Passenger Ferries, Air Quality, and Greenhouse Gases: Can System Expansion Result in Fewer Emissions in the San Francisco Bay Area?

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The views expressed herein are the authors' alone and do not necessarily represent the positions of the DOT, Brookhaven National Laboratory, the Gas Technology Institute, or any other organizations with which the authors are affiliated, or their sponsors.

Best Regards,

John Boesel
President
CALSTART

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Executive Summary

Continued interest in improving air quality in the United States along with renewed interest in the expansion of urban passenger ferry service has created concern about air pollution from these vessels. This study shows, as others have before, that emissions from ferries are significant. However, it also shows that there are no serious technical impediments to the development of passenger ferries with much lower emissions than those currently in service, so that ferry commuting can become an environmentally sound choice. Achieving this outcome will require research and development of new technologies, followed by their widespread use.

This study first analyzes air pollution (NO_X, HC, PM, CO, SO_2, and CO_2) emissions from three passenger ferries in the San Francisco Bay Area with existing engines (providing the most accurate emissions estimate currently available). It then applies a number of new engine and emissions control technologies to the same level of service in order to evaluate the potential of these new technologies. Eight ferry engines and emission-control technologies were studied:

(1) Existing engines
(2) EPA Tier 2 "Clean Diesel" Engines
(3) EPA Tier 2 + HAM (Humid Air Motor)
(4) EPA Tier 2 + ITD (Injection Timing Delay)
(5) EPA Tier 2 + CF (Catalyst Filter)
(6) EPA Tier 2 + SCR (Selective Catalytic Reduction)
(7) EPA Tier 2 + SCR + CF (Selective Catalytic Reduction and Catalyst Filter)
(8) CNG (Compressed Natural Gas engine)

Data for this study was obtained from Bay Area ferry operators; Bay Area ferry passenger surveys, peer-reviewed research publications, engine and emission control device manufacturers; local, state, and federal regulators; and other experts. Sources are identified in References. Emissions factors and technology cost data are sparse and uncertain, so the results reported here contain considerable uncertainty. However, the analysis was conducted with a consistent set of data and state-of-the-art techniques, so that while the absolute values reported are uncertain, comparisons across technologies or across different scenarios within the study are valid. Further, the results reported here are broadly consistent with all the other major studies of marine air pollution emissions conducted to date, providing added confidence in the analysis.

A key conclusion that emerges directly from the data collection effort is that all of the low-emission technologies examined for this study are currently in use in other transportation modes or onboard passenger ferries in Europe. Therefore, no serious impediments to commercialization for passenger ferry applications in this country currently appear to exist. The U.S. Coast Guard will have an important role in ensuring the safety of all these technologies, but for similar reasons this process is likely to proceed quickly, particularly if an expedited review process were adopted by the Coast Guard for demonstration projects.

The basic results of the analysis of ferry emissions are contained in Table ES-1. The adoption of Tier 2 engines (required for new vessels built after 2007) will reduce emissions of NO_X and PM relative to existing engines, but increase emissions of HC and CO. The increase in HC and CO emissions is due the fact that engines tuned for improved emissions performance generally are not as energy efficient as those tuned solely for economic performance, which results in unburned and partially burned fuel in the exhaust gas. The use of SCR and CF technologies can result in emission reductions of all four of these pollutants, relative to existing engines. The use of CNG engines will reduce emissions of NO_X and PM significantly, but will increase emissions of HC and CO. Liquefied natural gas (LNG) engines would have essentially the same effect. Emissions of SO_2 are likely to fall significantly as low-sulfur diesel fuel becomes the only type available in California, and they fall further if CNG is used as the fuel. Emissions of CO_2 do not change very much across the various technologies, unless CNG is used as the fuel, in which case they go down by about a quarter. There are no significant differences in these results across the three vessels, and these results should hold for ferry operations located elsewhere.

Table ES-1: Annual Emissions per Ferry (tons)

Pollutant	Existing Engines	Tier 2 Engines	Tier 2 + HAM	Tier 2 + ITD	Tier 2 + SCR	Tier 2 + CF	Tier 2 + SCR + CF	CNG
Larkspur								
NO_X	58	29	21	23	5.7	28	5.6	5.8
HC	1.2	3.2	3.2	3.5	0.80	0.26	0.06	1.5
PM	1.3	0.89	0.88	0.98	0.62	0.089	0.062	0.083
CO	11	22	22	25	5.5	3.3	0.8	51
SO_2	2.3	0.041	0.041	0.041	0.041	0.041	0.041	0.019
CO_2	4,400	4,400	4,500	4,500	4,400	4,400	4,400	3,300
Alameda/Oakland								
NO_X	69	34	25	28	6.9	33	6.6	6.9
HC	1.4	3.8	3.8	4.2	0.95	0.30	0.08	1.8
PM	1.59	1.06	1.05	1.17	0.74	0.106	0.074	0.099
CO	13.2	26	26	29	6.6	4.0	1.0	61
SO_2	2.4	0.044	0.044	0.044	0.044	0.044	0.044	0.021
CO_2	4,700	4,700	4,800	4,900	4,700	4,700	4,700	3,600
Vallejo								
NO_X	87	44	31	35	8.7	42	8.5	8.8
HC	1.8	4.8	4.80	5.4	1.21	0.39	0.10	2.3
PM	2.0	1.3	1.33	1.5	0.94	0.13	0.094	0.13
CO	17	34	33	37	8.4	5.0	1.3	78
SO_2	5.1	0.09	0.09	0.1	0.092	0.092	0.092	0.043
CO_2	9,800	9,800	10,000	10,000	9,800	9,900	9,900	7,500

Note: Shaded values indicate an increase in emissions. LNG-fueled vessels would have emissions very similar to those shown for CNG.

The basic results of the cost analysis of controlling ferry emissions are contained in Table ES-2, which accounts for both capital costs and increased annual costs. These costs range from zero to several hundreds of thousands of dollars. The least expensive option is Tier 2 + ITD, most expensive is CNG (which includes the cost of one refueling station).

Cost-effectiveness is show in Table ES-3, in which the NPV values in Table ES-2 are divided by the total emission reductions based on Table ES-1 over an assumed 15-year life. This approach means the values for each pollutant are independent – so that a cost effectiveness of \$1,400-\$1,800 per ton NO_X for Tier 2 + SCR implies the other reductions come at no cost. All of the technologies evaluated here are cost-effective methods of reducing NO_X, based on several comparisons: (1) California's Carl Moyer incentive program has an average cost effectiveness of about \$5,000/ton NO_X, (2) numerous regulatory programs have had cost effectiveness values of over \$5,000/ton NO_X (including the Low Emission Vehicle program, and regulations for motorcycles and small off-road engines), and (3) emission trading programs for large stationary sources in highly polluted areas generally have costs of over \$4,500/ton NO_X. The cost effectiveness of these technologies is sensitive to the discount rate, fuel costs, and capital costs. The price of fuel is particularly important for the natural gas engines, especially since a relatively expensive infrastructure is included in the costs used here. The use of LNG could significantly change these costs. These results should hold for ferry operations located elsewhere.

Table ES-2: Costs of Emission Control Technologies

	Tier 2 Engines	Tier 2 + HAM	Tier 2 + ITD	Tier 2 + SCR
Capital	None	\$71,000-\$128,000	\$0	\$160,000-\$280,000
O&M*	None	\$1,400-\$2,500	\$1,600-\$2,900	\$45,000-\$80,000
Fuel*	None	\$13,000-\$28,000	\$17,000-\$38,000	\$8,400-\$19,000
NPV	None	\$210,000-\$430,000	\$180,000-\$390,000	\$680,000-\$1,300,000
	Tier 2 + CF	**Tier 2 + SCR + CF**	**CNG**	
Capital	\$45,000-\$79,000	\$200,000-\$360,000	\$450,000-\$660,000	
O&M*	\$40,000-\$72,000	\$85,00-\$150,000	\$0	
Fuel*	\$4,200-\$9,400	\$13,000-\$28,000	\$120,000-\$280,000	
NPV	\$480,000-\$870,000	\$1,200,000-\$2,10,000	\$1,700,000-\$3,400,000	

* Annual. Values shown for all three vessels. NPV assumes 15-year lifetime and a 7% discount rate.

Table ES-3: Cost-Effectiveness of Emission Control Technologies (\$/ton)

	Tier 2 Engines	Tier 2 + HAM	Tier 2 + ITD	Tier 2 + SCR
NO_X	\$185	\$700-\$1,000	\$670-\$1,000	\$1,400-\$1,800
HC	N/A			\$156,000-\$210,000
PM	\$8,600	\$42,000-\$64,000	\$48,000-\$77,000	\$88,000-\$120,000
CO	N/A			\$11,000-\$15,000
SO_2	N/A	\$8,800-\$9,600	\$8,100-\$8,300	\$26,000-\$31,000
CO_2	N/A			
	Tier 2 + CF	**Tier 2 + SCR + CF**	**CNG**	
NO_X	\$1,700-\$2,200	\$2,200-\$2,900	\$2,800-\$4,400	
HC	\$47,000-\$63,000	\$94,000-\$130,000		
PM	\$34,000-\$48,000	\$84,000-\$110,000	\$120,000-\$180,000	
CO	\$5,700-\$7,600	\$10,000-\$14,000		
SO_2	\$18,000-\$22,000	\$44,000-\$54,000	\$69,000-\$76,000	
CO_2			\$150-\$160	

Note: Values for Tier 2 taken from [43]. Blanks indicate an increase or no significant change in emissions relative to existing engine technologies. Values are *not* additive.

The invention and use of environmental control technologies generally follows "technology-forcing" regulation, sometimes accompanied by market incentives for innovation. Many industries have responded successfully (if reluctantly) to such an approach. Thus, three trends in the cost and performance of marine emission control technologies can be expected: 1) the costs and performance of the technologies described here will improve, 2) new emissions control technologies will become available, and, 3) ferry engineers, builders, and operators will learn how to incorporate low-emission technologies into standard practices.

Calculating net emissions of ferry commuting requires estimating the changes on both the waterside and landside parts of the trip. The former is described above. The latter requires understanding several landside factors: vehicle emissions, travel patterns, and travel demand.

Landside vehicle emissions were estimated for the comparison year (2007) with the state-of-the-art emissions model used in California, EMFAC 2000. This analysis shows the importance of reducing the landside emissions of a commute trip that includes a ferry component. Passenger ferries are just one part of the regional transportation system. If strategies are implemented to reduce the use of single occupancy vehicles as the primary means of reaching the ferry terminal, the over-all emissions from the transportation system could decrease dramatically. If this approach was used in conjunction with advanced low-emission ferry propulsion technologies and cleaner fuels, emissions from ferry commuting can be dramatically reduced.

Landside travel patterns were taken from ferry rider surveys provided by ferry operators in the Bay Area, indicating that average daily occupancy (percent of total possible passengers carried onboard) ranges from 15% to 33%. During rush hour departures, ferries are full (or nearly so) in one direction and virtually empty in the other, while mid-day departures tend to be relatively empty. In these surveys, ferry riders report that a large majority of them drive alone to the ferry terminal, while a smaller fraction (less than one-quarter in one case) would drive alone all the way to work if ferry service was not available. Further details on travel patterns are presented in the text.

Landside travel demand was estimated based on the overwhelming evidence from across the United States (and in the United Kingdom) shows that increases in transportation system capacity that makes travel more convenient, less expensive, or otherwise better tends to create more trips, called induced travel demand. Because ferry system expansion is designed to improve travel conditions, it will induce travel demand. A review of the best available data and discussions with California officials indicated that a realistic short-term value for induced demand in the Bay Area is 30%, with higher values in the long term.

Results for many different combinations of occupancy and induced travel demand were calculated and are presented in the body of the report. For convenience, Table ES-4 shows the results for a scenario with 50% occupancy (higher than currently observed in any Bay Area ferry system), half of the existing landside trips replaced by zero-emission shuttle trips (which are not currently offered), and induced travel demand of zero and 30%. The values shown are the percentage changes in net emissions due to ferry commutes in each of the three services.

PM emissions always decrease due to ferry commuting (coarse material, or PM-10, only). Commutes on the two shorter, slower routes, Larkspur and Vallejo/Oakland show reductions in most emissions for all ferry technologies, many of them very significant cuts. However, emissions of NO_X increase due to ferry commuting on these routes for all but the SCR and CNG technologies. This would be true even if average ferry occupancy were 75%. These two technologies (in conjunction with the zero-emission shuttles, no induced demand, and increased occupancy) make ferry commuting the preferable option from an air quality standpoint on these two routes. In the absence of zero-emission shuttles, however, all ferry technologies here result in NO_X emission increases for the Larkspur and Alameda/Oakland services.

Table ES-4: Percent Change in Emissions Due to Changing From On-Land Commute to Ferry Commute, Half of Home-To-Terminal Trips Provided By Zero Emission Shuttle

Route	Pollutant	Existing Engines	Tier 2 Engines	Tier 2 + HAM	Tier 2 + ITD	Tier 2 + SCR	Tier 2 + CF	Tier 2 + SCR + CF	CNG
Larkspur									
Zero	NO_X	505%	200%	117%	144%	-39%	192%	-42%	-34%
Induced	HC	-87%	-66%	-67%	-63%	-92%	-97%	-99%	-84%
Demand	CO	-89%	--78%	-78%	-76%	-95%	-97%	-99%	-50%
	PM	-84%	-89%	-90%	-88%	-93%	-99%	-99%	-99%
	CO_2	-82%	-82%	-82%	-82%	-82%	-82%	-82%	-86%
30%	NO_X	568%	232%	140%	170%	-33%	223%	-36%	-27%
Induced	HC	-86%	-62%	-64%	-59%	-91%	-97%	-99%	-83%
Demand	CO	-80%	-76%	-76%	-73%	-94%	-96%	-99%	-44%
	PM	-82%	-88%	-88%	-87%	-92%	-99%	-99%	-99%
	CO_2	-80%	-80%	-80%	-80%	-80%	-80%	-80%	-85%
Alameda/ Oakland									
Zero	NO_X	530%	213%	125%	154%	-38%	204%	-39%	-36%
Induced	HC	-86%	-65%	-65%	-62%	-91%	-97%	-99%	-83%
Demand	CO	-89%	-77%	--77%	-75%	-94%	-97%	-99%	-47%
	PM	-83%	-89%	-89%	-88%	-92%	-99%	-99%	-99%
	CO_2	-79%	-79%	-79%	-79%	-79%	-79%	-79%	-84%
30%	NO_X	591%	244%	147%	179%	-32%	234%	-39%	-30%
Induced	HC	-85%	-61%	-61%	-58%	-90%	-97%	-99%	-82%
Demand	CO	-88%	-75%	-75%	-72%	-94%	-96%	-99%	-43%
	PM	-82%	-88%	-88%	-86%	-91%	-99%	-99%	-99%
	CO_2	-77%	-77%	-77%	-77%	-77%	-77%	-77%	-83%
Vallejo									
Zero	NO_X	2880%	1385%	969%	1103%	198%	1339%	188%	198%
Induced	HC	-37%	66%	66%	86%	-57%	-87%	-97%	-20%
Demand	CO	-46%	8%	7%	20%	-73%	-84%	-96%	150%
	PM	-22%	-48%	-48%	-40%	-63%	-95%	-96%	-95%
	CO_2	-2%	-2%	1%	1%	1%	1%	1%	-25%
30%	NO_X	3240%	1564%	1098%	1248%	234%	1513%	223%	234%
Induced	HC	-30%	85%	85%	108%	-52%	-85%	-96%	-11%
Demand	CO	-40%	20%	19%	33%	-70%	-82%	-96%	179%
	PM	-12%	-41%	-41%	-33%	-59%	-94%	--96%	-95%
	CO_2	11%	11%	14%	14%	14%	14%	14%	-15%

Note: Shaded values indicate an increase in emissions. Land route is 40 miles long (round trip) and includes two cold starts. Average ferry occupancy is 50% (ferries are, on average, half full at every departure). See Tables 18-27 in the text for other scenarios. LNG-fueled vessels would have emissions very similar to those shown for CNG.

The Vallejo route, however, is quite different. Even with the zero-emission shuttle assumption, emissions of HC, CO and CO_2 can either rise or fall, depending on the technology, while NO_X emissions always increase, and for some technologies do so very substantially.

These results are largely driven by the fact that Vallejo ferry passengers report that if the ferry was not available, that many of them would either take mass transit or simply not make the trip, while only a few would drive. The higher speed and longer distance the vessel travels also contribute. Even if the current Vallejo ferry riders who report they would not make the trip were to actually drive to work alone, the net effect of the ferry's operation would still be to increase NO_X emissions several times relative to the on-land travel that would take place.

These results show that commute patterns involving ferry trips are complex and vary considerably from one service to another (as have previous studies). Comparing the results across the three services studied illustrates how sensitive any analysis is to such landside factors as mode split among local commuters, and variations in landside commute distances. This sensitivity makes analyses based on average values suspect and suggests that extrapolation of these results to other cases is unadvisable.

A few general observations seem possible. First, emissions from existing ferry operations can be reduced significantly with technologies that are rapidly being commercialized (Tier 2 engines), and may be reduced even further by technologies that are being commercialized in other sectors, or in passenger ferry applications elsewhere. These technologies include advanced diesel engines, improved emission control devices, fuel cells, and clean fuels.

Second, technologies that can reduce emissions from Tier 2 levels by 85%-98% are needed to make the air pollution impacts of ferry commutes lower than those from on-land commutes (assuming no net induced travel demand). This result makes sense in light of the fact that on-road transportation modes (especially the automobile) have become extremely clean in the last decade, with emissions reduction levels (relative to direct engine exhaust) of 98% or more. However, it also depends on many context-dependent factors such as landside commute options.

Third, this study suggests that the proper framework for considering ferry system expansion is one that balances competing social and private objectives in transportation planning and operation, including providing affordable and equitable military options, protecting the environment, and providing communities with the opportunity to prosper. Such an analysis is clearly beyond the scope of this report, but is necessary. Factors, such as the impact of induced demand reviewed here, demonstrate that it is not possible to reduce congestion in urbanized areas by increasing transportation system capacity by any method.

Fourth, in keeping with the above theme and providing a foundation of good planning techniques is taken as a given, it should be feasible to design and implement an enhanced ferry scenario to conform to regional mobility and air quality planning goals. Such a scenario could provide new high-occupancy mobility options, possibly at a lower subsidy per passenger than other transit options, and almost certainly at a lower cost than the total cost of new freeway lanes and structures within a congested urban commute shed. Advantages of ferry over highway building options stem from the right-of-way, environmental and construction costs associated with lane additions in congested areas. In addition, ferry service could be implemented in a much quicker time period, thus bringing mobility, access and socioeconomic benefits on-line much sooner.

Finally, the development and deployment of new technologies to accomplish these goals will require government action. Possible next steps in development of low-emission ferry technologies include: 1) the collection of more accurate data on in-situ emissions and duty cycles; and 2) demonstration projects for promising technologies. Following this, the deployment of new low emission ferry technologies could be aided by performance-based incentive mechanisms that reward innovation and improved environmental performance.

I) Project Background, Goals, and Approach

a) Project Background and Goals

In a number of regions across the country, ferries hold great potential for expanding their capacity to carry a larger share of the daily commute trips for millions of people. However, research has shown marine sources are significant to tropospheric air pollution [1-7]. At the same time, urban passenger ferry service is expanding rapidly in many coastal regions as a means to add capacity to over-burdened land-transport systems. This development has been accelerated by the introduction of high-speed (>30 knot) craft, often using jet pump propulsion and catamaran hulls, which can cut commute times [8-16]. These trends combine to present a significant environmental problem for local air pollution managers [17, 18]. Since passenger ferries are an extremely visible and fast-growing segment of the transportation system, ferry emissions have become a new and important issue for air quality management [19].

This study looks across a range of new ferry engine technologies and determines the net emissions impact of ferry operations versus a ‘no ferry’ scenario in which ferry riders return to on-road commute patterns. Based on the interest in further development of ferry service in the San Francisco Bay Area and the availability of data to describe these operations, three ferries from the Bay Area were selected as cases for the analysis. It is necessary to ground such an analysis in empirical data, but by varying the key parameters of the analysis, generalizable results can be derived. In addition, this study should not be thought of as a substitute for a detailed transportation plan, which would be a much more ambitious undertaking.

Within a context of regional concern about emissions and providing new water-based mobility options, the purpose of this analysis is to assess the impacts of various promising ferry engine technologies, while holding constant as many other variables as possible. The analysis seeks to compare emissions from the ferries against emissions from non-ferry commute options.

WestStart’s goal in launching this study was to conduct an independent analysis of ferry emissions. As policymakers are considering plans to significantly expand the ferry system, it is critical that we have a solid understanding of the air quality impacts of ferries.

WestStar is a non-profit organization that works with the public and private sectors to identify and implement clean transportation solutions that improve air quality, increase energy efficiency, and create jobs. WestStart has a fuel neutral focus and works to find the best fuel for the given application.

Alameda/Oakland Ferry Docking in San Francisco

b) Methodological Approach

"Activity-based" methods for estimating emissions from mobile sources are the most widely recommended approaches and are employed here [20]. Emissions of six compounds are reported: oxides of nitrogen (NO_X), non-methane hydrocarbons (NMHC), particulate matter (PM), carbon monoxide (CO), sulfur dioxide (SO_2), and carbon dioxide (CO_2).[1] Only tailpipe emissions are reported since these are the relevant emissions for local regulators and because the majority of the analysis concerns the use of emission control devices, which essentially only change tailpipe emissions. PM emissions are coarse particles (under 10 microns in diameter) only. The year 2007 was selected for analysis because U.S. Environmental Protection Agency's (EPA) Tier 2 standards will begin to apply to new engines of the size used for ferries at that time.[2] In addition, the EPA's Tier 2 standards for new cars will also come into effect in 2007. Thus, this analysis is not rooted in the past – when marine engines were unregulated – but rather looks forward to and is relevant for the next several decades under the latest regulatory decisions.

For the waterside analysis, emissions are modeled using load duration curves constructed for the three vessels based on actual level of service data from published and private sources. Emission factors for the engines were developed from testing and published performance data. The emission factors were applied to the load duration curves to determine overall emissions for each of the technology alternatives.

For the landside analysis, a "commuter emissions factor" for each pollutant was calculated, expressed in grams of pollutant per ferry boarding. This factor varies according to route-specific commute behavior characteristics — ferry route and speeds, land-based mode split, emissions factors for each mode, and trip length (measured in vehicle mile traveled, or VMT). In this analysis, only the travel from the suburban ferry terminal to the San Francisco ferry terminal is examined – trips from home to the suburban ferry terminal are ignored. That is, we look only at the on-land travel for which the ferry ride substitutes. Therefore, this analysis assumes that the portion of the total trip that includes the cold start and VMT from home to each ferry terminal would occur whether or not ferry service was used.[3]

It will be helpful to consider as an example a typical commuter using the Vallejo ferry, who drives alone from his home in Fairfield, parks his vehicle at Vallejo, takes the ferry and walks to work in San Francisco, returning in the afternoon by ferry to Vallejo and driving back home. This creates two cold-starts and two trips from home to terminal. If he were to drive all the way into San Francisco, he would still cause two cold starts and would have to travel from home right past the ferry terminal, so only the VMT from Vallejo to San Francisco would be added. Because the emissions related to the home-to-terminal trip would be incurred for both ferry and land commutes in approximately the same amounts, they are eliminated from both sides of the equation. All analysis is based on weekday travel, because, in the Bay Area as in many regions across the nation, potential ferry expansion is focused on providing added mobility during peak commute periods.

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[1] NMHC is chosen because methane is essentially un-reactive in atmospheric photochemistry leading to secondary pollutants of concern, such as ozone and fine particles.

[2] See [21] for more information about EPA Tier 2 standards.

[3] The use of 'feeder buses' to provide door-to-terminal service has been suggested, but none are currently in use or proposed at this time, and this service has had only limited success elsewhere, so it is left out of this analysis.

The approach has been to determine the net emissions impact of substituting various ferry engine technologies for existing engines (year 2007) in comparison to a "no ferry" scenario which would put current ferry patrons back on the roads, buses and trains for their daily commutes.

Further, by showing the variation in commute patterns among the three selected case studies, the importance of landside trip behavior will be illustrated. The wide variation in these factors, coupled with scant data and the need to make simplifying assumptions, poses a challenge to extrapolating results beyond specific cases actually under analysis.

To make operational inputs and assumptions as realistic as possible, current operations along three San Francisco Bay Area routes were selected for study:

- Larkspur-San Francisco
- Alameda/Oakland-San Francisco
- Vallejo/Baylink-San Francisco

The ferry routes examined represent long, medium and short ferry routes, with associated landside commutes that represent medium and long commute trips.

The data from these ferry routes, including the mode splits, were then used to develop a per-ferry boarding "commuter emissions factor" for eliminated vehicle miles traveled (VMT)-related emissions.

Eight different engine and emission control strategies were evaluated. These were selected because they are the approaches most widely discussed in the literature and include essentially all of the technologies for which data was available. The engine and emission-control technologies studied were:

(9) Existing engines
(10) EPA Tier 2 "Clean Diesel" Engines
(11) EPA Tier 2 + HAM (Humid Air Motor)
(12) EPA Tier 2 + ITD (Injection Timing Delay)
(13) EPA Tier 2 + CF (Catalyst Filter)
(14) EPA Tier 2 + SCR (Selective Catalytic Reduction)
(15) EPA Tier 2 + SCR + CF (Selective Catalytic Reduction and Catalyst Filter)
(16) CNG (Compressed Natural Gas engine)

II) Landside Assessment

a) Summary of Approach

In order to compare the net emissions impact of a new or expanded ferry service with a land-travel alternative, it is first necessary to determine the amount of emissions generated by the vehicle trips that would be eliminated if a commuter were to take the ferry instead of the available land-based route. These land-based emissions are then subtracted from emissions generated by the ferry engines (for existing engine types, plus seven additional technologies) for the waterside commute to result in *net emissions impacts* for all scenarios examined. See Chapter IV for a full discussion of the net emission impacts. This chapter focuses on the emissions from the landside and the methodology used to obtain those figures.

Because net emissions is an expression of the difference between ferry engine emissions and the automobile emissions eliminated by ferry patrons, this figure will, naturally, vary in direct correlation to ferry ridership, if all other factors are held constant. This analysis seeks to compare engine technologies while holding ridership constant, and, on the other hand, to see the impact of increasing ferry occupancy (ridership) on net emissions. To accomplish this, it was necessary to calculate a factor that has been labeled here the "commuter emissions factor" for each pollutant, and is expressed in grams of emissions per ferry boarding. This factor varies according to site-specific route and commute behavior characteristics—primarily length of the land route alternative (vehicle miles traveled, or "VMT,") and the transportation mode from which the ferry trips were drawn. With respect to previous travel mode, it is important to understand that the higher the percentage of landside solo occupancy trips that are replaced by ferry trips, the higher the amount of vehicle emissions that will be subtracted from the ferry emissions on the waterside, and the more the results will favor the ferry alternative. Alternatively, to the extent that ferry patrons are pulled from other, relatively clean commute modes, such as carpooling and transit, fewer emissions will be eliminated as a result of these commuters' switch to ferries, and the net emissions figures will be less favorable to the ferry scenarios, all other things being equal.

In order to make the most realistic comparisons, and in order to see the impact of variability in factors that affect relative emissions profiles, this study uses data and operational parameters drawn from existing conditions at three sites within the San Francisco Bay Area: ferry operations originating from Larkspur, Alameda/Oakland and Vallejo, all terminating at the San Francisco ferry terminal. These routes were selected because they are appropriate for high-speed ferry operations, which is the focus of this study, and because they provide three different operational parameters (shorter, medium and longer land and ferry route mileage.)

As explained above, this landside emissions analysis quantifies emissions related to vehicle travel along the land-based alternative to each of the respective ferry routes. The analysis assumes that the portion of the total trip that includes the cold start and vehicle miles traveled (VMT) from home to each respective ferry terminal would occur whether or not ferry service was used. It will be helpful to consider as an example a typical commuter using the Vallejo ferry, who drives alone from his home in Fairfield, parks his vehicle at Vallejo, takes the ferry to work in San Francisco, returns by ferry to Vallejo, and drives his car back home to Fairfield. If he were to drive all the way into San Francisco, he would still incur a cold start in the morning, the VMT from Fairfield to Vallejo, and an afternoon cold start and return trip VMT. (Cold starts occur when an engine reaches ambient temperature, when emission controls are not yet able to operate efficiently. Cold starts are associated with the number of trips, or "trip ends," rather than trip length. It is assumed that cold starts would occur on each end of a commute trip.) Because the emissions related to the home-to-terminal trip (including cold starts and VMT) would be incurred for both ferry and land commutes in approximately the same amounts, they are eliminated from both sides of the equation. Therefore, this analysis quantifies only the emissions resulting from the terminal-to-terminal portion of the landside commute alternative. In Section IV of this report, these emissions are subtracted from emissions associated with the ferry engine technologies studied, to arrive at net emissions impacts of all scenarios. However, because the emissions related to the home-to-terminal trip can be reduced with focused trip-reduction strategies, this ferry access trip is the subject of a qualitative discussion in Section V.

b) Commuter Emissions Factors

This section describes each step used to create the commuter emissions factor for eliminated emissions, expressed in grams per ferry boarding (See Table 1, below.) Using available data, "commuter emission factors" were generated for each of three case studies: Larkspur, Vallejo and Alameda/Oakland. These represent three different distances and mode splits; to some extent they represent different trip purpose, though peak period trips are primarily work-related. All analysis is based on weekday, not weekend, travel, because, in the Bay Area, as in many regions across the nation, potential ferry expansion is focused on reducing peak period commuter-related congestion.

To estimate changes in emissions due to ferry service expansion, the accompanying changes in landside travel behavior must be estimated. This involves understanding ferry ridership, the on-road mode choice passengers would use if ferries were not available, and the potential for induced travel demand to take back reductions in on-road travel. Data collection included a series of telephone and personal interviews with ferry system operators, as well as reviews of passenger surveys plus published literature [8, 22-26].[4]

Data collected for this research indicates that ridership on current the three ferry routes examined here is ranges from 15% to 33%.[5] They exhibit similar patterns of use, defining three service periods: 1) heavy ridership towards San Francisco in a few morning rush hour departures; 2) relatively low ridership mi-day (often reduced service is offered); and 3) a somewhat more spread out peak of commuters traveling back from San Francisco during the afternoon and evening rush hour [26]. During peak hours, ferries are full (or nearly so) in one direction and virtually empty in the other, similar to other mass-transit modes.

Competing on-road mode choice varies significantly among the three routes. Table 1 shows that single occupancy vehicle (SOV) use varies from 39% to 66%. When rail (i.e. BART) can

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[4] Passenger surveys were as follows:

Larkspur – 1998 Survey of northbound patrons, n =1274;

Alameda/Oakland – Commute Profile 2000 (Bay Area Rides survey, Alameda County results, n=400), and Passenger survey, Tuesday December 17, 1996, n=53 (Oakland) and n=233 (Alameda);

Vallejo – Baylink Rider Survey, 1998, n=693, update from operator (May 2001).

[5] Data collection included a series of telephone and personal interviews with ferry system operators, as well as reviews of passenger surveys plus published literature.

substitute for the ferry routes, such as on the Vallejo route, this is popular. Otherwise bus or carpooling are used, or trips may not be taken.[6] One complication to mode choice analysis is the presence of carpools. Obviously, if a solo driver decides to take the ferry, a SOV trip segment has been eliminated from the highway network. However, if a carpooler decides to leave his or her carpool and take the ferry, the results are less certain. For example, if the carpool vehicle continues to make the same landside trip, whether as a carpool with one fewer occupant, or as a solo occupancy vehicle, then no vehicle trip is reduced. If the remaining carpooler convinces a solo driver to join him or her carpool, then one vehicle trip might be reduced. In a third scenario, all members of a given carpool might decide to use a ferry, eliminating one trip.

The commuter emissions eliminated, expressed in grams per ferry boarding, are then used in Section IV, Discussion of Net Impacts, to fill up the ferries (three routes and seven engine technologies) to different levels of capacity (25%, 50%, 75% and 100%), netting out emissions taken off-road in so doing. This provides an overview of where there are parity points—that is, where there are emissions benefits to be achieved through an expansion of ferries in using operational data for these specific cases, for each of the pollutants evaluated, when all other factors are held constant.

[6] We assume transit emissions are unchanged because changes in ferry ridership are very small compared to bus and rail ridership, and so will not cause changes in (and therefore emissions from) transit operations.

Table 1: Composite Emissions Factors For San Francisco Bay Area Ferry Route Land Commute Alternatives (gm/boarding)

	Current mode split for home-terminal trip	Alternative land route mode split	Eliminated landside trip segments	Criteria Pollutants	EMFAC 2000 Emission Factors (gm/mi)	EMFAC 2000 Commute Trip Start Factors (gm/trip)	Total landside emissions avoided per weekday, at current ferry occupancy (Kg)	**Commuter emissions factor (gm/Boarding)**
Larkspur – SF	74% solo driver	60% solo driver	3,598	NOx	0.51	0.66	30.52	**5.09**
Passenger capacity: **742**	6% transit	30.2% transit	0	HC	0.48	1.37	28.73	**4.79**
Percent of boardings that would be vehicle trips: **61%**	9% non-motorized	5% non-motorized	0	PM-10	0.466	0.015	27.89	**4.65**
Average weekday boardings (one way trips): **5,996**	6% carpool	5% auto plus transit, or rideshare	75	CO	5.22	13.58	312.48	**52.12**
Terminal-terminal alternative route trip distance (Miles): **16.3**	5% dropoff	Total vehicle trips eliminated: **3,673**		CO2	491		29,392.51	**4,902.02**
	Total landside VMT eliminated due to ferry usage: **59,863**							
Alameda/Oakland – SF	78% solo driver	63% solo driver	1,188	NOx	0.51	0.66	8.63	**4.54**
Passenger capacity: **388**	12% transit	19% transit	0	HC	0.48	1.37	8.12	**4.28**
Percent of boardings that would be vehicle trips: **66%**	4% non-motorized	4% other	0	PM-10	0.466	0.015	7.88	**4.15**
Average weekday boardings (one way trips): **1,900**	1% carpool	14% rideshare	67	CO	5.22	13.58	88.36	**46.51**
Terminal-terminal alternative route trip distance (Miles): **13.5**	5% dropoff	Total vehicle trips eliminated: **1,254**		CO2	491		8,312.13	**4,374.81**
	Total landside VMT eliminated due to ferry usage: **16,929**							
Vallejo – SF	80% solo driver	23% solo driver	512	NOx	0.51	0.66	13.55	**6.09**
Passenger capacity: **300**	5% transit	38% transit	0	HC	0.48	1.37	12.76	**5.73**
Percent of boardings that would be vehicle trips: **39%**	0% non-motorized	13% other	72	PM-10	0.466	0.015	12.38	**5.56**
Average weekday boardings (one way trips): **2,288**	0% carpool	26% no trip	290	CO	5.22	13.58	47.58	**62.29**
Terminal-terminal alternative route trip distance (Miles): **30.4**	15% dropoff	Total vehicle trips eliminated: **874**		CO2	491		13,052.98	**5,858.61**
	Total landside VMT eliminated due to ferry usage: **26,584**							

Average weekday boarding figures were obtained and used for each route because it is easier to understand the landside variations between the case studies if data is aggregated to the level of daily boardings per route, and because it provides readers with an understanding of the relative magnitude of ferry ridership for the cases under study.[7] As noted above, this represents between 17% and 33% of total capacity (seated and standing) for the vessels.

Average Weekday Boardings for each service (one-way)

- Larkspur: 5,996 (four ferries)
- Alameda/Oakland: 1,900 (one ferry)
- Vallejo: 2,228 (two ferries)

In order to determine total vehicle miles avoided (and emissions eliminated), the ferry operators provided one-way mileage for their customers' likely route, if they were to use land-based commute options. These one-way commutes are as follows:

Terminal-to-terminal Alternative Land Route Mileage

- Larkspur: 16.3 miles
- Alameda/Oakland: 13.5 (average distances from both terminals to San Francisco)
- Vallejo: 30.4 miles

Key to an accurate estimation of emissions that can be shown to have been eliminated through using a ferry alternative to a land commute, is information on motorists' travel behavior relative to what modes have ferry patrons been drawn, and from what mode are new patrons likely to be drawn. Solo automobile trips dominate all trips from home to terminal, accounting for over three-quarters of all trips.

Two steps were involved in allocating reduced trips to each ferry route. First, mode split data was obtained; second, that mode split data was used as the basis for assumptions related to how many trip segments could be considered to be "eliminated" if the commuter took one of the three ferry routes analyzed, rather than the land route to San Francisco. See Table 2, below for sources. *(Data sources for information relative to the home-to-terminal trip is included for reference, but is not used to calculate the Commuter Emissions Factor.)*

Table 2: Travel Behavior Data Sources

Route	Commute Behavior Prior to Ferry Usage (Home-San Francisco)	Current Mode Used to Access Terminal (Home-to-Terminal)
Larkspur-San Francisco	1998 Survey of northbound patrons n =1274	1998 Survey of northbound patrons n=1274
Alameda/Oakland-San Francisco	Commute Profile 2000 (Bay Area Rides survey; Alameda County results used; n=400)	Passenger survey, Tuesday December 17, 1996; n=53 (Oakland); n=233 (Alameda) Total n = 286
Vallejo-San Francisco	Baylink Rider Survey (1998) n=693	Baylink Rider Survey (1998) n=693; update from operator (May 2001)

The determination of the number of vehicle trips eliminated by the introduction of additional ferry capacity depends on the mode of travel from which passengers are drawn. Obviously, if a

[7] This information was not available on a per-vessel basis.

solo driver decides to take the ferry, a vehicle trip segment has been eliminated from the highway network. However, if a carpooler decides to leave his or her carpool and take the ferry, the results are less certain. For example, if the carpool vehicle continues to make the same landside trip, whether as a carpool with one fewer occupant, or as a solo occupancy vehicle, then no vehicle trip is reduced. If the remaining carpooler convinces a solo driver to join his or her carpool, then one vehicle trip might be reduced. In a third scenario, all members of a given carpool might decide to use a ferry, and the segment of the trip from terminal-to-terminal would be eliminated. There is evidence that carpooling is a relatively flexible approach to commuting and that all three activities can be expected.

Table 3, below, shows the number of trip segments that were assumed to be eliminated based on the previous mode choice of ferry patrons. These values are open to debate, however, the fact that more than three quarters of all current trips are by solo drivers, for which a trip elimination factor is 1.0 and without controversy suggests any errors introduced here are small.[8]

Table 3: Determination of Trip Elimination Factor

Previous mode choice	Trips Eliminated	Comment
Solo automobile trip	1	By definition
Transit	0	No adjustment made for emissions by bus or BART, under the assumption that service levels will be unaffected.
Ridesharing	0.25	Assumes that 75% of the time the carpool continues to operate, either as a carpool or as a solo commute.
Did not make trip	0.5	No data available, midpoint of possible range is chosen
Other	0.3	Due to the vague category, an estimate higher than ridesharing but lower than 'did not make trip' is chosen
Auto + transit/rideshare	0.3	Due to absence of data, an estimate higher than ridesharing but lower than 'did not make trip' is chosen

Current ferry boardings were multiplied by the above factors, according to mode choice data available for the three case study areas. The results for the different routes—that is, the percentage of daily ferry boardings that would otherwise be passenger vehicle trips, according to available survey data is as follows:

Daily ferry boardings that would otherwise be passenger vehicle trips

- Larkspur: 61%
- Alameda/Oakland: 66%
- Vallejo: 39%

[8] Looking ahead, the results presented in subsequent sections are of a magnitude that any error introduced here would have a minimal effect on the values in the tables and no effect on their interpretation.

The difference in this percentage of trips reduced between the Larkspur and Alameda/Oakland cases, compared to that of Vallejo, account for a portion of the difference in relative emissions benefits from ferry operations discussed in Section IV of this report.

The mileage figures for the alternative round trip by land (terminal-to-terminal) are multiplied by the "eliminated trips"(derived from mode split data, described above) to arrive at the total vehicle miles eliminated by a switch to ferry usage, for each case.

Table 4 provides readers with a quick view of the trend toward cleaner on-road fleets, and to give researchers detailed information of what each emission factor includes in California. The decrease in light duty vehicle fleet emission factors means that ferry technology must reduce its engine emissions by comparable amounts to retain any environmental advantage relative to land-based commutes.

Table 5 presents the California Air Resources Board's average auto emission factors. *Note that ROG (reactive organic gases) and HC (hydrocarbons) are terms used interchangeably in California.* Emissions factors for analysis year (2007) were obtained from the California Air Resources Board. Year 2007 was selected for analysis because the U.S. Environmental Protection Agency's Tier 2 standards will begin to apply to new engines of the size used for ferries, and expanded ferry service will occur after this point.

Table 4: Average Light-Duty Vehicles Emission Factors

Analysis Period	1-5 Years (2000-2004)	6-10 Years (2000-2009)	11-15 Years (2000-2014)	16-20 Years 2000-2019)
NOx				
VMT (g/mile)	0.90	0.70	0.57	0.48
commute trip ends (g/trip end)	0.92	0.79	0.68	0.58
average trip ends (g/trip end)	0.76	0.65	0.55	0.48
HC				
VMT (g/mile)	0.83	0.66	0.54	0.45
commute trip ends (g/trip end)	2.08	1.73	1.46	1.25
average trip ends (g/trip end)	1.44	1.18	0.99	0.84
PM10				
VMT (g/mile)	0.466	0.466	0.466	0.466
commute trip ends (g/trip end)	0.014	0.014	0.015	0.015
average trip ends (g/trip end)	0.008	0.008	0.008	0.008
CO				
VMT (g/mile)	8.74	7.00	5.77	4.87
commute trip ends (g/trip end)	20.15	16.89	14.51	12.60
average trip ends (g/trip end)	11.25	9.28	7.81	6.67

Source: Annual Average Emissions, EMFAC2000 Version 2.02. Includes average statewide emissions for light duty cars and trucks plus motorcycles.

TO USE TABLE to find annual emissions related to travel: 1) select time period that corresponds to life of project, 2) multiply annual miles traveled by the VMT factor, 3) multiply annual number of trips by the trip end factor, 4) add VMT emissions to trip end emissions, 5) divide by 454 grams/lb to get lbs of emissions per year, 6) repeat for each pollutant. (Note: Use the commute trip end factor when analyzing work trips. Use the average trip end factor when analyzing a variety of trip types. The VMT factor is the same in both instances.)

The VMT factors equal running exhaust plus running losses divided by daily VMT. Commute trips factor equals statewide start emissions for a commute-type pre-start soak distribution plus hot soak emission divided by daily trips. The commute-type pre-start soak distribution is based on an analysis of the 1991 Statewide Travel Survey all day home-to-work and work-to-home trips. Average trips factor equals statewide start emissions plus hot soak emissions divided by daily trips.

PM10 VMT factor includes motor vehicle exhaust (ranges from 0.0184 to 0.0197 g/mile depending on calendar year), tire wear (0.010 g/mile), brake wear (0.015 g/mile), and entrained road dust (0.422 g/mi.). The road dust portion of the PM10 factor is based on U.S. EPA's Compilation of Air Pollutant Emission Factors (AP-42, January 1995). Silt loading and vehicle weight data used as inputs to EPA's equation are from Improvement of Specific Emission Factors (BACM Project No. 1), Final Report, Midwest Research Institute, March 1996.

NOTES: (1) The factors do not include medium-duty vehicles (5751 to 8500 GVW); however, emissions from medium-duty vehicles used as passenger vehicles have an insignificant affect (1% or less) when added to the emission factors given for light-duty vehicles. (2) Light-duty vehicle emission standards require progressively cleaner fleet average emissions. This accounts for the gradual decrease in fleet average emission factors over time.

Table 5: CARB Yearly Average Auto Emissions (See year 2007, in BOLD, for factors used in calculations for this analysis.)[9]

2000 Total Average Auto Emissions	NOX	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	1.14	1.05	10.87	0.043	0.422	0.465
Average Trips (g/trip)	0.87	1.73	13.61	0.007		
Commute Trips (g/trip)	1.06	2.51	24.36	0.013		
2001 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	1.02	0.94	9.78	0.044	0.422	0.466
Average Trips (g/trip)	0.82	1.58	12.41	0.008		
Commute Trips (g/trip)	0.99	2.29	22.16	0.013		
2002 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.88	0.81	8.53	0.044	0.422	0.466
Average Trips (g/trip)	0.76	1.41	11.04	0.008		
Commute Trips (g/trip)	0.91	2.02	19.64	0.014		
2003 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.76	0.72	7.61	0.044	0.422	0.466
Average Trips (g/trip)	0.69	1.29	10.01	0.008		
Commute Trips (g/trip)	0.85	1.86	18.01	0.014		
2004 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.68	0.65	6.89	0.044	0.422	0.466
Average Trips (g/trip)	0.65	1.18	9.20	0.008		
Commute Trips (g/trip)	0.79	1.71	16.61	0.014		
2005 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.62	0.59	6.28	0.044	0.422	0.466
Average Trips (g/trip)	0.61	1.09	8.49	0.008		
Commute Trips (g/trip)	0.74	1.58	15.38	0.015		

9 Running HC emissions include running exhaust and running evaporative emissions. Total running PM10 emissions include running exhaust, tire wear, brake wear, and entrained road dust. Average trip emissions include hot soak and start exhaust based on a normal hot soak distribution as modeled in EMFAC2000. Commute trip emissions include hot soak and start exhaust based on a commute hot soak distribution developed form CALTRANS and local COG data.

2006 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.56	0.53	5.73	0.044	0.422	0.466
Average Trips (g/trip)	0.58	1.00	7.85	0.008		
Commute Trips (g/trip)	0.70	1.47	14.40	0.015		

2007 Total Average Auto Emissions	**NOx**	**HC**	**CO**	**Exhaust PM10**	**Road Dust PM10**	**Total Running PM10**
Running (g/mi)	**0.51**	**0.48**	**5.22**	**0.044**	**0.422**	**0.466**
Average Trips (g/trip)	**0.54**	**0.92**	**7.25**	**0.008**		
Commute Trips (g/trip)	**0.66**	**1.37**	**13.58**	**0.015**		

2008 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.46	0.44	4.75	0.044	0.422	0.466
Average Trips (g/trip)	0.50	0.85	6.70	0.008		
Commute Trips (g/trip)	0.62	1.28	12.78	0.016		

2009 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.42	0.39	4.33	0.044	0.422	0.466
Average Trips (g/trip)	0.46	0.78	6.19	0.008		
Commute Trips (g/trip)	0.58	1.18	11.98	0.016		

2010 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.38	0.36	3.94	0.044	0.422	0.466
Average Trips (g/trip)	0.43	0.71	5.70	0.008		
Commute Trips (g/trip)	0.53	1.09	11.18	0.016		

2011 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.34	0.32	3.60	0.044	0.422	0.466
Average Trips (g/trip)	0.40	0.65	5.26	0.008		
Commute Trips (g/trip)	0.49	1.00	10.43	0.016		

2012 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.31	0.29	3.29	0.044	0.422	0.466
Average Trips (g/trip)	0.36	0.60	4.84	0.008		
Commute Trips (g/trip)	0.45	0.92	9.72	0.016		

2013 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.29	0.27	3.01	0.045	0.422	0.467
Average Trips (g/trip)	0.33	0.55	4.46	0.008		
Commute Trips (g/trip)	0.42	0.84	9.05	0.017		

2014 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.26	0.25	2.76	0.045	0.422	0.467
Average Trips (g/trip)	0.31	0.50	4.10	0.008		
Commute Trips (g/trip)	0.38	0.77	8.42	0.017		

2015 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.24	0.23	2.54	0.045	0.422	0.467
Average Trips (g/trip)	0.28	0.46	3.78	0.008		
Commute Trips (g/trip)	0.35	0.71	7.84	0.017		

2016 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.22	0.21	2.34	0.045	0.422	0.467
Average Trips (g/trip)	0.26	0.43	3.49	0.008		
Commute Trips (g/trip)	0.32	0.65	7.31	0.017		

2017 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.21	0.19	2.16	0.045	0.422	0.467
Average Trips (g/trip)	0.24	0.39	3.22	0.008		
Commute Trips (g/trip)	0.30	0.60	6.81	0.017		

2018 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.19	0.18	1.99	0.045	0.422	0.467
Average Trips (g/trip)	0.22	0.36	2.97	0.008		
Commute Trips (g/trip)	0.27	0.55	6.34	0.017		

2019 Total Average Auto Emissions	NOx	HC	CO	Exhaust PM10	Road Dust PM10	Total Running PM10
Running (g/mi)	0.18	0.17	1.84	0.045	0.422	0.467
Average Trips (g/trip)	0.20	0.34	2.75	0.008		
Commute Trips (g/trip)	0.25	0.51	5.91	0.016		

For this analysis, CO_2 figures were obtained by averaging available figures for 2005 and 2010 to derive the 2007 California statewide vehicle miles traveled and the total CO_2 inventory, and dividing to find a resulting CO_2 factor that could be expressed in grams per mile, and thus associated to the eliminated miles for each of the respective ferry routes analyzed. (CARB obtains fuel consumption projections from the California Energy Commission, which then are used to calculate Daily Statewide CO_2 Emissions.)

Year	**Daily Statewide VMT**	**Daily Statewide CO2 Emissions**
2005	731,364,000	402,000 tons
2010	793,993,000	422,000 tons
2007	762,681,500	412,500 tons

Formula: 412,500 tons CO_2/762,681,500 miles = 490.9 grams of CO_2 per mile

The final step to arrive at the emissions factor used in this evaluation involved multiplying the adjusted VMT for eliminated trip segments by the CARB emission factors for 2007, and dividing that figure by the number of weekday boardings for each case scenario. The resulting "grams of pollutant per boarding" (see Table 6, below) yields a factor which was then used to "load up" the ferries to four capacity levels (25%, 50%, 75% and 100%) to determine and compare relative net emissions for the eight engine technologies and the three case study routes. (See Section IV of this report for the results and discussion of those results.)

Table 6: Commuter Emission Factors, in grams per boarding

Route	**HC**	**NOx**	**PM10**	**CO2**	**CO**
Larkspur	4.79	5.09	4.65	5,391.23	52.12
Alameda/Oakland	4.28	4.54	4.15	4811.40	46.51
Vallejo	5.73	6.09	5.56	6,443.28	62.29

The difference in emission factors in grams per boarding between Vallejo and the Larkspur and Alameda/Oakland cases is due to a relatively lower proportion of ferry trips that represent eliminated vehicle trips, and a longer landside commute trip length.

c) Induced Travel Demand

In order to estimate the net emissions change of utilizing new ferry engine and emission control technologies, compared to a no-ferry scenario, it is necessary to estimate the change in on-road traffic that the ferry will create. In congested areas such as the Bay Area, creating new transportation capacity by adding ferries to the mix of available commute modes, will, to some extent, merely accommodate currently unsatisfied demand for mobility. That is, one cannot assume that a trip diverted from the freeways to the ferries will result in a one-to-one reduction in associated vehicle emissions. The technical term for this effect is induced (or latent) travel demand, which is defined as the projected number of trips that would be generated if travel were more convenient, less expensive, or otherwise improved (*Academic Press Dictionary of Science and Technology*). It is a well-studied phenomenon that is supported by both economic theory and empirical evidence. The basic effect is that projects designed to relieve congestion by increasing transportation capacity tend to disappear as better travel conditions induce new trips that quickly clog roadways again. Thus, in congested areas such as the Bay Area, creating new capacity by adding ferries to the mix of available commute modes, will, to some extent, merely accommodate currently unsatisfied demand for mobility.

The basic theoretical observation is that travel has a cost, which travelers take into account when planning activities. Often this costs involves opportunities forgone due to the time spent traveling, as well as reductions in quality of life while stuck in traffic. Traditional 'derived demand' transportation models do not include these costs and thus are more or less unable to model them, while more recent approaches have successfully accounted for this effect [27, 28]. Perhaps more compelling is the very substantial body of empirical data that has been built up over the last several years showing the very large magnitude of this effect [29-36]. This research, consisting of the analysis of multiple panel data sets shows consistent, statistically significant results across a wide range of locations and levels of aggregation. Some of the highest values for induced demand are found in data for Californian metropolitan areas. These studies typically look at highway expansions (especially high occupancy vehicle construction), but there is no apparent reason why a different sort of capacity addition should have different results. As long as the project (such as ferry system expansion, or mass transit additions) makes travel more convenient, it will induce additional travel. The short term (less than three year) take-back of congestion relief is typically found to be 30% to 60%, while long-term effects are 70% to 100%, implying that capacity additions provide little or no congestion relief after several years. Discussions with CARB staff indicated that a realistic short-term value for induced demand take-back in the Bay Area was 30%.

To account for short-term induced demand effects, all commuter emissions factors are reduced by a factor of 30% in the net emissions tables included in Section IV of this report. As a sensitivity analysis, a zero-induced demand analysis is also included.

d) Extrapolation

The *methodology* explained in this report can be applied regionally and nationally by developing a commuter emissions factors, expressed in grams per ferry boarding, for specific cases—and subtracting landside from waterside emissions to arrive at net emissions from ferry operations that can then be used in comparative analyses like this one. However, *it is not advisable to extrapolate specific case findings to other cases* within the same region, and certainly not nationally, for a number of reasons. First, of course, ferry engine performance depends on factors of the duty cycle that are site-specific and not easily generalized. In addition, there are many factors that affect travel and trip-making behavior relative to attempts to increase ferry operations. These factors affect, by varying magnitudes, a net emissions benefit analysis, thus posing serious methodological challenges to any attempt to generalize results across cases.

The necessary process, described in this section and elsewhere in this report, of comparing and contrasting the conditions and survey and operational data among the Vallejo, Larkspur and Alameda/Oakland sites—ferry services which are operating in the same region—illustrates the variability of inputs into the analytic methodology involved in quantifying landside and waterside emissions, again pointing to the potential for significant differences between cases studied across regions. Among the factors that will vary from case to case, and can vary significantly from region to region, are the following:

- Variability in ferry service offered (availability of high-speed ferries; headways; cost; marketing; amenities)
- Ferry ridership potential
- Ferry terminal access factors (existence of feeder buses, park and ride lots, etc.)

- Differences in emission factors from state to state (e.g., California light duty vehicles are cleaner than fleets in the rest of the nation)
- Variability in meteorological conditions affecting smog formation
- Regulatory environment, institutional opportunities and barriers
- Parking availability and pricing of that parking (at both terminal and destination)
- Mobility limitations on competing land routes (congestion and geographical limits, etc.)
- Existence of tolls
- Propensity of population to use non-solo occupancy driver vehicles (regional mode split)
- Land use
- Population density

Golden Gate Transit District Ferries at Larkspur Terminal

III) Waterside Assessment

This section presents the methodology and emissions estimate results for three passenger ferries currently in service in San Francisco Bay. The section also presents emissions estimates and costs associated with a range of control options. Seven technologies (combinations of propulsion and emission control systems) are evaluated. The three vessels span a range of ages and technologies, from a 25-year-old monohull to a modern, high-speed catamaran built only four years ago. Current vessel designs fall within the parameters of these ferries, although by far the most popular new ferries are high-speed catamarans similar to the one evaluated here. By looking at a range of technologies and service conditions, a sense of the broader implications of controlling emissions from passenger ferries across a range of vessels and service profiles is provided. Emissions are modeled using load duration curves constructed for the three vessels based on actual level of service data from published and private sources. Emission factors for the engines were developed from testing and published performance data. The emission factors were applied to the load duration curves to determine overall emissions for each of the technology alternatives.

a) Literature review

As the largest sources of pollution have been identified and controlled through regulation, traditionally smaller source categories, such as ships, have gained attention [1, 37]. Recent research has shown marine sources are significant to global tropospheric photochemistry and local air quality [2-6, 38]. For instance, the California Air Resources Board (CARB) expects marine engines to be the only category of off-road sources that will increase particulate matter (PM) emissions by 2010, rising to 23% of the state-wide emission inventory from 16% in 2000 [18 pp. III-8 and III-10]. Most of these emissions come from large, international cargo ships, but passenger ferries can have significant emissions at the local level [39].

Efforts are currently underway to expand and modernize ferry systems to provide faster service to more passengers at both the federal and state levels [8]. The growth in interest in ferry service has been spurred by the deployment of high-speed (>30 knot) craft, often using jet pump propulsion and catamaran hulls [9-11]. Since passenger ferries are an extremely visible and fast-growing segment of the transportation milieu, ferry emissions considerations have become a new and important issue for air quality management [19, 40].

However, compared to other sectors, relatively little is known about maritime emissions and optimal control strategies. Information is inadequate in areas such as emissions and duty cycle relationships, in-situ emissions compared to engine test results, and emissions deterioration over engine life (which can be two to three decades). Virtually all information published to date comes from engineering estimates, since in-situ ship emissions testing has largely focused on engines that are much larger and operate at a slower speed than the engines installed on passenger ferries, although initial testing suggests that emissions rates from smaller marine engines are similar [41, 42]. However, these measurements have been made on older engines, and thus have limited relevance for modern ferries. Some comparisons can be made to railroad locomotive engines, but emissions profiles for rail may differ due to marinization of the engines, differences in vehicle operation, and variations between marine and rail fuels. Moreover, research on marine emissions has focused mostly on emissions of SO_2 and NO_X, and less so on other pollutants of concern such as PM, HC, and CO_2.

Marine Engines and Control Technologies

Seven major studies relevant to Bay Area ferry emissions are in progress or have been conducted, as summarized in Table 7, the last four of which are most relevant to this study. Much of the pre-1999 research on the subject is reviewed and analyzed in the EPA's Regulatory Impact Assessment (RIA), its marine emissions rulemaking, and in an associated consultant report commissioned by the EPA [43, 44]. The most important features of these two studies are the estimation of emission factors, and, in the RIA, the estimation of control costs. The consultant study evaluated all the then-available ship emissions monitoring by performing a statistical analysis that aggregates multiple tests at multiple load points to derive statistical relationships for the ensemble data. This approach showed a general relationship between engine load and emissions exists for marine compression-ignition engines, but because aggregated data was used, this approach cannot find any systematic differences across engine or vessel types. The RIA contains emission factors based on this information, as well as an analysis of a range of engine and fuel system modifications necessary to meet the "Tier 2" marine emission standards. The Tier 2 standards are much less strict than the emission levels that are examined in this study and can generally be met with currently available marine technologies, so the costs of meeting Tier 2 standards are much lower as well.[10]

As interest in Bay Area ferry system expansion has grown, Blue Water Network (BWN), an environmental advocacy group, issued a report highly critical of the environmental performance of passenger ferries [46].[11] However in the BWN report, only uncontrolled diesel and compressed natural gas (CNG) engines were examined and no control technologies were included. Liquefied natural gas (LNG) is a possibility as well. LNG has several potential advantages over CNG, it can be less expensive, take up less storage space, and allow for faster refuelings. LNG has long been used safely as a marine fuel – LNG tankers burn a small portion of their cargo. Emissions would be essentially the same. To date, however, all the analysis and available data for natural gas-powered ferries in the U.S. has assumed compressed gas storage, for comparability with these studies CNG is assumed here as well.[12]

The BWN study relied on limited data and relatively simple calculations to show that emissions from existing, uncontrolled marine diesel engines would be much greater (6-10 times) than highway modes on a gram/passenger-mile (gppm) basis. It also showed that newer-model diesel and natural gas transit buses could be much cleaner replacements for both automobiles and the ferry technologies studied.[13] Nonetheless, the BWN study demonstrated the need for further detailed study of the air and water quality impacts of ferries before service expansion.[14]

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[10] In comparison to on-road heavy-duty engines, marine engines are lightly regulated. By model year (MY) 2004, on-road diesel engine NO_X emissions must be reduced by about 50% from MY 1998 levels, and by MY 2007 NOX emissions must be reduced by a *further* 90%, and PM emissions must be reduced by 80%-90% [45].

[11] An extensive analysis by the Bay Area Council (BAC) first formally proposed a dramatic expansion of Bay Area ferry service [9]. As originally published, the BAC study simply asserted that emissions would be lower from ferry commutes than from the on-road trips they would replace. (Subsequently the study was modified to indicate that more research was needed.) See http://www.bayareacouncil.org/ for more information.

[12] There are significant challenges to the introduction of either form of natural gas storage, including increased capital costs, the cost of a refueling infrastructure and U.S. Coast Guard approval.

[13] This conclusion should have been no surprise. The current environmental performance of automobiles and other on-road vehicles is a result of longstanding regulations, whereas marine engines were previously unregulated.

[14] See http://www.bluewaternetwork.org for more information.

Probably the most detailed emission inventory of any major U.S. port is the study of Boston Harbor conducted by the Northeast States for Coordinated Air Use Management (NESCAUM) [38]. Ferry emissions accounted for a relatively small fraction of total harbor emissions, partly because of the inclusion of pleasure craft, which have very high NO_X, CO and HC emissions from their gasoline engines. Interestingly, the study also identifies eight installations of selective catalytic reduction (SCR) controls onboard ships, including four on large bulk cargo ships operating in California.

A more focused study by Farrell and Glick examined the emissions impacts of using CNG as a marine fuel [47]. This analysis develops two hypothetical, but not unrealistic scenarios consisting of single-ferry service, one for a 49-passenger vessel and the other for a 149-passenger vessel. The study estimates emissions reductions for CNG vessels compared to both uncontrolled and Tier 2 diesel engines. Emissions of the three pollutants reported (NO_X, SO_2, and PM) all showed significant decreases, but changes in greenhouse gas emissions were more complex. For example, CNG engines increased emissions of methane (CH_4) and nitrous oxide (N_2O), but reduced carbon dioxide (CO_2) emissions. In terms of mass emissions, the CO_2 decreases were several thousand times greater than the increases for the other two gases. These values were determined with a full-fuel-cycle analysis tool developed by Argonne National Laboratory [48] but assumed no efficiency losses in switching to CNG engines. Large CNG engines have efficiencies closely approaching to those of compression-ignition engines through the use of micro-pilot ignition and direct injection systems, which continue to improve through research and development [49, 50].[15] A preliminary analysis by these authors suggested the incremental cost of control for NO_X of $1,200-$1,900 per ton which they note compares favorably with other stationary and mobile source control programs. The authors also argue that passenger ferries are an attractive mode choice for the introduction of CNG as a transportation fuel for various engineering and institutional reasons.

A wider set of technologies is being examined by Art Anderson Associates (AAA), an engineering and consulting firm that includes Naval Architects and Marine Engineers [25].[16] This study compared passenger cars and buses (using CARB's MVIE7G model for calendar years 2000 and 2003) with a variety of ferry technologies.[17] Most of the focus of the AAA study was on "modern diesel engines" that exceed EPA Tier 2 standards, along with four emission control technologies and one combination (catalytic filter + SCR). In addition, major changes to propulsion systems were considered, including the use of gas turbine engines, three CNG technologies, and a combination of CNG engines with an emission control technology.[18] Table 8 contains the key results of the AAA study, which include the effect on emissions, capital and

[15] See for instance, http://www.cooperenergy.com/ or http://www.wartsila.com/ for firms such products.

[16] This study is ongoing and not yet complete. All results reported here are preliminary.

[17] AAA recommends that EMFAC 2000 be used for future studies once it becomes available.

[18] The AAA study is confusing about the combination natural gas engine and emission control technology it evaluated. The text is contradictory about the emissions of micro-pilot natural gas engines; page 14 attributes "stellar emission profiles" to them, while page 17 says they "emit much less NO_X than diesel engines," but "substantially more CO and HC." Further, the table in the Executive Summary (page iv) lists "Filter" as the emission control technology while the table in the body of the report (page 10) lists SCR, and the text itself (page 17) discusses a catalytic filter. However, it is not clear why a CPF would be preferred in this application, for which little PM control is needed, over a less expensive catalytic converter (page 18).

operating costs, and impact on vessel mass.[19] The AAA study also discusses some possibilities for integrating emissions controls into existing equipment, such as engine silencers.

The analysis in the AAA study is based on a hypothetical, but not unrealistic, service profile modeled on two existing high-speed 300+ passenger catamarans serving Larkspur and Vallejo. Emissions are calculated on a gram/passenger-mile (gppm) basis for NO_X, Total Hydrocarbons (THC), CO, and PM. Uncontrolled diesel engines (modern or Tier 2) are found to have considerably higher emissions than the on-road modes in almost all cases, even if one emission control technology is used. Only a combination of a SCR and CPF applied to a modern diesel engine is found to reduce vessel emissions to below the level of the on-road modes. Uncontrolled dual-fuel and spark-ignited CNG engines have higher emissions than the on-road sources, but this is partially an artifact of the choice of THC as the relevant measurement (see below).

The AAA study found that gas turbine engines are by far the most expensive option in terms of both capital and operating costs, although these engines can reduce the mass of the propulsion system.[20] Gas turbines could significantly reduce NO_X and HC emissions, but CO and CO_2 emissions would increase. The AAA study briefly discusses operational controls (e.g. lowering speeds and shutting engines off at dockside or during low-speed transits) but notes that there would be increased additional maintenance costs and emissions associated with more frequent engine starts. No quantitative estimates of these effects are given. The AAA study also noted that only SCR and fuel additives (i.e. water-fuel emulsion) technologies are not readily available for ferry applications, and they attribute this largely due to the lack of regulatory push of cleaner engines. The authors of the AAA study conclude that the other technologies are a few years from commercialization, but that no significant barriers exist to marine applications so this schedule could be hastened with appropriate incentives.

Corbett and Fischbeck conducted the most comprehensive study, in terms of costs and performance, although it only considers NO_X controls and uses data that is most relevant to large cargo ships [52]. Table 9 presents the main findings of the Corbett and Fischbeck study in terms of NO_X reduction and costs for nine technologies as they might be applied as *retrofits* to existing vessels. Their study is comprehensive in that it includes the design costs as well as changes in capital, fuel consumption, maintenance and other operating costs (e.g. reagent for SCR). Further, the net present value over 23 years at a 15% interest rate is calculated. Based on a net present value calculation[21], this analysis demonstrates that SCR is the most cost-effective approach at slightly under $6,000 for each percentage point of NO_X reduction. SCR is also shown to be the only technology that can achieve significantly greater than a 45% reduction in NO_X emissions. Disregarding one prohibitively expensive option (exhaust gas recirculation), the best-performing technologies in this study are: SCR, water/fuel emulsion, injector upgrades, and water addition to combustion air. The lowest-capital cost technology is injection-timing retard. However, this low-cost technology also has lower performance in emissions control, so its cost-effectiveness is about one-third of SCR.

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[19] Of course, size and weight considerations are also important when considering the feasibility of retrofitting emission control technologies into already-tight engine rooms.

[20] Fuel cell technologies are also being developed for marine applications, but they are still in the development stage and have even greater problems of high costs [51]. For these reasons, fuel cells are not considered further in this analysis.

[21] The NPV calculation is over a 23 year lifetime using a 15% discount rate.

Table 7: Previous major, relevant studies

Name	Description and Data	Major Conclusions
Final Regulatory Impact Analysis: Control of Emissions from Marine Diesel Engines, EPA (1999)	• Emissions factors developed. • Focused on controlling emissions to about Tier 2 levels.	• Emission factors (g/kW-hr): PM 0.30, NOX 13, SO_2 HC 0.27, CO 2.5 • Tier 2 incremental capital costs \$15-\$34 /kW. • Cost effectiveness of Tier 2 standards are estimated at \$87/ton HC+NO_X and \$1,642/ton PM.
Bay Area Transportation Options Emission Report, Long (1999)	• Case study comparison of the *Del Norte* in high-speed service from Larkspur to San Francisco with auto and bus trips. Includes CNG fuel alternatives. • Marine emissions assumed to be equivalent to EPA Tier 2. Bus emissions based on prior studies. Auto emissions based on an average of current and future standards. Ridership based on regional averages and expert opinion.	• 2010 emissions: NMHC NO_X PM (gppm) o Autos: 0.087 0.330 0.000 o Diesel bus: 0.016 0.293 0.020 o NG bus: 0.041 0.189 0.001 o Diesel Ferry: 0.0 3.557 0.099 o NG Ferry: 0.0 1.776 0.001
Boston Harbor Marine Vessel Emissions Inventory, Cooper (2000)	• 1997 Marine emissions estimate for Boston Harbor, includes 57 shuttle and sightseeing vessels. • Ferries produce 23% of harbor SO_2 emissions, 2% of PM, 13% of HC, and 8% NO_X	• Lists 8 installations of SCR on large bulk carriers (cargo ships) since 1990, including 4 in California. Average NO_X reduction of 93.5%. • Table of control option effectiveness, but not costs.
Analysis of Commercial Marine Vessels Emissions and Fuel Consumption Data, EEA, Inc. (2000)	• Review of 9 reports and develops emission factors. Data reports reviewed: Lloyds, BC Ferry Corp., Environment Canada, U.S. Coast Guard. Analytical reports reviewed: Booz-Allen, Lloyds, Acurex (91), Acurex (96)	• Point estimates of emission factors for 50% power rating taken from relatively flat curves (g/kW-hr): PM 0.26, NOX 11, SO_2 emissions = 2.37 x fuel sulfur, CO 0.36
Natural Gas as A Marine Transportation Fuel, Farrell & Glick (2000)	• Estimates annual mass emissions of NO_X, SO_2, PM, and Greenhouse Gases (GHG) from 49 and 149 passenger ferries.	• CNG engines reduce NO_X 57% to 77%, SO_2 by 99%, PM by 97%, but have mixed effects on different GHG. • Cost effectiveness for NO_X is \$1,200 - \$1,900.
Ferry Environmental Suitability Study, Art Anderson Associates (2001)	• Engineering – economic analysis of cars, buses, and 11 marine engine technologies for *new* vessels. • Route-specific engine loads and ridership data was gathered, but it is not clear how they were used to create the average values that are reported. • "Modern Diesel Engine" emissions (g/kW-hr) given as: Total HC 0.39, NO_X 9.38, CO 0.75, PM 0.17	• Only two technologies yield ferry emissions are as low as or lower than on-road (car or bus): modern diesel engines with catalytic filter and SCR, and micro-pilot ignited CNG engines with catalytic filter. • Commercialization of catalytic devices, and CNG fuels are a few years away, but incentives could hasten. • See table below for cost estimates, for a 350-passenger ferry with 4x1050 kW engines.
Commercial Marine Emissions – Life-Cycle Analysis of Retrofit Controls, Corbett & Fischbeck (2001)	• Comparison of life cycle costs of 9 NO_X control technologies for *retrofit.* • Data are most applicable to large, ocean-going vessels.	• See table below

Table 8: Cost and weight of emission control technologies for *new* marine engines for a 350 passenger with 4x 1050 kW engines, preliminary results (Art Anderson Associates, 2001)

Control Technology	Effect on Emissions	Capital Cost	Annual Operating Costs	Weight Impact
Turbine	Not specified	\$1,400,000	\$120,000	- 10 tons
Catalytic converter	Not specified	\$20,000	\$7,000	+ 0.25 tons
Catalytic filter	Up to 95% reductions in CO, HC, and PM	\$85,000	\$75,000	+ 0.50 tons
Selective catalytic reduction	Up to 95% NO_X reductions	\$350,000	\$90,000	+ 3 tons
Fuel additives (e.g. water)	5%-30% NO_X reductions	\$0	\$57,000	None
Micro-pilot CNG engine	Very low NO_X and PM, but CO and HC increase.	N/A	N/A	N/A
Dual-fuel engines	NO_X and PM decrease, but CO and HC increase	N/A	N/A	N/A

Table 9: Cost and performance of NO_X control technologies for marine engine *retrofits* on large vessels (Corbett and Fischbeck, 2001)

Control Technology	% NO_X Reduction	Fixed Costs – Hardware, Installation, Design	Annual Costs – Maintenance, Operating, Fuel	NPV Costs (15% over 23 years)	Cost-effectiveness (\$/ton NO_X)
Selective catalytic reduction	81	\$285,000	\$30,000	\$477,000	\$5,889
Water/fuel emulsion	42	\$119,000	\$32,000	\$324,000	\$7,714
Injector upgrade	16	\$41,000	\$24,000	\$195,000	\$12,188
Water in combustion air	28	\$134,000	\$36,000	\$364,000	\$13,000
Fuel pressure increase	14	\$36,000	\$29,000	\$222,000	\$15,857
Aftercooler upgrade	10	\$12,000	\$27,000	\$185,000	\$18,500
Injection Timing Retard	19	\$250	\$57,000	\$365,000	\$19,211
Engine derating	14	\$34,000	\$55,000	\$386,000	\$27,571
Exhaust gas recirculation	34	\$3,500	\$2,640,000	\$16,896,000	\$496,941

Marine Fuels

The type and quality of fuel is one of the most important factors affecting vessel emissions. All Bay Area ferries use compression-ignition engines and burn "marine distillate fuel." Fuel quality affects emissions performance in several ways. Most directly, the sulfur content of the fuel is directly responsible for the level of SO_2 emissions. However, sulfur also leads to the formation of PM and can severely reduce the effectiveness of catalysts designed to control NO_X and PM emissions. In order to determine the costs of the technologies evaluated here, the increased cost (if any) of using low-sulfur fuels will need to be determined.

There are currently no regulations at either the state or federal level for fuels used by commercial marine vessels, and international standards are not relevant for passenger ferries.[22] A review of fueling practices in the marine sector revealed that the fuels typically specified for engines used in passenger ferries (e.g. Marine Distillate Fuel A or DMA) vary only a little in sulfur content and other specifications from on-road fuels [53]. Refiners and retailers indicate that nearly all DMA is simply re-branded fuel originally manufactured for on-road use, although it may not meet color or other specifications. This is consistent with the observation that distillate marine fuel consumption is approximately 6% of total transportation use of distillate fuels – suppliers simply find it economically unattractive to manufacture, store, and deliver a separate product for marine use [54]. It is also consistent with the finding that, despite regulation, DMA has a sulfur content very similar to that of on-road diesel fuel (about 350 ppm). Thus, the availability and cost of low-sulfur marine fuels will depend on the on-road diesel fuel market.

Based on recent EPA rulemaking, on-road diesel vehicles (cars and trucks, including heavy duty trucks) will have to meet strict new emissions standards beginning in model year 2007.[55]. In order to meet these standards, the EPA simultaneously issued an on-road diesel fuel standard of 15ppm sulfur, down from the existing standard of 500ppm, to take effect in 2006. Off-road fuels would not be directly affected. Cost estimates of this regulation have ranged from about \$0.05 to \$0.10 per gallon, although there is the possibility of price volatility (i.e. spikes) due to supply limitations [45, 55].

California currently regulates on-road diesel formulations to the same sulfur standard, but also limits aromatic content to a maximum of 10% by volume [18, 56]. However CARB is currently considering requiring 15ppm fuel for non-road fuels, including fuels used by vessels that do not typically leave California waters (e.g. captive fleets). Vessels that installed retrofit equipment that included catalysts would almost certainly be required to use such fuel.[23]

Thus, ferries in the Bay Area are extremely likely to use low-sulfur distillate fuels before 2007 regardless of whether or not it is needed to facilitate the installation of catalyst air emission control devices, and they may be required to do so. Currently, and in the near term, however, low-sulfur fuel commands a cost premium of about 6 cents.

Other costs may accompany the use of low-sulfur fuel, the most important of which may be increased engine oil costs. Engine oils are selected to match the fuel type as well as engine

[22] Standards such as those issued by the International Maritime Organization focus on heavy fuels called "bunkers," which cannot be burned in the high-speed engines used by passenger ferries.

[23] This information was obtained by phone conversations with various CARB staff. This requirement may be accompanied by a requirement to retrofit existing captive fleets to meet EPA Tier 2 standards.

parameters, and low-sulfur diesel fuels may require the removal of some lubricity additives to match pH.[24] Solutions exist, such as the addition of biodiesel, which has good lubrication qualities and satisfactory chemistry, but they are typically expensive. On the other hand, cleaner fuels may reduce engine component wear or require reduced maintenance. Currently, no estimates of these costs are available in the open literature.

The cost of fuels purchased by ferry operators in the Bay Area has ranged from $0.95 to $1.07 per gallon over the last year.[25] Based on these values, a cost of $1.08 ($8.4/Million BTU) is assumed for 15 ppm fuel.

The use of CNG as a marine fuel is new, but it has increased recently as well, beginning with the first application in Australia in 1982 [57].[26] Although the National Academy of Sciences identified this potential over 20 years ago, there has been little development in the United States [58]. An LNG shrimp boat was operated on the Gulf of Mexico out of Alabama between 1987 and 1990[27], and one CNG ferry operates on the Elizabeth River in Virginia in a 20-minute round-trip river crossing service during the tourist season.[28] More CNG powered vessels are in use in Canada, Europe, and elsewhere. The dual-fuel ferries *Klatawa* and *Kulleet* have carried both automobiles (capacity 26) and passengers (capacity 150) in Canada since 1985 for the Albion Fraser River service.[29] The *Glutra* is a 100-car, 300-passenger ferry powered by LNG providing 35-minute round-trip service at 12 kts in Norway [59]. A number of smaller natural gas powered ferries also operate in Europe. One of the major marine engine manufacturers, Wartsila NSD claims that, "A shipping industry operating completely on liquefied natural gas is a technical possibility today. How fast this possibility becomes a reality is a question of the driving forces" [60]. The firm has sold over 100 dual-fuel engines, mostly for stationary offshore applications (i.e. petroleum production platforms), which have over 65,000 cumulative operating hours. To date, however, there are no applications of natural gas as fast ferry fuel.

Other research and development

Several related, but less relevant studies have also been conducted. The U.S. Coast Guard (USCG) has conducted some research aimed at developing emissions measurement devices and protocols for shipboard use, monitoring USCG cutters, and evaluating the carcinogenic emissions from marine diesel engines [61, 62]. Satisfactory performance was found using commercially available emissions monitoring technologies onboard various ships, and cutter emissions were measured at slightly lower levels (10 g/kW-hr) than those estimated by EPA. Natural gas was found to reduce emissions. Most carcinogenic compounds in diesel exhaust gas were found to come from the lubricating oil consumed during vessel operations. Ceramic-coated engine parts were found to substantially reduce carcinogenic emissions.

In Europe, at least one high-speed ferry application of SCR has been put into service [63]. This installation uses a Siemens SINOx SCR system with four Ruston 20RK270 engines of

[24] Some transit operators currently use 30ppm sulfur fuel without lubricity problems.

[25] Personal communication with ferry operators.

[26] This excludes LNG tankers, which utilize tank boil-off as a fuel and have been in service since the 1960s.

[27] See http://www.hurricane.net/~chrism/LNG.htm for more information

[28] See http://sites.netscape.net/frnkcol/NORFOLK.htm for more information

[29] See http://www.ohwy.com/bc/m/mintfras.htm and http://www.marinedesign.net for more information

7,080kW each, propelling a 700-passenger ferry at 35 kt. Each engine uses about 85 liters per hour of urea as the reagent, which reduces NO_X emissions about 90%. Factory tests showed an exhaust rate below 2 g/kW-hr, which is well below the value required by the EPA for Tier 2 emissions (7.2 g/kW-hr of NO_X +HC is the relevant standard). This performance approaches that of low-emission CNG engines certified for on-road use as part of California's Carl Moyer program (see www.arb.ca.gov/msprog/moyer/certs.htm). In another application, Wartsila NSD claims it will be able to use steam injection to reduce NO_X emissions to below 3 g/kW-hr. while increasing engine efficiency by 8% [60].

b) Methodology

All of the studies reviewed above use an "activity-based" methodology for estimating emissions, which is the method most widely recommended for this purpose [20]. This study will use the same approach, but provides more detailed and specific data. In this approach, simplified load duration curves are constructed for three vessels based on their actual level of service found in route and vessel data published in the *National Ferry Database* and obtained from survey forms completed by vessel operators. Manufacturers engine specifications are then used to determine power production (in kW-hr) and fuel consumption for each point on the load curve, and daily totals are calculated. The fuel consumption calculation is checked against actual consumption figures reported by operators. Engineering adjustments are made to ensure data validity. The daily power production values are then multiplied by the emissions factors for the various engines to yield daily emissions.

This approach differs from previous work on ferry emissions in that it does not attempt to develop a measure of emissions per passenger since 1) such calculations for transit modes are entirely dependent on ridership, 2) the relevant measure for meeting air quality goals is total mass emissions ('what the environment sees'), and 3) distances traveled by commuters on ferries and those taking alternate trips can vary greatly, as can total emissions on other modes. Rather than looking at vessels as devices that have some fixed emission rate per passenger, it is more illuminating to look at each vessel as part of a system that supplies mobility and has mass emissions levels independent of ridership. One can then investigate how mass emissions (or emission rates) for various combinations of technologies and ridership compare. Costs are easier to compare this way as well.

This study models the replacement of existing uncontrolled diesel engines installed onboard a specific vessel in real service with several potential emissions control technologies. This modeling is conducted for three different vessels. The landside analysis includes an estimate of the emissions created by trips that would be taken by ferry passengers if they had to commute by on-road modes.[30] Thus, the study provides estimates of the (kg/day) created by the segment of the commute trips currently served by the each of the three ferries, and which can be eliminated through ferry ridership, under a series of alternative technology scenarios. The study also allows the determination of the ridership needed to make any given set of land and waterside technologies equivalent in terms of emissions. This approach has the great advantage of showing what (if any) differences in route, vessel, and available alternative modes have on the air quality impacts of passenger ferry service.

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Emissions of six compounds are reported: the criteria pollutants nitrogen oxides (NO_X), hydrocarbons (HC), particulate matter (PM) and carbon monoxide (CO), as well as sulfur dioxide (SO_2), and carbon dioxide (CO_2). In this study PM implies coarse atmospheric particles (greater than 10 microns in diameter). Emissions factors for the four criteria pollutants are developed from the literature and applied to the load curves developed for each vessel to get total pollutants (daily and annual). For SO_2 and CO_2, a different approach is used. Essentially all of the exhaust emissions of these pollutants come from the sulfur and carbon content of the fuel, which can be easily determined. Therefore engine-specific data is not needed.

c) Data

The data gathered for this study comes from a wide array of sources. This includes marine-specific data for emissions and emissions control devices as well as data developed for engines similar to those used onboard passenger ferries but in other applications – such as "heavy, heavy duty on-road," off-road, industrial, and locomotive engines. Data was gathered from published sources (both peer-reviewed and trade literature), government emission certification reports, presentations by manufacturers and other vendors, and direct contact with the relevant firms. Data was gathered from both domestic U.S. and European sources. In many cases, careful analysis was required to understand how to apply the data and insights from these sources, since reporting conditions typically vary a great deal from one study to another.

A key conclusion that emerges directly from the data collection and analysis is that although none of the low-emission technologies examined for this study are commercially available in the U. S. for passenger ferries, all of them are currently in use in other transportation modes and no serious impediments to commercialization for passenger ferry applications currently exist.[31] This is to be expected; unless they improve overall performance, the invention and use of environmental control technologies always follows regulation, they doesn't precede regulation [64, 65]. As a result, governments have often developed "technology-forcing" environmental regulation, sometimes accompanied by market incentives for innovation, to which industry has typically responded successfully (if reluctantly at first). Thus, three trends can be expected: the costs and performance of the technologies described here will improve, new emissions control technologies will become available, and ferry engineers, builders, and operators will learn how to incorporate low-emission technologies into their standard practices. Even though marine propulsion is a relatively small and only recently regulated segment of the transportation sector, it uses engines that are closely related to engines long regulated in both stationary and transportation applications. Therefore, these improvements are likely to be rapid as lessons from other sectors spill over.

Another result of the scant and varied data currently available is that considerable uncertainty is associated with even the current and near-term performance of passenger ferry propulsion and emission control technologies. All technologies considered in this report are technically feasible, especially given the existing applications on other types of ships and in demanding on-road applications, where many current marine technologies were first applied.[32]

[31] The U.S. Coast Guard will have to approve the use of these technologies, of course, but their documented safety onboard European ferries and in other transportation applications should aid their approval. "Commercialized" means available for sale through the usual channels and under standard business conditions.

[32] Several potentially successful technologies were not investigated further in this analysis due to their developmental stage being even earlier than those which are included in this analysis. For instance, NO_X

Nonetheless, uncertainty currently extends across many dimensions – emissions rates, costs, design and operational challenges, and durability, to name the most important – and an exhaustive analysis over all these conditions is beyond the scope of the present analysis.

Marine propulsion and emission control technologies

In this study we examine a number of options for the use of internal combustion engines for propulsion of passenger ferries. Other technologies exist that could possibly power ferries in the future, or under different conditions other than those we are evaluating, but we do not consider these here. Renewable energy sources for marine transportation have attracted some interest. However such technologies cannot currently meet the requirements of the ferry services considered here.[33] Similarly, fuel cells are a possibility in the future and an active research program on marine applications of fuel cells is underway, but they are too far from commercialization to be examined here [51].

Marine NO_X emissions can be reduced through primary and/or secondary control mechanisms. Primary methods affect the engine process directly, and can reduce emissions by 10 to 50 percent. In-engine modifications or adding water to air intake are examples of primary control mechanisms. Secondary methods typically use equipment that is not integrally part of the engine itself to reduce emissions without changing optimal engine performance settings. [66]. Selective catalytic reduction technology (SCR) or catalyst-based diesel particulate filters (CB-DPF) are two examples of secondary control mechanisms.

An alternative taxonomy is based on the relative position of control measures in the combustion process. Control measures can occur at the pre-combustion stage, the combustion stage, or the post-combustion stage. Strategies that aim to modify fuel-air mixtures or pressures, for example, are considered pre-combustion strategies. Strategies that focus on engine modification, such as injection timing retard or engine derating, are considered combustion strategies. Finally, "end-of-pipe" strategies such as SCR or CB-DPF are considered post-combustion. This second classification system is used in the discussion below.

Existing Engines

In order to conduct a comparative analysis among control options, we identify a baseline for each of the vessels under study. The baseline is defined by the existing engines installed onboard each of the vessels. For the two smaller vessels, we apply emission factors based on existing data for marine diesel engines, relying on values determined by the EPA for existing engines in this size category [67]. For the largest vessel, we use engine test data provided by the operator.

EPA Tier 2

For most of the scenarios we investigate, we assume EPA Tier 2 engines are installed onboard the vessels. Tier-2-compliant engines typically require no emission control devices. Emissions are assumed to equal the standard set for these engines. This regulation includes a

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adsorbers have considerable potential for marine applications, but available data and discussions with vendors indicated more research and development is needed before they could be compared to the technologies considered here.

[33] For instance, the Solar Sailor is designed to operate under sail, solar-photoelectric, and propane engine power but it carries only 100 people (http://www.solarsailor.com). More importantly, it has a top speed of 7.5 knots under combined optimal sail and solar-photoelectric power, whereas the ferry services described here require 15-30+ knot capabilities in all weather conditions and at night. Even under propane engine power, it attains only 12 knots. Thus renewably-powered ferries are not considered in this study.

NO_X+HC standard. Based on available test data, we assume NO_X makes up 90% of engine exhaust, and HC compounds make up 10%.

EPA Tier 2 with Humid Air Motor

One pre-combustion method for reducing emissions is through a humid air motor (HAM). This device adds water to the air intake, thereby cooling the intake air. This cooling increases intake air density and lowers the charge-air temperature. Both of these factors act to reduce the peak combustion temperature and NO_X emissions.

Water injection into the air system (also referred to as fumigation) is easier to implement than water/fuel emulsions discussed next; however, fumigation can cause corrosion of engine parts and adversely impact water quality [44, 68]. Currently, the use of a HAM requires increased water distillation capacity and storage to supply up to 4,000 gallons of water per day. In addition, water quality requirements are expected to require either a two-pass reverse osmosis (RO) or a waste heat distillation system to be appended to the system. While the RO system is larger than the waste heat system, average values for the space and weight requirements of 38 m^3 and 19,000 kg, respectively, are used here to get an order-of-magnitude requirement [69]. This includes volume and mass for a separate day-tank for distilled water storage.

A benefit of this technology is that the percent of water injected into the intake air can be varied to achieve various levels of NO_X reduction. However, smoke and PM emissions may increase, and a nominal fuel penalty of 3% can be expected [70]. Reports indicate that NO_X reductions can range from 5% to 60% [68, 70-72]; an average value of 28% is used here.

EPA Tier 2 with Injection Timing Delay

One combustion control measure studied here is that of "injection timing delay." Reducing the pressure at auto-ignition by retarding the timing of fuel injection will lower the peak flame temperature and reduce NO_X; however, it also results in higher fuel consumption [66, 73]. This is one of the simplest control strategies to implement, particularly on marine propulsion engines with electronic controls that allow the operator to “dial in” the injection timing without engine shut down [74]. Space and weight requirements for this technology are negligible. NO_X reductions ranging between 10% and 30% are reported, with an average reported reduction of 19% [66, 73-76]. Fuel penalties are estimated to result in about a 4% increase, and increases in PM, hydrocarbons and carbon monoxide have been reported [77].

EPA Tier 2 with Catalyst-Based Diesel Particulate Filter

A post-combustion control technology that could possibly reduce PM emissions on marine vessels by more than 90% is the catalyst-based diesel particulate filter (CB-DPF). CB-DPFs are essentially advanced particulate traps that employ catalysts to passively regenerate the PM trap.[34]

Passive regeneration involves using a catalyst in the PM trap itself that can enhance the oxidation of PM by lowering the PM oxidation temperature to a value close to exhaust emission temperatures.[35] Most CB-DPF systems that are active in stationary and mobile systems are

[34] A PM trap consists of a filter positioned in the exhaust stream that is designed to collect diesel particulates as the exhaust is forced through the filter. A number of filtering materials have been tested including ceramic monoliths and woven fibers, woven silica fiber coils, ceramic foam, wire mesh, and sintered metal substrates. These collected particles have to be removed from the filter in order to prevent excessively high exhaust gas pressure drops that could adversely effect engine operation. Therefore, all PM trap systems must be equipped with a method for periodically or continuously "regenerating" the filters to restore their soot collection capacity.

[35] In *active* regeneration, mechanisms (such as electric heaters or fuel burners) are used to elevate the temperature of the exhaust gas. These mechanisms introduce additional hardware and fuel consumption costs, and can ultimately

capable of regeneration at temperatures of approximately 250° Celsius *if appropriately low sulfur diesel fuel is used*. These systems have demonstrated an ability to reduce the mass of PM emissions by greater than 90%, as well as reduce HC and CO emissions by 90%. The effect of CB-DPF on NO_X emissions is negligible, although some studies have identified reductions on the order of 1-10%. There is typically a fuel penalty of approximately 1% for these systems [18, 25, 78-80].[36]

Although CB-DPF systems have been successfully employed in stationary and mobile systems, there is very little experience in the marinization of such systems for ferry operations. CB-DPF manufacturers are only now testing their systems in marine applications and it is difficult to precisely predict the emissions and cost impacts of these systems. However, some believe that recent industry and regulatory initiatives will instigate the advancement of this technology so that it is market ready within several years [25] [55]. We use emissions reduction estimates based on these early market studies.

EPA Tier 2 with Selective Catalytic Reduction

Another post-combustion control strategy used primarily for NO_X reductions is selective catalytic reduction (SCR). SCR is currently used for stationary diesel engines and some prototypes have been developed for mobile heavy-duty applications.[37] SCR uses ammonia or urea as a reducing agent for NO_X over a catalyst composed of precious metals and base metals. SCR provides the greatest reductions in NO_X emissions of any of the technologies discussed above, and marine application of this technology has been the focus of considerable interest [7, 66, 68, 71, 81-83]. Catalytic reactions with ammonia or urea reduce the oxidized nitrogen to nitrogen gas according the following reactions:

For ammonia catalyst:

$$4\ NO + 4\ NH_3 + O_2 \rightarrow 4\ N_2 + 6\ H_2O \qquad (1)$$

$$6\ NO_2 + 8\ NH_3 \rightarrow 7\ N_2 + 12\ H_2O \qquad (2)$$

And for urea catalyst:

$$6NO + 2(NH_2)_2CO \rightarrow 5N_2 + 4H_2O + 2CO_2 \qquad (3)$$

$$6NO_2 + 4(NH_2)_2CO \rightarrow 7N_2 + 8H_2O + 4CO_2 \qquad (4)$$

Successful SCR installation onboard passenger ferries faces several challenges. Safety approval from the U.S. Coast Guard will be needed (largely due to the need to carry ammonia onboard). They will also take up valuable space onboard, as will the reagent storage.

Although both types of catalyst systems have been installed on marine vessels, urea may be favored because it is non-toxic and biologically harmless, and can be transported without

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fail resulting in exhaust stream plugging, runaway regeneration at high temperatures, trap melting, and engine stalling. For this reason, we do not consider active regeneration traps for this study.

[36] Additional information was gathered from emission control device manufacturers (Johnson-Mathey and Clean Air Systems) through personal communication.

[37] About 18 HD truck demonstrations have occurred since 1995 and over 20 marine vessel demonstrations since the mid-1990s (MECA, 2000).

problems. Installation of SCR systems imposes additional space and weight requirements, with an average of 33 m^3 and 3,100 kg reported taken from various reports in the literature cited above. However, Wartsila NSD has been developing a "compact SCR" system that equals the size of and replaces current silencer systems installed aboard ships [84].

Reported NO_X reductions can be as high as 98%, although the reduction at lower engine loads can be as low as 57% [66]. SCR tests of on-road heavy-duty diesel vehicles have demonstrated NO_X reductions in the range of 65 to 99% over steady-state conditions, with 77% reductions over the heavy-duty transient FTP [43]. An average of 81% from reported values is used here as the nominal NO_X reduction for SCR. In some applications, SCR have also reduced HC and CO by 50%-90%, while also reducing PM by 30-40% [25, 78, 85, 86].[38] While SCR does not increase fuel consumption and can be installed on engine systems using high-sulfur residual fuel, the technology involves the consumption of ammonia or urea. Catalyst consumption rates equal about 2% of the fuel consumption (about 16 kg/h of operation) [66, 83].

Natural Gas

A different approach is to replace distillate fuel with compressed natural gas (CNG), which necessitates replacement of the fuel system and changing (or modifying) the engine design. Numerous heavy-duty on-road natural gas engines are currently in use today. For instance about 3,500 transit buses in the United States currently use natural gas, and 20% or more of all buses on order will be powered by natural gas. A growing number of trucks and buses are also making use of liquefied natural gas (LNG), as are a few ferries in Europe, so LNG might also be appropriate fuel for high-speed ferries.

Heavy-duty natural gas engines are currently produced by most manufacturers and have been used onboard both oceangoing ships and passenger ferries for over a decade [87]. Interest in low-emission heavy-duty vehicles in recent years has led to the development of extremely clean natural gas engines for such applications. While marine natural gas engines are currently offered by several engine manufacturers, emission data is not yet available for them. However, following the EPA's line of reasoning that marine engines are derived from existing engine lines, certification data for heavy-heavy-duty on-road and for non-road natural gas engines are used as a guide to the performance of marine natural gas engines. In particular, the certification heaviest-duty engines that have been certified under the Carl Moyer program are used as representative of the emissions of larger models produced by the same manufacturers. For simplicity, the tables in this report indicates HC (hydrocarbons) as one of the categories of emission, but for natural gas engines, only non-methane hydrocarbons are reported. This is appropriate for the purposes of this study, since methane does not contribute to the formation of ozone or particulate matter.[39]

In estimating the cost of CNG engines, this analysis includes the additional cost of the engines themselves, as well as the cost of the fuel system (high-pressure storage tanks and piping) and of a methane detection system that meets U.S. Coast Guard standards. Cost data was assembled by reviewing the costs of existing CNG ferries (a limited set of somewhat unrepresentative vessels) and through discussions with appropriate vendors. Fuel costs were

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[38] Additional information was gathered from Siemens and Johnson-Mathey, two SCR vendors through telephone and fax communication.

[39] See, for example, "Control of Emissions of Air Pollution from New Marine Compression-Ignition Engines at or above 37kW: Final Rule" USEPA (64FR73300): December 29, 1999 at IV.E page 73308, which establishes NO_X+NMHC standards for natural-gas fueled, diesel-cycle marine engines.

estimated by discussing pricing with current large compressed CNG customers in California and elsewhere, and with potential suppliers in the Bay Area. CNG prices are assumed to be $1.40/gallon gasoline equivalent ($12.3/Million BTU).[40] This price is ten cents (about 7%) higher than the retail price of marine CNG fuel in British Columbia, suggesting the cost to that operator is about $1.20/gallon gasoline equivalent [88]. Of course, prices for natural gas are particularly low in Canada, and recent price volatility in natural gas, especially in California, creates considerable uncertainty about the best estimate of future fuel prices for CNG ferries.[41]

Engine efficiency is important, but little data is available. In general, spark-ignited engines are inherently less efficient than compression-ignition engines, but improved designs of recent models of natural gas engines have narrowed this difference to only a few percent.[42] These advances, in addition to the re-tuning of compression ignition engines that will be required to achieve the correct exhaust gas chemistry for proper catalytic control of emissions make the differences in efficiency very hard to judge, but likely very small. Thus, they are ignored here.

Vessel operations

All commute ferry vessels in the Bay Area have similar patterns of use; heavy ridership towards San Francisco in a few morning rush hour departures, followed by relatively low ridership mi-day (often reduced service is offered), followed by a somewhat more spread out peak of commuters traveling back from San Francisco during the afternoon and evening rush hour [26]. During peak hours, ferries are full (or nearly so) in one direction and virtually empty in the other. At other times, ferry usage is low, in some cases limited by parking lots that were filled by commuters that parked and boarded in the morning, or by a lack of transit opportunities at the non-San Francisco end of the trip. The system perspective taken in this study makes these patterns somewhat irrelevant; each of the three ferries is assumed to operate the same no matter what ridership is. The three different vessels analyzed in this study are described below.

Summary

The tables and figure below summarizes the engine, emission control device, and ferry service data developed for this study. Tables 10, 11, and 12 contain the performance and cost data used in this study for each of the technologies. Capital costs for CNG engines include an increased cost for maintenance, which varies by the size of the vessel.

Table 13 and Figure 1 show the emission rates for each of the technologies.[43] A few observations immediately stand out. First, some technologies have *higher* emissions than existing and Tier 2 engines for a few pollutants, most notably CO. The higher emissions

[40] The gallon gasoline equivalent may seem like an odd unit here, but it is frequently used in the natural gas industry. The $/Million BTU figures should be used for comparison.

[41] The Energy Information Agency reports a considerable discount in fuel costs for natural gas a vehicle fuel in California as $4 to $ 6 per Million BTU, but these data represent prices for fuel delivered *to* the fueling station, and often for gas company fleets, so they do not account for the cost of compression, for profit, or for taxes, and thus are inappropriate for comparison here [89].

[42] The main engineering changes have been to develop micro-pilot technologies that use enriched fuel chambers or a tiny amount of diesel fuel to start ignition, allowing a temperature and pressure profile similar to a compression-ignition engine.

[43] SO_X and CO_2 emissions vary only very slightly among technologies, and will be discussed in the Results section below.

estimates for HC from Tier 2 engines arise due to the assumption that to meet the new EPA standards, engine manufacturers will change marine engine performance to more closely match the performance of on-road truck engines, which have higher HC emissions. Second, the technologies can be put into two categories, those that offer only modest NO_X emission reductions (Tier 2, Tier 2 + ITD, Tier 2 + HAM, Tier 2 + CF) and those that offer NO_X emission reductions above 50% (Tier 2 + SCR, Tier 2 + SCR + CF, and CNG). Similarly, only three technologies offer PM emission reductions significantly above 50% (Tier 2 + CF, Tier 2 + SCR + CF, and CNG). For all pollutants, emissions are lowest from a Tier 2 engine equipped with both an SCR and a CF.

Table 10: Engine Emission Rates (g/kWh)

	NO_X	HC	PM	CO
DDC 16V149	13	0.27	0.30	2.5
MTU 16V396	7.92	0.308	0.0886	0.804
Tier 2 Engines	6.48	0.72	0.2	5.0
CNG*	1.31	.34	.02	11.59

* LNG-fueled engines would have similar emission rates.

Table11: Emission Control Device Performance (percent change)

	NO_X	HC	CO	PM
HAM	-28%	-1%	-1%	-1%
ITD*	-19%	11%	11%	11%
CF	-3%	-92%	-85%	-90%
SCR	-80%	-75%	-75%	-40%
SCR+CF	-81%	-98%	-96%	-94%

* Positive values (shaded) indicate increases in emissions

Table 12: Emission Control Device Costs

	Capital Cost ($/kW)	Operating Cost (non-fuel, $/kW-yr.)	Fuel Penalty
HAM	32	1	3%
ITD	0	1	4%
CF	20	18	1%
SCR	71	20	2%*
SCR+CF	91	38	3%*
CNG	165 - 202	0	30%**

* Includes a 2% penalty that models reagent (urea) costs
** Cost penalty based on differential in fuel prices: MDA $1.08/gallon, CNG $1.40/gge.

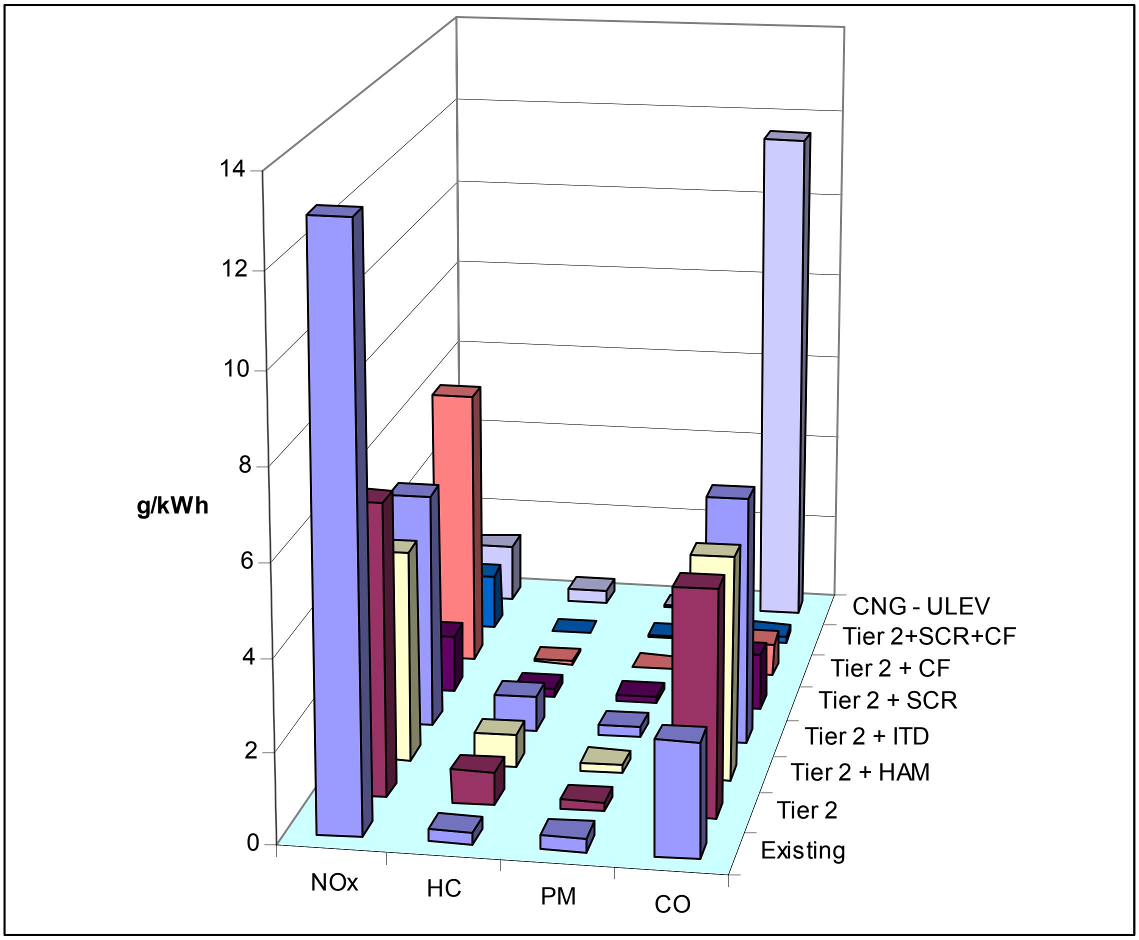

Figure 1: Emission Rates for Engine and Emission Control Device Combinations

Table 13: Emission Rates for Engine and Emission Control Device Combinations (g/kWh)

	NO_X	HC	CO	PM
Existing	13	0.27	0.30	2.5
Tier 2	6.5	0.72	0.20	5.0
Tier 2 + HAM	4.7	0.71	0.20	5.0
Tier 2 + ITD	5.2	0.80	0.22	5.6
Tier 2 + SCR	1.3	0.18	0.14	1.3
Tier 2 + CF	6.3	0.06	0.02	0.75
Tier 2+SCR+CF	1.3	0.01	0.01	0.19
CNG	1.3	0.34	0.02	12

* LNG-fueled engines would have similar emission rates.

Table 14 contains the basic vessel and weekday ferry service data that was used in this study. Every effort was made to model actual ferry service, but some operations are quite variable and a precise match could not be made. Further information about travel to the ferries is found in the landside part of the report.

Table 14: Passenger Ferry Service (Weekday)

	Hull Type	Engines	Distance (mi)	Avg. Speed (kts)	Hours/day
Larkspur	Monohull	DDC 16V149	11	16	14
Alameda/ Oakland	Catamaran	DDC 16V149	13	17.5	15
Vallejo	Catamaran	MTU 16V396	25	28	11

d) Results

This section contains the results of the analysis described above for all three ferry service conditions in terms of total emissions, total costs, and cost effectiveness. Although estimated from the best data available, emissions from these vessels have not been measured and actual emissions may (will) differ from these estimates. Therefore, limited weight should be placed on the absolute values presented, although the relative emissions between vessels and reduction technologies are considered to be reliable and provide greater insight.

Emissions

Total emissions and emissions reductions (from the existing engines) are reported for each vessel in daily (kg/day) and annual (tons/yr). Only annual emissions are reported for CO_2 emissions. All data is reported to two significant digits, the maximum justifiable precision. Tables 15A, 15B, and 15C contain data for the respective vessels. Uncertainties in the data could change these values by 20% or more. Note that the percent reductions reported in these tables are from a baseline of the existing engines, which includes reductions both due to cleaner Tier 2 engines *and* the effect of emission control devices. Thus, they are greater than the values reported in Table 10, which are for the emission control devices only.

Looking across the technologies, several observations emerge:

- The use of Tier 2 engines accounts for most of the NO_X emissions reductions and some of the PM emissions reductions shown.
- When added to Tier 2 engines, SCR and CF technologies alone can produce significant emissions reductions of some criteria pollutants.
- The combination of Tier 2 engines with SCR and CF technologies produces the greatest emissions reductions, achieving at least 90% reduction of all criteria pollutants from existing engines.
- Vessels equipped with CNG engines that have emissions performance similar to those of heavy duty on-road engines certified under California's Carl Moyer program have very low emissions of NO_X and PM, but have higher HC and CO emissions.

- The choice of technology has little effect on SO_2 emissions, which are dominated by the switch to low-sulfur fuel that will occur in the passenger ferry sector regardless of technology choice.
- The choice of emission control device has very little effect on CO_2 emissions, which are due to small changes in engine efficiency. Changing fuel to CNG or LNG could reduce CO_2, particularly if advanced high pressure direct injection technology was used. This emerging technology appears to offer to use natural gas and provide diesel like efficiency.

Table 15A: Vessel A Emissions

Daily Emissions (kg)	NO_X	HC	PM	CO	SO_X	CO_2
Existing	414	9	9.5	80	0.65	13,000
Tier 2	206	23	6.4	159	0.12	13,000
Tier 2 + HAM	148	23	6.3	158	0.12	13,000
Tier 2 + ITD	167	25	7.1	177	0.12	13,000
Tier 2 + SCR	41	5.7	4.5	40	0.12	13,000
Tier 2 + CF	200	1.8	0.64	24	0.12	13,000
Tier 2+SCR+CF	40	0.46	0.45	6.0	0.12	13,000
CNG	42	11	0.59	369	0.05	9,600
Daily Change (kg)*	**NO_X**	**HC**	**PM**	**CO**	**SO_X**	**CO_2**
Tier 2	-210	14	-3.2	80	-0.53	0
Tier 2 + HAM	-270	14	-3.2	78	-0.53	380
Tier 2 + ITD	-250	17	-2.5	97	-0.53	500
Tier 2 + SCR	-370	-2.9	-5.1	-40	-0.53	0
Tier 2 + CF	-210	-6.8	-8.9	-56	-0.53	130
Tier 2+SCR+CF	-370	-8.1	-9.1	-74	-0.53	130
CNG	-370	2.1	-9.0	290	-0.59	-2,900
Annual Emissions (tons)	**NO_X**	**HC**	**PM**	**CO**	**SO_X**	**CO_2**
Existing	69	1.4	1.6	13	2.4	4,700
Tier 2	34	3.8	1.1	26	0.044	4,700
Tier 2 + HAM	25	3.8	1.0	26	0.044	4,700
Tier 2 + ITD	28	4.2	1.2	29	0.044	4,900
Tier 2 + SCR	7	1.0	0.7	7	0.044	4,700
Tier 2 + CF	33	0.30	0.11	4.0	0.044	4,700
Tier 2+SCR+CF	7	0.08	0.07	1.0	0.044	4,700
CNG	7	1.8	0.10	61	0.021	3,600
Annual Change (tons)*	**NO_X**	**HC**	**PM**	**CO**	**SO_X**	CO_2
Tier 2	-34	2.4	-0.5	13	-2.4	0
Tier 2 + HAM	-44	2.3	-0.5	13	-2.4	140
Tier 2 + ITD	-41	2.8	-0.4	16	-2.4	190
Tier 2 + SCR	-62	-0.5	-0.8	-7	-2.4	0
Tier 2 + CF	-36	-1.1	-1.5	-9	-2.4	47
Tier 2+SCR+CF	-62	-1.4	-1.5	-12	-2.4	47
CNG	-62	0.4	-1.5	48	-2.4	-1,100
Percent Change*	**NO_X**	**HC**	**PM**	**CO**	**SO_X**	**CO_2**
Tier 2	-50%	167%	-33%	100%	-98%	0%
Tier 2 + HAM	-64%	164%	-34%	98%	-98%	3%
Tier 2 + ITD	-60%	196%	-26%	122%	-98%	4%
Tier 2 + SCR	-90%	-33%	-53%	-50%	-98%	0%
Tier 2 + CF	-52%	-79%	-93%	-70%	-98%	1%
Tier 2+SCR+CF	-90%	-95%	-95%	-93%	-98%	1%
CNG	-90%	25%	-94%	363%	-99%	-23%

* Relative to existing engines. Positive values (shaded) indicate an increase in emissions.

Note: LNG-fueled vessels would have similar emission results to those shown for CNG.

Table 15B: Vessel B Emissions

Daily Emissions (kg)	NO_X	HC	PM	CO	SO_X	CO_2
Existing	430	8.9	9.9	82	0.60	12,000
Tier 2	210	24	6.6	170	0.11	12,000
Tier 2 + HAM	150	23	6.5	170	0.11	12,000
Tier 2 + ITD	170	26	7.3	180	0.11	12,000
Tier 2 + SCR	43	5.9	4.6	41	0.11	12,000
Tier 2 + CF	210	1.9	0.66	25	0.11	12,000
Tier 2+SCR+CF	41	0.47	0.46	6.2	0.11	12,000
CNG	43	11	0.62	380	0.051	8,900
Daily Change (kg)*	NO_X	HC	PM	CO	SO_X	CO_2
Tier 2	-220	15	-3.3	82	-0.49	0
Tier 2 + HAM	-270	15	-3.4	81	-0.49	350
Tier 2 + ITD	-260	17	-2.6	100	-0.49	470
Tier 2 + SCR	-390	-3.0	-5.3	-41	-0.49	0
Tier 2 + CF	-220	-7.0	-9.2	-58	-0.49	120
Tier 2+SCR+CF	-390	-8.4	-9.4	-76	-0.49	120
CNG	-390	2.2	-9.3	300	-0.55	-2,700
Annual Emissions (tons)	NO_X	HC	PM	CO	SO_X	CO_2
Existing	58	1.2	1.3	11	2.3	4,400
Tier 2	29	3.2	0.89	22	0.041	4,400
Tier 2 + HAM	21	3.2	0.88	22	0.041	4,500
Tier 2 + ITD	23	3.5	0.98	25	0.041	4,500
Tier 2 + SCR	5.7	0.80	0.62	5.5	0.041	4,400
Tier 2 + CF	28	0.26	0.089	3.3	0.041	4,400
Tier 2+SCR+CF	5.6	0.06	0.062	0.8	0.041	4,400
CNG	5.8	1.5	0.083	51	0.019	3,300
Annual Change (tons)*	NO_X	HC	PM	CO	SO_X	CO_2
Tier 2	-29	2.0	-0.44	11	-2.2	0
Tier 2 + HAM	-37	2.0	-0.45	11	-2.2	130
Tier 2 + ITD	-34	2.3	-0.35	14	-2.2	170
Tier 2 + SCR	-52	-0.40	-0.71	-5.5	-2.2	0
Tier 2 + CF	-30	-0.94	-1.2	-7.8	-2.2	44
Tier 2+SCR+CF	-52	-1.1	-1.3	-10	-2.2	44
CNG	-52	0.29	-1.2	40	-2.2	-1,000
Percent Change*	NO_X	HC	PM	CO	SO_X	CO_2
Tier 2	-50%	167%	-33%	100%	-98%	0%
Tier 2 + HAM	-64%	164%	-34%	98%	-98%	3%
Tier 2 + ITD	-60%	196%	-26%	122%	-98%	4%
Tier 2 + SCR	-90%	-33%	-53%	-50%	-98%	0%
Tier 2 + CF	-52%	-79%	-93%	-70%	-98%	1%
Tier 2+SCR+CF	-90%	-95%	-95%	-93%	-98%	1%
CNG	-90%	25%	-94%	363%	-99%	-23%

* Relative to existing engines. Positive values (shaded) indicate an increase in emissions.

Note: LNG-fueled vessels would have similar emission results to those shown for CNG.

Table 15C: Vessel C Emissions

Daily Emissions (kg)	NO_X	HC	PM	CO	SO_X	CO_2
Existing	910	19	21	180	1.4	28,000
Tier 2	450	50	14	350	0.26	28,000
Tier 2 + HAM	330	50	14	350	0.26	29,000
Tier 2 + ITD	370	56	16	390	0.26	29,000
Tier 2 + SCR	90	13	9.8	87	0.26	28,000
Tier 2 + CF	440	4.0	1.4	52	0.26	28,000
Tier 2+SCR+CF	88	1.0	0.98	13	0.26	28,000
CNG	91	24	1.3	810	0.12	21,000
Daily Change (kg)*	**NO_X**	**HC**	**PM**	**CO**	**SO_X**	**CO_2**
Tier 2	-460	31	-7.0	175	-1.2	0
Tier 2 + HAM	-580	31	-7.1	171	-1.2	830
Tier 2 + ITD	-540	37	-5.5	213	-1.2	1,100
Tier 2 + SCR	-820	-6.3	-11	-87	-1.2	0
Tier 2 + CF	-470	-15	-20	-122	-1.2	280
Tier 2+SCR+CF	-820	-18	-20	-162	-1.2	280
CNG	-820	4.6	-20	635	-1.3	-6,500
Annual Emissions (tons)	**NO_X**	**HC**	**PM**	**CO**	**SO_X**	**CO_2**
Existing	87	1.8	2.0	17	5.1	9,800
Tier 2	44	4.8	1.3	34	0.092	9,800
Tier 2 + HAM	31	4.8	1.3	33	0.092	10,000
Tier 2 + ITD	35	5.4	1.5	37	0.092	10,000
Tier 2 + SCR	8.7	1.2	0.94	8.4	0.092	9,800
Tier 2 + CF	42	0.39	0.13	5.0	0.092	9,900
Tier 2+SCR+CF	8.5	0.10	0.09	1.3	0.092	9,900
CNG	8.8	2.3	0.13	78	0.043	7,500
Annual Change (tons)*	**NO_X**	**HC**	**PM**	**CO**	**SO_X**	**CO_2**
Tier 2	-44	3.0	-0.67	17	-5.0	0
Tier 2 + HAM	-56	3.0	-0.69	16	-5.0	290
Tier 2 + ITD	-52	3.6	-0.52	21	-5.0	390
Tier 2 + SCR	-79	-0.6	-1.1	-8.4	-5.0	0
Tier 2 + CF	-45	-1.4	-1.9	-12	-5.0	98
Tier 2+SCR+CF	-79	-1.7	-1.9	-16	-5.0	98
CNG	-79	0.45	-1.9	61	-5.0	-2,300
Percent Change*	**NO_X**	**HC**	**PM**	**CO**	**SO_X**	**CO_2**
Tier 2	-50%	167%	-33%	100%	-98%	0%
Tier 2 + HAM	-64%	164%	-34%	98%	-98%	3%
Tier 2 + ITD	-60%	196%	-26%	122%	-98%	4%
Tier 2 + SCR	-90%	-33%	-53%	-50%	-98%	0%
Tier 2 + CF	-52%	-79%	-93%	-70%	-98%	1%
Tier 2+SCR+CF	-90%	-95%	-95%	-93%	-98%	1%
CNG	-90%	25%	-94%	363%	-99%	-23%

* Relative to existing engines. Positive values (shaded) indicate an increase in emissions.

Note: LNG-fueled vessels would have similar emission results to those shown for CNG.

Costs

Total costs for each of the technologies is reported in Tables 16A, 16B, and 16C. Rather than re-estimate the costs of Tier 2 engines, which the EPA has already completed in detail for its Regulatory Impact Assessment, the values developed by the EPA are used here. Thus, only the incremental costs for each of the emission control devices and for the use of CNG are shown in Tables 16A, 16B, and 16C. Capital costs include the expenses associated with purchasing and installing the equipment. Operating costs include additional maintenance and service associated with the emission control devices, which do not vary with use. Fuel costs include any fuel penalty associated with the technology, along with the costs of catalyst and reagent (e.g. urea), which do vary with use. Capital costs for the CNG infrastructure is included in the fuel cost, using typical costs for large transit applications. For the natural gas engines, reduced maintenance has been reported in other applications (including the Albion ferry system [68]), but no credit is given here due to uncertainty. Instead, the cost of additional service is included in the capital figures for the CNG option, based on discussions with vendors. LNG would change these values, probably reducing total costs, but no effort is made to estimate them.

The costs shown in Tables 16A, 16B, and 16C are uncertain due to fact that none of these systems have been installed on a passenger ferry in the United States yet. There is little experience with them in the shipbuilding industry or in the U.S. Coast Guard. Design and manufacturing challenges, and safety requirements for new technologies help drive up the costs for early units. Therefore, the costs presented below will likely decline after the first several vessels have been outfitted.

The costs and cost structures of the technologies vary greatly; HAM, ITD and CF have relatively low capital costs, SCR has moderately high capital costs, and CNG engines have very high capital costs. Catalysts and reagent are also quite expensive, as is CNG relative to 15ppm sulfur marine diesel fuel. While inherently uncertain, it seems likely that the decline in capital costs for the CNG engines will be greater than the decline for emission control devices as there are significant one-time engineering costs that are included in the estimates for CNG engines given below. With experience, the capital costs of emissions control technologies might decline by 20% or so, while the capital cost of CNG engines may decline by as much as 40%. Capital costs for refueling infrastructure is included in the fuel costs.

The net present value (NPV) of each of the technologies is also shown in Tables 10A, 10B, and 10C, based on a 15 year life and a 7% discount rate. 15 years is a typical operating life for a passenger ferry engine, and 7% is a typical rate used for the analysis of public policy questions, such as emission control. The highest NPV costs are for Tier 2 + SCR + CF and for CNG, which are essentially the same for all three vessels. 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. 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 NPV of the CNG option is more sensitive to reductions in the capital cost (which might occur due to experience in manufacturing or through the application of a subsidy program) since it is the most capital-intensive technology.

Table 16A: Larkspur Costs

	Capital	Annual Operating	Annual Fuel	NPV (15 yrs, 7%)
Tier 2	*None*	*None*	*None*	*None*
Tier 2 + HAM	$71,000	$1,400	$13,000	$210,000
Tier 2 + ITD	$0	$1,600	$17,000	$180,000
Tier 2 + SCR	$160,000	$45,000	$8,400	$680,000
Tier 2 + CF	$45,000	$40,000	$4,200	$480,000
Tier 2+SCR+CF	$200,000	$85,000	$13,000	$1,200,000
CNG	$450,000	$0	$120,000	$1,700,000

Table 16B: Alameda/Oakland Costs

	Capital	Annual Operating	Annual Fuel	NPV (15 yrs, 7%)
Tier 2	*None*	*None*	*None*	*None*
Tier 2 + HAM	$76,000	$1,500	$13,000	$220,000
Tier 2 + ITD	$0	$2,000	$18,000	$190,000
Tier 2 + SCR	$170,000	$48,000	$9,000	$720,000
Tier 2 + CF	$48,000	$43,000	$4,500	$510,000
Tier 2+SCR+CF	$220,000	$91,000	$13,000	$1,200,000
CNG	$400,000	$0	$130,000	$1,700,000

Table 16C: Vallejo Costs

	Capital	Annual Operating	Annual Fuel	NPV (15 yrs, 7%)
Tier 2	*None*	*None*	*None*	*None*
Tier 2 + HAM	$128,000	$2,500	$28,000	$430,000
Tier 2 + ITD	$0	$2,900	$38,000	$390,000
Tier 2 + SCR	$280,000	$80,000	$19,000	$1,300,000
Tier 2 + CF	$79,000	$72,000	$9,400	$870,000
Tier 2+SCR+CF	$360,000	$150,000	$28,000	$2,100,000
CNG	$660,000	$0	$280,000	$3,400,000

Tables 17A, 17B, and 17C show the cost-effectiveness of each of the technologies for each vessel and service considered against the baseline of the existing engines. Cost-effectiveness in terms of reductions compared to landside emissions are *not* considered here. These values are the NPV of each technology divided by the cumulative emissions reductions expected over the 15-year life of the technologies. The entire cost of each technology is used for each calculation, so the values are *not* additive. The cost effectiveness for each pollutant should be evaluated individually. In cases where emissions increased, no value is shown.

Table 17A: Larkspur Cost Effectiveness ($/ton)

	NO_X	HC	PM	CO	SO2	CO2
Existing	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*
Tier 2*	$185	*N/A*	$8,600	*N/A*	*N/A*	*N/A*
Tier 2 + HAM	$760		$47,000		$9,600	
Tier 2 + ITD	$720		$53,000		$8,300	
Tier 2 + SCR	$1,500	$170,000	$98,000	$13,000	$31,000	
Tier 2 + CF	$1,800	$52,000	$39,000	$6,000	$22,000	
Tier 2+SCR+CF	$2,500	$100,000	$93,000	$12,000	$54,000	
CNG	$3,300		$140,000		$76,000	$170

*Values taken from EPA Regulatory Impact Assessment
Blanks indicate an increase or no change in emissions.

Table 17B: Alameda/Oakland Cost Effectiveness ($/ton)

	NO_X	HC	PM	CO	SO2	CO2
Existing	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*
Tier 2*	$185	*N/A*	$8,600	*N/A*	*N/A*	*N/A*
Tier 2 + HAM	$700		$42,000		$9,600	
Tier 2 + ITD	$670		$48,000		$8,300	
Tier 2 + SCR	$1,400	$156,000	$88,000	$11,000	$31,000	
Tier 2 + CF	$1,700	$47,000	$35,000	$5,700	$22,000	
Tier 2+SCR+CF	$2,200	$94,000	$84,000	$10,000	$53,000	
CNG	$2,800		$120,000		$73,000	$160

*Values taken from EPA Regulatory Impact Assessment
Blanks indicate an increase or no change in emissions.

Table 17C: Vallejo Cost Effectiveness ($/ton)

	NO_X	HC	PM	CO	SO2	CO2
Existing	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*
Tier 2*	$185	*N/A*	$8,600	*N/A*	*N/A*	*N/A*
Tier 2 + HAM	$1,000		$64,000		$8,800	
Tier 2 + ITD	$1,000		$77,000		$8,100	
Tier 2 + SCR	$1,800	$210,000	$120,000	$15,000	$26,000	
Tier 2 + CF	$2,200	$63,000	$48,000	$7,600	$18,000	
Tier 2+SCR+CF	$2,900	$130,000	$110,000	$14,000	$44,000	
CNG	$4,400		$180,000		$69,000	$150

*Values taken from EPA Regulatory Impact Assessment
Blanks indicate an increase or no change in emissions.

Both the numerator and denominator in the cost-effectiveness calculations are quite uncertain, so these values are only relative approximations of the actual costs of achieving emissions reductions. Nonetheless, some robust observations can be made:

- Installing Tier 2 engines are the most cost-effective means of reducing marine emissions reductions.
- Relative to other source categories, the cost of controlling NO_X and PM from marine engines is low on a dollar-per-ton basis for all the technologies examined here, especially for Tier 2, HAM and ITD technologies.
- The cost effectiveness of these technologies are sensitive to the discount rate, the cost of CNG fuel, capital costs, and may be affected by improvements in emissions control performance. In particular, even relatively reductions in the price of CNG can improve the cost effectiveness of that option significantly.

IV) Net Emissions Comparison For All Technologies

This section summarizes the waterside emissions results with respect to emissions and costs for the seven ferry engine technologies compared to the existing baseline conditions. Following that summary is a discussion of how the landside analysis affects the overall performance of the different engine scenarios studied for the three San Francisco Bay Area case study areas, Larkspur, Alameda/Oakland and Vallejo. As a reminder, these are the ferry engines that were studied, and the abbreviations used in the text below:

1. Existing engines (engine size and fuel type used currently at Larkspur, Alameda/Oakland and Vallejo)
2. EPA Tier 2 "Clean Diesel"
3. EPA Tier 2 + HAM (Humid Air Motor)
4. EPA Tier 2 + ITD (Injection Timing Delay)
5. EPA Tier 2 + CF (Catalyst Filter)
6. EPA Tier 2 + SCR (Selective Catalytic Reduction)
7. EPA Tier 2 + CF + SCR (with both Catalyst Filter and Selective Catalytic Reduction)
8. CNG (Compressed Natural Gas engine)

With respect to the emission rates for each of the technologies, a few observations immediately stand out. First, some technologies have *higher* emissions than existing and Tier 2 engines for a few pollutants, most notably CO. The higher emissions estimates for HC (also called ROG in California) from Tier 2 engines arise due to the assumption that to meet the new EPA standards, engine manufacturers will change marine engine performance to more closely match the performance of on-road truck engines, which have higher HC emissions. Second, the technologies can be put into two categories, those that offer only modest NO_X emission reductions (Tier 2, Tier 2 + ITD, Tier 2 + HAM, Tier 2 + CF) and those that offer NO_X emission reductions above 50% (Tier 2 + SCR, Tier 2 + SCR + CF, and CNG). Similarly, only three technologies offer PM emission reductions significantly above 50% (Tier 2 + CF, Tier 2 + SCR + CF, and CNG). For all pollutants, emissions are lowest from a Tier 2 engine equipped with both an SCR and a CF.

a) Results

This section contains the results of the assessment of all three-ferry service conditions in terms of total emissions, cost effectiveness of ferry engines in reducing pollutants, and net emissions results when landside commute trips eliminated are included in the analysis. Although estimated from the best data available, emissions from these vessels have not been measured and actual emissions may (will) differ from these estimates. Therefore, limited weight should be placed on the absolute values presented, although the relative emissions between vessels and reduction technologies are considered to be more reliable and provide greater insights.

Net Emission Comparisons (Including Landside Emissions Avoided)

This section provides the most significant findings when the landside and waterside analyses are compiled. Again, it must be stated that a study at this level of detail provides results that offer the most value in comparison with one another, rather than on an absolute basis. However, it is useful to note that the results presented here are largely in agreement with previous and ongoing research by others. This permits considerable confidence that the broad implications drawn here are reliable, even though the specific values calculated for various parameters are uncertain, and are, as we have indicated, subject to interpretation in many areas.

Looking at the net emission results (that is, ferry engine emissions minus the eliminated landside commute emissions associated with the most likely level of ridership (50%) across all three cases studied) the following observations can be made:

- As in the analysis of ferry engine performance in isolation, the inclusion of avoided emissions shows that the most promising scenario from an emissions perspective is the Tier 2 + SCR + CF engine. In the Larkspur and Alameda/Oakland cases, all pollutants except NOx are significantly improved.
- With the exception of NOx emissions, and NOx and CO for CNG engines, Tier 2 + SCR, Tier 2 + CF, Tier 2 + SCR + CF and CNG engines all represent an improvement in net emissions for Larkspur and Alameda/Oakland.
- In the Vallejo example, NOx and CO_2 are both worsened for all four best performing scenarios listed above; the five worst performers resulted in increased emissions for all pollutants. This is due in large part to the lower percentage of landside emissions avoided in the Vallejo case (more ferry patrons were pulled from transit, or reported making no trip at all.)
- Relative results (between the three sites studied) illustrate how sensitive any analysis is to such landside factors as mode split among local commuters, and variations in landside commute distances.
- Variations in key factors such as ferry trip length, home to terminal options, and alternative on-land commute options make simple extrapolations of these results to other locations difficult and unlikely to provide useful insights.

By looking at the emission control device performance and the land and water comparisons provided in this study, an interesting observation can be made. In general, only those technologies that show a *greater than 90% reduction in emissions* relative to current engines allow air pollution from passenger ferry systems to approximate those from on-road transportation modes providing a similar level of service. This result makes sense in light of the fact that on-road transportation modes (especially the automobile) have become extremely clean in the last decade, with emissions reduction levels (relative to direct engine exhaust) of 98% or more. Given the very tight on-road diesel engine standards that heavy-duty vehicles will have to meet in the next few years, it is not surprising to find that similar performance will be needed in the marine sector in order to show comparable emissions profiles under similar service conditions. It is also important to keep in mind that on-road vehicle fleets will be progressively reducing landside emissions after 2007, as ferry engine technology develops.

The variation across the vessel and service types has two implications. First, although it is difficult to have much confidence in average estimates of emissions across different situations, the broad patterns observed here are likely to be repeated in most applications. Second, because ridership is so important in the land/water comparison, the best outcome for the environment may well be a passenger ferry system that is both clean *and* full. It will be important to continued to explore options to reduce cold starts, perhaps by providing natural gas shuttles that can be dispatched on demand by commuters, electric station cars, parking disincentives, etc, where appropriate.

Induced (or, latent) transportation demand (i.e. the fact that transportation system expansion tends to increase transportation system use rather than reduce congestion and associated emissions) suggests the appropriate paradigm for considering passenger ferry system expansion not as competing with existing commute options, but as a complement to on-road travel. Thus, *the proper framework for considering ferry system expansion is balancing competing social and private objectives in transportation system planning and operation, including providing affordable and equitable mobility options, protecting the environment, and providing opportunities for communities to prosper*, rather than reducing total transportation system emissions.

Net Emissions

Table 1, contained in Section II, Landside Assessment, illustrates the steps and the data inputs used to create "Commuter Emissions Factors" in grams-per-ferry-boarding. These factors were used to "load up" the ferry vessels, under different engine technology scenarios, to arrive at net emissions for each engine technology.

Tables 18-25, shown here, give the net emissions for each engine technology using a range of ferry ridership occupancy assumptions: 25%, 50%, 75% and 100%. Current ferry occupancy probably ranges between 25% and 45%, on average, due to the highly directional peak period commute patterns found in the Bay Area. That is, ferries are likely to run full in the peak direction, but nearly empty in the reverse direction, thus reducing peak period occupancy; off-peak occupancy is, on average, lower than peak, by definition.

On Tables 18-25, the columns showing 50% and 75% absolute emissions, net emissions, and each respective scenario's fleet emissions are shaded. Ferry occupancy of 50% is believed to be a reasonable future operating scenario, if operators made modest improvements to service, marketing and feeder bus access services. Ferry occupancy of 75% is a very optimistic goal that represents the ceiling for highly directional commute areas. Ferry occupancy of 100% is included for completeness.

Table 26 provides a summary of net emissions for all engine scenarios, using the most realistic 50% occupancy assumption. The assumption that ferries will operate at an average occupancy rate of 50% represents a modest-to-significant increase over current ferry ridership levels. Such levels, although unattainable today, could come about with a focused effort to increase ferry utilization through the use of auxiliary facilities (feeder buses, timed transfers, park and ride lots, etc.) and services (guaranteed seating, marketing and educational programs, efforts to increase cross-commute ridership, etc.) that would combine to boost average ridership.

Shaded areas in the cells on Table 26 represent *increases* in net emissions from the landside commute alternative.

Table 27 shows the same data for a zero-induced demand case.

Table 18: 2001 Fleet (Existing) Ferry Engine Emissions, Net Of Avoided Landside VMT-Related Emissions For Three Bay Area Cases

	Criteria pollutants	Per boarding commuter emissions profile factor (grams per boarding)	Daily commute emissions avoided at 25% ferry occupancy (kg)	Commute emissions avoided at 50% ferry occupancy (kg)	50% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 75% ferry occupancy (kg)	75% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 100% ferry occupancy (kg)	Existing fleet daily emissions (kg)	Impact at 50% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 50 % occupancy and 30% induced demand factor	Impact at 75% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 75 % occupancy and 30% induced demand factor
Larkspur-SF													
Service A Ferry	HC	4.79	10.67	21.33	14.93	32.00	22.40	42.67	8.9	-6.03	-40%	-13.50	-60%
12 Daily departures	NOx	5.09	11.33	22.67	15.87	34.00	23.80	45.34	428	412.13	2597%	404.20	1698%
	PM 10	4.65	10.36	20.71	14.50	31.07	21.75	41.43	9.9	-4.60	-32%	-11.85	-54%
	CO 2	4902.02	10911.90	21823.80	15276.66	32735.70	22914.99	43647.60	11622	-3654.66	-24%	-11292.99	-49%
	CO	52.12	116.01	232.02	162.41	348.03	243.62	464.03	82	-80.41	-50%	-161.62	-66%
Alameda/Oakland – SF													
Service B Ferry	HC	4.28	9.13	18.25	12.78	27.38	19.17	36.51	9	-3.78	-30%	-10.17	-53%
22 daily departures	NOx	4.54	9.70	19.39	13.58	29.09	20.36	38.79	414	400.42	2950%	393.64	1933%
	PM 10	4.15	8.86	17.72	12.40	26.58	18.61	35.44	9.5	-2.90	-23%	-9.11	-49%
	CO 2	4374.81	9335.84	18671.69	13070.18	28007.53	19605.27	37343.38	12523	-547.18	-4%	-7082.27	-36%
	CO	46.51	99.25	198.51	138.95	297.76	208.43	397.01	80	-58.95	-42%	-128.43	-62%
Vallejo-SF													
Service C Ferry	HC	5.73	5.15	10.31	7.22	15.46	10.82	20.62	19	11.78	163%	8.18	76%
12 Daily departures	NOx	6.09	5.48	10.95	7.67	16.43	11.50	21.91	909	901.33	11755%	897.50	7803%
	PM 10	5.56	5.00	10.01	7.01	15.01	10.51	20.02	21	13.99	200%	10.49	100%
	CO 2	5,858.61	5272.75	10545.50	7381.85	15818.25	11072.77	21091.00	27691	20309.15	275%	16618.23	150%
	CO	62.29	56.06	112.11	78.48	168.17	117.72	224.23	175	96.52	123%	57.28	49%

Table 19: Tier 2 Ferry Engine Emissions, Net Of Avoided Landside VMT-Related Emissions For Three Bay Area Cases													
	Criteria pollutants	Per boarding commuter emissions profile factor (grams per boarding)	Daily commute emissions avoided at 25% ferry occupancy (kg)	Commute emissions avoided at 50% ferry occupancy (kg)	50% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 75% ferry occupancy (kg)	75% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 100% ferry occupancy (kg)	Existing fleet daily emissions (kg)	Impact at 50% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 50 % occupancy and 30% induced demand factor	Impact at 75% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 75 % occupancy and 30% induced demand factor
Larkspur-SF													
Service A Ferry	HC	4.79	10.67	21.33	14.93	32.00	22.40	42.67	24	9.07	61%	1.60	7%
12 Daily departures	NOx	5.09	11.33	22.67	15.87	34.00	23.80	45.34	213	197.13	1242%	189.20	795%
	PM 10	4.65	10.36	20.71	14.50	31.07	21.75	41.43	6.6	-7.90	-54%	-15.15	-70%
	CO 2	4902.02	10911.90	21823.80	15276.66	32735.70	22914.99	43647.60	11622	-3654.66	-24%	-11292.99	-49%
	CO	52.12	116.01	232.02	162.41	348.03	243.62	464.03	165	2.59	2%	-78.62	-32%
Alameda/Oakland – SF													
Service B Ferry	HC	4.28	9.13	18.25	12.78	27.38	19.17	36.51	23	10.22	80%	3.83	20%
22 daily departures	NOx	4.54	9.70	19.39	13.58	29.09	20.36	38.79	206	192.42	1417%	185.64	912%
	PM 10	4.15	8.86	17.72	12.40	26.58	18.61	35.44	6.4	-6.00	-48%	-12.21	-66%
	CO 2	4374.81	9335.84	18671.69	13070.18	28007.53	19605.27	37343.38	12523	-547.18	-4%	-7082.27	-36%
	CO	46.51	99.25	198.51	138.95	297.76	208.43	397.01	159	20.05	14%	-49.43	-24%
Vallejo-SF													
Service C Ferry	HC	5.73	5.15	10.31	7.22	15.46	10.82	20.62	50	42.78	593%	39.18	362%
12 Daily departures	NOx	6.09	5.48	10.95	7.67	16.43	11.50	21.91	453	445.33	5808%	441.50	3839%
	PM 10	5.56	5.00	10.01	7.01	15.01	10.51	20.02	14	6.99	100%	3.49	33%
	CO 2	5,858.61	5272.75	10545.50	7381.85	15818.25	11072.77	21091.00	27691	20309.15	275%	16618.23	150%
	CO	62.29	56.06	112.11	78.48	168.17	117.72	224.23	350	271.52	346%	232.28	197%

Table 20: Tier 2 + HAM Ferry Engine Emissions, Net Of Avoided Landside VMT-Related Emissions For Three Bay Area Cases

	Criteria pollutants	Per boarding commuter emissions profile factor (grams per boarding)	Daily commute emissions avoided at 25% ferry occupancy (kg)	Commute emissions avoided at 50% ferry occupancy (kg)	50% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 75% ferry occupancy (kg)	75% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 100% ferry occupancy (kg)	Existing fleet daily emissions (kg)	Impact at 50% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 50 % occupancy and 30% induced demand factor	Impact at 75% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 75 % occupancy and 30% induced demand factor
Larkspur-SF													
Service A Ferry	HC	4.79	10.67	21.33	14.93	32.00	22.40	42.67	23	8.07	54%	0.60	3%
12 Daily departures	NOx	5.09	11.33	22.67	15.87	34.00	23.80	45.34	154	138.13	871%	130.20	547%
	PM 10	4.65	10.36	20.71	14.50	31.07	21.75	41.43	6.5	-8.00	-55%	-15.25	-70%
	CO 2	4902.02	10911.90	21823.79	15276.66	32735.69	22914.98	43647.59	11971	-3305.66	-22%	-10943.98	-48%
	CO	52.12	116.01	232.02	162.41	348.03	243.62	464.03	163	0.59	0%	-80.62	-33%
Alameda/Oakland – SF													
Service B Ferry	HC	4.28	9.13	18.25	12.78	27.38	19.17	36.51	23	10.22	80%	3.83	20%
22 daily departures	NOx	4.54	9.70	19.39	13.58	29.09	20.36	38.79	148	134.42	990%	127.64	627%
	PM 10	4.15	8.86	17.72	12.40	26.58	18.61	35.44	6.3	-6.10	-49%	-12.31	-66%
	CO 2	4374.81	9335.84	18671.69	13070.18	28007.53	19605.27	37343.38	12898	-172.18	-1%	-6707.27	-34%
	CO	46.51	99.25	198.51	138.95	297.76	208.43	397.01	158	19.05	14%	-50.43	-24%
Vallejo-SF													
Service C Ferry	HC	5.73	5.15	10.31	7.22	15.46	10.82	20.62	50	42.78	593%	39.18	362%
12 Daily departures	NOx	6.09	5.48	10.95	7.67	16.43	11.50	21.91	326	318.33	4152%	314.50	2734%
	PM 10	5.56	5.00	10.01	7.01	15.01	10.51	20.02	14	6.99	100%	3.49	33%
	CO 2	5,858.61	5272.75	10545.50	7381.85	15818.25	11072.77	21091.00	28521	21139.15	286%	17448.23	158%
	CO	62.29	56.06	112.11	78.48	168.17	117.72	224.23	346	267.52	341%	228.28	194%

Table 21: Tier 2 + ITD Ferry Engine Emissions, Net Of Avoided Landside VMT-Related Emissions For Three Bay Area Cases													
	Criteria pollutants	Per boarding commuter emissions profile factor (grams per boarding)	Daily commute emissions avoided at 25% ferry occupancy (kg)	Commute emissions avoided at 50% ferry occupancy (kg)	50% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 75% ferry occupancy (kg)	75% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 100% ferry occupancy (kg)	Existing fleet daily emissions (kg)	Impact at 50% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 50 % occupancy and 30% induced demand factor	Impact at 75% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 75 % occupancy and 30% induced demand factor
Larkspur-SF													
Service A Ferry	HC	4.79	10.67	21.33	14.93	32.00	22.40	42.67	26	11.07	74%	3.60	16%
12 Daily departures	NOx	5.09	11.33	22.67	15.87	34.00	23.80	45.34	173	157.13	990%	149.20	627%
	PM 10	4.65	10.36	20.71	14.50	31.07	21.75	41.43	7.3	-7.20	-50%	-14.45	-66%
	CO 2	4902.02	10911.90	21823.80	15276.66	32735.70	22914.99	43647.60	11971	-3305.66	-22%	-10943.99	-48%
	CO	52.12	116.01	232.02	162.41	348.03	243.62	464.03	183	20.59	13%	-60.62	-25%
Alameda/Oakland - SF													
Service B Ferry	HC	4.28	9.13	18.25	12.78	27.38	19.17	36.51	25	12.22	96%	5.83	30%
22 daily departures	NOx	4.54	9.70	19.39	13.58	29.09	20.36	38.79	167	153.42	1130%	146.64	720%
	PM 10	4.15	8.86	17.72	12.40	26.58	18.61	35.44	7.1	-5.30	-43%	-11.51	-62%
	CO 2	4374.81	9335.84	18671.69	13070.18	28007.53	19605.27	37343.38	12898	-172.18	-1%	-6707.27	-34%
	CO	46.51	99.25	198.51	138.95	297.76	208.43	397.01	177	38.05	27%	-31.43	-15%
Vallejo-SF													
Service C Ferry	HC	5.73	5.15	10.31	7.22	15.46	10.82	20.62	56	48.78	676%	45.18	417%
12 Daily departures	NOx	6.09	5.48	10.95	7.67	16.43	11.50	21.91	367	359.33	4686%	355.50	3091%
	PM 10	5.56	5.00	10.01	7.01	15.01	10.51	20.02	16	8.99	128%	5.49	52%
	CO 2	5,858.61	5272.75	10545.50	7381.85	15818.25	11072.77	21091.00	28521	21139.15	286%	17448.23	158%
	CO	62.29	56.06	112.11	78.48	168.17	117.72	224.23	388	309.52	394%	270.28	230%

Table 22: Tier 2 + SCR Ferry Engine Emissions, Net Of Avoided Landside VMT-Related Emissions For Three Bay Area Cases

	Criteria pollutants	Per boarding commuter emissions profile factor (grams per boarding)	Daily commute emissions avoided at 25% ferry occupancy (kg)	Commute emissions avoided at 50% ferry occupancy (kg)	50% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 75% ferry occupancy (kg)	75% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 100% ferry occupancy (kg)	Existing fleet daily emissions (kg)	Impact at 50% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 50 % occupancy and 30% induced demand factor	Impact at 75% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 75 % occupancy and 30% induced demand factor
Larkspur-SF													
Service A Ferry	HC	4.79	10.67	21.33	14.93	32.00	22.40	42.67	5.9	-9.03	-60%	-16.50	-74%
12 Daily departures	NOx	5.09	11.33	22.67	15.87	34.00	23.80	45.34	43	27.13	171%	19.20	81%
	PM 10	4.65	10.36	20.71	14.50	31.07	21.75	41.43	4.6	-9.90	-68%	-17.15	-79%
	CO 2	4902.02	10911.90	21823.79	15276.66	32735.69	22914.98	43647.59	11971	-3305.66	-22%	-10943.98	-48%
	CO	52.12	116.01	232.02	162.41	348.03	243.62	464.03	41	-121.41	-75%	-202.62	-83%
Alameda/Oakland – SF													
Service B Ferry	HC	4.28	9.13	18.25	12.78	27.38	19.17	36.51	5.7	-7.08	-55%	-13.47	-70%
22 daily departures	NOx	4.54	9.70	19.39	13.58	29.09	20.36	38.79	41	27.42	202%	20.64	101%
	PM 10	4.15	8.86	17.72	12.40	26.58	18.61	35.44	4.5	-7.90	-64%	-14.11	-76%
	CO 2	4374.81	9335.84	18671.69	13070.18	28007.53	19605.27	37343.38	12898	-172.18	-1%	-6707.27	-34%
	CO	46.51	99.25	198.51	138.95	297.76	208.43	397.01	40	-98.95	-71%	-168.43	-81%
Vallejo-SF													
Service C Ferry	HC	5.73	5.15	10.31	7.22	15.46	10.82	20.62	13	5.78	80%	2.18	20%
12 Daily departures	NOx	6.09	5.48	10.95	7.67	16.43	11.50	21.91	91	83.33	1087%	79.50	691%
	PM 10	5.56	5.00	10.01	7.01	15.01	10.51	20.02	9.8	2.79	40%	-0.71	-7%
	CO 2	5,858.61	5272.75	10545.50	7381.85	15818.25	11072.77	21091.00	28521	21139.15	286%	17448.23	158%
	CO	62.29	56.06	112.11	78.48	168.17	117.72	224.23	87	8.52	11%	-30.72	-26%

Table 23: Tier 2 + CF Ferry Engine Emissions, Net Of Avoided Landside VMT-Related Emissions For Three Bay Area Cases

	Criteria pollutants	Per boarding commuter emissions profile factor (grams per boarding)	Daily commute emissions avoided at 25% ferry occupancy (kg)	Commute emissions avoided at 50% ferry occupancy (kg)	50% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 75% ferry occupancy (kg)	75% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 100% ferry occupancy (kg)	Existing fleet daily emissions (kg)	Impact at 50% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 50 % occupancy and 30% induced demand factor	Impact at 75% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 75 % occupancy and 30% induced demand factor
Larkspur-SF													
Service A Ferry	HC	4.79	10.67	21.33	14.93	32.00	22.40	42.67	1.9	-13.03	-87%	-20.50	-92%
12 Daily departures	NOx	5.09	11.33	22.67	15.87	34.00	23.80	45.34	207	191.13	1205%	183.20	770%
	PM 10	4.65	10.36	20.71	14.50	31.07	21.75	41.43	0.66	-13.84	-95%	-21.09	-97%
	CO 2	4902.02	10911.90	21823.80	15276.66	32735.70	22914.99	43647.60	11971	-3305.66	-22%	-10943.99	-48%
	CO	52.12	116.01	232.02	162.41	348.03	243.62	464.03	25	-137.41	-85%	-218.62	-90%
Alameda/Oakland - SF													
Service B Ferry	HC	4.28	9.13	18.25	12.78	27.38	19.17	36.51	1.8	-10.98	-86%	-17.37	-91%
22 daily departures	NOx	4.54	9.70	19.39	13.58	29.09	20.36	38.79	200	186.42	1373%	179.64	882%
	PM 10	4.15	8.86	17.72	12.40	26.58	18.61	35.44	0.64	-11.76	-95%	-17.97	-97%
	CO 2	4374.81	9335.84	18671.69	13070.18	28007.53	19605.27	37343.38	12898	-172.18	-1%	-6707.27	-34%
	CO	46.51	99.25	198.51	138.95	297.76	208.43	397.01	24	-114.95	-83%	-184.43	-88%
Vallejo-SF													
Service C Ferry	HC	5.73	5.15	10.31	7.22	15.46	10.82	20.62	4	-3.22	-45%	-6.82	-63%
12 Daily departures	NOx	6.09	5.48	10.95	7.67	16.43	11.50	21.91	439	431.33	5625%	427.50	3717%
	PM 10	5.56	5.00	10.01	7.01	15.01	10.51	20.02	1.4	-5.61	-80%	-9.11	-87%
	CO 2	5,858.61	5272.75	10545.50	7381.85	15818.25	11072.77	21091.00	28521	21139.15	286%	17448.23	158%
	CO	62.29	56.0	112.1	78.4	168.17	117.7	224.2	52	-26.48	-34%	-65.72	-56%

Table 24: Tier 2 + SCR + CF Ferry Engine Emissions, Net Of Avoided Landside VMT-Related Emissions For Three Bay Area Cases

	Criteria pollutants	Per boarding commuter emissions profile factor (grams per boarding)	Daily commute emissions avoided at 25% ferry occupancy (kg)	Commute emissions avoided at 50% ferry occupancy (kg)	50% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 75% ferry occupancy (kg)	75% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 100% ferry occupancy (kg)	Existing fleet daily emissions (kg)	Impact at 50% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 50 % occupancy and 30% induced demand factor	Impact at 75% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 75 % occupancy and 30% induced demand factor
Larkspur-SF													
Service A Ferry	HC	4.79	10.67	21.33	14.93	32.00	22.40	42.67	0.47	-14.46	-97%	-21.93	-98%
12 Daily departures	NOx	5.09	11.33	22.67	15.87	34.00	23.80	45.34	41	25.13	158%	17.20	72%
	PM 10	4.65	10.36	20.71	14.50	31.07	21.75	41.43	0.46	-14.04	-97%	-21.29	-98%
	CO 2	4902.02	10911.90	21823.80	15276.66	32735.70	22914.99	43647.60	11971	-3305.66	-22%	-10943.99	-48%
	CO	52.12	116.01	232.02	162.41	348.03	243.62	464.03	6.2	-156.21	-96%	-237.42	-97%
Alameda/Oakland – SF													
Service B Ferry	HC	4.28	9.13	18.25	12.78	27.38	19.17	36.51	0.46	-12.32	-96%	-18.71	-98%
22 daily departures	NOx	4.54	9.70	19.39	13.58	29.09	20.36	38.79	40	26.42	195%	19.64	96%
	PM 10	4.15	8.86	17.72	12.40	26.58	18.61	35.44	0.45	-11.95	-96%	-18.16	-98%
	CO 2	4374.81	9335.84	18671.69	13070.18	28007.53	19605.27	37343.38	12898	-172.18	-1%	-6707.27	-34%
	CO	46.51	99.25	198.51	138.95	297.76	208.43	397.01	6	-132.95	-96%	-202.43	-97%
Vallejo-SF													
Service C Ferry	HC	5.73	5.15	10.31	7.22	15.46	10.82	20.62	1	-6.22	-86%	-9.82	-91%
12 Daily departures	NOx	6.09	5.48	10.95	7.67	16.43	11.50	21.91	88	80.33	1048%	76.50	665%
	PM 10	5.56	5.00	10.01	7.01	15.01	10.51	20.02	0.98	-6.03	-86%	-9.53	-91%
	CO 2	5,858.61	5272.75	10545.50	7381.85	15818.25	11072.77	21091.00	28521	21139.15	286%	17448.23	158%
	CO	62.29	56.06	112.11	78.48	168.17	117.72	224.23	13	-65.48	-83%	-104.72	-89%

Table 25: CNG Ferry Engine Emissions, Net Of Avoided Landside VMT-Related Emissions For Three Bay Area Cases													
	Criteria pollutants	Per boarding commuter emissions profile factor (grams per boarding)	Daily commute emissions avoided at 25% ferry occupancy (kg)	Commute emissions avoided at 50% ferry occupancy (kg)	50% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 75% ferry occupancy (kg)	75% occupancy emissions avoided minus 30% induced demand factor (kg)	Commute emissions avoided at 100% ferry occupancy (kg)	Existing fleet daily emissions (kg)	Impact at 50% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 50 % occupancy and 30% induced demand factor	Impact at 75% ferry occupancy w/30% discount for induced demand	% change from landside to ferry use at 75 % occupancy and 30% induced demand factor
Larkspur-SF													
Service A Ferry	HC	4.79	10.67	21.33	14.93	32.00	22.40	42.67	11.1	-3.83	-26%	-11.30	-50%
12 Daily departures	NOx	5.09	11.33	22.67	15.87	34.00	23.80	45.34	47	31.13	196%	23.20	97%
	PM 10	4.65	10.36	20.71	14.50	31.07	21.75	41.43	0.62	-13.88	-96%	-21.13	-97%
	CO 2	4902.02	10911.90	21823.80	15276.66	32735.70	22914.99	43647.60	8904	-6372.66	-42%	-14010.99	-61%
	CO	52.12	116.01	232.02	162.41	348.03	243.62	464.03	381	218.59	135%	137.38	56%
Alameda/Oakland – SF													
Service B Ferry	HC	4.28	9.13	18.25	12.78	27.38	19.17	36.51	11	-1.78	-14%	-8.17	-43%
22 daily departures	NOx	4.54	9.70	19.39	13.58	29.09	20.36	38.79	42	28.42	209%	21.64	106%
	PM 10	4.15	8.86	17.72	12.40	26.58	18.61	35.44	0.59	-11.81	-95%	-18.02	-97%
	CO 2	4374.81	9335.84	18671.69	13070.18	28007.53	19605.27	37343.38	9594	-3476.18	-27%	-10011.27	-51%
	CO	46.51	99.25	198.51	138.95	297.76	208.43	397.01	369	230.05	166%	160.57	77%
Vallejo-SF													
Service C Ferry	HC	5.73	5.15	10.31	7.22	15.46	10.82	20.62	24	16.78	233%	13.18	122%
12 Daily departures	NOx	6.09	5.48	10.95	7.67	16.43	11.50	21.91	91	83.33	1087%	79.50	691%
	PM 10	5.56	5.00	10.01	7.01	15.01	10.51	20.02	1.3	-5.71	-81%	-9.21	-88%
	CO 2	5,858.61	5272.75	10545.50	7381.85	15818.25	11072.77	21091.00	21214	13832.15	187%	10141.23	92%
	CO	62.29	56.06	112.11	78.48	168.17	117.72	224.23	810	731.52	932%	692.28	588%

Note: LNG-fueled vessels would have similar emission results.

Table 26: Net Emission Impacts for all engine and control technology combinations relative to 'no-ferry' scenario, 50% ridership and 30% induced demand.

Shading shows increased emissions

	Pollutants	Current	Tier 2	Tier 2 + HAM	Tier 2 + ITD	Tier 2 + SCR	Tier 2 + CF	Tier 2 + SCR +CF	CNG
Larkspur									
	NOx	2597%	1242%	871%	990%	171%	1205%	158%	196%
	HC	-40%	61%	54%	74%	-60%	-87%	-97%	-26%
	PM 10	-32%	-54%	-55%	-50%	-68%	-95%	-97%	-96%
	CO	-50%	2%	0%	13%	-75%	-85%	-96%	135%
	CO 2	-31%	-31%	-29%	-29%	-29%	-29%	-29%	-47%
Alameda/Oakland									
	NOx	2950%	1417%	990%	1130%	202%	1373%	195%	209%
	HC	-30%	80%	80%	96%	-55%	-86%	-96%	-14%
	PM 10	-23%	-48%	-49%	-43%	-64%	-95%	-96%	-95%
	CO	-42%	14%	14%	27%	-71%	-83%	-96%	166%
	CO 2	-13%	-13%	-10%	-10%	-10%	-10%	-10%	-33%
Vallejo									
	NOx	11755%	5808%	4152%	4686%	1087%	5625%	1048%	1087%
	HC	163%	593%	593%	676%	80%	-45%	-86%	233%
	PM 10	200%	100%	100%	128%	40%	-80%	-86%	-81%
	CO	123%	346%	341%	394%	11%	-34%	-83%	932%
	CO 2	241%	241%	251%	251%	251%	251%	251%	161%

Note: LNG-fueled vessels would have similar emission results to those shown for CNG.

Table 27: Net Emission Impacts for all engine and control technology combinations relative to 'no-ferry' scenario, 50% ridership and zero induced demand.

Shading shows increased emissions

	Pollutants	Current	Tier 2	Tier 2 + HAM	Tier 2 + ITD	Tier 2 + SCR	Tier 2 + CF	Tier 2 + SCR +CF	CNG
Larkspur									
	NOx	1788%	840%	579%	663%	90%	813%	81%	107%
	HC	-58%	12%	8%	22%	-72%	-91%	-98%	-48%
	PM 10	-65%	-2%	-30%	-21%	-82%	-89%	-97%	64%
	CO	-52%	-68%	-69%	-65%	-78%	-97%	-98%	-97%
	CO 2	-47%	-47%	-45%	-45%	-45%	-45%	-45%	-59%
Alameda/Oakland									
	NOx	2035%	926%	663%	761%	111%	931%	106%	117%
	HC	-51%	26%	26%	37%	-69%	-90%	-97%	-40%
	PM 10	-60%	-20%	-20%	-11%	-80%	-88%	-97%	-86%
	CO	-46%	-64%	-64%	-60%	-75%	-96%	-97%	-97%
	CO 2	-33%	-33%	-31%	-31%	-31%	-31%	-31%	-49%
Vallejo									
	NOx	8199%	4036%	2876%	3251%	731%	3908%	703%	731%
	HC	84%	385%	385%	443%	-26%	-61%	-90%	133%
	PM 10	56%	212%	209%	246%	-22%	-54%	-88%	622%
	CO	110%	40%	40%	60%	-2%	-86%	-90%	-87%
	CO 2	163%	163%	170%	170%	170%	170%	170%	101%

Note: LNG-fueled vessels would have similar emission results to those shown for CNG.

V) Reducing Home-to-Ferry Terminal Emissions

This section discusses general factors that influence ferry passengers' decision on what mode to use to access the ferry terminal, which, in turn, affects overall emissions of the ferry mode relative to other modes. The section concludes with an assessment of the emissions impact of a door-to-door shuttle program utilizing zero-emission vehicles, that would be designed to attract and serve 50% of ferry passengers, thereby eliminating trips assumed to be solo drives.

a) Importance of Reducing Home-to-Terminal Emissions

In the Bay Area, adequate ferry demand exists to support increases in service along most routes. Recent survey data shows, specifically, that demand exists to support an expansion of the ferry's mode share for Vallejo-San Francisco trips. The challenge will be to add new ferry patrons while reducing the cold starts and VMT-related emissions associated with the home-to-terminal trip.

This section is focused on ways to reduce emissions caused by vehicles carrying ferry patrons to and from their homes to the ferry terminal. This segment of the commute trip is extremely important not only to reduce overall vehicle miles traveled to access ferry terminals, but also because of the portion of emissions that is associated with each access trip's cold start. Emission factors "per trip" (i.e., cold starts) are included in Section IV, Table 1 to illustrate the relative importance of these emission factors compared to the running emissions factors (the "per-mile" factors.)

Also important to note is that available data on home-to-terminal mode choice suggests that a higher percentage of these trips may involve cold starts than an equal number of home-to-San Francisco trips, although further research would be needed to confirm this pattern. Existing data does indicate, however, that a larger percentage of people drive alone to the ferry parking lot, or are dropped off and picked up by family members, than if the commuter were making the commute entirely by land. The data suggests people are more likely to take buses or trains to final destination rather than using public transit to reach the ferry terminal. Again, however, additional detailed travel behavior data would be required to determine how access to transit stops was made, and how many cold starts were generated as carpool partners joined each other for their daily commute.

The issue of home-to-terminal trip reduction is discussed generally, below, and may be extrapolated to other regions. Trip reduction strategies are often most effective when focused on the regular commute patterns of typical work-related trips; the regularity allows for better provision of transit and auxiliary services designed to reduce solo driving.

b) Transportation Demand Management Strategies for the Home-to-Terminal Transit Service

The success of any ferry operation will depend on the ability to develop and implement effective transportation demand strategies designed to take the load off terminal parking lots, and, from a regional perspective, reduce home-to-terminal trip related congestion and vehicle emissions.

In the case of a clean ferry engine scenario, if a solo driver travels to the terminal only to find a full parking lot, this driver will be forced to return to a landside travel pattern and eliminate the potential emission and congestion reductions that would have occurred had a space been available. Where additional parking can be developed at the terminal, expansion of parking spaces for ferry patrons is, of course, an option that can be exercised at the expense of increased vehicle emissions. As is evident in the Baylink situation, however, adding free or low-cost subsidized parking capacity will tend to encourage continued or expanded solo-drives from home to ferry terminal. Therefore, from a mobility and air quality perspective, the optimal strategy is to eliminate the auto trip *to* the terminal by developing services and facilities designed to support high-occupancy travel modes from home to ferry terminal. This can be accomplished in several ways, and can include the types of services tested by the Golden Gate Bridge Highway and Transportation District among Larkspur Ferry patrons:

- Door-to-Dock Service (bus stops within 500 feet of rider's doorstep)
- Guaranteed Boarding of Ferry (all shuttle bus customers will be guaranteed a place on the ferry)
- Reduced One-Way Ferry Fare (all shuttle bus customers will receive a reduced one-way ferry fare to San Francisco)
- Guaranteed Ride Home (customized shuttle bus service that meets every peak commute period ferry arrival)
- Frequent User Program (customers receive benefits for riding shuttle bus a specified number of times)

Additional potential emission reduction strategies could include:

- Electric car sharing programs whereby participants would participate on a subscription basis and be charged on a per-use or per mile basis. The small electric cars could be used for home to terminal and terminal to home trips. With valet service, the vehicles could be parked close together and make better use of existing parking facilities. (This option is discussed in more detail on the next page.)
- Demand responsive clean fuel shuttle van service somewhat similar to the shared ride service at airports
- Automated electric bike and scooter rental facilities for short distances
- Proper siting, quantity and quality of park and ride lots for commuters residing at a distance from the terminal
- Improved feeder bus service, utilizing clean fuel or zero-emission vehicles, and providing reliable, convenient service, using HOV lanes, timed transfers, real-time/next bus technologies (impacts of an intensive zero emission shuttle program are discussed in Section V(c) below)
- Amenities located at the terminal to reduce the need for a car to run personal errands (retail opportunities, centralized delivery lockers such as Delivery Node, e.g.)
- Effective marketing of service
- Employer incentives to use transit

Increasing the costs (measured in time or money) associated with landside commute behavior (e.g., market-rate parking at destination; tolls; congestion on the competing route; unavailability of HOV lanes, bus or rail transit alternatives).

The rapid growth of car sharing services in the United States suggests this might be an important factor in the expansion of ferry commute services. Urban communities face rapid growth in traffic and parking congestion as well as continuing concerns about poor air quality. The only long-term strategy for solving all these problems is to find alternatives to private automobile travel. Clean car sharing represents one such strategy, combining flexibility and convenience of the private automobile with mass transit. Conventional car sharing is already available in Portland, Seattle, Washington D.C., New York and Boston.

Electric car sharing represents the next step in car sharing. The California Air Resources Board's zero emission vehicle (ZEV) mandate is creating significant momentum in California and a number of automobile manufacturers are launching electric vehicles into the market which are ideally suited for car sharing applications. The ZEV mandate actually provides added incentives for electric vehicles to be used in car sharing systems.

Car sharing provides some important benefits to transit agencies and consumers. Typically one shared vehicle can service up to 30 individuals, greatly reducing the need for parking spaces at a transit station. Shared vehicle also enable greater use of mass transit by providing a means for individuals to travel to and from a transit station. Commuters who use their private automobile for less than 10,000 mile per year typically can reap a significant economic benefit by opting for a 'pay-per-use' model rather than leasing or purchasing a dedicated automobile.

Although car sharing is a relatively new concept in the United States it has already established a strong foothold in Europe. Mobility Car Sharing Switzerland currently provides 1750 cars at 900 locations in 350 communities for 44000 customers. In the U.S there are number of companies that are now offering car sharing services. Zipcar launched in Portland and has recently expanded services to Washington D.C. and New York. Flexcar launched in Seattle and has expanded service to Portland, Washington D.C. and soon will be in California. City Carshare is based in San Francisco and is focused on expanding service into the Bay Area.

Emotion Mobility (e-motion), based in Georgia, is taking the car sharing concept a step further, the company will produce electric versions of the Mercedes Smart car that is widely used throughout Europe. The electric Smarts will be integrated into a car sharing system tightly integrated with transit. "Pods" of the electric Smarts will be located at transit stations and thereby extend the reach of existing mass transit options. The goal of this new service will be to encourage the use of transit by providing convenient, zero emission mobility for commuters and travelers in metropolitan centers. Emotion will begin production of its electric vehicles in the Fall of 2002 and the initial cars will be deployed in Atlanta. E-motion will be targeting California for its second major market launch.

CALSTART is in the process of launching a number of electric car sharing services in California. One of these services is the Long Beach Clean Mobility Center where commuters can use a wide range of zero emission vehicles directly integrated with public transit. As a "member" of the CMC, commuters, employees, local businesses patrons and residents can "share" 1) Electric Cars, 2) Electric Scooters or 3) Electric Bicycles 4) Electronic Bike Lockers as well as the popular Bikestation valet bike parking service or other Bikestation amenities. The electric vehicle in this case is the Ford Think City and members can use Flexcar's phone based reservation system to reserve the vehicle. CALSTART also plans to launch clean car sharing with City Carshare at the Presidio Trust in the San Francisco Bay Area. City Carshare members working at the Presidio will be able to reserve one of 10 Ford Think City vehicles using the phone or internet and then gain access to the vehicle using an electronic key tag.

In 1996, CALSTART launched the nation's largest electric station car program in conjunction with the Bay Area Rapid Transit District (BART). CALSTART used federal funds to help secure the purchase of 40 PIVCO electric vehicles. These cars performed very well with zero battery failures over a two year period. On average, three different people used each car every day. The cars were used for home-to-station, station-to-work, and as pool cars during the business day.

In conclusion, the best strategy appears to be to learn from the ongoing efforts to implement station cars, car sharing and ZEVs, and to conduct market research on a project-by-project basis. This will help maximize the potential to reduce home-to-terminal trips while at the same time increasing ferry patronage.

c) Zero Emission Shuttle Home-To-Terminal Emissions Reduction Scenario Analysis

This study has thus far focused primarily on comparing isolated emissions impacts from different ferry engine technology that might be used as part of a large-scale penetration of ferry service into the commuter market of a specific geographical region such as the San Francisco Bay Area. However, if a well-planned program rollout in real world conditions is considered, regional planners could conceivably include program elements that would operate within an overall transit framework to further increase the potential for emission reductions. This section explores the impacts of a ferry program rollout that would incorporate an extremely intense shuttle program to eliminate 50% of ferry customer's emissions deriving from their home-to-terminal trips.

Table 28 below illustrates the comparative impacts of implementing such home-to-ferry terminal service utilizing zero-emission vehicles. As of this writing (2002), electric vehicles would be the only available alternative. However, by 2007 there are likely to be additional technology choices, including transit vehicles fueled by hydrogen fuel cells, as well as significantly improved operational parameters for electric vehicles.

As in all other emission tables, three routes were examined (Larkspur-San Francisco, Alameda/Oakland-San Francisco and Vallejo-San Francisco. The analysis was conducted using two assumptions with respect to induced demand (0% and 30%).

The analysis of the seven ferry engine technologies implemented in combination with a zero emission shuttle ferry terminal access program incorporates the following assumptions:

- An aggressive, well-marketed clean fuel (zero emission) vehicle shuttle service that provides high enough service quality and costs to attract enough ferry riders to eliminate half of all home-to-terminal trips
- All other vehicle trips would continue to create emissions as projected by the CARB EMFAC model for the 2007 average fleet.
- Each one-way trips eliminated is 20 miles long and includes a cold start

Because an intense data collection effort to determine precise length and characteristics of the average customer's home-to-terminal trip for the three scenarios studied was outside the scope of this project, an average round trip (home to ferry in the morning and ferry to home in the evening) was assumed to be 40 miles for all trips eliminated. Each trip eliminated would include a cold start in the morning and a cold start in the evening. It is further assumed that the shuttle would provide door-to-door service, so that there would be no cold starts involved in accessing shuttle pick-up points.

Note that these assumptions are very optimistic (no ferry system in the Bay Area even approaches these levels of ridership), and are decidedly favorable to ferry operations in this analysis. These assumptions are not intended to mislead readers, but rather to provide an upper bound on what might be possible if an ideal shuttle system were implemented effectively.

It is useful to compare Table 28 below to Tables 26 and 27, which indicates what a ferry roll-out implemented in combination with a clean shuttle program would mean that for the Larkspur and Alameda/Oakland routes, three ferry engine technologies would reduce total emissions relative to the available landside alternative: Tier 2 + SCR, Tier 2 + SCR + CF and CNG. Though the magnitude of reductions differs based on induced demand assumptions, both assumptions reflect positive and significant air quality benefits for Larkspur and Alameda/Oakland routes. The addition of the shuttle eliminates the NOx increases that would otherwise have occurred, and for most engine technologies, nearly doubles the benefits otherwise accrued for CO_2. The shuttle scenario impacts CO emissions for CNG ferries by transforming an increase of 64% to a decrease in CO of 50% over the landside alternative. Most other PM and CO impacts are positively, though less strongly, affected, as well, for the Larkspur and Alameda/Oakland routes.

While NOx emissions are still problematic for the Vallejo route, impacts are roughly halved with the addition of the zero-emissions shuttle program. In addition, CO_2 emission impacts become negligible (1%) under the 0% induced demand assumption, and are reduced from 251% to 14% under the 30% induced demand assumption, with the addition of the shuttle program as described.

While reviewing these tables, it is important to keep in mind the fact that the shift in results to a more favorable picture for ferry operations is due to the impact of the zero emission shuttle program itself. In addition, it is important to point out that the magnitude of the larger emission reductions is closely dependent upon the assumed length of the home-to-ferry trip distance. If, in a real world application, average round trips were shorter, there would be relatively less emission reductions; if the trips were much longer, there would be more emission reductions attributable to a ferry + shuttle operation. The emission reductions caused by eliminating two cold starts per shuttle passenger would remain constant regardless of trip length, though the relative importance of eliminating cold starts increases as trip lengths decline.

Finally, given the reliance of this factor in the analysis, it is important to point out that, were a successful zero-emission shuttle transit program to be implemented for ferries, it would also become an attractive commuter program for more generalized use. To the extent that a clean transit program penetrated other transit and commuter transportation alternatives, the relative benefit of the ferry system would be eroded. However, for at least some period of time after program implementation, the air quality benefits would be retained for the ferry + shuttle scenario.

Table 28: Zero Emission Shuttle Ferry Terminal Access Scenario
50% Of Home-To-Terminal Trip Emissions Eliminated *

Route	Pollutant	Existing Engines	Tier 2 Engines	Tier 2 + HAM	Tier 2 + ITD	Tier 2 + SCR	Tier 2 + CF	Tier 2 + SCR + CF	CNG
Larkspur									
Zero	NO_X	505%	200%	117%	144%	-39%	192%	-42%	-34%
Induced	NMHC	-87%	-66%	-67%	-63%	-92%	-97%	-99%	-84%
Demand	CO	-89%	--78%	-78%	-76%	-95%	-97%	-99%	-50%
	PM	-84%	-89%	-90%	-88%	-93%	-99%	-99%	-99%
	CO_2	-82%	-82%	-82%	-82%	-82%	-82%	-82%	-86%
30%	NO_X	568%	232%	140%	170%	-33%	223%	-36%	-27%
Induced	NMHC	-86%	-62%	-64%	-59%	-91%	-97%	-99%	-83%
Demand	CO	-80%	-76%	-76%	-73%	-94%	-96%	-99%	-44%
	PM	-82%	-88%	-88%	-87%	-92%	-99%	-99%	-99%
	CO_2	-80%	-80%	-80%	-80%	-80%	-80%	-80%	-85%
Alameda/ Oakland									
Zero	NO_X	530%	213%	125%	154%	-38%	204%	-39%	-36%
Induced	NMHC	-86%	-65%	-65%	-62%	-91%	-97%	-99%	-83%
Demand	CO	-89%	-77%	--77%	-75%	-94%	-97%	-99%	-47%
	PM	-83%	-89%	-89%	-88%	-92%	-99%	-99%	-99%
	CO_2	-79%	-79%	-79%	-79%	-79%	-79%	-79%	-84%
30%	NO_X	591%	244%	147%	179%	-32%	234%	-39%	-30%
Induced	NMHC	-85%	-61%	-61%	-58%	-90%	-97%	-99%	-82%
Demand	CO	-88%	-75%	-75%	-72%	-94%	-96%	-99%	-43%
	PM	-82%	-88%	-88%	-86%	-91%	-99%	-99%	-99%
	CO_2	-77%	-77%	-77%	-77%	-77%	-77%	-77%	-83%
Vallejo									
Zero	NO_X	2880%	1385%	969%	1103%	198%	1339%	188%	198%
Induced	NMHC	-37%	66%	66%	86%	-57%	-87%	-97%	-20%
Demand	CO	-46%	8%	7%	20%	-73%	-84%	-96%	150%
	PM	-22%	-48%	-48%	-40%	-63%	-95%	-96%	-95%
	CO_2	-2%	-2%	1%	1%	1%	1%	1%	-25%
30%	NO_X	3240%	1564%	1098%	1248%	234%	1513%	223%	234%
Induced	NMHC	-30%	85%	85%	108%	-52%	-85%	-96%	-11%
Demand	CO	-40%	20%	19%	33%	-70%	-82%	-96%	179%
	PM	-12%	-41%	-41%	-33%	-59%	-94%	--96%	-95%
	CO_2	11%	11%	14%	14%	14%	14%	14%	-15%

Note: Shaded values indicate an increase in emissions due to ferry commuting, compared with the same trip taken on a land route. LNG-fueled vessels would have similar emission results to those shown for CNG.

*Assumes average 40 mile round trip + 2 cold starts, for half of all home-to-ferry trips at 50% ferry occupancy level. Table compares engine technologies for three cases, and two induced demand assumptions.

VI) Areas For Further Research and Development

This study has shown that more data is required on both the landside and waterside of this analysis in order to develop robust recommendations for the choice of marine fuels, propulsion technologies, and emission controls. Similarly, more data and analysis is needed for ferry system expansion.

a) Areas of Research on the Landside

There is a vital need for focused, current survey work on existing and potential ferry patrons, with respect to travel behavior and preferences. Although specific questions will arise out of specific regional and local contexts, the following general questions represent a necessary foundation that will, itself, require extensive and careful survey effort to obtain:

- From what modes will ferry users be drawn? What factors determine that mode split, and how can solo drivers be attracted to the ferry?
- How does this market segment's preferences determine potential for ferry expansion?
- To what extent do access constraints (congestion and/or parking) obscure additional demand for ferry services?
- To what extent does free parking overcome all efforts to reduce SOV access to ferry terminals?
- How can clean fuel (natural gas, e.g.) ferry feeder services (transit and Para transit alternatives) be improved to increase the transit mode split for home-to-terminal trips?

b) Areas of Research on the Waterside

This analysis of passenger ferry air pollution emissions in a U.S. context is probably the most detailed and accurate possible at this time, given available data. The next steps for future research should focus on data collection, not analysis. The most important areas for further research are in a better characterization of vessel emission rates, in developing emission control devices and new fuels (such as CNG) for use onboard passenger ferries, including high-speed vessels. In-situ monitoring campaigns and technology demonstration projects may be useful next steps, and can be implemented together. Due to data and analytical limitations, this study should not be used to judge which fuel, propulsion technology and emissions control device(s) are best for any particular vessel; detailed engineering and economic analysis of specific vessels and service plans are required.

c) Technology Development & Demonstrations

On the landside, the federal government has sponsored a significant amount of research and development of clean fuel propulsion systems and fuels. There has been relatively little testing, development, and demonstration of cleaner marine propulsion systems and fuels. Some of the major engine manufacturers are reluctant to invest in new technology for the marine sector because the over-all sales volume is low compared to the landside vehicles. However, there is an urgent need to develop, test, and demonstrate cleaner fuels and emission control strategies in the marine sector. These new technologies could be done in coordination with the in-situ monitoring mentioned above. The emission control technologies mentioned in this paper should be considered for development and test programs. In addition, it would be valuable to test new fuels in the marine sector such as liquefied natural gas, compressed natural gas, hydrogen, bio-diesel, and gas-to-liquid fuels. These technology demonstrations should go beyond passenger ferries and should also be applied to the other vessels, such as tugboats, barges, and towboats, which are used widely in urban port areas.

VII. Strategies For An Enhanced Ferry System

As part of the normal planning and programming for large transportation investments, regional planners and policy makers who are contemplating strategies to shift some of the peak period commute load to an expanded network of ferries would need to conduct a transportation alternatives analysis. Notwithstanding the need for critical pieces of research into commute behavior, engine technologies and other issues bearing upon the use of ferries in a regional transportation modal mix, as described in Section VI of this report, this section will discuss, in general terms, the kinds of impacts and likely order-of-magnitude level of impacts likely to be encountered in such a comparative analysis. It must be understood that at this level of generalization, only the broadest trends and potential impacts can be identified. Naturally, these would be refined as part of a real-world planning process within an urbanized regional context.

Planning agencies considering increasing regional reliance on ferries for commuting and other transportation purposes would typically develop a number of potentially feasible scenarios for comparative evaluation and analysis. The range of scenarios would be designed to provide a framework to develop regional consensus on how best to maximize transportation investment, as well as to satisfy a variety of regional, state and federal planning and regulatory requirements, and determine implementation feasibility of a comprehensive range of strategies. This section is intended to explore, generically, the types of scenarios likely to be considered in such an exercise, and to consider how a variety of performance indicators and methods might be employed to ensure rigorous analysis. Finally, the section includes general observations with respect to how a regional ferry rollout alternative might compare to these other generic scenarios.

Although the specific mix of transportation alternatives to be analyzed for any region would be developed as part of an intensive public scoping process, the list below illustrates a typical range of multi-modal scenarios that would be likely compared for long-range system planning purposes within a congested, developed urban commute shed.

- No-build (i.e., maintain current transportation infrastructure and services)
- New general purpose lanes on regional freeways
- New high-occupancy vehicle (HOV) lanes on regional freeways – Express Bus or Bus Rapid Transit on HOV lanes
- Commuter rail transit improvement/capacity expansion scenario
- Enhanced Regional Ferry Service – Shuttle and Paratransit strategies for access to terminals

a) Description of Alternatives

This section describes typical long-range alternative transportation scenarios in very general terms. There are certain implementation requirements that would be common to all alternatives—the need to develop political and public support, the need to establish sources of capital and operating funds necessary for implementation, and the need to go through local, regional, state and federal transportation, regulatory, and environmental planning processes designed to protect public investment and ensure sound environmental design of major projects. In addition, there are a number of lower-cost, auxiliary strategies that are also included in most comprehensive regional planning processes. These are described in section (c) below.

No-Build

Under this scenario, the regional highway and transit infrastructure would remain at existing levels until the horizon year (planning horizon years are typically 20 to 25 years in the future.). Though no additional social spending on highways or transit facilities would occur, there would be a number of significant socioeconomic costs incurred by neglecting to improve the transportation system. Levels of congestion would increase, and in most urbanized areas, millions of dollars of time lost to daily traffic delay would impact workers, businesses, and communities.

New General Purpose Lanes On Regional Freeways

In urbanized areas where extreme peak period congestion is experienced, freeways are typically already built out to their original footprints. Generally, all the relatively inexpensive and least disruptive capacity-adding strategies have been implemented, such as utilizing medians and shoulders, and permitting deviations from standard widths to allow additional travel lanes. This means that new freeway lane construction is likely to involve the requirement for new right-of-way on one or both sides of the freeway alignment. Such requirements typically involve costly purchases of right-of-way from private property owners, and lengthy environmental clearance periods, as businesses and communities mount challenges to the highway project. Further, in regions where ferry service would be considered, it is likely that highway capacity expansion would involve extremely costly structures such as bridges over waterways, or tunnels under them. In regions that are not in compliance with state or federal air quality standards, further barriers to implementing general-purpose lanes will present themselves. The effects of induced travel demand discussed in Section II have been observed to apply to new highway lanes.

New High-Occupancy Vehicle (HOV) Lanes On Regional Freeways

Like the freeway option, new lanes mean high construction cost in urbanized areas, and may mean expensive bridge and/or tunnel construction and maintenance in regions where ferries are also a viable option. Further, because slower-moving vehicles can be a traffic problem in single-lane HOV facilities, it is often desirable to build two lanes, to permit passing. A two-lane facility would, of course, add to the cost of the facility, and would likely cause more socioeconomic and other environmental impacts along most alignments.

The advantage to this option is the potential to significantly enhance the person-throughput of the HOV lanes (and the entire freeway system) by using Bus Rapid Transit and other commuter express bus service to make optimal use of the lanes. However, an essential factor in realizing the maximum effectiveness of this strategy is the minimum threshold established for vehicle occupancy eligibility. If, for example, two-person carpools were allowed to use the lanes, a great deal of shifting from general purpose lanes to the new HOV lanes would occur, without significant creation of new carpools or increase in corridor average vehicle occupancy. In addition, the high demand for the lanes would soon lead to congestion, and the HOV lanes would lose their relative time advantage over the adjacent general-purpose lanes. However, if the minimum eligibility were established at three persons, or four persons per vehicle, the lanes would maintain the attractive time advantage for passenger vehicles as well as transit buses that could be deployed to effectively move more people at peak periods.

Induced demand impacts would occur here as well, but would be offset to some degree by the higher vehicle occupancies associated with an HOV strategy.

Commuter Rail Expansion

Commuter rail has the advantage of improving total person throughput of the regional transportation system. However, if new construction is required, this will represent a significant capital cost, and require a long planning and construction lead-time. Again, in regions where topography and waterways make ferries an option, it is also likely that new or expanded commuter rail lines would need to cross bodies of water, either with bridges or tunnels, both of which are expensive and can take many years to bring on line.

In addition to new routes that are developed in response to emerging centers of residential and employment development density, new service (additional departures) and/or new capacity (more cars and more passenger seating capacity per departure) would be considered to be part of this alternative. To the extent that such non-build expansion potential exists within a region, and to the extent that exploiting it would be productive, this alternative would fare relatively better in a comparison with the other alternatives under consideration with respect to timeliness, construction impacts, costs, right-of-way and environmental impacts.

Enhanced Regional Ferry Service

This option includes all capital improvements necessary to achieve stated and significant increases in ferry ridership within a region. Such improvements would likely include procurement of new vessels, expansion or upgrading of vessel servicing and fueling facilities, terminal construction, reconstruction or improvements, dredging, development of terminal access services at both trip ends, and staffing increases to accommodate desired levels of ridership increase. In many instances, upgrading of facilities to accommodate passengers with disabilities would also be required.

Improvements to service that reduce total door-to-door travel times, to make ferry travel competitive with other available alternatives might include purchase of newer, faster boats, routing adjustments to minimize wake restrictions, parking ingress/egress improvements to reduce time required to access the terminal, shuttle access to reduce terminal congestion caused by auto access, and improved boarding and alighting facilities to speed up passenger flow on and off the vessels. Coordination with transit agencies to maximize timed transfers at each terminal would also make total trip times more competitive with other modes. Service increases might include 15-minute headways at peak periods, and increased frequency during midday, to add to customer flexibility in return times.

b) Additional Transportation Strategies to be Considered as Part of All Major Alternative Scenarios

The following additional transportation enhancements would likely be developed for consideration as part of long-range system planning. These strategies, which could be usefully integrated into a locally-preferred system-wide regional strategy package, would typically include:

- Non-motorized transportation strategies
  - Pedestrian

    - Bicycle
- Transportation demand management (TDM) scenario
    - Parking management/pricing/parking cash-out programs
    - HOV auxiliary services
    - Marketing of rideshare services and auto alternatives – carsharing, station cars, paratransit (shuttles, jitneys, taxis) at origins and destinations of longer transit routes
    - Telecommuting
    - Flexible work schedules
    - Employer-provided benefits
- Highway Operational strategy improvement scenario
    - Ramp metering
    - Signal synchronization
    - Freeway traffic management strategies (incident clearing, e.g.)
    - Intelligent Vehicle/Highway Systems (IVHS)
- Land Use Policy
    - Livable Communities policies and incentives
    - Transit Oriented Development
    - Location Efficient Mortgages
    - Strengthened developer requirements for transportation impact mitigation
- Transportation User Fees
    - Road pricing – Emission fees, peak period corridor or zone fees
    - Distance-based vehicle insurance programs

Like the other major alternative scenarios, these lower-cost or innovative scenarios are typically developed with low, medium and high-intensity variations, and then are mixed in with different implementation levels of the four major build scenarios (highway, HOV, rail transit and ferry). Implementation of a significant parking pricing policy should not be considered to be of low potential consequence. Especially when implemented thoughtfully, and in concert with the expansion and effective marketing of transit alternatives, such a policy could be a least-cost means of achieving higher vehicle occupancy, and thus more person-carrying capacity for the entire transportation network. Parking policy is a potentially significant lever that, by imposing costs of solo driving more directly upon the motorists, serves to reduce the attractiveness of driving alone during peak periods.

Presumably, these TDM/TSM and non-motorized strategies could be crafted so as to benefit all scenarios under consideration. However, they would provide maximum benefit when implemented in careful coordination with one of the high-occupancy vehicle strategies (HOV lanes, commuter rail and/or ferries).

Finally, though still controversial in this country, a regional system of peak period road pricing is becoming more attractive as transportation funds based on gas taxes dwindle and congestion becomes increasingly unmanageable. Already successfully implemented in London, Singapore and Norway, such policies would also serve to rebalance consumer demand to favor higher-occupancy alternatives, including ferries.

c) Factors Influencing Commute Mode Choice

Research on traveler attitudes reveals that the following factors can influence an individual's ultimate choice in mode of travel. By maximizing service characteristics to appeal to consumers' needs and preferences, ferry operators could enhance the relative perceived value of their service in comparison with the personal automobile, or other transit choices. Such factors include:

- Total door-to-door travel time
- Perceived door-to-door travel time, especially "waiting time" at transit stops (commuters prefer "in-vehicle" time to waiting time outside the transit vehicle)
- Parking costs (at ferry terminal and at destination)
- Parking availability and security (at ferry terminal and at destination)
- Existence of tolls (peak period pricing, or bridge tolls) on alternative land routes
- Congestion on competing routes or modes, or at off-peak periods
- Level of transit service and number of alternative transit options available
- Individual needs (child or elder care; evening commitments, single-head of household)

d) Evaluation Considerations And Criteria

Regional Performance Indicators

In the United States, each regional planning agency legally mandated to perform long-range transportation planning, has developed and adopted its own set of performance indicators, upon which it evaluates proposed improvements to its transportation system. Though these performance indicators, and the specific measures of effectiveness which are used to determine performance, vary from region to region, the following is a list of typical transportation performance indicators that would be used in a long-range planning process:

- Regional connectivity
- System-wide travel time savings (amount and cost of delay)
- Regional mobility (traffic volumes and speeds)
- Regional accessibility (percentage of jobs and services accessible within a given commute distance or travel time)
- Regional air quality
- Cost effectiveness
- Vehicle miles traveled (VMT)
- Person-carrying capacity of network
- Mode shift

It should be noted that these measures do not register benefits solely in one direction, nor are they entirely easy to apply. That is, an increase in total VMT cannot equivocally be seen as positive. Though some see total network VMT as an indicator of economic vitality and positive growth, others see evidence of increased time required to be spent getting to jobs and services, and see it as a negative indication of sprawl, wasted fuel, and opportunity costs lost to an inefficient transportation system. Increasingly, quality of life factors are being incorporated into regional analyses, so that measures such as "accessibility" and "life-cycle cost effectiveness" gain in relative importance.

General Factors Impacting Ferry Service Performance Indicators

Naturally, the specific details of any scenario under consideration will influence its potential to satisfy regionally adopted performance indicators, or measures of effectiveness. One factor that is itself dependent upon a variety of other variables is the average ferry occupancy rate. Higher occupancy levels mean that the same amount of emissions can be allocated over more passengers—the higher the occupancy, the more air quality benefits can be attributed to a ferry strategy, all other factors remaining constant.

Factors that would tend to be favorable to a ferry scenario include:

- No or negligible right-of-way costs for expansion-related construction
- No or negligible community impacts due to ferry expansion
- To the extent that regional transit vehicles are using older, dirtier engines, there would be more advantage to the use of ferries in substituting for those trips
- High ferry occupancy rates, related to:
    - Customer out-of-pocket costs that compete with available alternatives
    - Reliable, safe service, which includes schedules that are convenient for commuters through proper choice of vessels and routing, commute times are competitive with available alternatives (auto, carpool/vanpool, bus and/or rail)
    - Pleasant in-vehicle time (i.e., time spent on ferry), so extra commute time penalties due to such factors as wake restricted channels or slower vessels are not perceived as negatively as time spent in auto congestion on freeways

Factors that might tend to be unfavorable to a ferry scenario include the following:

- Ferry service that carries vehicles as well as passengers
    - Because no downstream emissions would be avoided by eliminating passenger vehicle trips in favor of high-occupancy vehicle trips (primarily transit) there would be relatively lower reductions in emissions per mile of travel on the land portions of trips.
- Routes that require numerous intermodal transfers
    - If access to ferry requires more than one mode, on either end of the water-side portion of their trip, this inconvenience would tend to make the ferry less attractive in relation to a "straight shot" from home to destination.
- Water pollution impacts to critical ecosystems

Factors favorable to any transit or HOV scenario implemented in combination with expanded ferry service would include:

- Increases in residential densities near transit stops, including ferry terminals, and increases in employment or service provider densities at the destination terminals both tend to increase ridership and reduce terminal access emissions for both ferry and other transit alternatives.
- Likewise, elimination of parking subsidies, and implementation of true cost for parking, will tend to increase non-vehicle access to transit terminals for all transit alternatives, including the ferry.

d) Growth Inducing or Growth Accommodating

It is important to note that, regardless of mode, any transportation improvement that expands total system capacity carries with it the potential to accommodate growth and/or to induce growth. This issue is a point of debate in the literature, and reflects an apparent division in values and differing areas of concern on the part of researchers, planning practitioners, policy makers and the public at large. Those who see transportation system capacity as providing the means necessary to accommodate growth that would occur in any event, tend to see investment in transportation capacity in general as vital to continued economic growth that supports increases in population. Those who see capacity enhancements as growth inducing, see in most system-expansion plans a "business as usual" approach to growth that cannot continue because it is not sustainable in the long run. They therefore see most new capacity as fueling suburban and exurban development that is ultimately economically destabilizing in its effects.

With respect to the strategies described above, benefits that would accrue to highway travelers are related to increases in mobility, vehicle speed, and accessibility related to the expansion in capacity. To the extent that induced demand exists, these benefits will be temporary, as the net increase in vehicles now on the road return to approximate the previous regional equilibrium and its associated level of congestion. This tendency holds for all capacity-expansion strategies, but its impacts are most severe with the addition of general-purpose lanes, because the marginal increase in vehicles will consist of those with the lowest vehicle occupancy. The three high-occupancy vehicle scenarios will all offer an advantage over the general purpose lane scenario, because, though induced demand impacts would occur, they would be offset to some degree by the higher vehicle occupancies associated with a ferry, HOV lane or commuter rail, strategies, respectively.

e) Conclusion

The number and range of variables that would be encountered in a regional transportation planning context are so numerous and the interrelationships to consider so complex, that it is easy to understand why such studies can take years to complete, and often cost millions of dollars. However, considering the magnitude of the investment at stake, and the implications of such investment on the urban fabric and on peoples' lives, this time and effort may be a bargain, even so.

Notwithstanding such complexity, one may reasonably conclude that, with the foundation of good planning techniques taken as a given, it would be feasible to design and implement an enhanced ferry scenario to conform to regional mobility and air quality planning goals. Such a scenario could provide new high-occupancy mobility options, possibly at a lower subsidy per passenger than other transit options, and almost certainly at a lower cost than the total cost of new freeway lanes and structures within a congested urban commute shed. Advantages of ferry over highway building options stem from the right-of-way, environmental and construction costs associated with lane additions in congested areas. In addition, ferry service could be implemented in a much quicker time period, thus bringing mobility, access and socioeconomic benefits on-line much sooner.

Although detailed analysis of specific cases would reveal challenges to any implementation strategy, there are generic advantages to a ferry scenario that would seem to be constant across all modal comparisons. These advantages include:

- Relatively small ramp up time needed to implement program, bringing benefits to the region much sooner than freeway lane expansion or commuter rail construction
- High-occupancy capability (more passengers per dollar invested, more passengers per vehicle mile, system wide)
- Relatively lower capital cost to implement than most alternative scenarios
- Service that offers an attractive public transit alternative to solo driving
- State-of-the-art technology can mean a new mobility option that is relatively environmentally sound
- Lower vehicle accident costs
- Route flexibility

It is almost impossible to conceive of a successful ferry service expansion in the absence of complementary improvements to regional transit networks, which may include bus, rail or both, in addition to such paratransit services as clean-fuel shuttles, jitneys, carsharing and station cars to facilitate customer access to ferry trip ends. This means that, at least for walk-on passengers, the ferry can be viewed as an extension of the transit system where transit is utilized at one or both ferry terminals. As indicated in section V of this report, several ferry technologies incorporated with a clean shuttle program outperform the alternative landside commute for all criteria pollutants. An optimal ferry system would include such intensive clean-vehicle paratransit enhancements designed to reduce access-related vehicle emissions that would be part of an overall regional effort to reduce home-to-transit station vehicle emissions.

Also of importance in considering the value of enhancing the role of ferries in the multi-modal mix are the synergistic effects of improvements to one transit system that can spill over to result in better overall system performance with respect to mobility, access and air quality. Thus, the ferry strategy is attractive as part of a regional emphasis on transit and high-occupancy transportation modes.

Thus, a regional ferry network can be viewed as a capacity expanding option for peak period, peak direction commute, that serves essentially as a new high-occupancy mobility choice for commuters, offering new capacity, potentially new routes, and new access to jobs and services. Such service can be implemented relatively quickly, and can be designed to perform well with respect to most, if not all, regionally adopted performance indicators.

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