz Allen Hamilton evaluated more than ten alternative fuel options, some fourteen propulsion, and thirteen exhaust treatment technologies related to WTA plans for an expanded ferry fleet (John J. McMullen Associates and Booz Allen Hamilton 2002). They applied thirty-one attributes to these alternatives, with a simple scale of "red", "yellow", or "green" scores. JJMA summarized the attributes into categories – loosely parallel to grouping attributes by fundamental objectives. They chose the following nine categories (see their report for definitions and discussion):

- Maturity
- Performance
- Environmental Impact
- Physicals of System
- Reliability
- Safety
- Logistics
- Economics
- Lessons Learned

For each particular attribute, a unique meaning of "red", "yellow", and "green" was defined. For example, technology status was one of the attributes used in the WTA study. If the status of a technology was commercially available, it was called mature and given a "green" score; however, if the technology was a prototype it was assigned a "yellow" score; if the technology was still in laboratory development, it received a "red" score. As described in the report, the WTA study assigns numeric values to the qualitative color scoring, and then averages the attributes assigned to each category.

> "To create summary scores, consideration is given to the components of each attribute. For example, if all the cells under "Maturity" were red, then a single rating of "red" has been given to the cell for Maturity. If half of the cells had been red and half green, then the summary will be yellow. (The actual calculation process involved assigning a value of 1 to red, 2 to yellow, and 3 to green, and then calculating the mean value for each set of attributes.)"

Table 1. Example from environmental technology assessment for diesel engines from 1994 study for the U.S. Navy (NAVSEA 1994). Note that these specific rankings are significantly outdated today and may not be applicable to commercial vessels. They are presented as an example only.

	Technology	NOx Reduction	Retofit	Fuel Consumption	Maintenance	Reliability	Weight	Space	Other Emissions	Technical Status	Cost	Engine Performance	Weighted Results
	Weighting Factor	3	2	2	3	3	3	3	2	1	2	3	
Option 1	Selective catalytic reduction (SCR)	1	3	2	2-3	1	3	3	2	1	3	1	54-57
Option 2	Water in Air	3	2-3	2	2-3	2-3	3	3	3	3	1	1	61-69
Option 3	Water-fuel emulsion	2	2	2-3	2-3	2-3	3	3	3	3	3	2	65-73
Option 4	Low-emission diesel engine (Repower)	1	2-3	2	2	2	2	2	3	1	3	2	54-56
Option 5	Low-emission diesel fuel (Alternate fuel)	3	1	3	3	1	1	1	2	3	1	1	47

Technology Code Key - Weighting Factors in parentheses ( )

NOx Reduction
(3) = Very important
1 = Largest reduction (> 50%-90%)
2 = Reduction of 20%-50%
3 = Reduction of less than 20%
4 = Little to no reduction
5 = Increase in NOx

Retofit
(2) = Important
1 = Accomplished with little difficulty
2 = Accomplished with some difficulty
3 = Accomplished with much difficulty

Fuel Consumption
(2) = Important
1 = Decrease - 3% or more
2 = No change
3 = Increase - 3% or less
4 = Increase - greater than 3%

Maintenance
(3) = Very important
1 = Little effect
2 = Some effect - additional hours
3 = Major effect - additional manning

Reliability
(3) = Very important
1 = No change
2 = Decrease - 10% or less
3 = Decrease - greater than 10%

Weight
(3) = Very important
1 = Little to no increase
2 = Some increase
3 = Significant increase

Space
(3) = Very important
Same as weight

Effect on other emissions
(2) = Important
1 = Decrease
2 = No change
3 = Increase

Technology status
(1) = Somewhat important
1 = Presently in use
2 = Under research and development
3 = Currently being considered

Engine performance
(3) = Very important
1 = Improved
2 = No change
3 = Degraded

Cost
(2) = Important
1 = < $100,000
2 = $100,000 to $500,000
3 = > $500,000

Note: cost included R&D and purchase but not installation

Weighting factors are based on the following criteria:
1 = Somewhat important
2 = Important
3 = Very important

The WTA report then performs two operations on the matrix to synthesize rankings for alternatives. First, the analysis simply chooses an "objective" or primary attribute of importance (emissions performance) and identifies technologies that achieve reductions equal to or greater than 80%. Second, the study assigns weights to the remaining attribute categories, as shown in Table 2 reproduced from the WTA report.

Although this methodology is generally easy to follow, subjective elements of this approach can be problematic; for example, defining the difference between the red (not practical) score and the yellow (can be accomplished, but only with some difficulty) score in the suitability for retrofit attribute may be vague and open to interpretation. Even the WTA study results were applied given a set of "average vessel" assumptions (400 and 149 passenger ferries operating at either 25 or 35 knots) that may not apply to particular operators. Perhaps more important limitations are the shear size of the matrix, the potential for attributes to be duplicative or highly correlated. For example, suitability for retrofit really may be a function of other more primary attributes, such as weight or volume. Lastly, the approach can be a part of technology assessment, particularly at a fleet-wide level, but may be too cumbersome to apply by a single operator or to a single vessel. As the WTA report cautions, this analysis is a work in progress; the report's purpose is to assess technologies that may be suitable to ferries rather than to select technologies for specific vessels.

Table 2. Weighting scheme applied in WTA study, excerpted from Section 8, Page 45

Parameter:	**Has been weighted: (importance)**	**Reason:**
Maturity	0	Significantly less important than other parameters, if considered alone. Note however that Reliability is very highly weighted.
Performance	5	Vital to propulsive success of the ship
Physicals	8	Space and weight are highly constrained on high performance ferries
Reliability	10	Vital to the successful operation of the ferry system
Safety	7	Intermediate in importance
Logistics	7	Intermediate in importance
Economics	10	Vital to the successful operation of the ferry system
Lessons Learned	7	Intermediate in importance

2.2.3 ***Other Studies Considering Cost, Cost-effectiveness, and Policy Design***

Other examples have been more narrowly focused on primary tradeoffs between objectives such as cost and emissions. In this regard, it may be useful to describe in more detail the attribute "cost-effectiveness," a constructed attribute often used in analysis of emissions technologies for policy purposes. This attribute combines emissions reduction performance and cost in a way that is similar to other efficiency or effectiveness ratios with which operators may be familiar (e.g., engine thermal efficiency is the ratio of work output to energy input).

In a cost-effectiveness ratio, the reduction in pollution is divided by the cost of achieving that reduction. Importantly, because pollution occurring over time cannot be meaningfully “discounted” in a NPV context, the costs are generally annualized so the ratio is consistent: pollution per year over costs per year. In this constructed attribute, one may quickly identify alternatives that get more reduction for a given cost.

Cost-effectiveness may a useful attribute for comparing technologies at a policy level, or even a fleetwide level, but an operator making a decision for a particular vessel may choose to keep separate the natural attributes of cost and emissions reduction. One reason is that the cost-effectiveness ratio requires an estimate of annual NOx emissions (generally in tons per year); it is not meaningful using percent reduction values. Therefore, it would require an operator to know the vessel(s) emissions through estimates or monitoring. This represents additional background work that may not be completed at the time technology alternatives are considered.[1]

A study published in the Naval Engineers Journal considered technical feasibility of NOx controls for oceangoing vessels on the basis of life-cycle costs using both NPV and cost-effectiveness measures, and a related study published by Resources for the Future considered various policy strategies (port-based, regional, and global) in terms of NPV and cost-effectiveness (Corbett and Fischbeck 2001; Corbett and Fischbeck 2002). These studies considered the operator decision framework and the policy decision framework, although not at the level of detail that this report discusses. In these analyses, nine technologies were considered, using performance and cost data from demonstration studies, and concluded that often the least NPV cost alternative to the ship operator was different than the most cost-effective alternative for reducing NOx. Another important result for vessel operators is that operating costs contribute significantly to life-cycle NPV costs for many technologies. This suggests that selecting technologies considering capital costs primarily may not provide the lowest cost alternative.

In work more focused on passenger vessels, the costs and benefits of emissions reduction technologies are considered by evaluating cost-effectiveness of emissions reductions for seven near-term technological options for ferry transport. The results provide guidance to marine transit decision-makers and air quality managers considering modifications or expansion of existing ferry systems (Farrell, Corbett et al. 2002). In this study, estimates of emissions from particular vessels were made to enable comparison of cost-effectiveness with other air pollution reduction policies. The cost-effectiveness of the emissions control technologies examined varied, but many alternatives considered were quite cost effective, as measured only in $/t of NOx removed. This research, originally conducted for CALSTART-West-Start, was partially funded by the Department of Transportation Center for Climate Change and Environmental Forecasting, by the Gas Technology Institute, by the Department of Energy, and by the U.S. National Science Foundation through the Center for the Integrated Assessment of the Human Dimensions of Global Change at Carnegie Mellon University (Farrell, Corbett et al. 2002). The Calstart report can be found via DOT websites at http://climate.volpe.dot.gov/papers.html, or directly from the Calstart website at http://www.calstart.org/info/publications/ferryreport/ferryreport.pdf.

[1] A MARAD-sponsored report, Vessel Operator Engine Emissions Measurement Guide, is available at http://www.marad.dot.gov/nmrec/energy%5Ftechnologies/me%5Fceprogram/links%5Freports.html

3 APPLYING A DECISION FRAMEWORK TO MARINE EMISSIONS CONTROL

In this section, we apply fundamental decision-analysis concepts to develop a decision framework for considering emission control alternatives on marine vessels. While this example is based on technology performance for typical marine engines, it uses the available literature and is not specific to a particular vessel. This framework may provide a template that offers operators the ability to structure alternatives and apply their own context to choose emission reduction technologies that best meet their environmental performance goals.

3.1 Alternatives Identification

In evaluating emissions reduction alternatives, it is useful to apply an iterative approach. First, candidate technologies can be considered according to attributes that help meet objectives. Initial review may eliminate some technologies simply because they cannot meet minimum requirements on some basis, usually specific to vessel compatibility. For example, if using a retrofit technology provided by a third-party vendor violates an engine warranty, an operator may refuse to consider it even if it cost less and reduced emissions more than other options. Similarly, if safety standards cannot be met to the satisfaction of U.S. Coast Guard or other certifying body, the technology may not be ready for marine application. The remaining technologies would (at least theoretically) merit further review beyond the first iteration.

At the second iteration, the emission reduction achieved and the cost are obvious attributes that may be considered. Often the technology performance can be easily obtained – at least in terms of vendor claims; sometimes previous installations can also provide information on the sustained actual performance of a technology alternative. The cost may be more challenging to obtain. While the vendor may be able to provide equipment capital costs and some information on recurring costs associated with operation and maintenance of the vessel, some of these costs may be best obtained from prior experience on other vessels. These elements are rarely disqualifiers for a technology, but they may strongly determine operator preference among other candidate technologies.

Another attribute to consider is whether changes are required for the dockside infrastructure. Alternative fuels may require changes to fueling procedures, and other technologies may require catalysts or other consumables be loaded on the vessel. Generally, infrastructure considerations do not eliminate a technology from consideration, but would effect the time to implement an alternative. However, infrastructure modifications may not be justified unless enough vessels were included to justify the dockside investment; in these cases, infrastructure limitations could eliminate a technology from further consideration. Depending on the decision maker's perspective (i.e., if the operator also owns and/or maintains dockside facilities), costs associated with infrastructure may be included among vessel-specific costs.

Physical attributes of the equipment are also important, as discussed in Section 2. Again, it may be possible to consider these as disqualifying factors, but only if the vessel simply cannot accommodate them. In recent work, some ferry operators have claimed that some after treatment technologies can weigh as much as 8,000 lbs (3600 kg), and may represent a capacity loss of some 40 passengers on a 350 passenger design. Of course, this assumes that a retrofit vessel could not accommodate the additional equipment without passenger reduction; in most new-vessel designs, naval architects can meet these sorts of multiple criteria successfully.

Passenger revenue impacts may also be considered directly. Some literature suggests that where customers care about the environment, ridership or cargo volume on a cleaner vessel could be positively affected. These factors are being considered in marketing efforts for expanded ferry service (Outwater, Modugula et al. 2004). If the physical attributes of an alternative reduce vessel capacity, then there may be some negative revenue impacts.[2]

A set of technologies is presented in Table 3 that illustrates these attributes. These technologies represent a range of emission reductions achievable on marine engines and have all been demonstrated in maritime application, either in Europe or in the United States. As emphasized throughout the study, other technologies are available and many vendors have or are developing specific designs. Moreover, there are other fuel-based solutions that may be considered, including biofuels and additives. This report is not intended to represent the range of specific technologies that might be considered, but to provide a framework that can be used to consider them. Additionally, the attributes considered here are carefully chosen to be consistent with previous work in this area. More importantly, these attributes were selected because they appear to measure how well a technology meets the fundamental objectives described earlier; an operator may add attributes if their fundamental objectives require.

As discussed in Section 2.1.3, technologies typically cost money to purchase and install, and may cost (or save) money over time due to maintenance, fuel requirements, etc. The net present value (NPV) of each of the technologies is shown in Table 4, based on a 10-year period and a 7% discount rate. Similar to other studies, we choose a 10 year period for the technology investment decision even though the current average age of a ferry vessel is 24 years. We use 7% as a typical interest rate used for the analysis of public policy questions, such as pollution control. An individual operator will want to choose periods and interest rates appropriate to the vessel/fleet under consideration.

It is very important to note that a decision analysis may be very sensitive to the way in which NPV is calculated. For example, consider Figure 7, where the interest rate used to estimate NPV for water-fuel emulsion is varied from 5% to 15%. The NPV value can change by nearly 30%, simply by choosing different interest rates. Similarly, if the number of periods that the vessel (or the control technology) will operate varies, then the NPV will increase with the number of years assumed; if we vary the operating period from 5 to 25 years at a constant interest rate, the NPV assuming 25 years is nearly double the NPV assuming 5 years.

At an interest rate of i = 7%, the lowest NPV costs are for engine water-fuel emulsion and the highest costs are for CNG-fueled engines. However, due to differences in cost structure, the NPV calculation is sensitive to the choice of discount rate. A higher discount rate tends to make the less capital-intensive emission control devices more attractive, but discounts the long-term

[2] Loss of capacity due to emission control technology must be carefully considered. A loss of 11% in maximum capacity (e.g., 40 passengers on a 350 passenger ferry) may not mean losing 11% in revenue. Some vessels rarely travel at capacity, and an individual ferry typically is full only during one or two of the prime commute runs. For example, if a ferry operates 10 runs per day (50 runs per work-week), and is filled to capacity during two commute runs per weekday, then the 11% loss in capacity would be a real loss in ridership 20% of the time. This would result in a loss of ~2% revenue. In other words, revenue lost if 40 seats were eliminated may not be negligible, but is perhaps less than 11% of total operating cost.

Table 3. List of decision attributes important to an operator considering emission control alternatives. Example alternatives represent "generic" properties assumed for decision structures in this report.

	CAPITAL COST	**ANNUAL COST**		**NOMINAL EMISSION REDUCTION**		**INFRASTRUCTURE[1]**	**VOLUME AND/OR WEIGHT**		**REVENUE IMPACT[1]**	**VESSEL COMPATIBILITY OR RELIABILITY[1]**
Example Alternative		Maintenance	Fuel Penalty	NOx	Other (PM)	Fuel	Equip-ment	Fuel	Payload or Passengers	Other factors specific to vessel
Option 1: SCR	$283,000	$8,200	$0	81%	0%	Catalyst supply may be needed	Varies[2]	NA	Assumed not affected	Assumed not affected
Option 2: Water in air	$130,000	$2,600	$12,300	28%	1%	Not affected		Varies[2]	Assumed not affected	Assumed not affected
Option 3: Water in fuel	$117,000	$1,000	$8,200	42%	15%	Emulsifier supply may be needed		Varies[2]	Assumed not affected	Assumed not affected
Option 4a: EPA Tier 2 engine	$1,000,000	$0	$0	50%	33%	Not affected	NA	NA	Assumed not affected	Assumed not affected
Option 4b: EPA Tier 2 engine with 25% fuel economy	$1,000,000	$0	($103,000)	63%	93%	Not affected	NA	NA	Assumed not affected	Assumed not affected
Option 5: Alternative fuel engine CNG	$1,000,000	$0	$122,000	90%	63%	Alternate fuel supply needed	NA	Varies[2]	Assumed not affected	Assumed not affected

1. These attributes may be very important, but quantifying can be difficult and specific to the vessel/route/terminal combination. In the example analysis presented here, we assume that these factors are not constraints.
2. Weight and volume may be important constraints. For example, U.S. Navy studies suggest that SCR equipment can add 1200-4500 kg in weight and may require 5-29 cubic meters of space (NAVSEA 1994); some commercial designs (e.g., for ferries) may be much less constraining. The issue is not with the absolute size or weight, but whether the vessel configuration can accommodate the system. In the example analysis presented here, we assume that these factors are not constraints.

benefit of fuel economy for the repowering option. CNG fuel prices are also important; a ten percent decrease can lower the NPV of the CNG option for the two smaller vessels by several hundred thousand dollars. Finally, the CNG is the technology most sensitive to capital costs since it is the most capital-intensive.

Table 4. Simplified decision attributes, focusing on costs and emission reduction. This assumes that the other attributes are used primarily as screening attributes to disqualify technologies that cannot meet minimum requirements.

	NPV COST (*i*=7%, *n*=10 YEARS)	CAPITAL COST	ANNUAL COST		NOMINAL EMISSION REDUCTION	
Example Alternative			Maintenance	Fuel Penalty	NOx	Other (PM)
Option 1: SCR	$343,000	$283,000	$8,200	$0	81%	0%
Option 2: Water in air	$237,000	$130,000	$2,600	$12,300	28%	1%
Option 3: Water in fuel	$184,000	$117,000	$1,000	$8,200	42%	15%
Option 4a: EPA Tier 2 engine	$1,000,000	$1,000,000	$0	$0	50%	33%
Option 4b: EPA Tier 2 engine with 25% fuel economy	$277,000	$1,000,000	$0	($103,000)	63%	93%
Option 5: Alternative fuel engine CNG	$1,857,000	$1,000,000	$0	$122,000	90%	63%

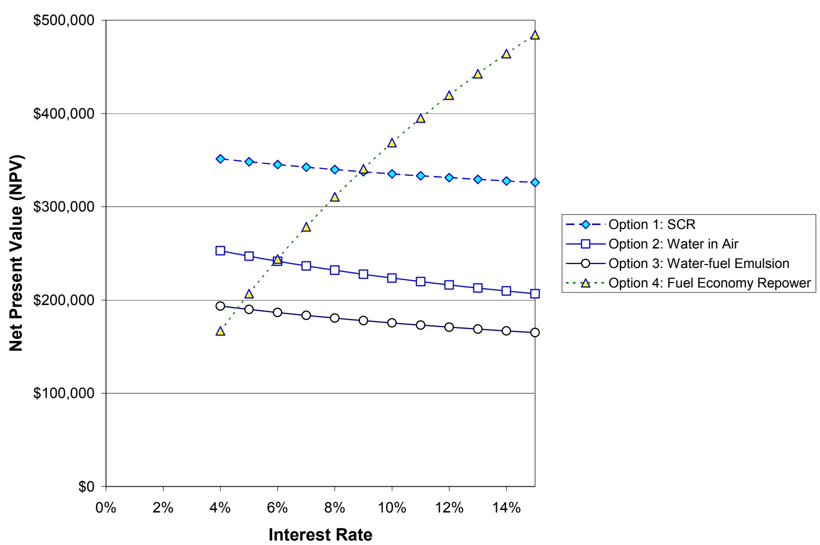

Figure 7. Example of variation in NPV with change in interest rate. This study used an interest rate of 7%; other assumptions per text. Option 4a and Option 5 not shown since they are off scale (> $1 Million NPV).

3.2 Alternatives Evaluation

After the alternatives and attributes are identified, attributes need to be scored so that a comparison can be made among the alternatives. Here, uncertainty in the attribute values may be considered explicitly, as discussed in Section 2.1.2 and Section 2.1.3. Based on previous studies, some lower- and upper-bounds can be assigned to environmental performance and cost.

For this study, the lower- and upper-bounds for performance of after treatment technologies were each assumed to be 5% likely and the best-estimate value was assumed to be 90% likely. New-engine technologies and CNG alternative fuel were assumed to be 100% likely to achieve their claimed reductions. This is partly because engine manufacturers are certifying that their engines can meet regulatory limits without providing guarantees that they reduce emissions more than EPA standards require; it is also partly to demonstrate the flexibility of the decision framework.

Costs are assigned upper- and lower-bounds by generally following previous studies that suggest significant variability in capital costs for vessel retrofit technologies. This is also consistent with EPA discussion (Environmental Protection Agency 1999) that indicates capital costs for engine technology in a retrofit context may be more expensive than technologies that come "standard" with a new engine. In this study, lower-bound values assume no costs for vessel-specific designs and upper-bound values assume capital costs are double the best-estimate values.

The likelihood of these costs is varied arbitrarily for different technologies, primarily to demonstrate flexibility of the decision framework; operators are encouraged to apply their own judgment in assigning likelihoods to bounded estimates. In some cases, it may be simplest to either choose the best estimate (ignore the bounds) or to assign equal likelihood to all bounded estimates. However, the results may be sensitive to these assumptions, and the decision framework presented here does not constrain the operator from using the best information available.

Scoring of these attributes needs to be done in an explicit manner that can be applied objectively, as discussed in Section 2.1.2. As shown in Table 5, scoring for all attributes conforms to a ten-point scale. This enables more resolution than a simpler scale, but avoids scales that are too large to be easily applied by operators. For emissions reduction performance, the percentage (a natural 100-point scale) is simply converted to at a ten-point scale; here 100% reduction is better than 0% reduction, so the scales are directly proportional. For NPV cost, lower costs are preferred so the scales need to be inversely proportional; the lowest cost is assigned the highest score (10) and the highest cost is assigned the lowest score (0). Then the cost estimates in between are assigned a score through interpolation, a commonly used method to assign proportional changes to different scales.

Using the probabilities and the scores together, one can compute the expected value of each alternative, according to the NOx reduction and NPV cost attributes, respectively. This is also demonstrated in Table 5.

Table 5. Elements of example decision framework, incorporating uncertainty in emission performance and cost. Pollution scores simply use the percent NOx reduction normalized to a 10 point scale. Cost scores interpolate NPV costs between the lowest cost (-$943 Thousand = 0 score) and the maximum cost among the alternatives ($2.9 Million = 10 score). Expected Values (EV) for NOx and NPV are calculated by adding the products of probabilities and scores for each alternative.

Example Alternative	NOx Reduction (with bounds)	Pollution Scores	Likelihood of Reduction[1]	NOx EV[2]	NPV Cost (with bounds)	Interpolated Cost Scores	Likelihood of NPV Cost[1]	NPV EV[2]
Option 1: SCR	Lower: 57% Best Estimate: 81% Upper: 98%	5.7 8.1 9.8	5% 90% 5% 100%	8.07	Lower: $341,000 Best Estimate: $343,000 Upper: $628,000	6.6 6.6 5.9	5% 90% 5% 100%	6.58
Option 2: Water in air	Lower: 5% Best Estimate: 28% Upper: 60%	0.5 2.8 6.0	5% 90% 5% 100%	2.85	Lower: $235,000 Best Estimate: $237,000 Upper: $369,000	6.9 6.9 6.5	25% 50% 25% 100%	6.81
Option 3: Water in fuel	Lower: 20% Best Estimate: 42% Upper: 70%	2.0 4.2 7.0	5% 90% 5% 100%	4.23	Lower: $182,000 Best Estimate: $184,000 Upper: $303,000	7.0 7.0 6.7	5% 40% 55% 100%	6.86
Option 4a: Repower EPA Tier 2 engine	Lower: 50% Best Estimate: 50% Upper: 50%	5.0 5.0 5.0	0% 100% 0% 100%	5.00	Lower: $500,000 Best Estimate: $1,000,000 Upper: $2,000,000	6.2 4.9 2.3	10% 85% 5% 100%	4.89
Option 4b: Repower EPA Tier 2 engine with 25% fuel economy	Lower: 50% Best Estimate: 50% Upper: 50%	5.0 5.0 5.0	0% 100% 0% 100%	5.00	Lower: ($943,000) Best Estimate: $277,000 Upper: $1,640,000	10.0 6.8 3.2	10% 85% 5% 100%	6.93
Option 5: Alternative fuel engine CNG	Lower: 90% Best Estimate: 90% Upper: 90%	9.0 9.0 9.0	0% 100% 0% 100%	9.00	Lower: $1,356,000 Best Estimate: $1,856,000 Upper: $2,856,000	3.9 2.6 0.0	5% 50% 45% 100%	1.51

1. Specific probabilities assigned to the likelihood of reduction and the likelihood of NPV cost estimates are presented for example only. Pollution reduction probabilities are loosely based on the authors' judgment of the available literature of in-service performance; NPV cost probabilities are essentially arbitrary and chosen to illustrate the flexibility of this decision approach if different likelihood values are assigned. See text for further discussion.
2. Expected value calculation example (for Option 1 NOx Reduction Score): EV = 5.7 * 5% + 8.1 * 90% + 9.8 * 5% = 8.07.

3.3 Matching and Constraining Choices

Up to this point, application of a decision framework has been designed to avoid including individual subjectivity – either by using natural attribute data, or by enabling and encouraging consensus. Data used to represent attributes would be obtained from literature (as in this report) or directly from vendors. While NPV cost calculations can vary if individuals choose different interest rates and/or periods of performance, these parameters can be collectively agreed. Where subjective judgment may vary, transparency is advocated.

However, subjective judgment is required to make good decisions. In this decision framework, the places where individuals may exert influence differently from one another would be at the technology disqualification stages (perhaps, although this can be done objectively) and through assigning weights to attributes. This section discusses how weights can effectively do this.

Weights can be assigned in many ways. If a zero weight is assigned to an attribute, then that attribute is effectively ignored. (Note that assigning zero to a weight is ***not*** the same as disqualifying an alternative, as done in the first screening iteration. An alternative can still be scored based on weights applied to other attributes.) If maximum weight is assigned to an attribute, then that attribute score will matter most; its influence will depend upon the attribute score for that alternative. In the examples of previous work discussed in Section 2.2.3, a three-level weight scale was applied without constraining the total weight; in other words, all attributes could receive the highest weight (3 of 3), representing equal weighting. Another approach is to define a total weight limit (e.g., 1.00) that must be divided among the attributes; one assigns weights to each attribute that add up to the weight limit. For example, to assign equal weights across ***n*** attributes, one would assign a weight of $\frac{1}{n}$ to each attribute.

In this example, weights are constrained to total 1.00. This is analogous to providing 100 "poker chips" to each decision maker (each representing a weight of 0.01) and allowing them to place these chips across the attributes according to the attributes' importance. If 50 chips are placed on environment (weight of 0.50), then 50 chips are left to assign to cost (weight of 0.50). The weighted scores using these equal weights are shown in Table 6. In Figure 8, a decision tree that conforms to the framework described in Table 6 is shown, also with equal weighting of the two attributes.

A benefit of constraining the total weight applied to attributes is that the weighted score conforms to a uniform upper bound among multiple decision makers. This makes comparing relative scores among decision makers easier to understand. For example, in a three-level weighting scheme (as used in prior studies described in Section 2.2.2) it is unclear what the differences may mean if one decision maker assigns a 1 to all attributes and another decision maker assigns 3 to all attributes. Both would be equal weighting, but they are difficult to directly compare since the weighted scores do not conform to the same scale. Another benefit is that one can perform sensitivity analysis on the weights in a straightforward way, as discussed below.

Table 6. Results of example decision framework, combining scores in Table 5 with attribute preferences weighted. Weights are constrained to add to 1, and can vary between 0 and 1.

Weights:	**0.50**	**0.50**	
Example Alternative	**NOx EV**	**NPV EV**	**Weighted Score[1]**
Option 1: SCR	8.07	6.58	7.32
Option 2: Water in air	2.85	6.81	4.83
Option 3: Water in fuel	4.23	6.86	5.55
Option 4a: Repower EPA Tier 2 engine	5.00	4.89	4.95
Option 4b: Repower EPA Tier 2 engine with 25% fuel economy	5.00	6.93	5.96
Option 5: Alternative fuel engine CNG	9.00	1.51	5.26

1. Weighted Score calculation example (for Option 1 NOx Reduction Score): Weighted Score = 8.07 * 0.50 + 6.58 * 0.50 = 7.32.

As shown in Table 6, the preferred technology for this decision is Option 1, the one with the highest score (7.32 of possible 10.00). But how sensitive is that outcome to the subjective weights assigned (equally among the attributes in this example)? Often an analysis becomes more useful when a decision maker can consider how recommended alternatives may switch under different weights. Figure 6 presents a summary of the weighted scores for each alternative as the weights are varied from favoring only lower cost to favoring only environmental performance attributes.

As illustrated in Figure 6, Option 1 appears to be very robust. When cost is favored (environment weighted at 0.00 or 0.10), repowering with a more fuel efficient engine that meets EPA Tier 2 standards is preferred. When environment is favored more than cost (environment weighted at 0.90 or 1.00), installing an alternative fuel (CNG) engine is preferred. However, over most of the possible ranges of weights, selective catalytic reduction (SCR) has the highest expected value. Interestingly, it may be noted that in Europe SCR systems are among the most often selected systems for controlling NOx emissions. Current studies for specific vessels in the U.S. fleet, particularly smaller passenger ferries in San Francisco Bay and New York/New Jersey, may identify SCR as one of the primary candidates as well.

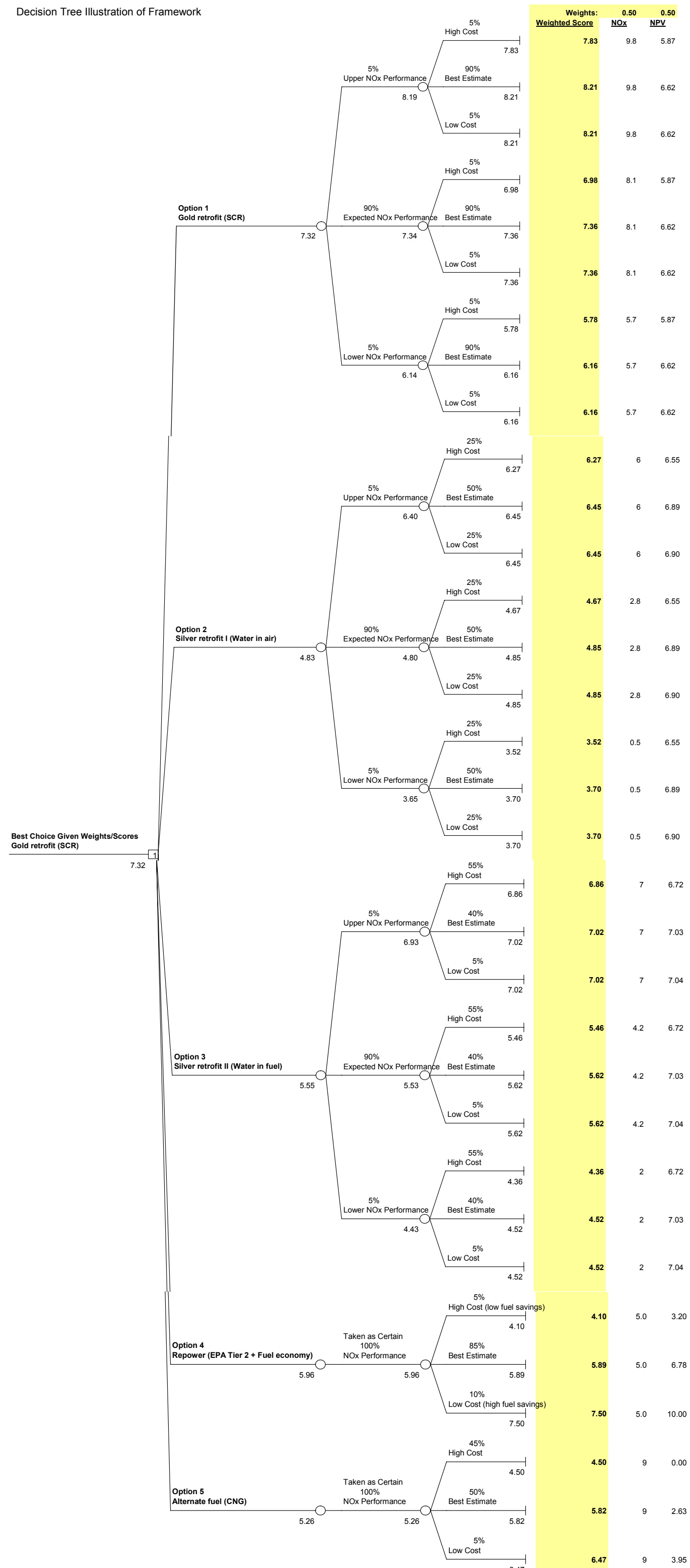

Figure 8. Decision tree illustration of example framework. Note the two sets of "branches" for each uncertain event (environmental performance and cost). Also, the weights can be applied to the scores before calculating the expected value, because of commutative mathematical properties (See Table 5.)

However, the main insight that may be drawn from this decision framework could be to identify which technologies never rank highly, rather than attempting to optimize which single technology to select. In Figure 6, one notes that humidification (Option 2: water in air) is always less preferred than the other alternatives, under the assumptions developed here. This can help assist an operator in narrowing down options to a set of alternatives that generally meet objectives across the subjective weights. Such a satisficing approach can be useful when soliciting bids or looking for partnerships that may provide funding for demonstration projects with conditions about which technologies must be chosen (see discussion in Section 2.1.6).

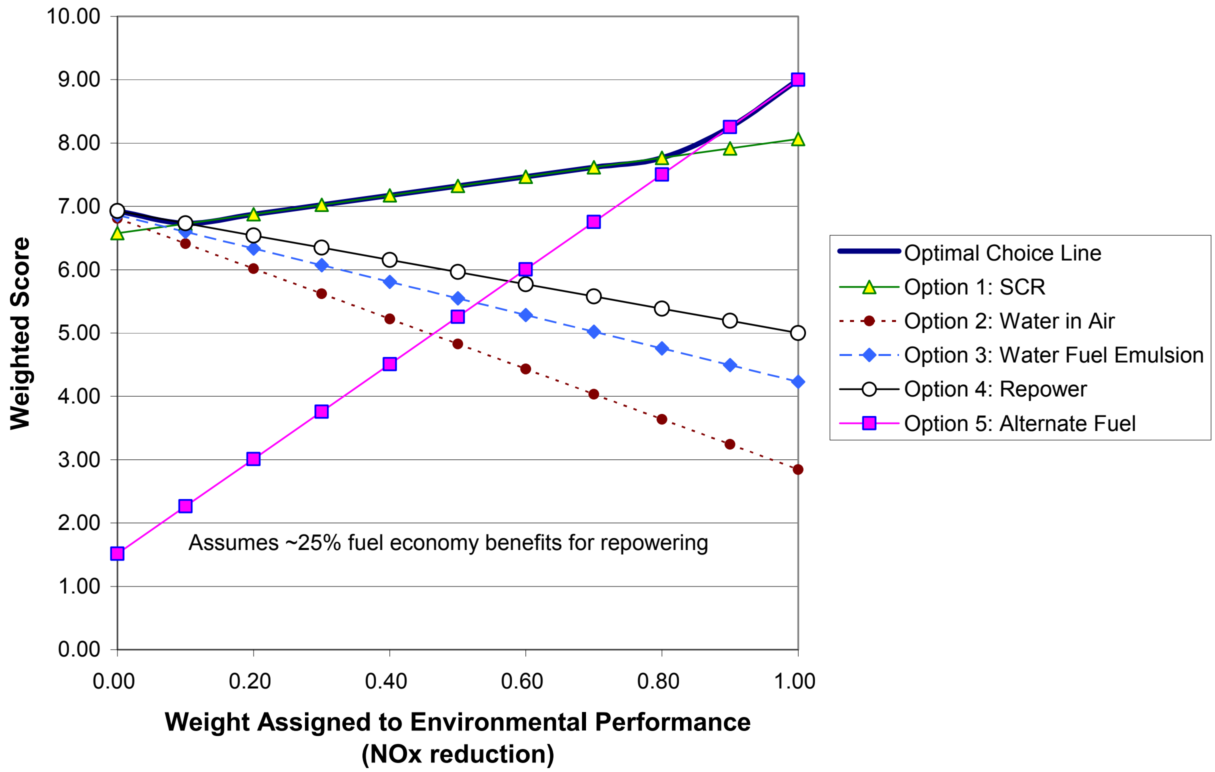

Figure 9. Sensitivity of optimal choice to tradeoffs to various preferences for weighting NOx performance and NPV cost. Dominant alternatives have high scores, and fall on the Optimal Choice Line, shown. Repowering alternative assumes cost benefits for repowering with an EPA Tier 2 engine to achieve 25% greater fuel economy. Options 2 and 3 are dominated by the other alternatives under all weight preferences, and Option 1 (SCR) dominates over most of the domain. (Illustration applies to conditions used for this example (e.g., interest rate *i* = 7%, investment period *n* = 10 years, costs and uncertainties as shown in Table 5.); application of this decision framework to operator specifications for particular vessels and technologies may differ.)

4 CONCLUSIONS

This document develops a decision framework applicable for considering emission control technologies on marine engines. The framework is informed by standard decision theory, and maintains an open structure so that it may be adapted by operators with specific vessel and technology attributes that may differ from those provided here. Attributes are chosen carefully to relate objectives important to choosing control technologies with specific alternatives that may meet several of the objectives differently. The framework is transparent, which enables multiple stakeholders to understand how different subjective judgments and varying attribute properties may result in different technology choices. The analysis uses standard scoring techniques to ensure that attributes are not biased by subjective scoring and that weights are the primary quantitative input where subjective preferences are exercised. An expected value decision structure is adopted that considers probabilities (likelihood) that a given alternative can meet its claims; alternative decision criteria are discussed. Capital and annual costs are combined using standard discounting techniques to compare costs for each alternative using a net present value (NPV) approach. An iterative approach is advocated that allows for screening and disqualifying alternatives that do not meet minimum conditions for acceptance, such as engine warranty or U.S. Coast Guard requirements. Lastly, the decision framework does not substitute for a decision maker in any way, but helps an operator structure the decision so that important attributes are considered explicitly and can be represented clearly to other stakeholders.

4.1 General Insights

This analysis demonstrated one very interesting result with regard to engine modernization through repowering. Without fuel economy improvement, the repowering option appears less cost-preferred than other emission control technologies. At least a 25% improvement in fuel economy is needed to make repowering a preferred choice under the decision structure and parameters presented. Of course, using this framework with actual bids and performance guarantees that differ from those assumed here may change the specific results. The point is that repowering can be an attractive alternative if fuel economy gains are significant enough. This insight will also apply when vessel replacement affords an operator more fuel efficient propulsion designs than the retired vessel.

When considering a new ferry for a new route (i.e., a ferry expansion scenario), a similar decision framework can be applied. However, there may be some differences in how performance attributes are defined. For example, in a new ferry there may be no reason include a repower option comparing the new engine to an older engine that is not currently available in the market. One reason is that if the new engine meets current regulatory standards, then no benefit should be assigned to the emission reduction; that reduction is not an option for the decision maker – essentially achieving some emission reductions from the new engine is not a choice but a requirement. Another reason is that a new engine may be the only choice for a new vessel – again, there is no decision to be considered; this is because an operator planning a new vessel is already committed to installing a new engine. However, if two new engines are available with different environmental performance attributes, then only the differences in engine cost would be considered, not the total new engine cost as in the repowering scenario.

4.2 Role of Regulations in Operator Decision Context

Increasingly, policy makers are interested in achieving reductions in marine engine emissions. In particular, local and regional policy makers are interested in reducing emissions from existing vessels in the fleet sooner than new-engine standards and fleet modernization may achieve needed reductions. Taking a mid-term or long-term view, it appears that efforts to comply with current international or federal standards may not be sufficient. In fact, local efforts to help encourage technology retrofit demonstrations and promote low-emission fleet expansion (particularly in the ferry sector) have already set emissions reduction goals as much as 85% lower than current standards.

This suggests that a decision framework that looks to maximize environmental performance beyond meeting near-term limits may be strategic for operators. Such a framework could help identify the level of partnership needed with public or non-governmental organizations to leverage available funds for early demonstration of technologies. The framework can also help justify why an operator may not be willing to select an alternative that is a poor fit with a given vessel, even if certain stakeholders strongly advocate such a technology.

In any case, policy action (mandatory, voluntary, or incentive-based) will continue to develop. In the future, some technologies may be disqualified if they cannot achieve "best practice" among a set of technologies that emerges as cost-effective. With a clear decision context, an operator can update information about alternatives and their attributes to continue meet objectives of environmental performance, cost management, revenue growth, and other factors affected by emission control technologies.

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