Appendix D

Emissions Estimation Methodology for Ocean-Going Vessels

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Emissions Estimation Methodology for Ocean-Going Vessels

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California Air Resources Board
Planning and Technical Support Division

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Ocean-Going Vessel Emission Estimation Methodology

I. Executive Summary

Air Resources Board (ARB) staff have revised the methodology to calculate emissions from ocean-going vessels in California. This revised inventory will be used to support regulatory analysis of statewide regulations to reduce emissions from ocean-going vessels.

The inventory presented here is an update to those developed by staff in May, 2008 in support of a number of programs, including the Fuel Regulation for Ocean-Going Vessels and the 2007 Shore Power Regulation.

The update includes a number of minor revisions and corrections that include: recoding the model to increase calculation speed, updated auxiliary engine information, updated ship routing, revised vessel speed reduction compliance rates, an adjustment factor to estimate the effects of the recession and improvements in the user interface of the model.

Emissions are calculated by estimating ship emissions on a ship by ship and a port call by port call basis, using actual ship engine power estimates, speeds, and actual ship hoteling times where possible. Base year emissions were forecasted using a set of growth factors specific to each port and each ship type.

Emissions were calculated for the 100 nautical mile zone that is used for ARB's emissions inventory system. They include the benefits of the 2007 Shore Power Regulation, the benefits of the San Pedro Bay Ports voluntary vessel speed reduction program, the proposed benefits of the current proposal, the fuel-related benefits of the North American Environmental Control Area (ECA), but not the NOx benefits of IMO Tier 3 engine standards.

Using the proposed methodology, we estimate 2005 statewide emissions from ocean going vessels in the 100 nautical mile regulatory zone were over 14 tons per day of diesel PM, over 155 tons per day of oxides of nitrogen (NOx), and over 7,400 tons per day of carbon dioxide (CO_2). Detailed emission estimates are presented in Table ES-1.

The emissions model that produced these estimates is publicly available in accordance with AB 1085 and is available at http://www.arb.ca.gov/ports/marinevess/ogv/ogv1085.htm.

Table ES-1 summarizes the emissions by district for the 100 nautical mile SIP zone. In 2005, emissions were almost evenly split between Southern and Northern California.

Table ES-1 2005 Ship Emissions by District (tons/day) in the 100 nm Zone

2005 Total Emissions in 100 nm Zone				
District	**NOx**	**PM2.5**	**SOx**	**CO2**
	tons/day			**mmtCO2**
Bay Area AQMD	44.3	4.0	32.3	0.7
Mendocino County AQMD	9.3	0.8	5.7	0.1
Monterey Bay Unified APCD	17.8	1.5	10.9	0.2
North Coast Unified APCD	14.0	1.2	8.6	0.2
Northern Sonoma County APCD	4.2	0.3	2.5	0.0
San Diego County APCD	5.1	0.5	3.8	0.1
San Joaquin Valley Unified APCD	0.1	0.0	0.1	0.0
San Luis Obispo County APCD	11.4	1.0	6.9	0.1
Santa Barbara County APCD	53.1	4.5	32.1	0.6
South Coast AQMD	44.8	4.6	42.8	0.9
Ventura County APCD	16.1	1.4	10.1	0.2
Yolo/Solano AQMD	0.2	0.0	0.2	0.0
Total	**220.2**	**19.6**	**155.8**	**3.2**

The following section provides background on the ship emissions inventory, the purpose and goals in preparing this emissions inventory, and a general overview of the methodology used to estimate emissions.

A. Background

For the purposes of this inventory, an ocean-going vessel (OGV) is a commercial vessel greater than or equal to 400 feet in length or 10,000 gross tons; or propelled by a marine compression ignition engine with a displacement of greater than or equal to 30 liters per cylinder.

The ARB California Emissions Inventory Data and Reporting System (CEIDARS) includes all OGV emissions occurring within 100 nautical miles of the California coastline. This zone is also used for State Implementation Plan (SIP) purposes. Figure 1 shows this zone, as well as the 24 nm regulatory zone used for the 2008 low sulfur fuel rule and the amended regulatory zone used in the current regulation.

OGV emissions occur during three distinct operating modes: transit (emissions from vessel operations between ports), maneuvering (slow speed vessel operations while in-port areas), and hoteling (also known as berthing; in-port emissions while moored to a dock).

Two types of engines are found on OGVs, main engines and auxiliary engines. The main engine is a very large diesel engine used primarily to propel the vessel at sea. Main engines are used during the transit and maneuvering modes. Auxiliary engines on OGVs provide power for uses other than propulsion (except for diesel-electric vessels). Typically, an OGV will have a single, large main engine used for propulsion, and several smaller auxiliary “generator-set” engines. Auxiliary engines are used during all three operating modes. An exception to this configuration is diesel-electric vessels where diesel engine generator sets provide power for both propulsion and auxiliary power needs.

In addition to the engines, most ships have auxiliary boilers to provide steam heat for a variety of uses, including fuel heating and hot water. Some crude oil tankers also use boilers for moving crude oil product on and off the ship. Boilers are used during slow speed vessel operations or in port; at cruise speed, most vessels are equipped with an “economizer” at cruise speeds which uses exhaust gas to provide heat. Below certain engine loads, however, there is not sufficient waste heat available from the exhaust, and boilers are activated. For the purposes of this inventory, it is assumed that boilers are operated during maneuvering, hoteling, and during anchorage.

There are a number of types of ocean-going vessels including: auto carriers, bulk cargo carriers, container vessels, general cargo carriers and other miscellaneous vessels, passenger vessels, reefers (refrigerated vessels), roll-on-roll-off vessels (also known as a Ro-Ro: vessels in which vehicles can be driven on or off the vessel). A list of the different types of ocean-going vessels and a brief description of the goods transported by them presented in Table I-1.

Table I-1: Categories of Ocean-Going Vessels Included in the Emissions Inventory

Vessel Type	Description
Auto	Vessels designed to carry autos and trucks
Bulk Cargo	Bulk carriers are vessels used to transport bulk items such as mineral ore, fertilizer, wood chips, or grain.
Container	Container vessels are cargo vessels that carry standardized truck-sized containers.
General Cargo	Vessels designed to carry non-contaminated cargo such as steel, palletized goods, and heavy machinery.
Passenger	Passenger cruise vessels are passenger vessels used for pleasure voyages.
Reefers	Vessels used to transport perishable commodities which require temperature-controlled transportation, mostly fruits, meat, fish, vegetables, dairy products, and other foods.
Ro-Ro	A vessel designed to carry large wheeled cargo such as large off-road equipment, trailers or railway carriages. RORO is an acronym for “roll on/roll off”.
Tankers	Vessels designed to transport liquids in bulk.

B. Purpose and Overview

The ARB is revising the emission inventory for ocean-going vessels to reflect new information and improved methodologies. The new information includes updated activity data, additional sources of ship hoteling and anchorage information and ship-specific engine and speed data. Additionally, the growth assumptions were updated with additional years of trend data, the effects of the recession, and the benefits of recent regulations. This document describes the inventory methodology and data inputs that were developed in support of the shore power regulation and the proposed main engine regulation.

2005 was chosen as the base year; this year was chosen to be consistent with the modeling performed for the current regulation. Because gridded emissions are required for modeling, a gridded inventory developed for this document; grid cells were mapped to the appropriate zone to summarize the data. Base year emissions were forecasted by assessing trends in the growth of vessel net registered tonnage for the years 1994-2010. Net registered tonnage (NRT) is a measure of the volume of a ship's cargo capacity; the growth in NRT is directly proportional to the growth in installed power of a vessel's main propulsion engine. Controlled future year emissions for 2010 and 2015 were forecasted with the benefits of the 2007 shore power regulation, the expanded San Pedro Bay ports voluntary 40 nautical mile vessel speed reduction zone, and the benefits of the North American Environmental Control Area.

C. Public Process

Allowing stakeholders and the general public to review and comment on a product associated with a rulemaking process is a critical element of that rulemaking process. The following steps were taken to ensure interested parties could provide input.

Multiple public workshops or workgroups were held beginning in 2007 and continuing through 2010 that provided the stakeholders and the general public the opportunity to review and comment on the inventory. A number of teleconferences were conducted with port representatives and port consultants as well. We provided local air districts the opportunity to review, comment on the methodology and the inventory by conducting meetings and teleconferences. Comments obtained through these meetings, teleconferences and workshops were used to assess and modify the inventory.

II. EMISSION ESTIMATION METHODOLOGY

Ship emissions were calculated, to the extent possible, on a vessel and port call specific basis. Where possible, vessel specific power data was used, and port call specific hoteling times were used to calculate emissions.

A. Emission Inventory Inputs

Data needed for estimating ship emissions include:

- Base year vessel population
- Operating Mode specific activity hours
- Main engine, auxiliary engine, & auxiliary boiler power
- Vessel type and mode specific engine load
- Emission factors
- Vessel type and port growth rate
- Control measures

1. Base Year Vessel Population

There were several sources of activity data that were used for the inventory. First, vessel port calls were obtained from a database maintained by the California Lands Commission (SLC, 2007). This database includes vessel identification, port of arrival, previous port, next port, and date and time of arrival. The Lands Commission compiles this database from marine exchanges and port authorities statewide. 2005 was chosen as the base year for this inventory for consistency with the air quality modeling done for this regulation. Second, vessel specific hoteling times and berth locations were obtained from port officials responsible for ship docking, or Wharfingers, in Los Angeles, Long Beach, Oakland, San Diego, San Francisco and Hueneme. Data was obtained for 2004 through 2006, but only 2005 data was used for this inventory. These data were reconciled to the extent possible with the port call data from the Lands Commission (SLC, 2007); for all ports, approximately 94-98% of the port calls were reconciled between the two databases. The remaining port calls in the Lands Commission database which could not be reconciled were assigned the port average hoteling times by vessel type.

Table II-1 summarizes the number of port calls by ship type and by port.

Table II-1 2005 Port Calls in California

Arrival Port	Auto	Bulk	Container	Cruise	General & Miscellaneous	Reefer	Ro-ro	Tanker	Total
Avalon/Catalina				134				8	**142**
Carquinez	49	74		2	5			330	**460**
El Segundo								223	**223**
Humboldt					13				**13**
Long Beach	168	291	1385	148	181	38	82	532	**2825**
Los Angeles	61	152	1525	274	91	48	2	314	**2467**
Monterey				9	3				**12**
Oakland		16	1793		94		17		**1920**
Pacific Lightering Zone								132	**132**
Port Hueneme	211	1		3	9	155	11	13	**403**
Redwood		56			1			1	**58**
Richmond	55	42	9		4		9	333	**452**
Sacramento		19			38		1	5	**63**
San Diego	129	43	2	230	57	80	22	2	**565**
San Francisco		54	2	77	58		1	100	**292**
Stockton		94			23			50	**167**
Total	**673**	**842**	**4716**	**877**	**577**	**321**	**145**	**2043**	**10194**

2. Operating Mode Specific Activity Hours

Three operating modes are used to characterize OGV activity: transit (emissions from vessel operations between ports), maneuvering (slow speed vessel operations while in-ports), and hoteling (also known as berthing; in-port emissions while moored to a dock or at anchor). For regulatory purposes, hoteling emissions in this inventory will be termed “hoteling” for ships moored at dock, and “anchorage” for ship activity at anchor at or near a port, but not moored to a dock. Main engine emissions occur during transit and maneuvering modes. Auxiliary engine emissions occur during all modes. Auxiliary boilers are operated during maneuvering, hoteling, and anchorage. Separate emission factors have been developed for main engines in the transit and maneuvering modes. Main engines do not operate during hoteling except for the generator sets on diesel-electric vessels. For the purposes of this emissions inventory, all diesel-electric vessel emissions are reported as auxiliary engine emissions.

a. Transit Mode

Operating hours in transit mode is calculated as distance traveled divided by vessel speed. Distance traveled is determined by evaluating the route taken between ports by the vessel; speed is a function of both the speed of which a vessel is capable of and of any speed limitations in effect.

Distance Traveled: Vessel Traffic Lanes

The lanes used to estimate ship activity at sea were a composite of three sources. First, near-port vessel lanes were extracted from the Army Corps of Engineers (ACE) National Waterway Network (USACE, 2007). The portions of this network that reflect the vessel traffic patterns defined in navigational charts were used; other parts of the ACE network that did not reflect actual ship traffic patterns were not used. The vessel traffic separation scheme used in the Santa Barbara Channel, in which vessels traveling south travel further west than those going north, is an example of the ACE data that was used for the model. For vessel traffic further out at sea, the Ship Traffic, Energy and Environment Model

(STEEM) developed by Dr. Chengfeng Wang and Dr. James Corbett (Wang, 2007) was used to define traffic lanes. Third, automated instrumentation system (AIS) telemetry data collected during 2007 was used to define the traffic lanes that connect these two networks.

Figure 1 shows the vessel traffic lane network used for the inventory. Figures 2 and 3 show a close-up of the Northern California and Southern California portions of the network.

Vessel routing between ports for the 2008 and updated inventory was defined by the assumption that ships will take the shortest route between origin and destination on the vessel traffic network. The shortest path was calculated using Arc GIS Network Analyst.

Since the 2008 inventory, minor adjustments to the shipping lane network have been made to ensure that vessel routes conform to known transit routes, such as in the Santa Barbara Channel. Vessel routes were verified with automated instrumentation system (AIS) ship data to the extent possible. Additionally, the current inventory routes tankers travelling to and from Northern and Southern California further away from shore, to conform with existing practice.

Vessel traffic lane locations with respect to the main coastline of California were identified and cataloged to identify how far off the coastline ship activity occurred.

Figure 1
Vessel Traffic Lanes

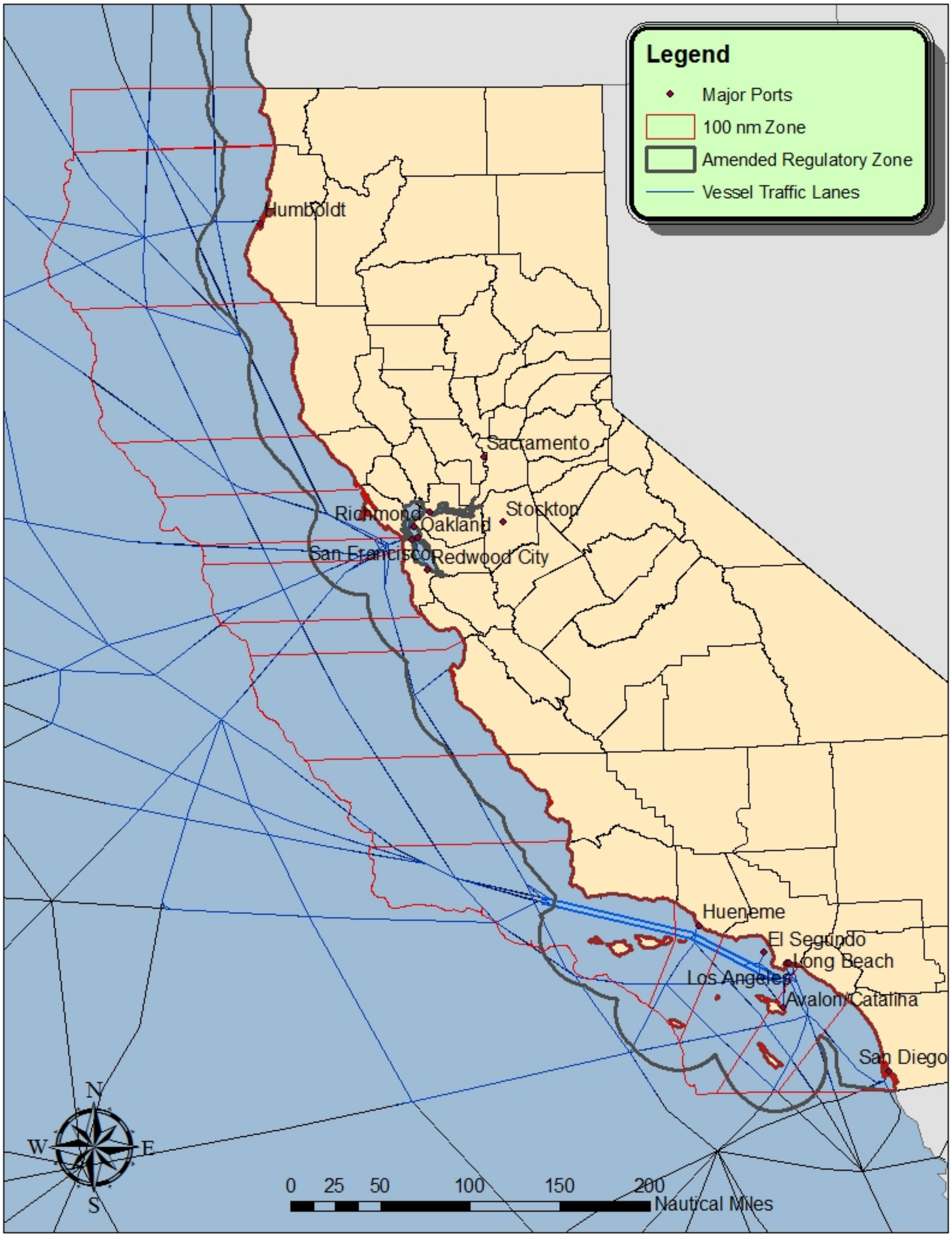


Figure 2

Vessel Traffic Lanes – Northern California

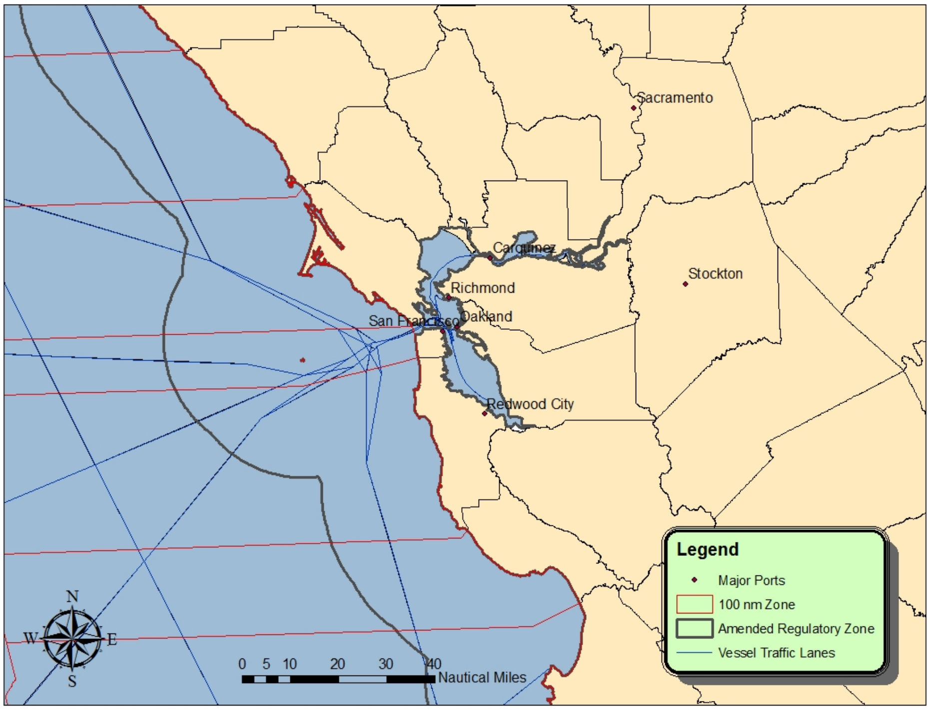
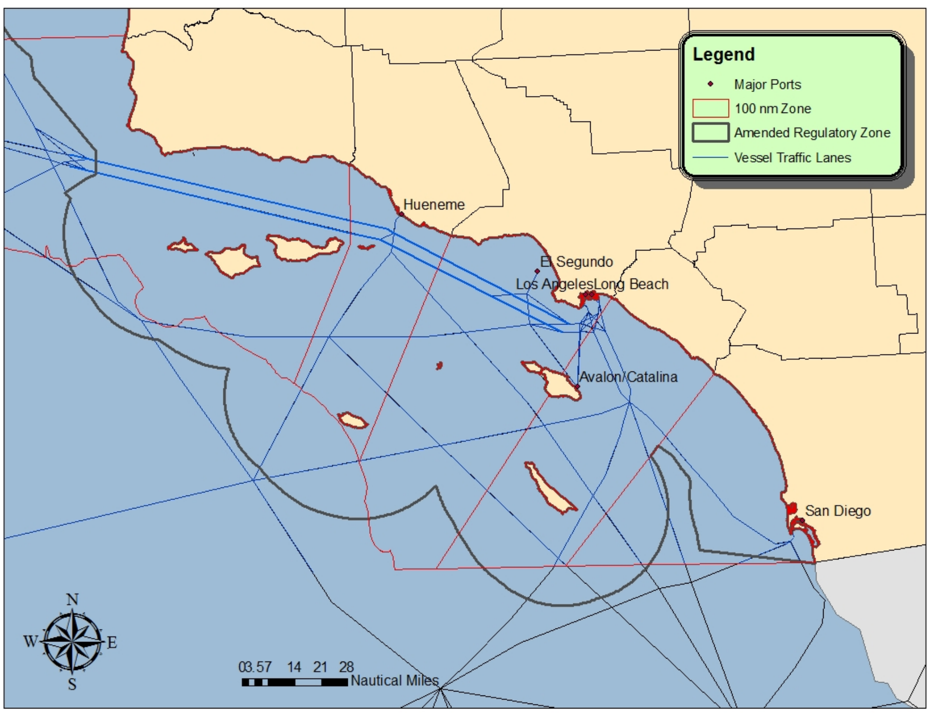


Figure 3

Vessel Traffic Lanes – Southern California



Vessel Speed

The maximum vessel speed was obtained from the 2007 version of Lloyds-Fairplay PC Register (Lloyds-Fairplay, 2007). The cruise speed was estimated to be 0.937 times the maximum speed, which results in a load factor of 0.823 during cruise mode. These figures were obtained from a survey performed for the Port of Los Angeles emission inventory (Starcrest, 2005 and 2007). It was assumed that vessels traveled at cruise speed in areas without specific speed restrictions.

Vessel speed restrictions for traffic lanes in various areas were determined from nautical charts. One such example is the precautionary zone in Los Angeles and Long Beach harbor, in which speed is restricted to either 11 or 9 knots depending on the type of ship. Vessel speeds within the Southern California voluntary vessel speed reduction zone were obtained from the Southern California Marine Exchange (MXSOCAL, 2007).

b. Maneuvering

Maneuvering time was calculated as the distance traveled during maneuvering divided by speed, plus 15 minutes for docking or undocking. For coastal ports, maneuvering was assumed to begin at the point where the pilot boarded the vessel and ended at the berth. For ports within the San Francisco Bay Area, maneuvering distances were estimated based on the Environ (Environ, 2007) Port of Oakland inventory, AIS data, or discussions with port officials. It was assumed that fast ships (container ships, cruise ships, reefers) maneuvered inbound at 7 knots and slow ships (all other types) at 5 knots; all outbound ships were assumed to maneuver at 8 knots.

c. Hoteling

Hoteling time can be defined as beginning when a ship ties up at a berth, and ends when it leaves that berth. Likewise, anchorage is defined as beginning when a ship drops anchor and ends when the anchor is raised and the ship begins moving again. During hoteling and anchorage, vessels use at least one of their auxiliary engines to generate electric power for the ship. Auxiliary boilers are also used. Some ships will shift berths during a given port call for various reasons; for the purpose of this inventory, the hoteling time used for calculations combines the total hoteling time for all berths visited during a given port call.

Hoteling times used for the inventory obtained were specific to individual port calls and were obtained from port Wharfingers. Port calls that could not be identified in Wharfinger data were assigned average hotelling times by port and by vessel type from the Wharfinger data that was available. Table II-2 summarizes the average hoteling times by vessel type for 2006.

Table II-2 2005 Hoteling Time Averages (hours per visit)

Arrival Port	Auto	Bulk	Container	Cruise	General & Miscellaneous	Reefer	Ro-ro	Tanker
Avalon/Catalina				13				34
Carquinez	18	65		13	43			34
El Segundo								34
Humboldt					61			
Long Beach	16	64	54	13	39	33	30	34
Los Angeles	21	73	50	12	53	42	36	36
Monterey				13	45			
Oakland		15	21		15		43	
Pacific Lightering Zone								34
Port Hueneme	16	12		7	61	71	11	21
Redwood		62			54			34
Richmond	19	64	32		61		32	34
Sacramento		57			49		32	34
San Diego	18	82	44	11	58	57	29	34
San Francisco		66	32	11	62		30	34
Stockton		61			42			34

Although the number of port calls by container ships to Oakland is roughly equivalent to the number of port calls at either Los Angeles or Long Beach, the hotelling time of these ships in Oakland is much shorter. Often, container ships will call on both Oakland and either Los Angeles or Long Beach; presumably, fewer containers are loaded or unloaded in Oakland than in southern California.

d. Anchorage

Ship and visit-specific anchorage data (ship identification, hours anchored, and anchorage location) was obtained from MXSOCAL in Southern California (MXSOCAL, 2007) and the US Coast Guard Vessel Traffic Service (USCG,

2007) in the San Francisco Bay Area. Table II-3 summarizes average anchorage times for ships that anchored. It was assumed that ship operations during anchorage were the same as during hoteling; that is, auxiliary engines and boilers operated at hoteling loads, and the main engine was not in operation.

Table II-3 2006 Average Anchorage Times (hours per visit)

Arrival Port	Auto	Bulk	Container	Cruise	General & Miscellaneous	Reefer	Ro-ro	Tanker
Carquinez	5	27			20			19
Long Beach	14	41	12		35	11	17	73
Los Angeles	9	30	12	2	31	16	5	32
Oakland		35	9		21			
Redwood		25			7			
Richmond	15	51			5			20
Sacramento		23			15			46
San Francisco		11	193	2	12			23
Stockton		52			38			29

3. Main engine, auxiliary engine, & auxiliary boiler power

The main source of engine power was the PC-Register commercial ship database obtained from Lloyds-Fairplay (Lloyds-Fairplay 2007). Information from this database that was used in the inventory included main engine power, auxiliary engine generation capacity, main engine speed, vessel type, date of build, cruise speed, and flag of vessel. This data was supplemented with data collected by Starcrest and the Ports of Los Angeles and Long Beach as part of their Vessel Boarding Program (Starcrest 2005, 2007a and 2007b). Current and former vessel names were also used to identify vessels in activity records that were lacking IMO (International Maritime Organization) ID numbers. Vessel averages by vessel type were used if data were missing; if main engine speed data were missing it was assumed that they were slow speed engines. Ship auxiliary boiler power ratings were assigned averages developed by Starcrest (Starcrest 2007a and 2007b) from the vessel boarding program.

The 2008 inventory used average auxiliary engine power from the 2005 ARB Ocean Going Vessel Survey. In the current inventory, approximately 60% of ship auxiliary engine power ratings are based on auxiliary power generation capacity from the Lloyds-Fairplay PC Register database (Lloyds-Fairplay, 2007). Another 15% of ships have auxiliary engine power ratings from the Port of Los Angeles/Port of Long Beach vessel boarding program, and the remaining ships utilize the average power ratings from the 2005 survey.

Table II-4 Average Vessel Characteristics

Vessel Type	Speed	Main Power	Auxiliary Power	Boiler Power
	(knots)	(kilowatts)		
Auto	19	11593	2999	278
Bulk	15	7803	2459	82
Container	23	37265	8156	380
Cruise	21	0	44042	750
General	15	7580	1799	99
Reefer	20	11091	3605	348
Ro-ro	18	12181	2605	82
Tanker	15	13034	2339	1593

Table II-4 summarizes the average vessel speed and main engine, auxiliary engine, and boiler power by vessel type. For boilers, fuel use rates were converted to equivalent kilowatts.

4. Load Factor

a. Main Engines

At cruise speed, the main engine load is 82.5%; as has been previously described, this estimate was based on a vessel boarding program and survey done by Starcrest as part of the POLA and POLB inventories (Starcrest 2005, 2007a and 2007b). At higher loads, fuel consumption and engine maintenance costs go up dramatically, so vessel operators tend to operate at this level. At slower speeds, main engine load was calculated using the propeller law, which states that propulsion load varies by the cube of the vessel speed. Main engine load was calculated by dividing the actual vessel speed by the maximum vessel speed and cubing the result.

At main engine loads of less than 20%, engine emissions are multiplied by an adjustment factor which accounts for higher emission rates at low loads. The adjustment factor is calculated using an exponential equation developed by Sierra Research for the U.S. Environmental Protection Agency (USEPA, 2000).

b. Auxiliary Engines

The auxiliary engine load factor represents the actual engine power used divided by the total installed auxiliary engine power. Table II-5 shows the load factors, in percent, by vessel type.

The primary source of data on auxiliary engine load was the 2005 and 2007 ARB OGV surveys and the vessel boarding program done by Starcrest for the Port of Los Angeles and the Port of Long Beach emission inventories (Starcrest 2005, 2007a and 2007b).

Table II-5: OGV Auxiliary Engine Load Characteristics (percent load)

Vessel Type	Load Factor (%)		
	Hoteling	Maneuvering	Transit
Auto Carrier/Ro-Ro	26%	45%	15%
Bulk Carrier/General Cargo	10%	45%	17%
Container Ship	18%	50%	13%
Passenger	16%	64%	80%
Reefer	32%	45%	15%
Tanker	26%	33%	24%

5. Emission Factors

Emission factors for OGVs vary by pollutant, operating mode (transit, maneuvering, or hoteling), engine type (main engine/slow speed, main engine/medium speed, or auxiliary/medium speed), and fuel type (heavy fuel oil-HFO or marine distillate). Emission factors for diesel particulate matter (PM), oxides of nitrogen (NOx), sulfur dioxide (SO2), hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO2) were compiled. Emission factors for main and auxiliary engines of ocean-going vessels are expressed as grams of pollutant emitted per kilowatt-hour of energy (g/kW-h). Although emission factors for auxiliary boilers are usually expressed in terms of grams of pollutant emitted by metric tonne of fuel burned, they were converted to g/kW-h using a methodology defined by Starcrest (Starcrest, 2007a).

Tables II-6, II-7, and II-8 below present the emission factors used in the development of the ocean-going vessel emissions inventory. Table II-6 presents the emission factors for main engines during transit or high load operation while at sea. If data on main engine speed for a given vessel was not known, it was assumed the engine was slow speed.

Table II-6: Main Engine Emission Factors – Transit Mode (g/kW-hr)

Engine Speed	Fuel	CH_4	CO	CO_2	NO_x	PM_{10}	$PM_{2.5}$	ROG	SO_x
Slow	Marine Distillate (0.1% S)	0.07	1.10	588	17.0	0.25	0.23	0.78	0.36
Slow	Marine Distillate (0.5% S)	0.07	1.10	588	17.0	0.38	0.35	0.78	1.90
Slow	Heavy Fuel Oil	0.08	1.38	620	18.1	1.50	1.46	0.69	10.50
Medium	Marine Distillate (0.1% S)	0.08	1.10	645	13.2	0.25	0.23	0.65	0.40
Medium	Marine Distillate (0.5% S)	0.08	1.10	645	13.2	0.38	0.35	0.65	2.08
Medium	Heavy Fuel Oil	0.09	1.10	677	14.0	1.50	1.46	0.57	11.50
High	Marine Distillate (0.1% S)	0.08	1.10	645	12.1	0.25	0.23	0.65	0.40
High	Marine Distillate (0.5% S)	0.08	1.10	645	12.1	0.38	0.35	0.65	2.08
High	Heavy Fuel Oil	0.09	1.10	645	12.7	1.50	1.46	0.23	11.50

Table II-7 presents the emission factors for main engines during maneuvering or low load operation near ports.

Table II-7: Main Engine Emission Factors –Maneuvering (g/kW-hr)

Engine Speed	Fuel	CH_4	CO	CO_2	NO_x	PM_{10}	$PM_{2.5}$	ROG	SO_x
Slow	Marine Distillate (0.1% S)	0.07	1.10	588	17.0	0.25	0.23	0.78	0.36
Slow	Marine Distillate (0.5% S)	0.07	1.10	588	17.0	0.38	0.35	0.78	1.90
Slow	Heavy Fuel Oil	0.08	1.38	620	18.1	1.50	1.46	0.69	10.50
Medium	Marine Distillate (0.1% S)	0.08	1.10	645	13.2	0.25	0.23	0.65	0.40
Medium	Marine Distillate (0.5% S)	0.08	1.10	645	13.2	0.38	0.35	0.65	2.08
Medium	Heavy Fuel Oil	0.09	1.10	677	14.0	1.50	1.46	0.57	11.50
High	Marine Distillate (0.1% S)	0.08	1.10	645	12.1	0.25	0.23	0.65	0.40
High	Marine Distillate (0.5% S)	0.08	1.10	645	12.1	0.38	0.35	0.65	2.08
High	Heavy Fuel Oil	0.09	1.10	645	12.7	1.50	1.46	0.23	11.50

Table II-8 presents the emission factors for auxiliary engines, including diesel-electric vessels. As shown in the table, the emission factors for auxiliary engine vary depending on the type of fuel used.

Table II-9 presents the emission factors for auxiliary boilers, which use heavy fuel oil. These emission factors were converted to grams per kilowatt hour from grams per tonne of fuel using methodology developed by Starcrest (Starcrest, 2007a).

Table II-8: Auxiliary Engine Emission Factors – Transit, Maneuvering, and Hotelling (g/kW-hr)

Engine Speed	Fuel	CH_4	CO	CO_2	NO_x	PM_{10}	$PM_{2.5}$	ROG	SO_x
Medium	Marine Distillate (0.1% S)	0.09	1.10	690	13.9	0.25	0.23	0.52	0.40
Medium	Marine Distillate (0.5% S)	0.09	1.10	690	13.9	0.38	0.35	0.52	2.10
Medium	Heavy Fuel Oil	0.09	1.10	722	14.7	1.50	1.46	0.46	11.10

Table II-9: Auxiliary Boiler Emission Factors (g/kW-hr)

Fuel	CH_4	CO	CO_2	NO_x	PM_{10}	$PM_{2.5}$	ROG	SO_x
Heavy Fuel Oil	0.03	0.20	970	2.1	0.80	0.78	0.11	16.50

The emission factors for main engines, auxiliary engines and auxiliary boilers used by ARB staff are generally consistent with the emission factors used by Starcrest in developing the 2005 Port of Los Angeles emissions inventory and the updates done in 2007. The Starcrest emission factors were based on work done by Entec (Entec, 2002). The Entec emission factors were developed using Lloyd's of London and IVL Swedish Environmental Institute data that related emissions to engine speed and the type of fuel used.

ARB staff developed an alternate particulate matter emission factor for engines burning heavy fuel oil based upon an extensive review of emission tests described in scientific literature. This emission factor, set at 1.5 grams/kilowatt-hour, is based upon the use of HFO fuel with 2.5% sulfur content. The basis of this emission factor is fully described in a white paper written by ARB staff in 2007, which is available on the ARB web site (CARB, 2008).

For CO emissions from the main engines during transit, staff elected to use a U.S. EPA emission factor published in the Environ report (Environ, 2007). This emission factor is consistent with the CO emission factors used by Starcrest for the Port of Los Angeles emission inventory (Starcrest, 2005).

6. Fuel Consumption

It was assumed that all main engines and auxiliary boilers burned heavy fuel oil. The main engine assumption was based on the 2005 ARB OGV survey; the auxiliary boiler assumption was based on communications with boiler manufacturers. For auxiliary engines, it was assumed that 92% of cruise ships burned heavy fuel oil and 8% distillate. For all other ships, it was assumed that 71% use heavy fuel oil and 29% use distillate in their auxiliary engines. These data were obtained from the 2005 ARB OGV survey.

Table II-10 Fuel Consumption Rates (g/kW-hr)

Engine	Engine Speed	Mode	Fuel	Fuel Use Rate
Auxiliary	All	All	Marine Distillate	217
	All	All	Residual	227
Boiler	N. A.	All	Residual	305
Main	High	Transit	Residual	213
	Medium	Transit	Marine Distillate	203
	Slow	Transit	Marine Distillate	185
	Medium	Transit	Residual	213
	Slow	Transit	Residual	195
	High	Maneuvering	Residual	213
	Medium	Maneuvering	Marine Distillate	203
	Slow	Maneuvering	Marine Distillate	185
	Medium	Maneuvering	Residual	213
	Slow	Maneuvering	Residual	195

Fuel consumption rates were obtained from Entec (Entec, 2002) and vary by engine, engine speed, and mode of operation. Fuel use rates are expressed in the same units as emission factors; in grams per kilowatt hour. Table II-10 summarizes the fuel consumption rates used.

7. Growth rate

Growth rates were estimated by vessel type and by port. These growth rates were based upon an analysis of US Army Corps of Engineers vessel call data (USACE, 2006) between the years 1994-2005. The total net registered tonnage (NRT), a measure of the volume of cargo a ship can carry, was determined by vessel type and by port. Previous ARB OGV growth rates were based on total installed main engine power determined from vessel call data between the years 1997 and 2003. Growth in NRT is directly proportional to growth in installed power. NRT was used to estimate growth because it was not possible to determine main engine power for many of the records; in contrast, NRT data was available for almost 99% of the records analyzed. The growth rates selected are the midpoint between the best fit compounded annual growth rate in NRT between 1994 through 2005 and the best fit linear (arithmetic) growth rate in NRT for the same time period. The sum of growth of all California ports was set to equal to the statewide growth with the assumption that the ports will grow proportionally to their historical NRT growth between the years 1994-2005.

Growth rates developed using this methodology were checked and verified against other studies, including the Port of Los Angeles and Port of Long Beach emission inventory updates done in 2007 (Starcrest, 2007a and 2007b), the Port of San Diego emission inventory (Starcrest, 2007c), and the Port of Oakland emission inventory (Environ, 2007).

Table II-11 Growth Rates by Port and Vessel Type

Port	Auto	Bulk	Container	Cruise	General	Reefer	Roro	Tanker
Avalon/Catalina				3.9%				1.0%
Carquinez	-4.0%	-0.7%	-4.0%		0.3%		-4.0%	-0.9%
El Segundo								5.4%
Hueneme	5.9%	-27.0%	8.3%	7.3%	8.3%	1.4%	5.9%	5.0%
Humboldt		-13.4%		0.0%	-0.7%			
Los Angeles-Long Beach	1.4%	-2.3%	6.8%	3.9%	1.0%	-8.0%	1.4%	1.0%
Monterey				0.0%	0.0%			
Oakland		-3.8%	4.4%		4.4%		4.4%	
Pacific Lightering Zone								5.4%
Redwood		5.2%			5.2%			
Richmond	-1.4%	-3.8%	-5.4%		-5.4%		-1.4%	0.0%
Sacramento		-5.4%			-1.9%		-1.9%	-2.1%
San Diego	4.0%	1.5%	6.8%	8.7%	2.7%	7.0%	4.0%	5.0%
San Francisco	-0.9%	3.4%	-0.9%	5.3%	-0.9%	0.0%	0.0%	0.0%
Stockton		3.4%			1.9%	1.9%		5.3%

Table II-11 summarizes the growth rates by port and by vessel type. Growth rates are stated in this table as annual compound growth rates.

The economic recession that officially started in December of 2007 and ended in June 2009 was the most severe since the Great Depression, and had a severe impact on industries throughout California. In addition to the methodological improvements staff incorporated the impacts of the recession on OGV emissions.

To forecast activity following the recession, staff developed three recovery scenarios to encompass the possible rate of growth ("fast", "slow", and "average"). The fast recovery scenario assumed that total activity would return to projected historically average levels in 2017 and then grow at the historical average rate. A return to trend by 2017 was based on the Congressional Budget Office forecast which indicated that real gross domestic product at a nationwide level will converge with potential gross domestic product trends no later than 2015. This forecast was modified with the assumption that California's recovery will lag the nation by several years, yielding the 2017 recovery date assumed for the fast recovery scenario. For the slow recovery scenario, staff assumed that activity would be permanently depressed relative to historical levels, but continue to grow at the growth rate in the 2009 San Pedro Bay Ports Forecast Update beginning in 2011(Tioga, 2009). The average scenario is the average of the fast and slow scenarios.

The impact of the recession on net registered tonnage in 2009 was estimated from port call and TEU data spanning January 1, 2009 through July 31, 2009 and scaling the results to the entire year. These totals were then checked at the beginning of 2011 with the final totals from 2009 and 2010.

Given the uncertainty in forecasting emissions after such a deep recession, staff relied on the average recovery scenario. This scenario, for the years of interest for these regulatory amendments, is also supported by the most recent San Pedro Bay forecasts.

8. Control Measures

There are several control measures built into the ship inventory:

- 1997 MARPOL Annex VI Emission Standards (IMO Tier 1)
- 2004 Los Angeles/Long Beach 20 nm Voluntary Speed Reduction Zone
- 2005 US EPA Category 3 Engine Standards (MARPOL Annex VI)
- 2005 Auxiliary Engine Regulation (not currently enforced)
- 2007 Shore Power Regulation
- 2009 Los Angeles/Long Beach 40 nm Voluntary Speed Reduction Zone
- 2012 North American Environmental Control Area

The 1997 MARPOL standards were established by the International Maritime Organization (IMO) at the International Convention on the Prevention of Pollution from Ships", known as MARPOL. It provides for limits on NOx emissions from ships, depending on engine speed. For slow speed engines, NOx is limited for ships built after 1999 to 17 gms/kw-hr, which is a six percent reduction.

The Los Angeles/Long Beach Voluntary Speed Reduction (VSR) Zone was established by the Southern California Marine Exchange (MXSOCAL) in 2004. This is a voluntary control measure which requests that ships not exceed a speed of 12 knots within 20 nautical miles of Point Fermin. In 2009, this zone was expanded to 40 nautical miles from Point Fermin. This inventory calculates the benefits of this control by the inclusion of ship and port call specific speed data obtained from the Southern California Marine Exchange. The approximate compliance rate for the 2006 base year was 65%. For forecasted years, it was assumed that full compliance would be attained by 2014.

	%Compliance	
Year	**0-20nm**	**20-40nm**
2005	48%	0
2006	65%	0%
2007	72%	0%
2008	81%	0%
2009	91%	48%
2010	100%	63%
2011	100%	70%
2012	100%	80%
2013	100%	90%
2014	**100%**	**100%**

The 2005 US EPA category 3 standards are an implementation of the International Maritime Organization (IMO) Tier 1 standards agreed to by 136 countries; the agreement is commonly known as MARPOL Annex VI (MARPOL stands for Marine Pollution). Ships built on or after 2000 are required to emit approximately 6-12% less NOx, depending on engine speed. In 2008, the IMO expanded the tier 1 standard to apply retroactively to ships built before 2000, and also added a Tier 2 standard which applies to ships built after 2010, and a Tier 3 standard which applies to post-2015 ships in environmental control areas (ECAs). IMO Tier 2 and Tier 3 standards are not included in this inventory in this document for consistency with the inventory used for modeling.

In 2005, the ARB approved a regulation which requires ship auxiliary engines to use 0.5% sulfur fuel on or after 2007, and 0.1% sulfur after 2010. The final rule was approved by the Office of Administrative Law in October, 2007. Enforcement of the regulation was suspended in 2008 due to a legal challenge. The regulation was enforced for 7 months in 2007, and for 116 days in 2008.

In 2007, the ARB approved a regulation which requires container ships, cruise ships, and reefer ships visiting five California ports to use shore power. Fleets with less than 25 visits per year are exempt; ships are permitted 3 hours of auxiliary engine use per visit after the regulation goes into effect. By 2014, fleets are required to use shore power for 50% of visits; by 2020, they are required to use shore power for 80% of visits.

In 2010, the International Maritime Organization officially accepted the North American Environmental Control Area (ECA), beginning in August, 2012. At that date, the sulfur content of fuel will be limited to 1% sulfur within 200 nautical miles of the coastline; in 2015, this limit will drop to 0.1% sulfur. Also, Tier III NOx emission standards, requiring advanced emission controls such as SCR systems, will have to be met in the ECA for ships built on or after 2016.

For standards based on age of the ship, it was assumed for forecasting purposes that the age profile by ship type will be the same as the average age profile for ships observed for the years 2004-2006. This assumption will be revisited as new data is received; the recession has delayed new ship orders and it is likely that compliance rates for the IMO NOx standards will be less since ship fleets will tend to be older.

B. Methodology

The basic equation used for estimating emissions from ocean-going vessels is:

$$E_{y, t, om, e} = \Sigma\ Pop_{t} * EF_{e, om, f} * Hrs_{om, t} * VP_{om, t} * \%Load_{om, t}$$

where

E	=	pollutant specific emissions (tons per year of NOx, HC, CO2, SO2, and diesel PM)
Pop	=	population of ocean-going vessels by vessel type
EF	=	emission factor by engine type, operating mode, and fuel (units of glkw-hr)
Hrs	=	average annual use in hours by operating mode and vessel type
VP	=	average power by operating mode and vessel type
% Load	=	average engine load by operating mode and vessel type
y	=	inventory year
om	=	operating mode (transit, maneuvering, hoteling)
t	=	vessel type (auto, container, bulk cargo, etc.)
f	=	fuel (HFO or MGO/MDO)
e	=	engine type

Each of these elements, and how they were incorporated into the ocean-going vessel emission estimates, are discussed below.

III. Results

A. Emissions in the 100 nautical mile CEIDARS zone

Ship emissions presented here include all emissions within the 100 nautical mile zone used for the CEIDARS database system and for State Implementation Plan (SIP) purposes. They include the benefits of the 2007 Shore Power Regulation, the benefits of the San Pedro Bay Ports voluntary vessel speed reduction program, the proposed benefits of the current proposal, the fuel-related benefits of the North American Environmental Control Area (ECA), but not the NOx benefits of IMO Tier 3 engine standards.

Emissions are presented for the years 2005, 2010, and 2015. Table III-1 summarizes ship emissions by district. It is important to note here that the assignment of emissions to districts is for comparison purposes only. The ARB California Emissions Inventory Data and Reporting System (CEIDARS) emission inventory database requires emissions occurring in the Outer Continental Shelf (OCS) Air Basin to be assigned to specific counties and specific air pollution control districts. It is important to note that meteorology defines how OCS emissions impact land; assignment of specific OCS areas to counties and districts is done for database reasons and for comparison, and not to indicate that a specific county or district is either responsible or impacted by a specific OCS area. There exists no official federal or state governmental assignment of OCS waters to specific counties, districts or air basins.

Table III-1
Total Emissions by District in 100 nm Regulatory Zone

2005 Total Emissions in 100 nm Zone				
District	NOx	PM2.5	SOx	CO2
	tons/day			mmtCO2
Bay Area AQMD	44.3	4.0	32.3	0.7
Mendocino County AQMD	9.3	0.8	5.7	0.1
Monterey Bay Unified APCD	17.8	1.5	10.9	0.2
North Coast Unified APCD	14.0	1.2	8.6	0.2
Northern Sonoma County APCD	4.2	0.3	2.5	0.0
San Diego County APCD	5.1	0.5	3.8	0.1
San Joaquin Valley Unified APCD	0.1	0.0	0.1	0.0
San Luis Obispo County APCD	11.4	1.0	6.9	0.1
Santa Barbara County APCD	53.1	4.5	32.1	0.6
South Coast AQMD	44.8	4.6	42.8	0.9
Ventura County APCD	16.1	1.4	10.1	0.2
Yolo/Solano AQMD	0.2	0.0	0.2	0.0
Total	**220.2**	**19.6**	**155.8**	**3.2**
2010 Total Emissions in 100 nm Zone				
District	**NOx**	**PM2.5**	**SOx**	**CO2**
	tons/day			**mmtCO2**
Bay Area AQMD	39.2	1.6	10.3	0.6
Mendocino County AQMD	8.2	0.3	1.8	0.1
Monterey Bay Unified APCD	16.7	1.2	8.1	0.2
North Coast Unified APCD	12.5	0.6	3.8	0.2
Northern Sonoma County APCD	3.8	0.1	0.5	0.0
San Diego County APCD	4.7	0.1	0.7	0.1
San Joaquin Valley Unified APCD	0.1	0.0	0.0	0.0
San Luis Obispo County APCD	10.8	0.8	5.9	0.1
Santa Barbara County APCD	51.5	2.2	14.4	0.6
South Coast AQMD	37.8	1.1	7.3	0.8
Ventura County APCD	15.1	0.3	1.8	0.2
Yolo/Solano AQMD	0.1	0.0	0.1	0.0
Total	**200.5**	**8.3**	**54.8**	**2.9**
2015 Total Emissions in 100 nm Zone				
District	**NOx**	**PM2.5**	**SOx**	**CO2**
	tons/day			**mmtCO2**
Bay Area AQMD	50.0	0.8	1.6	0.7
Mendocino County AQMD	10.9	0.2	0.2	0.1
Monterey Bay Unified APCD	21.9	0.3	0.5	0.3
North Coast Unified APCD	16.2	0.2	0.4	0.2
Northern Sonoma County APCD	4.9	0.1	0.1	0.1
San Diego County APCD	6.1	0.1	0.2	0.1
San Joaquin Valley Unified APCD	0.1	0.0	0.0	0.0
San Luis Obispo County APCD	14.1	0.2	0.3	0.2
Santa Barbara County APCD	72.8	1.1	1.6	0.9
South Coast AQMD	43.8	0.9	2.7	0.9
Ventura County APCD	21.2	0.3	0.5	0.3
Yolo/Solano AQMD	0.1	0.0	0.0	0.0
Total	**262.3**	**4.2**	**8.1**	**3.7**

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