ATTACHMENT D

EMISSIONS INVENTORY DEVELOPMENT

TABLE OF CONTENTS

LIST OF TABLES

Emissions Inventory Development

As part of this rulemaking effort, staff reviewed the assumptions and work in the Recreational Marine Emission Inventory published in December 1998 (ARB 1998c). Additional data pertaining to engine performance, activity, and emissions characteristics have been analyzed and used to modify several elements of the inventory baseline for gasoline inboards and sterndrives. The process of refining the inventory is ongoing and results presented in this report represent the most current conclusions of the Air Resources Board. Prior to incorporation of the inventory estimate, ARB will conduct meetings, consider comment, and present the revised inventory to the Board for approval.

1. Population/Turnover

Our primary source for the number of gasoline inboards and sterndrives in the state is the Department of Motor Vehicles registration information. Listed below in Table D-1 are the inboard/sterndrive boat-hull registration counts for the years 1990 through 1997 and 2000. NMMA publishes the number of inboard and sterndrive engines sold in the country each year (NMMA, 2000). From these data the population of inboard boat engines in California was extrapolated forward to 2010 and 2020. Those figures are shown in Table D-1 below.

Table D-1

Inboard/Sterndrive Engine Population in California

	Total California Inboard/Sterndrive registrations	Assumed number of engines per boat	Calculated extrapolated California inventory of inboard/sterndrive boat engines
2020			448,572
2010			386,479
2000	296,624	1.126	333,999
1997	267,153	1.126	300,814
1996	263,218	1.126	296,383
1995	258,179	1.126	290,709
1994	252,968	1.126	284,842
1993	250,047	1.126	281,553
1992	247,629	1.126	278,830
1991	244,769	1.126	275,610
1990	237,816	1.126	267,781

The age distribution for inboard boats in California was calculated using data from the California Department of Motor Vehicles for the 2000 model year, and is shown below in Table D-2 for the year 2020. The number of hulls in each vintage year was multiplied by the composite number of engines per boat from NMMA sales data (national) (NMMA 2000).

It can be determined from Table D-2 that the median engine age is about 13 years, and the 90th percentile age is about 33 years. The apparent turnover (ratio of total population to new or one-year old engines) is about 20 years for this distribution. Based on sales rates in the 1990s, we would expect a turnover rate of about 20 to 30 years, so this has good agreement with observables.

Table D-2

Assumed 2020 Inboard/Sterndrive Boat-Engine Age Distribution

Vintage year	Number of boats per vintage	Number of engines per boat	Number of engines per vintage
2020	20,023	1.126	22,546
2019	20,686	1.126	23,293
2018	18,732	1.126	21,092
2017	16,869	1.126	18,994
2016	14,934	1.126	16,816
2015	13,780	1.126	15,517
2014	14,592	1.126	16,431
2013	13,613	1.126	15,328
2012	12,285	1.126	13,833
2011	11,732	1.126	13,210
2010	11,460	1.126	12,903
2009	10,854	1.126	12,222
2008	10,214	1.126	11,501
2007	9,790	1.126	11,023
2006	9,082	1.126	10,227
2005	8,414	1.126	9,474
2004	7,760	1.126	8,738
2003	7,375	1.126	8,304
2002	10,575	1.126	11,908
2001	5,903	1.126	6,647
2000	15,237	1.126	17,157
1999	7,109	1.126	8,004
1998	6,625	1.126	7,459
1997	7,376	1.126	8,305
1996	7,593	1.126	8,549

Table D-2 Continued

Assumed 2020 Inboard/Sterndrive Boat-Engine Age Distribution

1995	7,668	1.126	8,635
1994	7,058	1.126	7,947
1993	5,918	1.126	6,663
1992	5,805	1.126	6,537
1991	5,855	1.126	6,593
1990	8,613	1.126	9,698
1989	9,232	1.126	10,395
1988	9,458	1.126	10,650
1987	8,654	1.126	9,744
1986	7,652	1.126	8,616
1985	6,998	1.126	7,880
1984	6,787	1.126	7,642
1983	4,877	1.126	5,491
1982	3,536	1.126	3,982
1981	3,645	1.126	4,104
1980	4,008	1.126	4,513
	398,376		448,572

2. Activity

The existing model parameters for average activity are specified as 93 hr/yr for inboards, 73 hr/yr for sterndrives, and 73 hr/yr for jet-drives. These values were determined using survey data provided by a contractor (ARB 1998c).

Mercury Marine did a survey of 35 boats that came in for service in September of 2000 at two or three Mercury Marine service sites in California. Most of the boats were less than one year old. Serial number information was consulted to determine purchase dates of the engines or boats. The average use was about 58 hours per year. If only the boats over 1 year old were considered (17 out of the 35), the average was about 55 hours per year.

In 1994, Mercury Marine surveyed eleven old boats in California and Florida to determine long-term usage rates and useful life (Mercury Marine 1994). Three of the eleven were nine years old, and no boat was younger than two or older than nine. The average use was 68 hours per year.

As part of a study for ARB, Science Applications International (SAI) surveyed 1500 inboard boat owners in California by random mail questionnaire (SAI, 1995). A summary of these data is shown in Table D-3. The recipients were asked about their usage in the previous two weeks before receiving or filling out the survey. Questionnaires were sent in all months of the year, but most of the respondents sent in responses in August. The recipients were asked what their total elapsed boating time was, and their percent engine-off time. The annual usage was inferred by multiplying the reported two-week usage times 26. The average usage rate determined this way was 3.1 hours per engine per two weeks, (out of 5.8 hr/2-wk total on-the-water time) or about 81 hours per year per engine. Many respondents answered that they had not used their boats at all in the previous two weeks.

Table D-3
Results of SAI Inboard/Sterndrive Boat-Owner Mail Survey

Number of boats	1459
Number of engines	1529
Fuel use per engine, gal/2-wk	13.85
Composite number average power, hp	211
Hours of engine-on use per 2 weeks	3.1
Hours of boating per 2 weeks	5.8
Average fuel use gal/h	4.5
Theoretical rated fuel use gal/h	21
Average load factor	21%

Additionally, the U.S. Coast Guard estimates average boating activity to be approximately 100 hours per year according to its 1998 recreational boating survey (Mangione *et al.*, 1999). The intended purpose of this study was to calculate the risk to boat occupants associated with boating activity, and in so doing the survey measured the amount of time boat occupants used their boats. So this 100 hours might include engine-off time as well as engine-on time.

Based on this information, staff concludes that modification of the existing inventory activity numbers is not warranted. Therefore, the activity numbers of 93 hr/yr for inboards, 73 hr/yr for sterndrives, and 73 hr/yr for jet-drives are retained for calculation of the revised emission inventory. With the population breakdown from Department of Motor Vehicles registration data, this averages to a value of 78 hr/yr over all three categories.

3. Average rated power.

The existing model parameter for average rated power is 164 hp. This value was calculated using data provided by an ARB contractor in 1998 (ARB 1998c). Since that time, 1997-1999 sales breakdowns have been provided to the ARB from industry indicating that the 350 cubic-inch engine represents the average size for inboard/sterndrive engines and has the highest sales volume. Based on this information, the sales-weighted average power for inboard/sterndrive engines is about 275 hp. Staff proceeded to analyze the SAI survey representing approximately 1459 inboard and sterndrive boat owners and found that the average name-plate power for the inboards, sterndrives and jet-drives was 211 hp. Accordingly, the existing model parameter for average rated power was changed to a composite value of 211 hp and used in calculating the emissions inventory numbers presented in this report.

4. Average load-factor.

The weighted power for the ISO 8178-4 E4 recreational marine test cycle is 21% of rated or maximum power. This was generated from actual time-at-speed or throttle-position determinations of average outboard boaters in Wisconsin (Morgan and Lincoln 1990). The SAI study commissioned for California asked approximately 1459 inboard and sterndrive boat owners how much fuel they consumed, how many hours on the water, percent of time the engine was on, what was the rated power of the engines, and number of engines per boat. As shown in Table D-3, the mail-out survey confirmed the average load factor of 21%.

5. Emission Factors/Deterioration

The emission factors used in our modeling are shown in Table D-4. Results of baseline engines were gathered from the manufacturers new-engine data and several tests done by the U.S. EPA at their facilities. The results from 12 carbureted engines from the early 1990s have been gathered along with 4 runs from rich-calibration electronically fuel-injected engines from the last 5 years. These revised results differ with respect to the existing model parameters, 12.2 g/kW-hr for HC and 7.2 g/kW-hr for NOx, and are shown in Table C-1 of Attachment C to this staff report.

Table D-4

Engine Emissions, New Engines

	HC g/kW-hr	NOx g/kW-hr
Carbureted	7.8	6.2
Electronically fuel-injected	4.7	9.9
Three-way Catalyst, Feedback A/F	1.9	2.0

A/F means air-fuel ratio

The engine manufacturers are making a shift away from carbureted engines to fuel-injected engines over the next five years. This will tend to lower HC emissions but raise the NOx emissions.

The three-way catalyst entry was based on the results from recent testing at Southwest Research Institute on catalyst-controlled marine engines. These data are presented in Table C-7 of Attachment C to this staff report. The values chosen for use in the controlled inventory calculations were an average of the 200 cell-per-square-inch rectangular riser catalyst result and an early result from the external cylindrical catalyst.

Deterioration is the assumed increase of exhaust emissions as a function of engine age. For automobiles, this is done on a mileage basis. For boats and generators and other off-road engines this is done on an engine-hour basis. For automobile gasoline engines at present, the deterioration of performance is mostly due to deactivation of the catalyst with age, due to poisoning or thermal sintering of the sites. It is the full-deteriorated emission value (evaluated at the compliance lifetime period) that is to be compared with the standards.

To model the deterioration of emissions with age for the uncontrolled boat engines, staff compiled carbureted automotive data of emissions versus mileage, and fit the best line to determine the slope (grams per kilowatt-hour per hour). The area of interest for boat engines is at about 480 hours, about one fifth of the equivalent hours to 100,000 miles of car travel. The EFI deterioration rates at 480 hours were calculated using the same percent increase in emissions attributed to a carbureted engine using carbureted deterioration factors. This was assumed because deterioration data for engines that are EFI-controlled but without catalysts is rare. The deterioration rate for the catalyst-controlled engine was chosen such that deteriorated emission levels would minimally comply with the combined HC+NOx standard of 5 g/kW-hr after 480 hours of use. This equates to approximately 1 g/kW-hr growth (about 25% of zero hour emissions) over the 480 hours. This is the value of deterioration allowance estimated by the engine manufacturers for a catalyst-controlled engine.

Table D-5 below shows the effect of the incorporation of deterioration estimates. The deteriorated emission factors for carbureted baseline engines, electronically fuel-injected baseline engines, and three-way catalyst/oxygen feedback air-fuel controlled engines were determined by staff from automobile data (ARB 1998c). For HC and NOx, the new-engine (or new-catalyst) emission rates and the 480-hr rates are shown. The zero-hour values are what would be expected from a new engine test, the most common basis to test at the factory or in development. The figure of 480 hours for compliance life is much smaller than that expected for automobiles, or even smaller than assumed in the age distribution of Table D-2 above. It is based on the assumed usage period from the engine manufacturers.

Table D-5

Effect of Deterioration on Boat-Engine Emissions

	HC Zero-hour	HC 480-hr	NOx Zero-hour	NOx 480-hr
Carbureted emission rates, g/kW-hr	7.8	8.0	6.2	6.3
Deterioration rate, $g/kW\text{-}hr^2$	3.15×10^{-4}		1.81×10^{-4}	
EFI emission rates, g/kW-hr	4.7	5.0	9.9	9.9
Deterioration rate, $g/kW\text{-}hr^2$	4.89×10^{-4}		3.07×10^{-5}	
TWC emission rates, g/kW-hr	1.9	2.4	2.0	2.6
Deterioration rate, $g/kW\text{-}hr^2$	1.01×10^{-3}		1.30×10^{-3}	

EFI means electronically fuel-injected
TWC means three-way catalyst