



Analysis of Goods Movement Emission Reduction Strategies

Task 1 Final Report

January 2008

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Prepared for

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1. Introduction

This report presents results from Task 1 of our project, “Environmental Mitigation Plan for Goods Movement in Southern California.” Under Task 1, we have identified and analyzed emission reduction strategies for goods movement. Our analysis focuses on the emission reduction benefit, cost, and cost-effectiveness of individual strategies.

This Task 1 Final Report revises the Draft Report dated May 14, 2007. The revisions are based on:

- New information that has become available since the draft report was completed (e.g., proposed new EPA locomotive emission standards),
- Comments received at three SCAG public meetings (in downtown Los Angeles, San Bernardino, and Wilmington) at which findings from the draft report were presented,
- Comments received directly from members of SCAG’s technical advisory committee for this study and other stakeholders,
- Comments provided by SCAG’s Goods Movement Task Force, and
- Comments provided by SCAG staff.

1.1. Scope of Task 1 Analysis

Our general approach to Task 1 can be summarized as follows:

- Review and summarize existing transportation and emission reduction regulations, plans, or studies related to the goods movement system in Southern California.
- Perform a qualitative screening review of goods movement emission reduction strategies identified in transportation plans, emission reduction regulation or plans, or past and ongoing studies for Southern California or other regions. The results of this screening review were presented in our Literature Review Technical Memorandum, final version dated September 20, 2006.
- Obtain and review existing emission inventories and emission forecasts for goods movement sources in order to develop a baseline of emissions, against which we can compare mitigation strategies.
- Perform in-depth analyses of emission reduction strategies, focused on emission reduction benefits, costs, and cost-effectiveness.

It should be noted that the cost effectiveness figures in the report are solely based upon emission reductions. The report does not consider other project impacts, such as safety, economic impacts, or congestion reduction benefits. These additional impacts would need to be considered when making decisions about strategy investments.

This report does not address the implementation feasibility of emission reduction strategies. We recognize that some of the strategies analyzed in this report have significant barriers to implementation. Likewise, the report does not address how the strategies will be implemented, such as whether regulatory or voluntary approaches would be used. Under Task 3 of our project, we will use the results of this report, together with an assessment of feasibility and SIP credit potential, in order to develop an action plan (discussed below) that offers recommendations for which strategies to pursue and the potential combined emissions benefit of a package of strategies.

This report considers emissions at a regional scale only (primarily the South Coast Air Basin). The study does not involve air quality modeling to determine how changes in emissions would affect air pollutant concentrations. For example, the location and timing of emissions affect ozone formation. These issues are considered outside the scope of this study.

Similarly, the study does not consider the localized impacts of emission reduction strategies. Some strategies might reduce regional-level emissions but increase emissions in certain locations (e.g., particulate matter hot spots). By extension, this study does not examine the public health impacts of emission reduction strategies.

1.2. Study Context and Next Steps

SCAG recognizes that other agencies are developing or implementing plans, regulations, and other initiatives to address goods movement emissions in Southern California (see Section 1.4 for a summary of major efforts). Likewise, there are numerous agencies and organizations that have jurisdictional authority to implement goods movement emission reduction strategies. This study is intended to complement these other efforts. SCAG has responsibility for ensuring that the long-term transportation planning requirements for emission reductions from on-road mobile sources are met by SCAG's Regional Transportation Plan (RTP). SCAG also has responsibility to ensure that the short-term implementation requirements of the Transportation Conformity Rule are met by SCAG's biennial Regional Transportation Improvement Program (RTIP). The purpose of this overall study is to help SCAG and other agencies achieve the region's air quality goals as they make decisions about investments in the region's transportation infrastructure.

The remaining efforts in this study (Tasks 3 and 4) will focus on developing a plan to mitigate the emissions from the goods movement infrastructure planned by SCAG. SCAG is currently considering three types of goods movement system improvements: dedicated lanes for clean technology trucks, railroad mainline improvements, and an advanced technology container movement system. The action plan to be developed in Tasks 3 and 4 will provide decision makers with information to help mitigate the adverse air quality impacts of these systems.

Since the advanced technology container movement system would, by design, produce relatively few local emissions, the action plan will focus on truck and railroad emission reduction strategies. The action plan will not focus on emissions sources operating entirely within the ports (cargo handling equipment) or marine vessels (ocean going vessels and harbor craft), because these sources are being addressed by the ports and CARB, and because SCAG does not (directly) plan for improvements to these systems. Similarly, the action plan will focus on trucks and locomotives operating throughout the region, and not the trucks and locomotives that primarily serve the ports, since emission reduction strategies for the latter are being developed in detail as part of the ports' Clean Air Action Plan (reviewed below).

The action plan created in Tasks 3 and 4 will clearly describe the benefits, costs, and feasibility of emission reduction strategies that could be implemented in some future year (e.g., 2020). Thus, it will present the maximum emission reduction that could be achieved through the strategy, the total cost, and cost-effectiveness. It will identify the highest priority emission reduction strategies for the region's truck and railroad systems. For strategies that have many variants (such as various retrofit technologies), the plan will bundle the appropriate variants into a package that can be easily communicated to and understood by decision makers.

1.3. Overview of Goods Movement Emissions

Goods movement is currently responsible for 37% of total NO_x emissions in the South Coast Air Basin and 15% of total PM_{2.5} emissions. (According to current emission inventories, the bulk of PM-2.5 comes from road dust, wildfires, and construction activity.) Changes in goods movement emissions over time are driven by changes in activity levels, which are growing across all modes, and changes in average emission factors, which are declining for most modes.

Heavy-duty trucks are currently the largest source of goods movement emissions. However, as trucks meeting the stringent 2007/2010 EPA emission standards come to dominate the fleet, NO_x and PM emissions from trucks will drop markedly, despite growth in truck VMT. By 2030, total NO_x emission from goods movement trucks in the region will drop to 25% of 2005 levels under the baseline emissions forecast. In contrast, emissions from ocean-going vessels (OGVs) will continue to grow, absent additional control measures. In 2030, OGV emissions in the South Coast Air Basin will be three times current levels. By 2020, OGVs will surpass trucks as the largest source of goods movement NO_x and PM in the region. Locomotive emissions will also grow over the next two decades without additional control measures. Harbor craft and port cargo handling equipment (CHE) emissions will decline.

In order to estimate a baseline inventory and forecast of goods movement emissions, we relied primarily on the 2007 Air Quality Management Plan (AQMP) for the South Coast Air Basin, which contains annual emissions by source type to 2030.¹ However, the AQMP lumps together ocean going vessels and commercial harbor craft, so we obtained emissions from those sources from ARB's emission inventory. In addition, the AQMP does not distinguish cargo handling equipment emissions from other off-road mobile sources, so we obtained cargo handling equipment from ARB's *Emission Reduction Plan for Ports and Goods Movement in California*.²

It should be noted that the Port of Long Beach and Port of Los Angeles have both prepared detailed inventories of goods movement emissions at the ports for the year 2005.^{3 4} Because these inventories do not include emissions forecasts, and because they do not cover all goods movement activity within the region, we have not used these inventories for the purposes of analyzing strategy impacts.

Figure 1-1 shows South Coast goods movement NO_x emissions by source from 2010 to 2030. Total goods movement NO_x emission will drop between 2005 and 2020, but then increase by 2030.

¹ South Coast Air Quality Management District (2007)

² California Air Resources Board (2006c)

³ Port of Long Beach (2007)

⁴ Port of Los Angeles (2007)

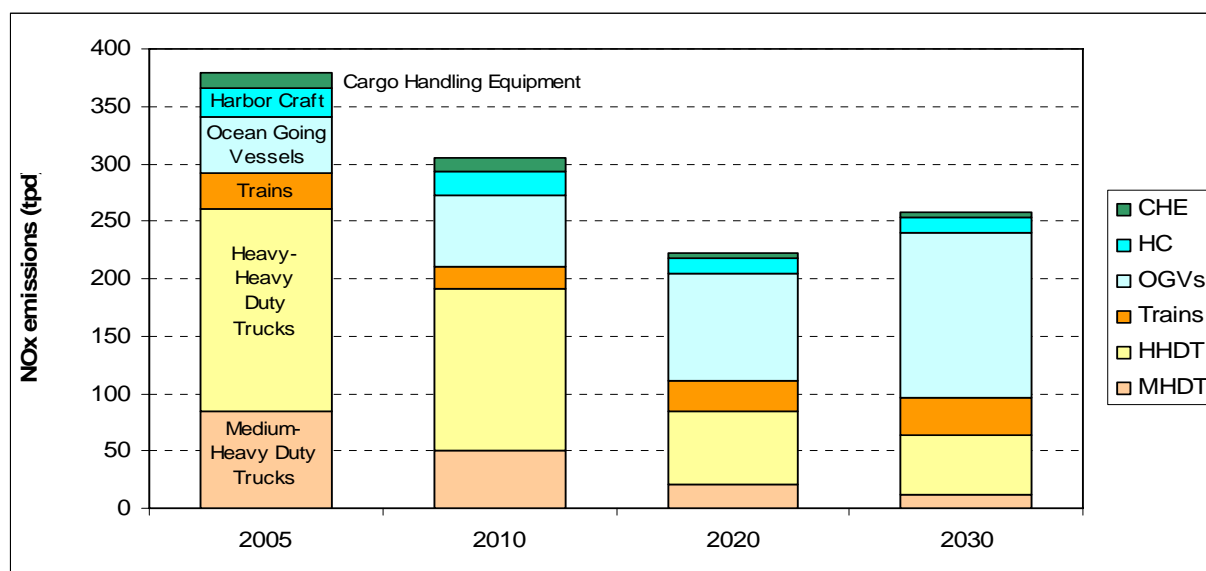
Figure 1-1: South Coast Air Basin NO_x Emissions from Goods Movement Sources

Figure 1-2 shows a similar pattern for South Coast goods movement PM-2.5 emissions. Absent additional control measures, PM emissions from goods movement will be higher in 2030 than in 2005, 2010, or 2020. Figure 1-2 illustrates the dramatic growth in the contribution of ocean going vessels to total goods movement emissions, with a share rising from 24% in 2005 to 73% in 2030.

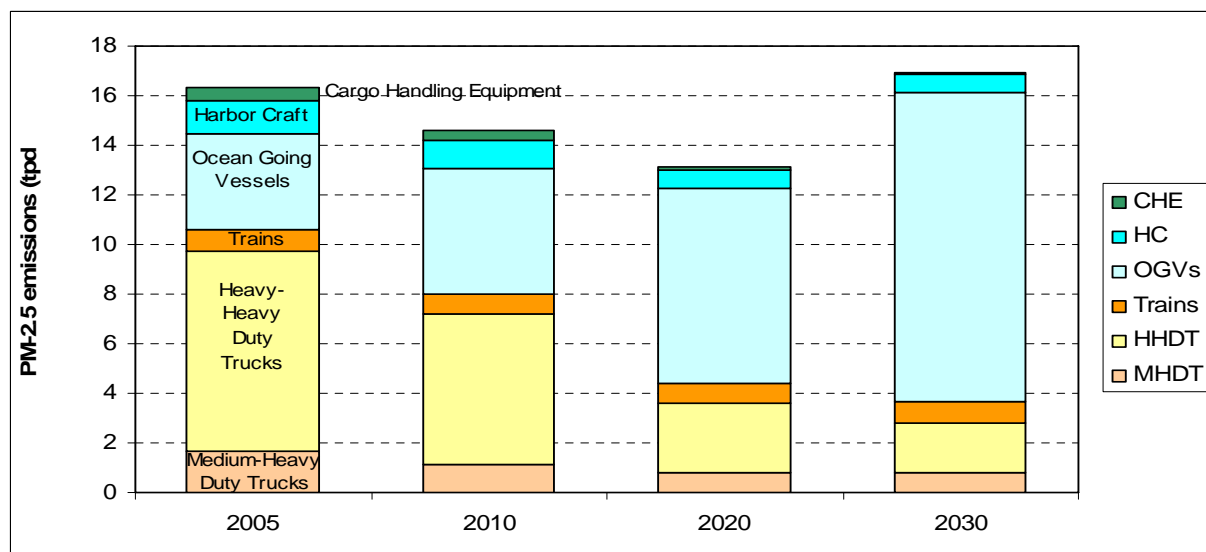
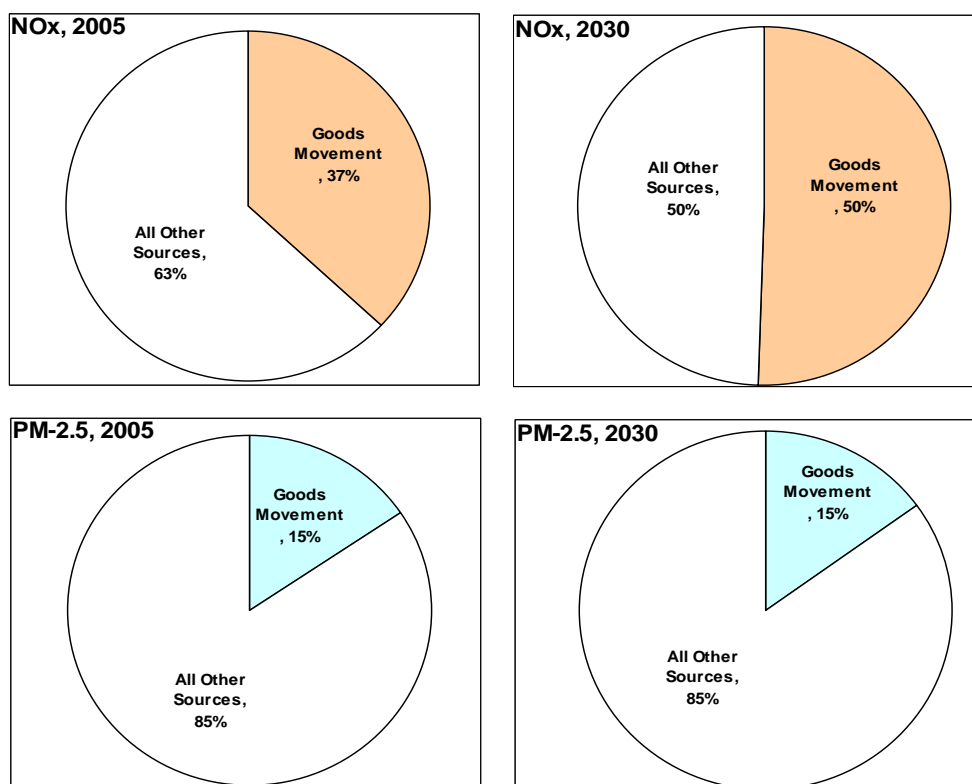
Figure 1-2: South Coast Air Basin PM_{2.5} Emissions from Goods Movement Sources

Figure 1-3 shows goods movement emissions as a percent of total (anthropogenic) emissions in the Basin.

Figure 1-3: Contribution of Goods Movement to Total South Coast Air Basin Emissions

1.4. Related Efforts

There are numerous other on-going and recent efforts in Southern California to address the contribution of goods movement to the region's air quality problems. In particular, since this project was initiated, several key documents have been released that describe goods movement emission reduction strategies. These key documents are reviewed below.

San Pedro Bay Ports Clean Air Action Plan

In November 2006, the Ports of Los Angeles and Long Beach released the first *San Pedro Bay Ports Clean Air Action Plan*.⁵ This plan describes the measures that the two ports will take to reduce emissions related to port operations. The Clean Air Action Plan (CAAP) reflects an unprecedented degree of high-level cooperation between the ports on air quality issues. The South Coast Air Quality Management District (AQMD), California Air Resources Board (CARB), and U.S. Environmental Protection Agency (U.S. EPA) assisted in developing the plan.

The CAAP is a five-year action plan that identifies goals, emission reductions, and budgetary needs for FY 2006/2007 through FY 2010/2011. It includes 12 source-specific control measures, summarized in Table 1-1.

⁵ Port of Los Angeles and Port of Long Beach (2006)

Table 1-1: Control Measures in Clean Air Action Plan

Source	Measure Number	Name
Trucks	SPBP-HDV1	Performance Standards for On-Road Heavy-Duty Vehicles
	SPBP-HDV2	Alternative Fuel Infrastructure for Heavy-Duty Natural Gas Vehicles
Ocean-Going Vessels	SPBP-OGV1	OGV Vessel Speed Reduction (VSR)
	SPBP-OGV2	Reduction of At-Berth OGV Emissions
	SPBP-OGV3	OGV Auxiliary Engine Fuel Standards
	SPBP-OGV4	OGV Main Engine Fuel Standards
	SPBP-OGV5	OGV Main & Auxiliary Engine Emissions Improvements
Cargo-Handling Equipment	SPBP-CHE1	Performance Standards for CHE
Harbor Craft	SPBP-HC1	Performance Standards for Harbor Craft
Railroads	SPBP-RL1	PHL Rail Switch Engine Modernization
	SPBP-RL2	Existing Class 1 Railroad Operations
	SPBP-RL3	New and Redeveloped Rail Yards

Source: San Pedro Bay Ports Clean Air Action Plan, November 2006.

The CAAP also includes a Technology Advancement Program, envisioned as “the catalyst for identifying, evaluating, and demonstrating/piloting new and emerging emissions reduction technologies/strategies that could then be utilized in future updates to the Clean Air Action Plan as new control measures, alternatives to existing strategies, or as additional mitigation options for new projects.”

In April 2007, the ports announced a Clean Truck Program that is intended to implement many of the goals for reducing truck emissions contained in the CAAP. The program would allow only licensed “clean” truck concessions access to terminals without paying a new Truck Impact Fee. A concession trucking fleet would be required to meet CAAP “clean truck” standards (i.e., diesel trucks manufactured in 2007 or newer, retrofitted trucks manufactured in 1994 to 2006, or Gateway Cities program trucks). In addition, progressive bans of older trucks would phase in starting in 2008.

If implemented as planned, the CAAP would reduce port-related truck, OGV, and CHE emissions of NO_x and diesel particulate matter by 46% and 52%, respectively, as compared to baseline emissions in 2011 that incorporate all existing regulations. (Reductions from railroads and harbor craft are not fully quantified in the plan.)

The total cost of the plan is estimated to be \$2 billion, or approximately \$500 million per year from FY 2007/08 through FY 2010/11. The vast majority of funds (87.5%) target heavy-duty vehicles, with another 10% targeting OGVs. More than three quarters (77.5%) of the funds would come from bonds and impact fees. The two ports would contribute approximately 20% of the necessary funds.

2007 Air Quality Management Plan

On June 1, 2007, the Governing Board of the South Coast Air Quality Management District adopted the *2007 Air Quality Management Plan* (AQMP).⁶ The AQMP is prepared every three years and is submitted to CARB for inclusion in the State Implementation Plan (SIP). The AQMP estimates current and projected baseline emissions as well as the emission reduction targets necessary to achieve attainment of the PM_{2.5} and 8-hour ozone standards. These targets are shown in Table 1-2.

⁶ South Coast Air Quality Management District (2007)

Table 1-2: Emission Reduction Targets for Attainment, South Coast Air Basin (tons per day)

Standard and Date	NO _x	VOC	PM _{2.5}	SO _x
PM _{2.5} Standard, by 2014	192	59	14	24
Ozone Standard, by 2023	383	116	N/A	N/A

Source: Final 2007 Air Quality Management Plan.

The AQMP identifies emission control strategies that fall under AQMD's jurisdiction. Several of these relate to goods movement, including a control measure based on implementation of the Carl Moyer Program. This involves projects such as on-road heavy-duty vehicle modernization, installation of retrofit units, and engine repowers.

The AQMP also identifies proposed a Goods Movement Control Measure developed as part of SCAG's on-going Goods Movement Program. This measure has two components:

- High Speed Transport System – This involves a high performance, environmentally sensitive regional movement system based on the introduction of a high speed regional transport system (HSRT). This system is envisioned to move both cargo and people throughout the region, with zero local emissions.
- Truck-Only Lanes – SCAG is formulating a business plan for a regional system of dedicated lanes for clean technology trucks, comprising 142 center-line miles of dedicated truck lanes extending from the San Pedro Bay ports eastward toward Barstow. Truck-only lanes would potentially allow each truck to carry multiple containers, improving the efficiency and financial viability of the system. Trucks using these facilities would be required to utilize alternative clean technology.

CARB Emission Reduction Plan for Ports and Goods Movement in California

In April 2006, the California Air Resources Board approved the *Emission Reduction Plan for Ports and Goods Movement in California*.⁷ The plan establishes the following statewide and Southern California goals related to goods movement emissions:

- Statewide 2010 Goal: Reduce projected 2010 statewide emissions of diesel PM, NO_x, SO_x, and ROG from ports and goods movement to 2001 levels or below.
- Statewide 2020 Goal: Reduce the health risk from diesel PM from ports and goods movement by 85%, compared to 2000 levels.
- South Coast 2015 Goal: Reduce projected 2015 emissions of NO_x from ports and international goods movement in the South Coast by 30 percent to aid attainment of the federal PM_{2.5} standards.
- South Coast 2020 Goal: Reduce projected 2020 emissions of NO_x from ports and international goods movement in the South Coast by 50 percent to aid attainment of the federal 8-hour ozone standard.

Most of the plan focuses on regulatory strategies to reduce emissions from trucks, locomotives, ocean-going vessels, and harbor craft. Table 1-3 lists the strategies included in the plan.

⁷ California Air Resources Board (2006c)

Other Efforts

In addition to these efforts, SCAG and other agencies have commissioned or participated in a variety of studies that examine potential improvements to the efficiency of goods movement in Southern California. A number of these studies provided information that was used in this report and are referenced throughout the report.

Table 1-3: Strategies in CARB's Emission Reduction Plan for Ports and Goods Movement

Source	Implementation Possible By	Strategies
Ocean Going Vessels	2010	ARB Rule for Ship Auxiliary Engine Fuel (Adopted Dec 2005) Cleaner Marine Fuels for Main Engines Emulsified Fuels Expanded Vessel Speed Reduction Programs Install Engines that Exceed IMO Standards in New Vessels Dedicate the Cleanest Vessels to California Service Shore Based Electrical Power
	2015	Extensive Retrofit of Existing Engines Highly Effective Emission Controls on Main Engines and Auxiliary Engines Sulfur Emission Control Area (SECA) or Alternative Build New Ships that Far Exceed IMO Standards or Expand the Use of Cleanest Vessels in California Service Expanded Shore Power and Alternative Controls
	2020	Full Use of Cleanest Vessels in California Service Maximum Use of Shore Power or Alternative Controls
Commercial Harbor Craft	2010	ARB Rule to Clean Up Existing Engines Shore Based Electrical Power
	2015	U.S. EPA or ARB New Engine Emission Standards
Cargo Handling Equipment	2010	ARB Cargo Handling Equipment Rule (Adopted Dec 2005) ARB Rule for Gas Industrial Equipment
	2015	Upgrade to 85 Percent Diesel PM Control or Better
	2020	Zero or Near-Zero Emission Equipment
Trucks	2010	ARB Private Truck Fleets Rule Port Truck Modernization Enhanced Enforcement of Truck Idling Limits ARB Rule for International Trucks (Adopted Jan 2006)
Locomotives	2010	Upgrade Engines in Switcher Locomotives Retrofit Diesel PM Control Devices on Existing Engines Use of Alternative Fuels
	2015	More Stringent National Requirements Concentrate Tier 3 Locomotives in California

Source: Emission Reduction Plan for Ports and Goods Movement in California, March 21, 2006.

1.5. Cost Effectiveness Methodology

We considered several methods for calculating cost-effectiveness, reviewed below.

ARB Carl Moyer Program Method

The method used to evaluate grant applications to the Carl Moyer Program considers only the annualized capital cost in the numerator of the cost effectiveness ratio.⁸ The capital cost in this case is the amount of the grant given to the applicant for retrofitting existing equipment or purchasing new, lower-emission equipment. The annualized capital cost (ACC) is calculated by the following formula:

$$ACC = CC \times CRF$$

where CC is the capital cost and CRF is the capital recovery factor. The CRF is defined as follows:

$$CRF = [(1 + i)^n i] / [(1 + i)^n - 1]$$

where n is the project life in years, and i is the interest rate (as a decimal fraction). ARB uses a 4% interest rate, which is based on the average annual yields for U.S. Treasury securities.

The annualized capital cost is, in essence, the amount of money that would have to be invested at the given interest rate and for the given number of years to earn a total equal to the capital cost. Another way of looking at capital recovery is that it is the number of dollars that would have to be set aside each year to repay the value lost due to depreciation, and to pay interest costs. Use of the ACC allows one to add the cost of capital and annual operating costs on the same basis. However, the Carl Moyer method does not include annual operating costs.

The denominator of the cost-effectiveness ratio is a weighted sum of the annual reduction in NO_x, ROG, and PM₁₀ emissions, with PM₁₀ weighted by a factor of 20. Thus, the formula for cost-effectiveness is:

$$\frac{\text{Annualized Capital Cost (in \$/year)}}{(\text{NO}_x \text{ reductions} + \text{ROG reductions} + 20 * \text{combustion PM}_{10} \text{ reductions}) \text{ (in tons/year)}}$$

Current Moyer Program guidelines cap cost-effectiveness at \$14,300 per ton. We determined this method was not appropriate for our analysis because it ignores operations and maintenance costs (which are significant for some strategies) and because it sums all pollutants and therefore does not indicate which strategies should be pursued as part of a plan for achieving PM attainment versus ozone attainment.

Annualized Cost Effectiveness Method

ARB and other agencies (such as U.S. EPA) often use a modified version of the Carl Moyer methodology to calculate the cost-effectiveness of rules and regulations. This involves calculating the annualized capital cost, as described above, and adding to that any annual operations and maintenance (O&M) cost. The denominator of the cost-effectiveness ratio is the annual reduction of individual pollutants. Thus, annual emission reduction cost-effectiveness is calculated separately for NO_x, ROG, and PM. If O&M costs or emission reductions vary by year, typically the first full year values are used. The formula for cost-effectiveness is:

⁸ California Air Resources Board (2005e)

$$\frac{\text{Annualized Capital Cost} + \text{Annual O\&M Cost (in \$/year)}}{\text{Annual emission reduction (in tons/year of NO}_x\text{, ROG, or PM)}}$$

This method is appropriate for assessing cost-effectiveness in a particular year. It works well for strategies that involve a one-time lump sum capital cost, constant O&M costs, and constant emissions benefits. Thus, this approach works well when analyzing the emissions benefits and costs at the level of an individual piece of equipment (engine, vehicle, vessel, etc.).

This method is less appropriate for strategies that involve capital costs spread over multiple years and varying from year to year, such as major infrastructure projects. It is also less appropriate for strategies that exhibit changes in O&M costs or emissions benefits over time.

South Coast AQMD BACT Analysis Method

In calculating costs as part of Best Available Control Technology determinations, SCAQMD uses the discounted cash flow method.⁹ In this method one first calculates the present value of all annual or operating costs over the life of the equipment. To this value, one then adds the initial capital cost. All BACT determinations use an interest rate of 4 percent and a 10-year equipment life. Annual costs include expenditures associated with raw materials, utilities (including fuel), waste treatment/disposal, labor, maintenance materials, replacement parts, plus indirect costs (overhead, insurance, etc.).

The present value of a future cost is calculated with the following formula:

$$NPV = C_j / (1 + i)^j$$

where C_j is the cost in year j and i is the interest rate. This calculation is performed for each year of the equipment life and then all the annual values are summed. Note that expenses are assumed to occur at the end of each year. This methodology can be applied for any number of years, not just the ten years that the SCAQMD uses. Also, costs can vary from year to year.

The denominator in the cost-effectiveness ratio is the sum of all emission reductions (per pollutant) over the lifetime of the strategy. The formula for cost-effectiveness is:

$$\frac{NPV \text{ (all Capital Costs} + \text{all O\&M Costs) (in \$)}}{\text{Total emission reduction (in tons of NO}_x\text{, ROG, or PM)}}$$

This method can be applied to all strategies, and works particularly well for strategies that exhibit changes in annual O&M costs or emissions benefits. This approach provides the best measure of the overall benefit to society that can be achieved per dollar of cost. The downside of this methodology is that it requires calculation of costs and benefits for every year over the strategy lifetime. In addition, the results of this approach are less appropriate for comparing the effectiveness of strategies in a single given year. As part of SIP development, for example, agencies are often interested in the emission reduction that can be achieved in each year leading to an attainment date.

Approach Used in This Report

Given the pros and cons of the alternative methods, we have chosen to present cost-effectiveness estimates using the latter two methods discussed above: the annualized cost effectiveness and the BACT

⁹ South Coast Air Quality Management District (2006a)

method. In all calculations, we use a 4% discount rate. Our cost figures are presented in constant 2007 dollars (i.e., ignoring inflation effects).

1.6. Summary of Results

Tables 1-4 and 1-5 present summaries of the analysis results. Table 1-4 shows annual NO_x and PM_{2.5} emission reduction and cost effectiveness (calculated according to the South Coast AQMD BACT Analysis Method described above) by strategy for 2010. Table 1-5 provides the same information for 2020. Many of the on-road truck, railroad, and CHE strategies involve an assumption about level of penetration (shown in parentheses in Table 1-4); the emission reductions from these strategies are generally scalable. Thus, the emission reduction at 20% penetration would be approximately twice the reduction achieved at 10% penetration.

Many of the strategies analyzed in this report overlap, meaning that they affect the same vehicles, vessels, or equipment. Because we analyze each control strategy independent of other strategies, the emissions reductions from two strategies together cannot be added if they address the same emission source.

Table 1-4: Summary of Emission Reduction and Cost Effectiveness by Strategy – 2010

	Emission Reduction (tons/year)		Cost Effectiveness (\$/ton)	
	NO _x	PM _{2.5}	NO _x	PM _{2.5}
On-Road Truck Strategies				
Replacement w/ Cleaner Diesels – MHDDT MY 1994-2006 w/ 2007+ (10%)	1,020	18	\$18,763	\$1,049,676
Replacement w/ Cleaner Diesels – HHDDT MY 1994-2006 w/ 2007+ (10%)	3,788	193	\$4,904	\$96,359
Truck Replacement with Hybrid Technology – MHDDT MY pre-2007 w/ 2010 (10%)	301	6	\$39,403	\$1,841,849
Truck Replacement with Hybrid Technology – HHDDT MY pre-2007 w/ 2010 (10%)	355	19	\$21,412	\$399,824
Truck Retrofit w/ DOC MY 1994-2002 MHDDT (10%)	N.E.	4	N.E.	\$88,868
Truck Retrofit w/ DOC MY 1994-2002 HHDDT (10%)	N.E.	20	N.E.	\$17,879
Truck Retrofit w/ FTF MY 1994-2002 MHDDT (10%)	N.E.	7	N.E.	\$101,828
Truck Retrofit w/ FTF MY 1994-2002 HHDDT (10%)	N.E.	40	N.E.	\$20,114
Truck Retrofit w/ DPF MY 1994-2002 MHDDT (10%)	N.E.	13	N.E.	\$152,470
Truck Retrofit w/ DPF MY 1994-2002 HHDDT (10%)	N.E.	68	N.E.	\$22,349
Truck Retrofit w/ DPF+LNC MY 1993-2003 MHDDT (10%)	196	15	\$43,995	\$575,397
Truck Retrofit w/ DPF+LNC MY 1993-2003 HHDDT (10%)	640	82	\$9,385	\$73,328
Truck Repowering MY 2003-06 MHDDT w/ 2007+ engine (10%)	175	4	\$27,299	\$1,147,996
Truck Repowering MY 2003-06 HHDDT w/ 2007+ engine (10%)	344	39	\$7,295	\$64,575
Use of Biodiesel (B20) in MY 1994-2006 (10%)	(70)	34	(increase)	\$222,872
Truck Replacement with LNG MHDDT (10%) – Moderate Scenario	1,441	32	\$34,128	\$1,558,297
Truck Replacement with LNG HHDDT (10%) – Moderate Scenario	3,718	188	\$12,353	\$244,059
Longer Combination Vehicles				
Virtual Container Yard - 10% reuse	95	4	\$1,922	\$50,610
Expanded Incident Management for Trucks on I-710	132	32	\$6,260	\$26,313
Expanded Use of PierPass Program	20	1	\$7,799	\$132,110
Railroad Strategies				
Clean Switching Locomotive (50%)	467	16	< 0	< 0
Retrofit Switching Locomotives w/ DOC (50%)	N.E.	6	N.E.	\$70,469
Retrofit Line-haul Locomotives w/ DOC (50%)	N.E.	29	N.E.	\$41,710
Retrofit Switching Locomotives w/ DPF (50%)	N.E.	14	N.E.	\$106,373
Retrofit Line-haul Locomotives w/ DPF (50%)	N.E.	63	N.E.	\$36,212
Retrofit Switching Locomotives w/ SCR (50%)	432	N.E.	\$8,555	N.E.
Retrofit Line-haul Locomotives w/ SCR (50%)	2323	N.E.	\$1,988	N.E.
Accelerated Tier 2 Switching Locomotive Rebuilds (50%)	47	7	\$10,284	\$57,008

	Emission Reduction (tons/year)		Cost Effectiveness (\$/ton)	
	NO _x	PM _{2.5}	NO _x	PM _{2.5}
Accelerated Tier 2 Line-haul Locomotive Rebuilds (50%)	260	57	\$992	\$6,903
Accelerated Tier 3 Switching Locomotive Replacement (50%)				
Accelerated Tier 3 Line-haul Locomotive Replacement (50%)				
Accelerated Tier 4 Switching Locomotive Replacement (50%)				
Accelerated Tier 4 Line-haul Locomotive Replacement (50%)				
Idle Reduction for Switching Locomotives (75%)	108	3	< 0	< 0
Idle Reduction for Line-haul Locomotives (75%)	150	7	< 0	< 0
Alameda Corridor Electrification	546	22	\$9,053	\$303,953
Full Railroad Mainline Electrification	5,401	218	\$25,205	\$846,587
Expansion of On-Dock Rail Service	387	16	\$100,361	\$2,243,141
Expansion of Near-Dock Rail Service	281	12	\$63,443	\$1,412,798
Inland Rail Improvements	1,668	56	\$42,181	\$1,370,537
Grade Crossing Separation - multiple sites (131 separation projects)	6	0.5	\$56,575,168	\$322,150,574
Ocean-Going Vessel Strategies				
Speed Reduction (High Cost)	5,801	N.E.	\$7,525	N.E.
Cold Ironing	1,358	27	\$5,573	\$229,815
Expanded Auxiliary Engine Fuel Requirements	24	5	\$80,171	\$294,395
Main Engine Fuel Requirements	491	328	\$48,238	\$72,049
Engine Improvements: Slide Valve Injectors	1,472	128	\$359	\$4,409
Engine Improvements: SCR	3,389	122	\$917	\$27,111
Engine Improvements: EGR	1,318	(3)	\$25	(increase)
Harbor Craft Strategies				
Emulsified Fuel	1,423	66	\$17,663	\$393,685
Biodiesel	0	78	(increase)	\$108,209
Harbor Craft Retrofit w/ DOC	N.E.	78	N.E.	\$9,675
Harbor Craft Retrofit w/ DPF with NO _x Catalyst	2,247	331	\$1,486	\$10,465
Harbor Craft Retrofit w/ SCR	5,992	155	\$2,676	\$106,766
Shore Power for Harbor Craft	5,762	431		
Harbor Craft Repowering – best case	N/A	N/A	\$1,470	\$37,497
Cargo Handling Equipment				
Yard Truck Replacement (10%)	42	1	\$2,373	\$98,853
CHE Replacement (10%)	18	1	\$3,609	\$87,259
Forklift Replacement (10%)	2	0.2	\$7,229	\$102,529
Crane Replacement (10%)	16	0.4	\$2,790	\$131,799
LNG for Yard Trucks (10%) (w/o CAAP)	35	1	\$4,424	\$140,264
LPG for Yard Trucks (10%)	31	1	< 0	< 0
LNG for Forklifts (10%)	2	0.1	\$80,628	\$1,920,311
LPG for Forklifts (10%)	2	0.1	\$76,377	\$1,610,564
Electrification of RTG Cranes (10%)	7	0.1	\$58,705	\$1,750,690
Electrification of Forklifts (10%)	1	0.0	\$234,120	\$11,173,662
Retrofit Yard Trucks with LNC (10%)	39	N.E.	\$9,885	N.E.
Retrofit Yard Trucks with SCR (10%)	125	N.E.	\$6,378	N.E.
Retrofit Yard Trucks with EGR (10%)	62	N.E.	\$6,406	N.E.
Retrofit Container Handling Equipment with LNC (10%)	20	N.E.	\$8,624	N.E.
Retrofit Container Handling Equipment with SCR (10%)	63	N.E.	\$5,703	N.E.
Retrofit Container Handling Equipment with EGR (10%)	31	N.E.	\$5,925	N.E.
Retrofit RTG Cranes with LNC (10%)	9	N.E.	\$14,714	N.E.
Retrofit RTG Cranes with SCR (10%)	28	N.E.	\$10,918	N.E.
Retrofit RTG Cranes with EGR (10%)	14	N.E.	\$9,257	N.E.
Retrofit Forklifts with LNC (10%)	1	N.E.	\$21,309	N.E.
Retrofit Forklifts with SCR (10%)	4	N.E.	\$19,724	N.E.
Retrofit Forklifts with EGR (10%)	2	N.E.	\$10,597	N.E.

Note 1: Values in parentheses indicate strategy penetration assumption; Note 2: Blank cells indicate that the strategy would not be implemented in this year or values could not be calculated; Note 3: "N.E." indicates no effect (strategy does not affect emissions of the pollutant); Note 4: "(increase)" indicates that the strategy increases emissions of the pollutant; Note 5: "< 0" indicates that the strategy results in a net cost reduction.

Table 1-5: Summary of Emission Reduction and Cost Effectiveness by Strategy – 2020

	Emission Reduction (tons/year)		Cost Effectiveness (\$/ton)	
	NO _x	PM _{2.5}	NO _x	PM _{2.5}
On-Road Truck Strategies				
Truck Replacement with Cleaner Diesels – MHDDT MY 1994-2002 w/ 2010+ (10%)	511	9	\$9,329	\$5,338,953
Truck Replacement with Cleaner Diesels – HHDDT MY 1994-2002 w/ 2010+ (10%)	1,607	57	\$1,822	\$509,673
Truck Replacement with Hybrid Technology – MHDDT MY pre-2010 w/ 2010+ (10%)	122	3	\$29,950	\$1,167,292
Truck Replacement with Hybrid Technology – HHDDT MY pre-2010 w/ 2010+ (10%)	113	5	\$5,076	\$116,485
Truck Retrofit w/ DOC MY 1994-2002 MHDDT (10%)	N.E.	1	N.E.	\$154,210
Truck Retrofit w/ DOC MY 1994-2002 HHDDT (10%)	N.E.	4	N.E.	\$35,523
Truck Retrofit w/ FTF MY 2003-2006 MHDDT (10%)	N.E.	2	N.E.	\$148,745
Truck Retrofit w/ FTF MY 2003-2006 HHDDT (10%)	N.E.	10	N.E.	\$21,201
Truck Retrofit w/ DPF MY 2003-2006 MHDDT (10%)	N.E.	4	N.E.	\$222,719
Truck Retrofit w/ DPF MY 2003-2006 HHDDT (10%)	N.E.	18	N.E.	\$23,556
Truck Retrofit w/ DPF+LNC MY 1993-2003 MHDDT (10%)	53	5	\$81,346	\$963,487
Truck Retrofit w/ DPF+LNC MY 1993-2003 HHDDT (10%)	124	17	\$17,613	\$128,330
Truck Repower MY 2003-06 MHDDT w/ 2007+ engine (10%)	N/A	N/A	N/A	N/A
Truck Repower MY 2003-06 HHDDT w/ 2007+ engine (10%)	N/A	N/A	N/A	N/A
Use of Biodiesel (B20) in MY 1994-2006 (10%)	(18)	10	(increase)	\$176,432
Truck Replacement with LNG MHDDT (10%) – Moderate Scenario	439	12	\$61,845	\$2,233,548
Truck Replacement with LNG HHDDT (10%) – Moderate Scenario	877	51	\$22,195	\$382,619
Longer Combination Vehicles	1,868	114	< 0	< 0
Virtual Container Yard - 10% reuse				
Expanded Incident Management for Trucks on I-710				
Expanded Use of PierPass Program	0.6	0.02	\$69,203	\$1,822,697
Railroad Strategies				
Clean Switching Locomotive (50%)	466	16	< 0	< 0
Retrofit Switching Locomotives w/ DOC (50%)	N.E.	6	N.E.	\$76,556
Retrofit Line-haul Locomotives w/ DOC (50%)	N.E.	37	N.E.	\$49,627
Retrofit Switching Locomotives w/ DPF (50%)	N.E.	14	N.E.	\$109,161
Retrofit Line-haul Locomotives w/ DPF (50%)	N.E.	82	N.E.	\$39,839
Retrofit Switching Locomotives w/ SCR (50%)	431	N.E.	\$8,645	N.E.
Retrofit Line-haul Locomotives w/ SCR (50%)	2,999	N.E.	\$2,086	N.E.
Accelerated Tier 2 Switching Locomotive Rebuilds (50%)	47	7	\$10,284	\$57,008
Accelerated Tier 2 Line-haul Locomotive Rebuilds (50%)	336	61	\$992	\$6,903
Accelerated Tier 3 Switching Locomotive Replacement (50%)	158	7	\$125,472	\$2,347,403
Accelerated Tier 3 Line-haul Locomotive Replacement (50%)	336	61	\$67,780	\$466,972
Accelerated Tier 4 Switching Locomotive Replacement (50%)	414	12	\$51,123	\$1,479,456
Accelerated Tier 4 Line-haul Locomotive Replacement (50%)	2,746	103	\$8,555	\$286,632
Idle Reduction for Switching Locomotives (75%)	107	3	< 0	< 0
Idle Reduction for Line-haul Locomotives (75%)	193	7	< 0	< 0
Alameda Corridor Electrification	831	26	\$9,053	\$303,953
Full Railroad Mainline Electrification	7,557	235	\$25,205	\$846,587
Expansion of On-Dock Rail Service	516	23	\$100,361	\$2,243,141
Expansion of Near-Dock Rail Service	112	5	\$63,443	\$1,412,798
Inland Rail Improvements	2,069	69	\$42,181	\$1,370,537
Grade Crossing Separation - multiple sites (131 separation projects)	4	0.6	\$64,579,443	\$367,728,556
Ocean-Going Vessel Strategies				
Speed Reduction (High Cost)	8,748	N.E.	\$6,681	N.E.
Cold Ironing	11,675	264		
Expanded Auxiliary Engine Fuel Requirements	40	7	\$149,848	\$946,203
Main Engine Fuel Requirements	2,078	1,318	\$49,100	\$76,699
Engine Improvements: Slide Valve Injectors	3,661	304		
Engine Improvements: SCR	8,415	291		

	Emission Reduction (tons/year)		Cost Effectiveness (\$/ton)	
	NO _x	PM _{2.5}	NO _x	PM _{2.5}
Engine Improvements: EGR	3,273	(6)		
Harbor Craft Strategies				
Emulsified Fuel	948	42		
Biodiesel	0	49		
Harbor Craft Retrofit w/ DOC	N.E.	61		
Harbor Craft Retrofit w/ DPF with NO _x Catalyst	1,497	208		
Harbor Craft Retrofit w/ SCR	3,992	98		
Shore Power for Harbor Craft	3,078	262		
Harbor Craft Repowering – best case	N/A	N/A		
Cargo Handling Equipment				
Yard Truck Replacement (10%)				
CHE Replacement (10%)				
Forklift Replacement (10%)				
Crane Replacement (10%)				
LNG for Yard Trucks (10%)				
LPG for Yard Trucks (10%)				
LNG for Forklifts (10%)				
LPG for Forklifts (10%)				
Electrification of RTG Cranes (10%)				
Electrification of Forklifts (10%)				
Retrofit Yard Trucks with LNC (10%)	4	N.E.	\$81,368	N.E.
Retrofit Yard Trucks with SCR (10%)	14	N.E.	\$55,754	N.E.
Retrofit Yard Trucks with EGR (10%)	7	N.E.	\$24,777	N.E.
Retrofit Container Handling Equipment with LNC (10%)	2	N.E.	\$74,729	N.E.
Retrofit Container Handling Equipment with SCR (10%)	7	N.E.	\$49,428	N.E.
Retrofit Container Handling Equipment with EGR (10%)	4	N.E.	\$23,335	N.E.
Retrofit RTG Cranes with LNC (10%)	1	N.E.	\$94,872	N.E.
Retrofit RTG Cranes with SCR (10%)	2	N.E.	\$76,510	N.E.
Retrofit RTG Cranes with EGR (10%)	1	N.E.	\$30,858	N.E.
Retrofit Forklifts with LNC (10%)	0.2	N.E.	\$145,026	N.E.
Retrofit Forklifts with SCR (10%)	0.8	N.E.	\$134,388	N.E.
Retrofit Forklifts with EGR (10%)	0.4	N.E.	\$32,734	N.E.

Note 1: Values in parentheses indicate strategy penetration assumption; Note 2: Blank cells indicate that the strategy would not be implemented in this year or values could not be calculated; Note 3: “N.E.” indicates no effect (strategy does not affect emissions of the pollutant); Note 4: “(increase)” indicates that the strategy increases emissions of the pollutant; Note 5: “< 0” indicates that the strategy results in a net cost reduction.

1.7. Report Organization

The remaining sections of this report are organized by source type, as follows:

Section 2: On-Road Truck Strategies

Section 3: Railroad Strategies

Section 4: Ocean Going Vessel Strategies

Section 5: Harbor Craft Strategies

Section 6: Port Cargo Handling Equipment Strategies

Section 7: References

Note that some strategies involve multiple source types and therefore do not fall cleanly in one section. For example, strategies that involve railroad infrastructure improvements can result in a mode shift from

truck to rail. We classified these strategies according to where the bulk of the investment is targeted. So, for example, railroad infrastructure strategies are included in Section 3: Railroad Strategies.

2. On-Road Truck Strategies

2.1. Introduction

On-road trucks perform the bulk of goods movement in the SCAG region. ARB defines heavy-duty trucks to be those with a gross vehicle weight rating (GVWR) of more than 8,500 lb. This 8,500 lb threshold is roughly the boundary between 4-tire trucks used for personal travel (e.g., pick-ups and SUVs) and 4-tire or 6-tire trucks used for commercial purposes. ARB uses three classes of heavy-duty trucks, as follows:

- Light-heavy-duty (8,501 – 14,000 lbs GVW)
- Medium-heavy-duty (14,001 – 33,000 lbs GVW)
- Heavy-heavy-duty (33,001 + lbs GVW)

In ARB's *Emission Reduction Plan for Ports and Goods Movement in California*, "goods movement trucks" are defined as all heavy-heavy-duty trucks (GVW greater than 33,000 lbs), which generally includes all combination trucks plus most 3-axle single-unit trucks and excludes 2-axle trucks. For purposes of analyzing emission reduction strategies, we expand the definition of goods movement trucks to encompass diesel-powered medium-heavy duty trucks (14,001 – 33,000 lbs GVW), since these vehicles contribute significantly to regional NO_x and PM emissions and many are involved in goods movement.

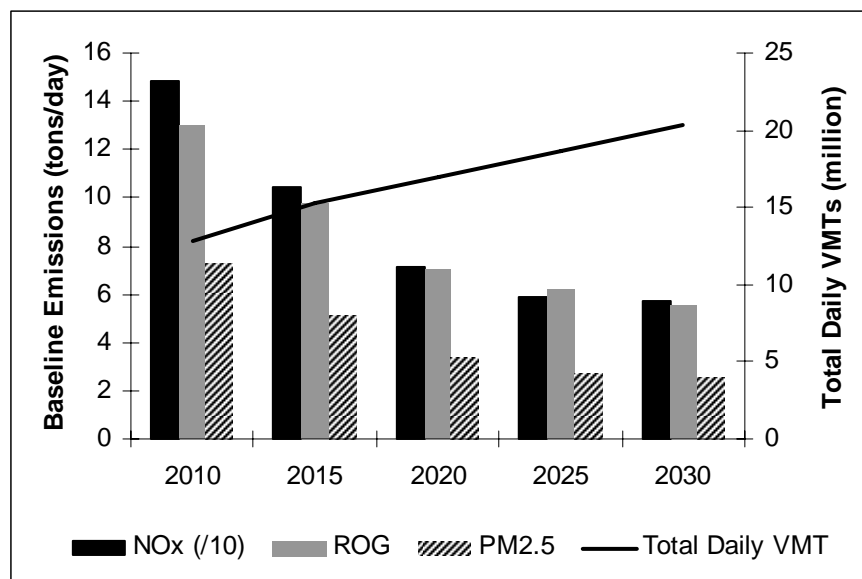
Baseline Emissions

EPA has adopted strict new emission standards for on-road heavy-duty vehicles that take effect in 2007 and 2010. Under these new standards, both NO_x and PM emissions must be ten times lower than under the previous standard, and the 2007 standards represent a 25-fold reduction compared to emission standards in the early 1990s. Thus, emissions from 2007 model year and later trucks will be dramatically lower than most trucks currently in use today. As a result of these new standards, ARB expects on-road truck emissions to decline significantly over the next decade. By 2020, goods movement trucks will produce 39% of goods movement NO_x emissions and 30% of goods movement diesel PM emissions in the South Coast Air Basin. Table 2-1 presents the projected emissions, estimated using the ARB EMFAC2007 model, from goods movement trucks in the South Coast Air Basin and Ventura County combined to represent the SCAG region. The data in Table 2-1 were used as the baseline in estimating the emission reductions that would be obtained from the on-road truck strategies.

Table 2-1: Baseline Emissions from Goods Movement Trucks in the SCAG Region

Year	Vehicle Class	Population	Total Daily VMT	Baseline Emissions (tons/day)		
				ROG	NO _x	PM _{2.5}
2010	Medium Heavy-Duty Diesel	75,331	4,858,368	1.0	48.4	1.1
	Heavy Heavy-Duty Diesel	41,990	7,980,497	12.0	143.5	6.1
2015	Medium Heavy-Duty Diesel	85,084	5,242,151	0.9	31.5	0.9
	Heavy Heavy-Duty Diesel	49,149	10,100,688	8.9	101.3	4.2
2020	Medium Heavy-Duty Diesel	92,226	5,475,279	0.8	20.4	0.8
	Heavy Heavy-Duty Diesel	53,226	11,447,037	6.2	69.6	2.6
2025	Medium Heavy-Duty Diesel	99,494	5,814,073	0.7	14.5	0.7
	Heavy Heavy-Duty Diesel	59,810	12,826,253	5.5	57.5	2.0
2030	Medium Heavy-Duty Diesel	107,294	6,244,891	0.7	11.6	0.7
	Heavy Heavy-Duty Diesel	66,457	14,090,202	4.9	55.8	1.8

Figure 2-1 illustrates baseline daily emissions of NO_x, PM_{2.5}, and ROG from medium heavy-duty diesel and heavy heavy-duty diesel trucks over time, as compared to VMT. Emissions of all three pollutants decline rapidly between 2010 and 2020 as trucks meeting the new emission standards come to dominate the fleet. Between 2020 and 2030, baseline truck missions decline modestly, as the benefits of the EPA standards slightly offset the steady growth in VMT.

Figure 2-1: Baseline Emissions from Goods Movement Trucks in the SCAG Region

To meet the 2007 standards, truck engine manufacturers will need to use exhaust after-treatment devices for the first time. The emission control devices that will allow engine manufacturers to meet the new standards typically cannot tolerate high sulfur levels in fuel. U.S. EPA and ARB have adopted companion standards for diesel fuel sulfur levels. Starting in 2006, on-road diesel fuel has been required to have no more than 0.15 parts per million (ppm) sulfur, known as ultra-low sulfur diesel (ULSD), compared to the previous standard of 500 ppm. Note that all of the U.S. EPA and ARB emission standards apply only to

new vehicles in the year of their manufacture; there currently are no emission standards that apply to in-use vehicles, other than state regulations on exhaust smoke opacity.

Overview of Engine and Fuel-Based Emission Control Strategies

A variety of engine and fuel strategies can reduce emissions from on-road trucks. Most such strategies can be grouped into the following categories:

- **Engine Controller Reprogramming (“Chip Reflash”)** – In the early 1990s, engine manufacturers began producing heavy-duty engines with engine control software that produced higher NO_x emissions and better fuel economy when the controller sensed the truck was operating in a mode other than the certification cycle (such as long periods of constant higher speeds like driving on a freeway). By 1994, these “defeat devices” were widespread on virtually all of the Class 8B heavy-duty truck engines. US EPA and the engine manufacturers signed a Consent Decree to mitigate these off-cycle NO_x emissions. The Consent Decree required engine manufacturers to stop building engines with off-cycle emission increases beginning with the 1999 model year, to remove the device when 1994-1998 engines were rebuilt (the Rebuild program), and to produce engines that met the 2004 emission standards starting in October 2002 (the Pull-Ahead program). However, the affected engines have lasted much longer before rebuilds than EPA or ARB considered and thus many trucks still contain the defeat device. While there are NO_x benefits for reflashing the engine controller to remove the defeat device, the lifetime of those emission benefits is unknown because it would only last until the engine was rebuilt and the defeat device removed. Because of this unknown lifetime, a scenario evaluating the removal of the defeat device was not examined in this study.
- **Replacement (Accelerated Turnover)** – Replacing older trucks with newer, cleaner diesel trucks can significantly reduce PM and NO_x emissions. This strategy can work well when directed at a specific truck population that tends to be older than average, such as port-serving trucks. Emerging hybrid technologies (diesel-electric and diesel-hydraulic) are being commercialized rapidly and several hybrid truck platforms in the MHDDT class are expected to be in full commercial production by 2010. Hybrids deliver the greatest emission reductions under stop-and-go and idling conditions, and thus are good candidates for replacing older diesel trucks in applications such as port drayage, refuse collection, and local urban delivery. The purchase cost of new hybrid trucks is considerably higher than that of new conventional trucks, although the reduced fuel usage of hybrids offsets some of the higher cost over time.
- **Repowering** – By replacing an older existing diesel engine with a newer, cleaner diesel engine, significant NO_x and PM emission reductions can be obtained at lower cost than replacing the entire truck. This is generally feasible for pre-1994 trucks, though case-by-case evaluation is necessary due to physical and cost constraints. A recent CARB report states the following:¹⁰

“Repowering to a 0.01 g/bhp-hr [PM] engine is not always possible. The engine compartment may not be large enough to install a newer, electronically controlled engine where previously a mechanical engine was housed. The cost of converting from mechanical to electronic fuel injection may outweigh the value of the vehicle or remaining vehicle life.”

Repowering a pre-1994 truck with a 2004-2006 model year engine, where feasible, could reduce NO_x emissions by 50% or more and PM emissions by 60% or more. However, according to the CARB report, “replacing a mechanical fuel injection engine [i.e., pre-1994 model] with a newer mechanical fuel injection engine would not be practical for port trucks due to minimal emissions benefits.”

Repowering pre-2007 trucks with 2007+ engines is not feasible because 2007+ engine technology will include exhaust aftertreatment which may require substantial modifications to the truck chassis.

¹⁰ California Air Resources Board (2006).

- **Retrofit** – Exhaust treatment devices often can be retrofitted to existing trucks with only minor modifications to the exhaust system. The three main retrofit technologies currently in use are:
 - Diesel oxidation catalysts (DOCs)
 - Flow-through filters (FTFs), and
 - Diesel particulate filters (DPFs).

All of these devices provide substantial reductions in PM emissions. DOCs reduce PM emissions by more than 25% (ARB verification level 1), FTFs reduce PM emissions more than 50% (ARB verification level 2), and DPFs reduce PM emissions more than 85% (ARB verification level 3). Some emission control manufacturers also sell low-NO_x catalysts (LNC) or exhaust gas recirculation systems that will reduce NO_x emissions by about 25% and selective catalytic reduction systems that will reduce NO_x emissions by 70 to 90%. Some combination DPF and LNC systems are also available that reduce PM, NO_x, and ROG emissions. One widely used DPF+LNC device (the Cleaire Longview™) reduces PM by 85% and NO_x by 25 % (ARB levels 3 and 1 respectively). DPF+LNC systems require greater modifications to the chassis and engine than do DPFs, and thus fewer trucks are candidates for DPF+LNC retrofit.

DPFs are termed passive or active, depending on the method used to regenerate, or oxidize the captured particulate matter. Passive and semi-active DPFs require operating temperatures above certain thresholds for a percentage of the operating time in order to regenerate. Fleets that are considering these devices must take into account the exhaust temperature variations generated by their trucks. Duty cycles that involve extreme stop-and-go or idling conditions, such as refuse collection or port drayage, may not produce sufficiently high exhaust temperatures for sufficient time to allow passive DPF systems to regenerate properly. A study by the Port of Long Beach¹¹ of 30 port drayage trucks found that some port trucks are routinely used in duty cycles that do not provide sufficient exhaust temperature/time conditions for regeneration. The time/temperature requirements of passive DPFs limit the population of trucks that can accept these retrofits. Active DPF systems, which do not have this limitation, are becoming available but they cost significantly more than passive retrofit systems.

- **Combination Replace and Retrofit** – Replacement and retrofit can be combined when the replacement truck is of model year 2006 or earlier. These trucks do not use the exhaust aftertreatment necessitated by the 2007 emissions standards. A model year 2006 or earlier truck could replace an earlier truck, and the replacement truck could be retrofit with a DPF or DPF+LNC. This combination strategy was not analyzed because of the relatively high total cost, the limited universe of trucks that can accept a DPF+LNC, and the low NO_x reduction (25%) obtainable.
- **Alternative Fuels** – A variety of alternative fuels can reduce truck emissions. Alternative forms of diesel fuel, such as emulsified diesel or biodiesel, can be used by most diesel trucks without modification to the engine. Other alternative fuels include natural gas, propane, and new hybrid-electric technologies. Liquid natural gas, compressed natural gas, and propane technologies are proven and commercially available, while hybrid diesel-electric trucks in the over-33,000 lb GVWR class are only beginning to reach the market.

All of these strategies involve upgrading the engine emissions performance or the effectiveness of exhaust emission controls on the targeted truck fleet. The in-use truck fleet in the SCAG region consists of a mix of varying numbers of each model year (MY) truck as different numbers of new trucks enter the fleet each year, and some trucks of each MY are scrapped or leave the SCAG region each year. As U.S. EPA and ARB have adopted stricter emission standards over time, the average emission rate per truck is decreasing

¹¹ TIAX (2007a)

as older “dirtier” trucks are replaced in the mix by newer “cleaner” trucks. In any calendar year, the commercially available trucks with the lowest emissions (in terms of certification values) are those of the current model year. Thus, most of these strategies are methods of speeding the modernization of the truck fleet. Emissions from in-use vehicle fleets vary from the certification values due to engine deterioration and, for NO_x, the presence of “consent decree” engines in the fleet. The emissions estimated in this study were based on emission factors calculated using the ARB EMFAC model and not on certification values.

In some ways, achieving emission reductions from on-road trucks is significantly more challenging than in the other goods movement sectors because ownership is dispersed across so many different entities. While locomotives, port CHE, OGVs, and harbor craft are owned and operated by relatively few companies, there are tens of thousands of truck owners in the SCAG region. Some large carriers own and operate many trucks, but a large portion of the truck population is in the hands of independent owner-operators or small fleets. Many owner-operators would have difficulty obtaining affordable financing for costly emission controls, and would not participate in voluntary incentive programs without deep subsidies. Some owner-operators personally maintain older trucks that have mechanical engine control systems in order to reduce costs. Those owners who lack the expertise and equipment to maintain newer, electronically-controlled engines and emission controls may resist emission reduction strategies because of the increased costs to have a professional mechanic maintain the truck.

The existing Carl Moyer Program offers monetary incentives to reduce diesel NO_x and PM emissions below current required levels. Some air districts have supplemented Moyer incentives with other funds. For example, the Gateway Cities Clean Air Program provides financial incentives for truck fleet modernization and installation of emission reduction devices on port trucks and port off-road equipment. The total benefits of each strategy will depend on the available funding. Higher levels of funding can achieve a greater “market penetration” rate by inducing a larger percentage of truck owners to participate. For lower rates of participation the program costs likely are scalable – the cost of achieving a 10% truck participation rate would be roughly twice the cost of achieving a 5% participation rate, the cost of achieving 15% is three times the cost for 5%, and so on. To achieve relatively high participation rates, the program cost is likely to be disproportionately higher because the most willing truck owners will already have participated and greater incentives are needed to induce the remaining owners to participate. For all the truck engine and fuel-based strategies, we assumed a participation rate of 10% for illustrative purposes.

We determined truck fleet populations, vehicle miles traveled (VMT), and emissions using ARB’s EMFAC 2007 model for each analysis year. The analysis accounted for the fact that older trucks are typically driven less than newer trucks. Truck fleet data for the South Coast Air Basin and Ventura County were combined to represent the SCAG region. Only medium heavy-duty diesel trucks (MHDDT) and heavy heavy-duty diesel trucks (HHDDT) are considered in this analysis because they provide by far the largest benefits in terms of NO_x and PM. MHDDTs are defined as class 4 through 7 trucks (14,001 - 33,000 lb GVWR), while HHDDTs are defined as class 8 trucks (greater than 33,000 lb GVWR). Within each GVWR class, trucks of specific groups of model years have common technology characteristics. Logical MY groups were defined for each emissions reduction strategy based on the applicable technologies.

A number of truck engine and fuel-based strategies are discussed in this report. These are shown in Table 2-2 and discussed in more detail in the following subsections.

Table 2-2: Possible On-Road Truck Engine- and Fuel-Based Strategies

Strategy Analysis Year*	Target MY Group	Truck Replacement Strategies	DOC Retrofit Strategies (ARB Level 1)	FTF Retrofit Strategies (ARB Level 2)	DPF and DPF+LNC Retrofit Strategies (ARB Level 3)	Repowering Strategies
2010	MY 1988-1993	Replace MY 1988-1993 trucks with MY 1998-2002 trucks	Retrofit MY 1988-1993 trucks with DOC	Retrofit MY 1994-2002 trucks with FTF	Retrofit MY 1994-2002 trucks with DPF	Replace engines in MY 1988-1993 trucks with MY 1998-2002 engines
	MY 1993-2003	N.A.**	N.A.	N.A.	Retrofit MY 1993-2003 trucks with DPF+LNC	N.A.
	MY 1994-2002	Replace MY 1994-2002 trucks with MY 2003-2006 trucks	Retrofit MY 1994-2002 trucks with DOC	N.A.	N.A.	N.A.
	MY 1998-2002	N.A.	N.A.	N.A.	N.A.	Replace engines in MY 1998-2002 trucks with MY 2003-2006 engines
	MY 1994-2006	Replace MY 1994-2006 trucks with MY 2007+ trucks	N.A.	N.A.	N.A.	N.A.
	MY 2003-2006	N.A.	N.A.	N.A.	Retrofit MY 2003-2006 trucks with DPF	Replace engines in MY 2003-2006 trucks with 2007+ engines
	MY Pre-2007	Replace Pre-MY 2007 trucks with new hybrid trucks	N.A.	N.A.	N.A.	N.A.
2020	MY 1988-2002	N.A.	Retrofit MY 1988-2002 trucks with DOC	N.A.	N.A.	N.A.
	MY 1993-2003	N.A.	N.A.	N.A.	Retrofit MY 1993-2003 trucks with DPF+LNC	N.A.
	MY 1994-2006	Replace pre-MY 2010 trucks with MY 2010+ trucks (conventional or hybrid)	N.A.	Retrofit MY 1994-2006 trucks with FTF	Retrofit MY 1994-2006 trucks with DPF	N.A.
	MY Pre-2010	Replace pre-MY 2010 trucks with MY 2010+ trucks (conventional or hybrid)	N.A.	N.A.	N.A.	N.A.

Strategy Analysis Year*	Target MY Group	Truck Replacement Strategies	DOC Retrofit Strategies (ARB Level 1)	FTF Retrofit Strategies (ARB Level 2)	DPF and DPF+LNC Retrofit Strategies (ARB Level 3)	Repowering Strategies
2030	MY 1988-2002	N.A.	Retrofit MY 1988-2002 trucks with DOC	N.A.	N.A.	N.A.
	MY 1993-2003	N.A.	N.A.	N.A.	Retrofit MY 1993-2003 trucks with DPF+LNC	N.A.
	MY 2003-2006	N.A.	N.A.	Retrofit MY 2003-2006 trucks with FTF	Retrofit MY 2003-2006 trucks with DPF	N.A.
	MY Pre-2010	Replace pre-MY 2010 trucks with MY 2010+ trucks (conventional or hybrid)	N.A.	N.A.	N.A.	N.A.

* Assumes full implementation of strategy by the end of the given calendar year.

** N.A. indicates that the MY group/technology combination was not analyzed because it is not feasible, is known to have very poor cost-effectiveness, or the model year/control strategy combination does not apply.

Note that the San Pedro Bay Ports *Clean Air Action Plan* includes several control measures for on-road trucks that are similar to the strategies described above. Control measure HDV1 would involve replacement of older trucks with new cleaner diesel trucks or LNG trucks, and retrofits for model year 1993-97 trucks using a DPF, a lean NO_x catalyst, and a chip reflash. Control measure HDV2 would provide natural gas fueling infrastructure to support measure HDV1. Because these measures target only port trucks and include some different assumptions about the baseline fleet, we have not attempted to compare the results of our analysis directly with the *Clean Air Action Plan* findings.

Overview of Operational Emission Control Strategies for Trucks

Operational strategies are associated with the efficiency of the transportation system. They aim to maximize economic output (e.g., goods transported) while minimizing economic input (e.g., transportation equipment, infrastructure, fuel). They have the potential to reduce emissions in four ways.

- **Travel reduction** - New infrastructure can reduce travel circuitry and shorten the distance between freight origin and destination. Other strategies reduce trucks miles traveled (VMT) through information technology, which support load matching, route planning, dynamic traffic information, and vehicle tracking systems.
- **Idling reduction** - When freight vehicles and equipment are idling, they consume fuel and produce emissions without productivity. Some idling is unavoidable, but there are many opportunities to reduce idling. Trucks idle overnight to provide heating, cooling, or driver other driver amenities. Queuing and idling at pick-up and drop-off locations, toll stations, and intermodal facilities contribute significantly to inefficiency in truck freight movement and to excessive emissions. Locomotives idle excessively in switching yards or on railroad main lines due to system congestion. Ocean-going vessels “idle” when engines are operating while at berth (termed hotelling).
- **Mode shift** - Environmental benefits can also be realized by shifting freight to cleaner modes. In general, rail transportation is associated with lower emissions (on a ton-mile basis) than truck

transportation, although these benefits depend on details such as the length of haul and the use of drayage trucks to access rail facilities. Emission rates for new trucks will drop significantly in the coming years, which may negate environmental advantages of rail in some instances.

- **Congestion reduction/Speed increase** - Vehicle emissions in congested corridors tend to be higher, since acceleration and deceleration generate higher emissions (in grams per hour). The impacts of the associated speed increase on vehicle emissions are somewhat uncertain.

This report analyzes four operational strategies for trucks and discusses two others on a more qualitative basis.

2.2. Truck Replacement with Cleaner Diesels

Overview

Monetary incentives for truck replacement can promote more rapid turnover of the truck fleet, accelerating retirement of older vehicles that have higher emission rates. This strategy assumes that the truck owner scraps his/her current truck and replaces it with a newer truck. There must be proof of disposal of the older truck to ensure that it is not resold into the SCAG truck population.

The newer truck is estimated to be used for 10 years as specified in ARB's *Evaluation of Port Trucks and Possible Mitigation Strategies*.¹² In this analysis, no value is given to the scrapped truck. The capital cost on which the incentive is based is the purchase price of the replacement truck. Prices for HHDDTs were taken from the 2005 California Used HDDV Market Survey, while prices for MHDDTs were taken from data for used Chevrolet Kodiak C6500 trucks (a typical 19,500-26,000 lbs GVWR delivery box truck).¹³

For all estimates the market penetration rate, or the percentage of eligible trucks that actually participate and are replaced, is assumed to be 10% for each GVWR class. Each scenario could be applied to MHDDTs, HHDDTs, or both. The life of the strategy is assumed to be 10 years.

Truck Replacement Diesel Scenarios in 2010

Three truck replacement diesel scenarios were defined depending on the targeted MY range. Table 2-3 presents the emissions benefits of the three truck replacement diesel scenarios considered for implementation in 2010.

Table 2-3: 2010 Emissions Reductions with Truck Replacement Diesel Strategies (10% participation)

Scenario	Vehicle Class	Scrapped MY Age Group	Replacement MY Age Group	Replaced Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
						ROG	NO _x	PM _{2.5}
1	MHDDT	1988-1993	1998-2002	353	16,411	3.0	84.8	4.5
1	HHDDT	1988-1993	1998-2002	299	40,015	36.9	-9.6	36.9
2	MHDDT	1994-2002	2003-2006	1,378	83,403	14.0	490.1	5.7
2	HHDDT	1994-2002	2003-2006	890	176,816	241.1	2,000.3	5.1
3	MHDDT	1994-2006	2007+	2,262	160,387	21.5	1,019.6	18.2
3	HHDDT	1994-2006	2007+	1,204	300,482	346.5	3,788.2	192.8

2010 Diesel Scenario #1: Replace MY 1988-1993 Trucks

For 2010, Scenario 1 replaces MY 1988-1993 trucks with newer MY 1998-2002 model year trucks. 1988 through 1990 MY trucks emit 6 grams of NO_x per brake-horsepower-hour (g/bhp-hr) and 0.25 g/bhp-hr PM, measured as the USEPA/ARB certification levels. 1991-1993 MY trucks emit 5 g/bhp-hr NO_x and 0.25 g/bhp-hr PM. 1994-1997 MY trucks emit 5 g/bhp-hr NO_x and 0.1 g/bhp-hr PM, while 1998-2002 MY trucks emit 4 g/bhp-hr NO_x and 0.1 g/bhp-hr PM. From about 1994 through about 1998, engine manufacturers used a defeat device that allowed NO_x emissions to increase under certain conditions while still meeting the emissions standards for HHDDTs. In a consent decree, the federal government required

¹² California Air Resources Board (2006)

¹³ As advertised at <http://www.truckpaper.com>

those manufacturers to introduce engines that met the 2004 emission standards starting in October 2002, and to remove the defeat device (through a software modification or “chip reflash”) on those trucks as they were rebuilt. In the 2010 scenarios, not all 1998-2002 MY engines have been rebuilt and higher emissions are predicted by EMFAC 2007 for those trucks. By 2010, most trucks older than 1988 MY will have been retired through normal fleet turnover and therefore are not included in this strategy scenario.

2010 Diesel Scenario #2: Replace MY 1994-2002 Trucks

For Scenario 2, 1994 through 2002 MY trucks are replaced with 2003-2006 MY trucks meeting an emission standard of 2.5 g/bhp-hr NO_x and 0.1 g/bhp PM. Table 2-3 indicates that the benefits of scenario 2 are greater than those of scenario 1 because of the larger target truck population and larger daily VMT. The difference is especially pronounced for the HHDDT class. Scenario 2 is not an exclusive alternative to scenario 1. As the target truck populations do not overlap, both scenarios could be implemented.

2010 Diesel Scenario #3: Replace MY 1994-2006 Trucks

For Scenario 3, 1994 through 2006 MY trucks are replaced with 2007-2009 MY trucks meeting an emission standard of 0.5 g/bhp-hr NO_x and 0.01 g/bhp PM. Table 2-3 indicates that the benefits of scenario 3 are greater than those of scenario 2 because of the larger target truck population and larger daily VMT. The HHDDT class provides greater benefits than the MHDDT class. The target MY range for Scenario 3 includes that of scenario 2. Scenario 3 and scenario 1 could be implemented together, and this option would provide the greatest MY coverage in 2010.

Truck Replacement Diesel Scenarios in 2020

Table 2-4 presents the emissions benefits of the three truck replacement scenarios considered for implementation in 2020.

Table 2-4: 2020 Emissions Reductions with Truck Replacement Diesel Strategies (10% participation)

Scenario	Vehicle Class	Scrapped MY Age Group	Replacement MY Age Group	Replaced Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
						ROG	NO _x	PM _{2.5}
1	MHDDT	1994-2002	2010+	712	44,435	12.6	511.2	8.9
1	HHDDT	1994-2002	2010+	349	72,773	167.3	1,606.5	57.4
2	MHDDT	2003-2006	2010+	597	37,259	3.3	198.7	5.0
2	HHDDT	2003-2006	2010+	244	50,770	34.6	518.5	43.8
3	MHDDT	2007-2009	2010+	568	35,481	2.1	96.8	2.9
3	HHDDT	2007-2009	2010+	292	60,777	23.0	345.6	3.5

2020 Diesel Scenario #1: Replace MY 1994-2002 Trucks

For Scenario 1 in 2020, 1994 through 2002 MY trucks are replaced with 2010+ MY trucks meeting an emission standard of 0.2 g/bhp-hr NO_x and 0.01 g/bhp PM. Scenario 1 in 2020 targets the same MY range as scenario 2 in 2010 and almost the same MY range as scenario 3 in 2010. Thus, scenario 1 in 2020 would be an option if the scenarios for 2010 were not implemented.

2020 Diesel Scenario #2: Replace MY 2003-2006 Trucks

For Scenario 2 in 2020, MY 2003 through 2006 trucks are replaced with MY 2010+ trucks. Table 2-4 indicates that the benefits of scenario 2 are less than those of scenario 1 because of the smaller target truck population and lower daily VMT. Scenario 2 is not an exclusive alternative to scenario 1. As the target truck populations do not overlap, both scenarios could be implemented.

2020 Diesel Scenario #3: Replace MY 2007-2009 Trucks

For Scenario 3 in 2020, MY 2007 through 2009 trucks are replaced with MY 2010+ trucks. Table 2-4 indicates that the benefits of scenario 3 are less than those of scenarios 1 and 2, primarily because the trucks being replaced would be relatively new and thus “cleaner” than the typical target truck population. Scenario 2 is not an exclusive alternative to scenario 1. As the target truck populations do not overlap, both scenarios could be implemented or all three scenarios could be implemented.

Truck Replacement Diesel Scenarios in 2030

Table 2-5 presents the emissions benefits of the three truck replacement scenarios considered for implementation in 2030.

Table 2-5: 2030 Emissions Reductions with Truck Replacement Diesel Strategies (10% participation)

Scenario	Vehicle Class	Scrapped MY Age Group	Replacement MY Age Group	Replaced Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
						ROG	NO _x	PM _{2.5}
1	MHDDT	1994-2002	2010+	304	16,438	5.3	197.9	3.6
1	HHDDT	1994-2002	2010+	65	11,381	33.9	322.3	10.3
2	MHDDT	2003-2006	2010+	263	14,222	1.6	80.8	2.1
2	HHDDT	2003-2006	2010+	37	6,447	6.3	90.2	6.3
3	MHDDT	2007-2009	2010+	286	15,479	1.3	46.9	1.6
3	HHDDT	2007-2009	2010+	123	21,655	13.1	186.3	3.3

2030 Diesel Scenario #1: Replace MY 1994-2002 Trucks

For Scenario 1 in 2030, 1994 through 2002 MY trucks are replaced with 2010+ MY trucks. These are the same target and replacement fleets as scenario 1 in 2020. Thus, scenario 1 in 2030 would be a comparable option if scenario 1 for 2020 were not implemented. Table 2-5 indicates that the benefits of 2030 scenario 1 are less than those of 2020 scenario 1 because of the smaller remaining population of target trucks and lower daily VMT.

Cost of Replacement Diesel Strategies

Table 2-6 presents the costs of truck replacement strategies in terms of the capital cost per replacement truck and the equivalent annualized cost. The truck replacement strategies analyzed here are assumed to have an initial capital cost and no recurring costs¹⁴. Capital costs were estimated using the used truck price data discussed above. The capital costs were annualized by the Capital Recovery Factor method,

¹⁴ In some cases the more modern, electronically controlled engine of the replacement truck may deliver greater fuel economy than the old engine, thus resulting in savings in operational costs to the trucker.

over the assumed 10-year strategy lifetime and using a 4% discount rate consistent with ARB and SCAQMD practice.

Table 2-6 indicates that the per-truck costs generally are higher in 2020 than in 2010 or 2030. Most costs are higher in 2010 than for the corresponding scenario in 2030. This cost pattern is determined by the selection of the allowable MY range for the replacement truck in the given implementation year. For example, under Scenario 3 in 2010 the replacement truck would be at most 3 model years old, and hence relatively expensive.

Table 2-6: Costs of Truck Replacement Diesel Strategies

Scenario	Vehicle Class	2010		2020		2030	
		Cost of Replacement Truck	Annualized Cost (\$/year per truck)	Cost of Replacement Truck	Annualized Cost (\$/year per truck)	Cost of Replacement Truck	Annualized Cost (\$/year per truck)
1	MHDDT	\$19,384	\$2,390	\$33,503	\$4,131	\$23,966	\$2,955
1	HHDDT	\$15,088	\$1,860	\$41,922	\$5,169	\$21,501	\$2,651
2	MHDDT	\$31,828	\$3,924	\$33,503	\$4,131	\$23,966	\$2,955
2	HHDDT	\$37,150	\$4,580	\$41,922	\$5,169	\$21,501	\$2,651
3	MHDDT	\$42,290	\$5,214	\$33,503	\$4,131	\$23,966	\$2,955
3	HHDDT	\$77,156	\$9,513	\$41,922	\$5,169	\$21,501	\$2,651

Cost Effectiveness of Truck Replacement Diesel Strategies

The cost effectiveness of truck replacement strategies is calculated as the cost per ton of emissions reduced. Table 2-7 provides estimated cost effectiveness for NO_x and PM_{2.5} which are the pollutants of greatest concern. For this study the cost effectiveness is calculated by both the ARB method and the SCAQMD method as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%. For the truck replacement strategies the ARB and SCAQMD methods give similar cost effectiveness estimates with the SCAQMD results being slightly lower.

Table 2-7: Cost Effectiveness of Truck Replacement Diesel Strategies

Year	Scenario	Vehicle Class	ARB Annualized Method				SCAQMD BACT Method			
			Annual Benefits (tons/year)		Cost Effectiveness (\$/ton)		Lifetime Benefits (tons)		Cost Effectiveness (\$/ton)	
			NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}
2010	1	MHDDT	85	5	\$19,910	\$371,275	848	45	\$16,149	\$301,137
	1	HHDDT	(10)	37	(\$115,470)	\$30,160	(96)	369	(\$93,656)	\$24,462
	2	MHDDT	490	6	\$22,066	\$1,897,644	4,901	57	\$17,898	\$1,539,159
	2	HHDDT	2,000	5	\$4,075	\$1,592,538	20,003	51	\$3,305	\$1,291,691
	3	MHDDT	1,020	18	\$23,132	\$1,294,156	10,196	182	\$18,763	\$1,049,676
	3	HHDDT	3,788	193	\$6,046	\$118,802	37,882	1,928	\$4,904	\$96,359
2020	1	MHDDT	511	9	\$11,502	\$658,245	5,112	89	\$9,329	\$5,338,953
	1	HHDDT	1,607	57	\$2,246	\$62,838	16,065	574	\$1,822	\$509,673
	2	MHDDT	199	5	\$24,812	\$991,358	1,987	50	\$20,125	\$8,040,801
	2	HHDDT	519	44	\$4,856	\$57,440	5,185	438	\$3,938	\$465,890
	3	MHDDT	97	3	\$48,503	\$1,593,645	968	29	\$39,340	\$12,925,891
	3	HHDDT	346	3	\$8,721	\$861,792	3,456	35	\$7,074	\$6,989,902
2030	1	MHDDT	198	4	\$9,074	\$499,640	1,979	36	\$7,359	\$405,253
	1	HHDDT	322	10	\$1,064	\$33,227	3,223	103	\$863	\$26,950
	2	MHDDT	81	2	\$19,229	\$739,449	808	21	\$15,597	\$599,759
	2	HHDDT	90	6	\$2,153	\$30,645	902	63	\$1,746	\$24,856
	3	MHDDT	47	2	\$36,092	\$1,047,957	469	16	\$29,274	\$849,987
	3	HHDDT	186	3	\$3,500	\$199,663	1,863	33	\$2,839	\$161,944

2.3. Truck Replacement with Hybrid Technology

Overview

Hybrid vehicles contain a secondary energy source (usually batteries or hydraulic accumulators) in addition to the primary engine, and electronic control systems to allow both energy sources to power the truck in varying combinations depending on operating conditions. Hybrid truck technology is developing rapidly. Diesel-electric and diesel-hydraulic MHDDTs for specific applications have entered commercial production, and hybrid MHDDTs and HHDDTs are expected to be widely available by 2010. A truck replacement strategy with hybrids would be implemented the same way as a pure diesel strategy, except that the target markets or truck populations must be more precisely defined in order to gain the emissions benefits of hybrid technology.

The emissions performance of hybrids is very sensitive to the truck's operating characteristics (duty cycle). Hybrids gain their performance advantage in two primary ways: (1) by substituting energy from the secondary power source for the diesel engine under conditions such as idling, in which the diesel would be operating inefficiently; and (2) by supplementing the diesel engine under short-duration maximum-load conditions (e.g., uphill starts), thus allowing the engine to be smaller than in a conventional truck. For trucks that must provide on-site power to run truck-mounted equipment, such as bucket trucks used by electric utilities and telecommunications companies, hybrids provide a further advantage in being capable of running the equipment from the secondary power source, thus allowing the diesel engine to be shut off entirely.

These characteristics make hybrids most suitable for duty cycles that involve stop-and-go traffic, frequent idling, and stationary operation. Hybrid technology provides little benefit for high-speed, over-the-road trucking. Candidate truck populations for replacement with hybrids need not be defined by model year, but in order to maximize emission reductions trucks must be selected that engage in the duty cycles in which hybrids perform best. Primary candidate fleets by application include the following:

- Utility/telecommunications (bucket truck, boom truck, "trouble truck", etc.). These trucks may make frequent stops and often need to provide on-site power. Most of these trucks are MHDDTs.
- Van-body trucks (single-unit trucks with closed cargo boxes) used in urban delivery operations. Typical examples include grocery trucks, furniture trucks, and local for-hire services. The total van truck population comprises many sizes of both MHDDTs and HHDDTs.
- Parcel delivery trucks including walk-in and "high cube" vans. These trucks typically are lighter-weight MHDDTs. Many major parcel delivery firms including FedEx, United Parcel Service, and the U.S. Postal Service currently have their own programs to adopt hybrid technology.
- Refuse collection, recycling trucks, and similar specialized trucks. These trucks undergo the most extreme stop-and-go/idling conditions of all common truck applications. Trucks engaged in port drayage service operate under similar extreme stop-and-go/idling conditions. Most trucks in these groups are HHDDTs.

In order to provide a reasonable maximum fleet scenario for this strategy, data by vehicle type and weight class for the Los Angeles County truck population were examined, and type/weight class groups that may be likely candidates for hybridization (similar to those noted above) were selected. Table 2-8 lists the selected groups.

Table 2-8: Target Truck Population for Hybrid Technology in Los Angeles County

Target Body Type	MHDDT	HHDDT
Utility	3,044	246
Van	18,398	317
Step Van (Walk-in)	478	4
Parcel Delivery	128	1
Refuse Collection	533	3,883
Total	22,581	4,451
All trucks in weight class, Los Angeles County	75,473	36,152
Target trucks as percent of all trucks in weight class (percentages were applied to SCAG region truck population)	29.9%	12.3%

Source: Metropolitan Transportation Authority (2004)

The percentage represented by the selected groups out of all trucks in Los Angeles County was applied to the SCAG truck population to estimate the potential eligible population for hybridization. The assumed 10% market penetration rate, or the percentage of eligible trucks that actually participate and are replaced, was applied to this potentially eligible population.

Because of the newness of the technology, reliable data on the emissions reductions obtainable with in-use truck fleets are scarce. Information on the long-term performance of hybrids exists for transit buses but not for large truck fleets. Research reports generally concern prototype vehicles rather than in-use trucks. Industry reports on production fleets often state emissions and fuel savings as reductions rather than absolute values, omit descriptions of the baseline to which the reductions were compared, and lack details such as the specific weight class and duty cycle of the hybrid trucks. A literature and internet search of the industry was conducted for the most recent emissions and fuel use data.^{15 16} The following representative average values for emissions and fuel benefits, over all candidate truck types and duty cycles, were selected from among the data that appeared to be most valid and applicable. These assumed reductions with hybrids are relative to a conventional truck of the same model year operating on the same duty cycle.

- 40% NO_x reduction
- 30% PM reduction (set equal to fuel use reduction as much of the reported PM data claim very large reductions, e.g. 90%-96%, that appear to be overly optimistic)
- 30% ROG reduction (set equal to fuel use reduction as very little ROG data has been reported for hybrids)
- 30% fuel use reduction

¹⁵ Smith, Daniel (2006)

¹⁶ Internet sites reviewed include: <http://www.calstart.org>,
<http://www.roadranger.com/Roadranger/productssolutions/HybridPower/index.htm>,
http://eaton.com/EatonCom/OurCompany/InvestorRelations/CT_112375,
http://www.peterbilt.com/index_new_mor.asp?file=2093

Because of the high level of uncertainty in the emissions data, the estimated emissions benefits and cost effectiveness of the hybrid truck replacement strategy should be considered illustrative rather than predictive.

As with the pure diesel replacement strategy, the hybrid strategy assumes that the truck owner scraps his/her current truck and replaces it with a newer truck. There must be proof of disposal of the older truck to ensure that it is not resold into the SCAG truck population.

The newer truck is estimated to be used for 10 years as specified in ARB's *Evaluation of Port Trucks and Possible Mitigation Strategies*.¹⁷ In this analysis, no value is given to the scrapped truck. The capital cost on which the incentive is based is the purchase price of the replacement truck. The prices used for the replacement trucks in the Truck Replacement – Cleaner Diesel strategy are only partially applicable to the hybrid strategy because the many of the trucks being replaced have specialized body types that are relatively costly. For the hybrid strategy, representative prices by body type were used, weighted by the proportion of each type in the target fleet.

For all estimates the market penetration rate, or the percentage of eligible trucks that actually participate and are replaced, is assumed to be 10% for each GVWR class. Each scenario could be applied to MHDDTs, HHDDTs, or both. The life of the strategy is assumed to be 10 years.

Truck Replacement Hybrid Scenario in 2010

One generalized, illustrative truck replacement hybrid scenario was defined encompassing the overall target truck population except for the most recent four model years (2007-2010). Trucks of MY 2007-2010 are relatively clean as they are subject to the most recent emissions standards, and replacing them would not be cost effective. Table 2-9 presents the emissions benefits of this scenario considered for implementation in 2010.

Table 2-9: 2010 Emissions Reductions with Truck Replacement Hybrid Strategies (10% participation)

Vehicle Class	Scrapped MY Age Group	Hybrid Replacement MY Age Group	Replaced Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
					ROG	NO _x	PM _{2.5}
MHDDT target pop.	Pre-2007	2010 (New)	1,677	74,209	6.7	301.4	6.4
HHDDT target pop.	Pre-2007	2010 (New)	417	46,875	34.3	354.7	19.0

This scenario replaces MY pre-2007 trucks with newer MY 2010 hybrid trucks. As with the replacement diesel scenarios above, in the 2010 scenario not all 1998-2002 MY engines have been rebuilt and higher emissions are predicted by EMFAC 2007 for those trucks. By 2010, most trucks older than 1988 MY will have been retired through normal fleet turnover and therefore are not included in this strategy scenario. The hybrid trucks are assumed to be new since there will not have been time for a significant used hybrid market to develop by 2010. Hybrid truck emissions for 2010 were developed by applying the emission reduction percentages above to the emissions for MY 2010 diesel trucks. Because of the uncertainties in the assumptions for the hybrid scenarios, such as target truck populations, participation rates, and the in-use performance of hybrids, these results must be considered illustrative only.

¹⁷ California Air Resources Board (2006)

Truck Replacement Hybrid Scenario in 2020

Table 2-10 presents the emissions benefits of the truck replacement hybrid scenario considered for implementation in 2020.

Table 2-10: 2020 Emissions Reductions with Truck Replacement Hybrid Strategies (10% participation)

Vehicle Class	Scrapped MY Age Group	Replacement MY Age Group	Replaced Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
					ROG	NO _x	PM _{2.5}
MHDDT target pop.	Pre-2010	2010+	1,257	35,870	3.0	122.1	3.1
HHDDT target pop.	Pre-2010	2010+	242	18,142	9.9	113.2	4.9

For this scenario in 2020, pre-2010 MY trucks are replaced with 2010+ MY hybrid trucks. The analysis assumes that the 2010 emissions standards are still current in 2020 but the hybrid replacement trucks need not be new, because a used hybrid truck market would develop by 2020. If the replacement truck requirements were more restrictive, e.g., MY 2017-2020 rather than MY 2010-2020, then the replaced population and the emissions benefits would be greater. As it is not known what emissions standards will apply by 2020, nor how hybrid technology will evolve, this scenario is illustrative only.

Truck Replacement Hybrid Scenario in 2030

Table 2-11 presents the emissions benefits of truck replacement hybrid scenario considered for implementation in 2030.

Table 2-11: 2030 Emissions Reductions with Truck Replacement Hybrid Strategies (10% participation)

Vehicle Class	Scrapped MY Age Group	Replacement MY Age Group	Replaced Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
					ROG	NO _x	PM _{2.5}
MHDDT target pop.	Pre-2010	2010+	725	9,490	1.0	38.2	1.0
HHDDT target pop.	Pre-2010	2010+	74	2,184	1.4	16.2	0.5

For this scenario in 2030, pre-2010 MY trucks are replaced with 2010+ MY trucks. Table 2-11 indicates that the benefits of the 2030 scenario are less than those of the 2020 scenario because of the smaller remaining population of target trucks and lower daily VMT.

Cost of Replacement Hybrid Strategies

Table 2-12 presents the costs of truck replacement strategies in terms of the capital cost per replacement truck and the equivalent annualized cost. The truck replacement strategies analyzed here are assumed to have an initial capital cost and no recurring costs. Capital costs were estimated using the used truck price data discussed above. Based on industry data, the incremental capital cost of a hybrid truck over a conventional truck was estimated to decrease as hybrid technology matures. The incremental capital cost of a hybrid truck was assumed to be +50% in 2010, +20% in 2020, and +10% in 2030. The resale value of used hybrid trucks was assumed to decrease over time at the same percentage rate as for conventional trucks. The capital costs were annualized by the Capital Recovery Factor method, over the assumed 10-year strategy lifetime and using a 4% discount rate consistent with ARB and SCAQMD practice. Fuel

savings with hybrid trucks were assumed to remain a constant percentage of a conventional diesel's fuel usage. The dollar value of fuel savings was calculated based on U.S. Department of Energy forecasts of diesel fuel prices.¹⁸ The annualized costs in Table 2-12 are the sum of the annualized capital costs and the annual fuel savings.

Table 2-12 indicates that the per-truck costs of the hybrid strategy decrease for succeeding years. This is due to lower average prices for used hybrid trucks as more model years enter the MY 2010+ group, and the capital cost of a given hybrid truck decreasing over time as the incremental cost of hybrid technology (over conventional diesel) decreases. If the capital cost is low enough and the fuel savings are great enough, the annualized cost over the 10-year strategy lifetime can be very low, as occurs with HHDDTs in 2030. If the replacement truck requirements were more restrictive, e.g., MY 2017-2020 rather than MY 2010-2020 in calendar year 2020, then the costs of replacement trucks would be higher. Because of the uncertainties in the assumptions for the hybrid scenarios, these results must be considered illustrative only.

Table 2-12: Costs of Truck Replacement Hybrid Strategies

Vehicle Class	2010		2020		2030	
	Cost of Replacement Truck	Annualized Cost (\$/year per truck)	Cost of Replacement Truck	Annualized Cost (\$/year per truck)	Cost of Replacement Truck	Annualized Cost (\$/year per truck)
MHDDT	\$102,252	\$9,464	\$56,712	\$4,229	\$37,187	\$2,424
HHDDT	\$254,412	\$24,155	\$84,130	\$4,335	\$39,553	\$498

Cost Effectiveness of Truck Replacement Hybrid Strategies

The cost effectiveness of truck replacement hybrid strategies is calculated as the cost per ton of emissions reduced. Table 2-13 provides estimated cost effectiveness for NO_x and PM_{2.5} which are the pollutants of greatest concern. For this study the cost effectiveness is calculated by both the ARB method and the SCAQMD method as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%. For the truck replacement hybrid strategies the ARB and SCAQMD methods give similar cost effectiveness trends but the SCAQMD results give lower costs per ton.

¹⁸ Energy Information Administration (2006)

Table 2-13: Cost Effectiveness of Truck Replacement Hybrid Strategies

Year	Vehicle Class	ARB Annualized Method				SCAQMD BACT Method			
		Annual Benefits (tons/year)		Cost Effectiveness (\$/ton)		Lifetime Benefits (tons)		Cost Effectiveness (\$/ton)	
		NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}
2010	MHDDT	301	6	\$52,653	\$2,461,203	3,014	64	\$39,403	\$1,841,849
	HHDDT	355	19	\$28,372	\$529,786	3,547	190	\$21,412	\$399,824
2020	MHDDT	122	3	\$43,552	\$1,697,440	1,221	31	\$29,950	\$1,167,292
	HHDDT	113	5	\$9,263	\$212,567	1,132	49	\$5,076	\$116,485
2030	MHDDT	38	1	\$46,061	\$1,755,712	382	10	\$29,603	\$1,128,400
	HHDDT	16	1	\$2,285	\$69,420	162	5	\$(1,938)	\$(58,871)

2.4. Truck Retrofit with DOC

Overview

Monetary incentives for truck retrofit can encourage emissions reductions from the in-use fleet at relatively low cost. Exhaust treatment devices often can be retrofitted to existing trucks with only minor modifications to the exhaust system. This section analyzes scenarios for the installation of diesel oxidation catalysts (DOCs) on trucks that can accept this technology. DOCs are certified by ARB to reduce PM emissions by at least 25% (verification level 1); they also reduce ROG emissions, but do not affect NO_x.

The capital cost on which the incentive is based is the purchase price of the DOC kit plus installation.¹⁹ For all estimates the market penetration rate is assumed to be 10% for each GVWR class. Each scenario could be applied to MHDDTs, HHDDTs, or both. The life of the strategy is assumed to be 10 years.²⁰ Ten years is longer than the typical 5-year manufacturer's emissions warranty DOCs; however, ARB experience with DOC retrofits supports the assumption of an actual 10-year life for this strategy.

DOC Retrofit Scenarios in 2010

Two DOC retrofit scenarios for 2010 were defined by targeted MY range. Table 2-14 presents the emissions benefits of the two DOC retrofit scenarios considered for implementation in 2010.

Table 2-14: 2010 Emissions Reduction with DOC Retrofit Strategies (10% participation)

Scenario	Vehicle Class	Retrofitted MY Age Group	Retrofitted Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
					ROG	NO _x	PM _{2.5}
1	MHDDT	1988-1993	353	8,417	1.9	0.0	1.1
1	HHDDT	1988-1993	299	18,188	25.6	0.0	7.5
2	MHDDT	1994-2002	1,378	59,327	8.7	0.0	3.7
2	HHDDT	1994-2002	890	104,693	105.0	0.0	19.9

2010 Scenario #1: Retrofit MY 1988-1993 Trucks with DOC

In Scenario 1, 1988 through 1993 MY trucks are retrofitted with DOCs. By 2010, most trucks older than 1988 MY will have been retired through normal fleet turnover and therefore are not included in this strategy scenario.

2010 Scenario #2: Retrofit MY 1994-2002 Trucks with DOC

In Scenario 2, 1994 through 2002 MY trucks are retrofitted with DOCs. Table 2-14 indicates that the benefits of scenario 2 are greater than those of scenario 1 because of the larger target truck population and larger daily VMT. Scenario 2 is not an exclusive alternative to scenario 1; as the target truck populations do not overlap, both scenarios could be implemented.

¹⁹ California Air Resources Board (2006)

²⁰ California Air Resources Board (2006)

DOC Retrofit Scenario in 2020

Two DOC retrofit scenarios were defined by targeted MY range. Table 2-15 presents the emissions benefits of the two DOC retrofit scenarios considered for implementation in 2020.

Table 2-15: 2020 Emissions Reduction with DOC Retrofit Strategies (10% participation)

Scenario	Vehicle Class	Retrofitted MY Age Group	Retrofitted Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
					ROG	NO _x	PM _{2.5}
1	MHDDT	1988-1993	151	1,818	0.5	0.0	0.2
1	HHDDT	1988-1993	63	1,302	2.5	0.0	0.6
2	MHDDT	1994-2002	712	15,011	2.7	0.0	1.1
2	HHDDT	1994-2002	349	17,403	22.3	0.0	3.9

2020 Scenario #1: Retrofit MY 1988-1993 Trucks with DOC

In Scenario 1, 1988 through 1993 MY trucks are retrofitted with DOCs. Scenario 1 in 2020 targets the same MY range as scenario 2 in 2010. Thus, scenario 1 in 2020 would be an option if the scenarios for 2010 were not implemented. The benefits of 2020 scenario 1 are less than those of 2010 scenario 1 because of the smaller remaining population of target trucks and lower daily VMT.

2020 Scenario #2: Retrofit MY 1994-2002 Trucks with DOC

In Scenario 2, 1994 through 2002 MY trucks are retrofitted with DOCs. Table 2-15 indicates that the benefits of scenario 2 are greater than those of scenario 1 because of the larger target truck population and larger daily VMT. Scenario 2 is not an exclusive alternative to scenario 1; as the target truck populations do not overlap, both scenarios could be implemented.

DOC Retrofit Scenario in 2030

2030 Scenario #1: Retrofit MY 1994-2002 Trucks with DOC

One DOC retrofit scenario was identified for 2020 as shown in Table 2-16. Scenario 1 in 2030 targets the same MY range as scenario 2 in 2010. Thus, scenario 1 in 2030 would be an option if the scenarios for 2020 were not implemented. The benefits of 2030 scenario 1 are less than those of 2020 scenario 1 because of the smaller remaining population of target trucks and lower daily VMT.

Table 2-16: 2030 Emissions Reduction with DOC Retrofit Strategies (10% participation)

Scenario	Vehicle Class	Retrofitted MY Age Group	Retrofitted Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
					ROG	NO _x	PM _{2.5}
1	MHDDT	1994-2002	304	3,464	0.7	0.0	0.3
1	HHDDT	1994-2002	65	1,113	1.8	0.0	0.3

Cost of DOC Retrofit Strategies

Table 2-17 presents the costs of DOC retrofit strategies in terms of the capital cost per DOC and the equivalent annualized cost. The DOC retrofit strategies analyzed here are assumed to have an initial capital cost and no recurring costs. Capital costs were estimated using the price data discussed above. The capital costs were annualized by the Capital Recovery Factor method, over the assumed 10-year strategy lifetime and using a 4% discount rate consistent with ARB and SCAQMD practice. Within truck GVWR classes, the costs per truck are the same for all implementation years.

Table 2-17: Costs of DOC Retrofit Strategies

Scenario	Vehicle Class	2010		2020		2030	
		Cost of DOCs	Annualized Cost (\$/year)	Cost of DOCs	Annualized Cost (\$/year)	Cost of DOCs	Annualized Cost (\$/year)
1	MHDDT	\$1,200	\$148	\$1,200	\$148	\$1,200	\$148
1	HHDDT	\$2,000	\$247	\$2,000	\$247	\$2,000	\$247
2	MHDDT	\$1,200	\$148	\$1,200	\$148	N/A	N/A
2	HHDDT	\$2,000	\$247	\$2,000	\$247	N/A	N/A

Cost Effectiveness of DOC Retrofit Strategies

The cost effectiveness of DOC retrofit strategies is calculated as the cost per ton of emissions reduced. Table 2-18 provides estimated cost effectiveness for NO_x and PM_{2.5} which are the pollutants of greatest concern. For this study the cost effectiveness is calculated by both the ARB method and the SCAQMD method as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%. For the DOC retrofit strategies the ARB and SCAQMD methods give similar cost effectiveness estimates with the SCAQMD results being slightly lower.

Table 2-18: Cost Effectiveness of DOC Retrofit Strategies

Year	Scenario	Vehicle Class	ARB Annualized Method		SCAQMD BACT Method	
			PM _{2.5} Annual Benefits (tons/year)	PM _{2.5} Cost Effectiveness (\$/ton)	PM _{2.5} Lifetime Benefits (tons)	PM _{2.5} Cost Effectiveness (\$/ton)
2010	1	MHDDT	1.1	\$99,075	10.5	\$80,359
	1	HHDDT	7.5	\$19,714	74.8	\$15,990
	2	MHDDT	3.7	\$109,567	37.2	\$88,868
	2	HHDDT	19.9	\$22,044	199.1	\$17,879
2020	1	MHDDT	0.2	\$180,483	2.5	\$146,388
	1	HHDDT	0.6	\$51,457	6.1	\$41,736
	2	MHDDT	1.1	\$190,128	11.1	\$154,210
	2	HHDDT	3.9	\$43,796	39.3	\$35,523
2030	1	MHDDT	0.3	\$319,951	2.8	\$259,509
	1	HHDDT	0.3	\$111,851	2.9	\$90,721
	2	MHDDT	N/A	N/A	N/A	N/A
	2	HHDDT	N/A	N/A	N/A	N/A

2.5. Truck Retrofit with FTF

Overview

Monetary incentives for truck retrofit can encourage emissions reductions from the in-use fleet at relatively low cost. As with DOCs, flow-through filter (FTF) devices often can be retrofitted to existing trucks with only minor modifications to the exhaust system. This section analyzes scenarios for the installation of FTFs on trucks that can accept this technology. FTFs are certified by ARB to reduce PM emissions by at least 50% (verification level 2). They do not affect NO_x emissions.

The capital cost on which the incentive is based is the purchase price of the FTF kit plus installation.²¹ For all estimates the market penetration rate is assumed to be 10% for each GVWR class. Each scenario could be applied to MHDDTs, HHDDTs, or both. The life of the strategy is assumed to be 10 years.²² Ten years is longer than the typical 5-year manufacturer's emissions warranty FTFs; however, ARB experience with FTF retrofits supports the assumption of an actual 10-year life for this strategy.

FTF Retrofit Scenarios in 2010

Two FTF retrofit scenarios for 2010 were defined by targeted MY range. Table 2-19 presents the emissions benefits of the two FTF retrofit scenarios considered for implementation in 2010.

Table 2-19: 2010 Emissions Reduction of FTF Retrofit Strategies (10% participation)

Scenario	Vehicle Class	Retrofitted MY Age Group	Retrofitted Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
					ROG	NO _x	PM _{2.5}
1	MHDDT	1988-1993	353	8,417	2.8	0.0	2.1
1	HHDDT	1988-1993	299	18,188	38.5	0.0	15.0
2	MHDDT	1994-2002	1,378	59,327	13.0	0.0	7.4
2	HHDDT	1994-2002	890	104,693	157.5	0.0	39.8

2010 Scenario #1: Retrofit MY 1988-1993 Trucks with FTF

In Scenario 1, 1988 through 1993 MY trucks are retrofitted with FTFs. By 2010, most trucks older than 1988 MY will have been retired through normal fleet turnover and therefore are not included in this strategy scenario.

2010 Scenario #2: Retrofit MY 1994-2002 Trucks with FTF

In Scenario 2, 1994 through 2002 MY trucks are retrofitted with FTFs. Table 2-19 indicates that the benefits of scenario 2 are greater than those of scenario 1 because of the larger target truck population and larger daily VMT. Scenario 2 is not an exclusive alternative to scenario 1. As the target truck populations do not overlap, both scenarios could be implemented in 2010.

²¹ California Air Resources Board (2006).

²² California Air Resources Board (2006).

FTF Retrofit Scenario in 2020

Two FTF retrofit scenarios were defined by targeted MY range. Table 2-20 presents the emissions benefits of the two FTF retrofit scenarios considered for implementation in 2020.

Table 2-20: 2020 Emissions Reduction of FTF Retrofit Strategies (10% participation)

Scenario	Vehicle Class	Retrofitted MY Age Group	Retrofitted Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
					ROG	NO _x	PM _{2.5}
1	MHDDT	1994-2002	712	15,011	4.1	0.0	2.2
1	HHDDT	1994-2002	349	17,403	33.4	0.0	7.9
2	MHDDT	2003-2006	597	19,389	2.5	0.0	2.2
2	HHDDT	2003-2006	244	21,149	15.0	0.0	10.3

2020 Scenario #1: Retrofit MY 1994-2002 Trucks with FTF

In Scenario 1, 1994 through 2002 MY trucks are retrofitted with FTFs. Scenario 1 in 2020 targets the same MY range as scenario 2 in 2010. Thus, scenario 1 in 2020 would be an option if the scenarios for 2010 were not implemented. The benefits of 2020 scenario 1 are less than those of 2010 scenario 1 because of the smaller remaining population of target trucks and lower daily VMT.

2020 Scenario #2: Retrofit MY 2003-2006 Trucks with FTF

In Scenario 2, 2003 through 2006 MY trucks are retrofitted with FTFs. Table 2-20 indicates that the PM_{2.5} benefits of scenario 2 are similar to those of scenario 1. Scenario 2 is not an exclusive alternative to scenario 1; as the target truck populations do not overlap, both scenarios could be implemented

FTF Retrofit Scenarios in 2030

Two FTF retrofit scenarios were defined for 2030 by targeted MY range. Table 2-21 presents the emissions benefits of the two FTF retrofit scenarios considered for implementation in 2030.

Table 2-21: 2030 Emissions Reduction of FTF Retrofit Strategies (10% participation)

Scenario	Vehicle Class	Retrofitted MY Age Group	Retrofitted Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
					ROG	NO _x	PM _{2.5}
1	MHDDT	1994-2002	304	3,464	1.1	0.0	0.6
1	HHDDT	1994-2002	65	1,113	2.7	0.0	0.6
2	MHDDT	2003-2006	263	4,002	0.2	0.0	0.1
2	HHDDT	2003-2006	37	1,136	1.1	0.0	0.6

2030 Scenario #1: Retrofit MY 1994-2002 Trucks with FTF

Scenario 1 in 2030 targets the same MY range as scenario 1 in 2020. Thus, scenario 1 in 2030 would be an option if the scenarios for 2020 were not implemented. The benefits of 2030 scenario 1 are less than those of 2020 scenario 1 because of the smaller remaining population of target trucks and lower daily VMT.

2030 Scenario #2: Retrofit MY 2003-2006 Trucks with FTF

Scenario 2 in 2030 targets the same MY range as scenario 2 in 2020. Thus, scenario 2 in 2030 would be an option if the scenarios for 2020 were not implemented. The benefits of 2030 scenario 2 are less than those of 2020 scenario 2 because of the smaller remaining population of target trucks and lower daily VMT.

Cost of FTF Retrofit Strategies

Table 2-22 presents the costs of FTF retrofit strategies in terms of the capital cost per FTF and the equivalent annualized cost. The FTF retrofit strategies analyzed here are assumed to have an initial capital cost and no recurring costs. Capital costs were estimated using the price data discussed above. The capital costs were annualized by the Capital Recovery Factor method, over the assumed 10-year strategy lifetime and using a 4% discount rate consistent with ARB and SCAQMD practice. Within truck GVWR classes, the costs per truck are the same for all implementation years.

Table 2-22: Costs of FTF Retrofit Strategies

Scenario	Vehicle Class	2010		2020		2030	
		Cost of FTFs	Annualized Cost (\$/year)	Cost of FTFs	Annualized Cost (\$/year)	Cost of FTFs	Annualized Cost (\$/year)
1	MHDDT	\$2,750	\$339	\$2,750	\$339	\$2,750	\$339
1	HHDDT	\$4,500	\$555	\$4,500	\$555	\$4,500	\$555
2	MHDDT	\$2,750	\$339	\$2,750	\$339	\$2,751	\$339
2	HHDDT	\$4,500	\$555	\$4,500	\$555	\$4,500	\$555

Cost Effectiveness of FTF Retrofit Strategies

The cost effectiveness of FTF retrofit strategies is calculated as the cost per ton of emissions reduced. Table 2-23 provides estimated cost effectiveness for NO_x and PM_{2.5} which are the pollutants of greatest concern. For this study the cost effectiveness is calculated by both the ARB method and the SCAQMD method as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%. For the FTF retrofit strategies the ARB and SCAQMD methods give similar cost effectiveness estimates with the SCAQMD results being slightly lower.

Table 2-23: Cost Effectiveness of FTF Retrofit Strategies

Year	Scenario	Vehicle Class	ARB Annualized Method		SCAQMD BACT Method	
			PM _{2.5} Annual Benefits (tons/year)	PM _{2.5} Cost Effectiveness (\$/ton)	PM _{2.5} Lifetime Benefits (tons)	PM _{2.5} Cost Effectiveness (\$/ton)
2010	1	MHDDT	2.1	\$113,524	21.1	\$92,078
	1	HHDDT	15.0	\$22,178	149.6	\$17,989
	2	MHDDT	7.4	\$125,545	74.4	\$101,828
	2	HHDDT	39.8	\$24,799	398.2	\$20,114
2020	1	MHDDT	2.2	\$217,854	22.2	\$176,699
	1	HHDDT	7.9	\$49,271	78.6	\$39,963
	2	MHDDT	2.2	\$183,389	22.1	\$148,745
	2	HHDDT	10.3	\$26,139	103.4	\$21,201
2030	1	MHDDT	0.6	\$366,611	5.6	\$297,354
	1	HHDDT	0.6	\$125,832	5.7	\$102,061
	2	MHDDT	0.1	\$1,263,919	1.4	\$1,025,151
	2	HHDDT	0.6	\$64,982	6.3	\$52,707

2.6. Truck Retrofit with DPF

Overview

Monetary incentives for truck retrofit can encourage emissions reductions from the in-use fleet at relatively low cost. As with DOCs and FTFs, diesel particulate filter (DPF) devices often can be retrofitted to existing trucks with only minor modifications to the exhaust system. Several models of DPF are verified by CARB for Level 3 PM reduction (85%). This section analyzes scenarios for the installation of DPFs on trucks that can accept this technology.

The capital cost on which the incentive is based is the purchase price of the DPF kit plus installation.²³ For all estimates the market penetration rate is assumed to be 10% for each GVWR class. Each scenario could be applied to MHDDTs, HHDDTs, or both. The life of the strategy is assumed to be 10 years.²⁴ Ten years is longer than the typical 5-year manufacturer's emissions warranty on DPFs; however, ARB experience with DPF retrofits supports the assumption of an actual 10-year life for this strategy.

DPF Retrofit Scenarios in 2010

Two DPF retrofit scenarios for 2010 were defined by targeted MY range. Table 2-24 presents the emissions benefits of the two DPF retrofit scenarios considered for implementation in 2010.

Table 2-24: 2010 Emissions Reduction of DPF Retrofit Strategies (10% participation)

Scenario	Vehicle Class	Retrofitted MY Age Group	Retrofitted Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
					ROG	NO _x	PM _{2.5}
1	MHDDT	1994-2002	1,378	59,327	15.6	0.0	12.7
1	HHDDT	1994-2002	890	104,693	189.0	0.0	67.7
2	MHDDT	2003-2006	884	53,510	6.0	0.0	8.3
2	HHDDT	2003-2006	314	62,399	36.1	0.0	38.8

2010 Scenario #1: Retrofit MY 1994-2002 Trucks with DPF

In Scenario 1, 1994 through 2002 MY trucks are retrofitted with DPFs. Trucks older than MY 1994 generally have particulate matter emissions that are too high for proper operation of DPF and therefore cannot be retrofitted with this device.

2010 Scenario #2: Retrofit MY 2003-2006 Trucks with DPF

In Scenario 2, 2003 through 2006 MY trucks are retrofitted with DPFs. Table 2-25 indicates that the benefits of scenario 2 are less than those of scenario 1 because of the smaller target truck population and lower daily VMT. Scenario 2 is not an exclusive alternative to scenario 1; as the target truck populations do not overlap, both scenarios could be implemented in 2010.

²³ California Air Resources Board (2006).

²⁴ California Air Resources Board (2006).

DPF Retrofit Scenario in 2020

Two DPF retrofit scenarios for 2020 were defined by targeted MY range. Table 2-25 presents the emissions benefits of the two DPF retrofit scenarios considered for implementation in 2020

Table 2-25: 2020 Emissions Reduction of DPF Retrofit Strategies (10% participation)

Scenario	Vehicle Class	Retrofitted MY Age Group	Retrofitted Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
					ROG	NO _x	PM _{2.5}
1	MHDDT	1994-2002	712	15,011	4.9	0.0	3.8
1	HHDDT	1994-2002	349	17,403	40.1	0.0	13.4
2	MHDDT	2003-2006	597	19,389	3.0	0.0	3.8
2	HHDDT	2003-2006	244	21,149	18.0	0.0	17.6

2020 Scenario #1: Retrofit MY 1994-2002 Trucks with DPF

In Scenario 1, 1994 through 2002 MY trucks are retrofitted with DPFs. Scenario 1 in 2020 targets the same MY range as scenario 1 in 2010. Thus, scenario 1 in 2020 would be an option if the scenarios for 2010 were not implemented. The benefits of 2020 scenario 1 are less than those of 2010 scenario 1 because of the smaller remaining population of target trucks and lower daily VMT.

2020 Scenario #2: Retrofit MY 2003-2006 Trucks with DPF

In Scenario 2, 2003 through 2006 MY trucks are retrofitted with DPFs. Table 2-25 indicates that the PM_{2.5} benefits of scenario 2 are similar to those of scenario 1. Scenario 2 is not an exclusive alternative to scenario 1; as the target truck populations do not overlap, both scenarios could be implemented

DPF Retrofit Scenarios in 2030

Two DPF retrofit scenarios were defined for 2030 by targeted MY range. Table 2-26 presents the emissions benefits of the two DPF retrofit scenarios considered for implementation in 2030.

Table 2-26: 2030 Emissions Reduction of DPF Retrofit Strategies (10% participation)

Scenario	Vehicle Class	Retrofitted MY Age Group	Retrofitted Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
					ROG	NO _x	PM _{2.5}
1	MHDDT	1994-2002	304	3,464	1.3	0.0	1.0
1	HHDDT	1994-2002	65	1,113	3.3	0.0	1.0
2	MHDDT	2003-2006	263	4,002	0.2	0.0	0.2
2	HHDDT	2003-2006	37	1,136	1.3	0.0	1.1

2030 Scenario #1: Retrofit MY 1994-2002 Trucks with DPF

Scenario 1 in 2030 targets the same MY range as scenario 1 in 2020. Thus, scenario 1 in 2030 would be an option if the scenarios for 2020 were not implemented. The benefits of 2030 scenario 1 are less than

those of 2020 scenario 1 because of the smaller remaining population of target trucks and lower daily VMT.

2030 Scenario #2: Retrofit MY 2003-2006 Trucks with DPF

Scenario 2 in 2030 targets the same MY range as scenario 2 in 2020. Thus, scenario 2 in 2030 would be an option if the scenarios for 2020 were not implemented. The benefits of 2030 scenario 2 are less than those of 2020 scenario 2 because of the smaller remaining population of target trucks and lower daily VMT. Scenario 2 is not an exclusive alternative to scenario 1; as the target truck populations do not overlap, both scenarios could be implemented

Cost of DPF Retrofit Strategies

Table 2-27 presents the costs of DPF retrofit strategies in terms of the capital cost per DPF and the equivalent annualized cost. The DPF retrofit strategies analyzed here are assumed to have an initial capital cost and no recurring costs. Capital costs were estimated using the price data discussed above. The capital costs were annualized by the Capital Recovery Factor method, over the assumed 10-year strategy lifetime and using a 4% discount rate consistent with ARB and SCAQMD practice. Within truck GVWR classes, the costs per truck are the same for all implementation years.

Table 2-27: Costs of DPF Retrofit Strategies

Scenario	Vehicle Class	2010		2020		2030	
		Cost of DPFs	Annualized Cost (\$/year)	Cost of DPFs	Annualized Cost (\$/year)	Cost of DPFs	Annualized Cost (\$/year)
1	MHDDT	\$7,000	\$863	\$7,000	\$863	\$7,000	\$863
1	HHDDT	\$8,500	\$1,048	\$8,500	\$1,048	\$8,500	\$1,048
2	MHDDT	\$7,000	\$863	\$7,000	\$863	\$7,000	\$863
2	HHDDT	\$8,500	\$1,048	\$8,500	\$1,048	\$8,500	\$1,048

Cost Effectiveness of DPF Retrofit Strategies

The cost effectiveness of DPF retrofit strategies is calculated as the cost per ton of emissions reduced. Table 2-28 provides estimated cost effectiveness for NO_x and PM_{2.5} which are the pollutants of greatest concern. For this study the cost effectiveness is calculated by both the ARB method and the SCAQMD method as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%. For the DPF retrofit strategies the ARB and SCAQMD methods give similar cost effectiveness estimates with the SCAQMD results being slightly lower.

Table 2-28: Cost Effectiveness of DPF Retrofit Strategies

Year	Scenario	Vehicle Class	ARB Annualized Method		SCAQMD BACT Method	
			PM _{2.5} Annual Benefits (tons/year)	PM _{2.5} Cost Effectiveness (\$/ton)	PM _{2.5} Lifetime Benefits (tons)	PM _{2.5} Cost Effectiveness (\$/ton)
2010	1	MHDDT	12.7	\$187,982	126.5	\$152,470
	1	HHDDT	67.7	\$27,555	676.9	\$22,349
	2	MHDDT	8.3	\$183,761	83.0	\$149,047
	2	HHDDT	38.8	\$16,961	388.1	\$13,757
2020	1	MHDDT	3.8	\$326,199	37.7	\$264,577
	1	HHDDT	13.4	\$54,745	133.7	\$44,403
	2	MHDDT	3.8	\$274,593	37.5	\$222,719
	2	HHDDT	17.6	\$29,043	175.8	\$23,556
2030	1	MHDDT	1.0	\$548,936	9.6	\$445,236
	1	HHDDT	1.0	\$139,814	9.7	\$113,401
	2	MHDDT	0.2	\$1,891,811	2.4	\$1,534,428
	2	HHDDT	1.1	\$72,203	10.6	\$58,563

2.7. Truck Retrofit with DPF+LNC

Overview

Monetary incentives for truck retrofit can encourage emissions reductions from the in-use fleet at relatively low cost. DPF+LNC devices often can be retrofitted to existing trucks but require greater modifications to the exhaust system than do DPFs because the additional NO_x catalyst typically is a separate unit. This section analyzes scenarios for the installation of DPF+LNC systems on trucks that can accept this technology. This strategy assumes that trucks of MY 1993-2003, which is the range for which the Cleaire Longview™ is ARB-verified, can accept a DPF+LNC. This device is verified by CARB for Level 3 PM reduction (85%) and Level 1 NO_x reduction (25%).

The capital cost on which the incentive is based is the purchase price of the DPF+LNC kit plus installation. This analysis used quoted prices for the Cleaire Longview™.²⁵ For all estimates the market participation rate is assumed to be 10% for each GVWR class. Each scenario could be applied to MHDDTs, HHDDTs, or both. The life of the strategy is assumed to be 10 years.²⁶ Ten years is longer than the typical 5-year manufacturer's emissions warranty for DPF+LNCs; however, as with DPFs an actual 10-year life is assumed for this strategy.

DPF+LNC Retrofit Scenarios in 2010

One DPF+LNC retrofit scenario for 2010 was defined by targeted MY range. Table 2-29 presents the emissions benefits of the DPF+LNC retrofit scenario considered for implementation in 2010.

Table 2-29: 2010 Emissions Reduction of DPF+LNC Retrofit Strategies (10% participation)

Vehicle Class	Retrofitted MY Age Group	Retrofitted Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
				ROG	NO _x	PM _{2.5}
MHDDT	1993-2003	3,199	146,884	17.2	195.5	14.9
HHDDT	1993-2003	2,053	247,332	205.5	639.9	81.9

In this scenario, 1993 through 2003 MY trucks are retrofitted with a DPF+LNC. Trucks older than this range generally have particulate matter emissions that are too high for proper operation of DPF+LNC and therefore cannot be retrofitted with this device.

DPF+LNC Retrofit Scenario in 2020

One DPF+LNC retrofit scenario for 2020 was defined by targeted MY range. Table 2-30 presents the emissions benefits of the DPF+LNC retrofit scenario considered for implementation in 2020

²⁵ City of Fresno (2007).

²⁶ California Air Resources Board (2006).

Table 2-30: 2020 Emissions Reduction of DPF+LNC Retrofit Strategies (10% participation)

Vehicle Class	Retrofitted MY Age Group	Retrofitted Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
				ROG	NO _x	PM _{2.5}
MHDDT	1993-2003	1,677	36,632	5.6	53.4	4.5
HHDDT	1993-2003	827	43,149	44.3	124.4	17.1

In this scenario, 1993 through 2003 MY trucks are retrofitted with a DPF+LNC. Scenario 1 in 2020 targets the same MY range as scenario 1 in 2010. Thus, scenario 1 in 2020 would be an option if the scenarios for 2010 were not implemented. The benefits of 2020 scenario 1 are less than those of 2010 scenario 1 because of the smaller remaining population of target trucks and lower daily VMT.

DPF+LNC Retrofit Scenarios in 2030

One DPF+LNC retrofit scenario was defined for 2030 by targeted MY range. Table 2-31 presents the emissions benefits of the DPF+LNC retrofit scenario considered for implementation in 2030.

Table 2-31: 2030 Emissions Reduction of DPF+LNC Retrofit Strategies (10% participation)

Vehicle Class	Retrofitted MY Age Group	Retrofitted Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
				ROG	NO _x	PM _{2.5}
MHDDT	1993-2003	719	5,833	1.2	10.7	1.0
HHDDT	1993-2003	155	1,978	2.7	6.8	1.0

Scenario 1 in 2030 targets the same MY range as scenario 1 in 2020. Thus, scenario 1 in 2030 would be an option if the scenarios for 2020 were not implemented. The benefits of 2030 scenario 1 are less than those of 2020 scenario 1 because of the smaller remaining population of target trucks and lower daily VMT.

Cost of DPF+LNC Retrofit Strategies

Table 2-32 presents the costs of DPF+LNC retrofit strategies in terms of the capital cost per device and the equivalent annualized cost. The DPF+LNC retrofit strategies analyzed here are assumed to have an initial capital cost and no recurring costs. The ARB estimated that in actual use the Cleaire Longview™ might decrease fuel economy by 3 to 7%²⁷; we assumed 5% for the purposes of calculating operating costs. Capital costs were estimated using the price data discussed above. The capital costs were annualized by the Capital Recovery Factor method, over the assumed 10-year strategy lifetime and using a 4% discount rate consistent with ARB and SCAQMD practice. Within truck GVWR classes, the costs per truck are assumed to be the same for all implementation years.

²⁷ California Air Resources Board (2004a).

Table 2-32 Costs of DPF+LNC Retrofit Strategies

Vehicle Class	2010		2020		2030	
	Cost of DPF+LNC	Annualized Cost (\$/year)	Cost of DPF+LNC	Annualized Cost (\$/year)	Cost of DPF+LNC	Annualized Cost (\$/year)
MHDDT	\$25,291	\$3,315	\$25,291	\$3,193	\$25,291	\$3,213
HHDDT	\$25,291	\$3,605	\$25,291	\$3,267	\$25,291	\$3,330

Cost Effectiveness of DPF+LNC Retrofit Strategies

The cost effectiveness of DPF+LNC retrofit strategies is calculated as the cost per ton of emissions reduced. Table 2-33 provides estimated cost effectiveness for NO_x and PM_{2.5} which are the pollutants of greatest concern. For this study the cost effectiveness is calculated by both the ARB method and the SCAQMD method as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%. For the DPF+LNC retrofit strategies the ARB and SCAQMD methods give similar cost effectiveness estimates with the SCAQMD results giving somewhat lower costs per ton.

Table 2-33: Cost Effectiveness of DPF+LNC Retrofit Strategies

Year	Vehicle Class	ARB Annualized Method				SCAQMD BACT Method			
		Annual Benefits (tons/year)		Cost Effectiveness (\$/ton)		Lifetime Benefits (tons)		Cost Effectiveness (\$/ton)	
		NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}
2010	MHDDT	195.5	14.9	\$54,241	\$709,413	1,954.9	149.5	\$43,995	\$575,397
	HHDDT	639.9	81.9	\$11,570	\$90,406	6,398.8	818.9	\$9,385	\$73,328
2020	MHDDT	53.4	4.5	\$100,293	\$1,187,892	533.8	45.1	\$81,346	\$963,487
	HHDDT	124.4	17.1	\$21,715	\$158,219	1,243.8	170.7	\$17,613	\$128,330
2030	MHDDT	10.7	1.0	\$215,867	\$2,202,938	107.0	10.5	\$175,088	\$1,786,780
	HHDDT	6.8	1.0	\$75,564	\$522,837	68.5	9.9	\$61,289	\$424,067

2.8. Truck Repowering

Overview

Truck repowering strategies are similar in approach to truck replacement strategies. Monetary incentives for truck repowering can promote retirement of older engines that have higher emission rates, at lower capital costs compared to replacement of the entire truck. This strategy assumes that the truck owner scraps his/her current truck's engine and replaces it with a new engine or a newer used engine. The most common action is repowering of an older diesel truck with a cleaner diesel or alternative fuel engine. There must be proof of disposal of the older engine to ensure that it is not resold into the SCAG market for used engines.

The newer engine is estimated to be used for 10 years.²⁸ In this analysis, no value is given to the scrapped engine. The capital cost on which the incentive is based is the purchase price of the replacement engine. Prices for truck engines were taken from the ARB report on port truck emission reduction strategies.²⁹

For all estimates the market penetration rate, or the percentage of eligible trucks that actually participate and are repowered, is assumed to be 10% for each GVWR class. Each scenario could be applied to MHDDTs, HHDDTs, or both. The life of the strategy is assumed to be 10 years.

Truck Repowering Scenarios in 2010

Three truck repowering scenarios were defined depending on the targeted MY range. Table 2-34 presents the emissions benefits of the three truck repowering scenarios considered for implementation in 2010.

2010 Scenario #1: Repower MY 1988-1993 Trucks with MY 1998-2002 Engines

For 2010, Scenario 1 replaces MY 1988-1993 engines with newer MY 1998-2002 engines. As in the truck replacement strategy, the emissions benefits of the 2010 repowering strategy are affected by the NO_x defeat device and subsequent consent decree. In the 2010 scenarios, not all 1998-2002 MY engines have had the defeat device removed and higher emissions are predicted by EMFAC 2007 for those trucks. If these trucks have in fact been reflashed to remove the defeat device prior to repowering, the results would be different. By 2010, most trucks older than 1988 MY will have been retired through normal fleet turnover and therefore are not included in this strategy scenario.

²⁸ California Air Resources Board (2006).

²⁹ California Air Resources Board (2006).

Table 2-34: 2010 Emissions Reduction with Repowering Strategies (10% participation)

Scenario	Vehicle Class	Scrapped Engine MY Age Group	Replacement Engine MY Age Group	Replaced Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)		
						ROG	NO _x	PM _{2.5}
1	MHDDT	1988-1993	1998-2002	353	8,417	1.5	43.5	2.3
1	HHDDT	1988-1993	1998-2002	299	18,188	16.8	(4.4)	16.8
2	MHDDT	1994-2002	2003-2006	1,378	59,327	10.0	348.6	4.1
2	HHDDT	1994-2002	2003-2006	890	104,693	142.8	1,184.4	3.0
3	MHDDT	2003-2006	2007+	884	53,510	2.5	174.9	4.2
3	HHDDT	2003-2006	2007+	314	62,399	18.6	344.4	38.9

2010 Scenario #2: Repower MY 1994-2002 Trucks with MY 2003-2006 Engines

For Scenario 2, 1994 through 2002 MY engines are replaced with 2003-2006 MY engines. Table 2-34 indicates that the benefits of scenario 2 are greater than those of scenario 1 because of the larger target truck population and larger daily VMT. The difference is especially pronounced for the HHDDT class. Scenario 2 is not an exclusive alternative to scenario 1; as the target truck populations do not overlap, both scenarios could be implemented.

2010 Scenario #3: Repower MY 2003-2006 Trucks with MY 2007+ Engines

For Scenario 3, 2003 through 2006 MY engines are replaced with 2007+ MY engines. Table 2-34 indicates that the benefits of scenario 2 are less than those of scenario 1 because of the smaller population of target trucks and lower daily VMT. Scenario 3 is not an exclusive alternative to scenarios 1 and 2; as the target truck populations do not overlap, all 3 scenarios could be implemented.

No feasible repowering scenarios were identified for 2020 and 2030 because the remaining population of trucks that could accept a significantly cleaner engine than the original will be quite small.

Cost of Repowering Strategies

Table 2-35 presents the costs of truck repowering strategies in terms of the capital cost per replacement engine and the equivalent annualized cost. The truck repowering strategies analyzed here are assumed to have an initial capital cost and no recurring costs. Capital costs were estimated using the used engine price data discussed above. The capital costs were annualized by the Capital Recovery Factor method, over the assumed 10-year strategy lifetime and using a 4% discount rate consistent with ARB and SCAQMD practice.

Table 2-35: Costs of Repowering Strategies

Scenario	Vehicle Class	2010		2020		2030	
		Cost of Repower	Annualized Cost (\$/year)	Cost of Repower	Annualized Cost (\$/year)	Cost of Repower	Annualized Cost (\$/year)
1	MHDDT	\$25,000	\$3,082	N/A	N/A	N/A	N/A
1	HHDDT	\$40,000	\$4,932	N/A	N/A	N/A	N/A
2	MHDDT	\$20,000	\$2,466	N/A	N/A	N/A	N/A
2	HHDDT	\$30,000	\$3,699	N/A	N/A	N/A	N/A
3	MHDDT	\$27,000	\$3,329	N/A	N/A	N/A	N/A
3	HHDDT	\$40,000	\$4,932	N/A	N/A	N/A	N/A

Cost Effectiveness of Repowering Strategies

The cost effectiveness of truck repowering strategies is calculated as the cost per ton of emissions reduced. Table 2-36 provides estimated cost effectiveness for NO_x and PM_{2.5} which are the pollutants of greatest concern. For this study the cost effectiveness is calculated by both the ARB method and the SCAQMD method as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%. For the truck repowering strategies the ARB and SCAQMD methods give similar cost effectiveness estimates with the SCAQMD results being slightly lower.

Table 2-36: Cost Effectiveness of Repowering Strategies in 2010

Scenario	Vehicle Class	ARB Annualized Method				SCAQMD BACT Method			
		Annual Benefits (tons/year)		Cost Effectiveness (\$/ton)		Lifetime Benefits (tons)		Cost Effectiveness (\$/ton)	
		NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}
1	MHDDT	43.5	2.3	\$50,067	\$933,635	434.9	23.3	\$40,609	\$757,262
1	HHDDT	(4.4)	16.8	(\$673,522)	\$175,920	(43.8)	167.6	(\$546,287)	\$142,687
2	MHDDT	348.6	4.1	\$19,493	\$1,676,341	3,486.0	40.5	\$15,810	\$1,359,663
2	HHDDT	1,184.4	3.0	\$5,558	\$2,171,998	11,843.7	30.3	\$4,508	\$1,761,685
3	MHDDT	174.9	4.2	\$33,657	\$1,415,375	1,748.6	41.6	\$27,299	\$1,147,996
3	HHDDT	344.4	38.9	\$8,994	\$79,615	3,443.8	389.0	\$7,295	\$64,575

2.9. Use of Biodiesel (B20) in Heavy-Duty Trucks

Description of Strategy

This strategy involves the use of a biodiesel blend (B20) in heavy-duty diesel trucks. Biodiesel is a renewable fuel made of vegetable oils, animal fats, and recycled cooking oils. Based on estimates from the National Biodiesel Board, California is responsible for about 25% of all biodiesel consumed nationwide, which was estimated at 20 million gallons in 2005.³⁰

A B20 blend indicates that the fuel is composed of 20% biodiesel and 80% regular diesel. B20 is currently the most common biodiesel blend in the United States because it is comparable to conventional diesel fuel in terms of performance and cost, and does not require engine modifications. B20 is also the minimum blend level allowed for Energy Policy Act of 1992 (EPAct) compliance.³¹

Higher blend levels, such as B50 or B100, were not included in this analysis. They require special handling and may require equipment modifications such as the use of heaters (in colder climates) or changing seals and gaskets that come in contact with the fuel. A B100 blend also reduces fuel efficiency by approximately 10%.³²

Previous research has shown that biodiesel and biodiesel blends have environmental advantages over No. 2 diesel that is generally used in heavy-duty trucks, and emission reduction can be achieved from the use of biodiesel blends.

This strategy was only applied to pre-2007 model years because trucks complying with 2007 emissions standards will be substantially cleaner, and the use of B20 would provide only marginal emissions benefits. Because the share of pre-2007 model year trucks will decrease over time, the effectiveness of this strategy is reduced after 2010.

Emissions Reduction Potential

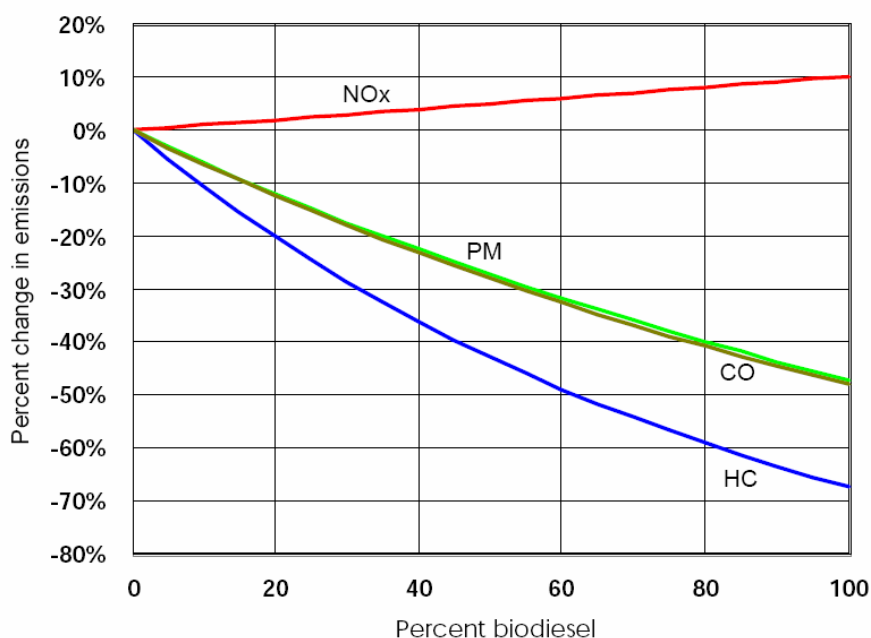
EPA has conducted a comprehensive analysis of the emissions impacts of biodiesel.³³ Figure 2-2 illustrates the effects on NO_x, PM, CO, and HC from the use of biodiesel when compared to No. 2 diesel fuel.

³⁰ California Energy Commission (2005).

³¹ U.S. Department of Energy (2006a).

³² U.S. Department of Energy (2006a).

³³ U.S. Environmental Protection Agency (2002).

Figure 2-2: Average Emission Impacts of Biodiesel for Heavy-Duty Highway Engines

Source: U.S. Environmental Protection Agency (2002)

While the emissions of in PM, CO, and HC decline as the concentration of biodiesel increases, NO_x emissions increase with higher concentrations of biodiesel. Because biodiesel does not contain nitrogen, increasing NO_x emissions are not a result of the fuel nitrogen content. NO_x is created as the nitrogen in the intake air reacts with oxygen during the combustion process. The observed NO_x increase is believed to occur primarily at low engine speed but high load conditions. Ongoing testing of B20 in heavy-duty trucks at the National Renewable Energy laboratory shows that NO_x emissions do not always increase for B20 and in some cases a decrease in NO_x emissions is observed. Because of the conflicting results of engine stand and vehicle tests, the impact of B20 on NO_x emissions must be regarded as unknown at this time.³⁴

Some studies suggest that a B20 blend will reduce fuel economy by about 1-2%, although previous studies were not able to identify any significant difference in exhaust CO₂ emissions between B20 and conventional diesel. This analysis assumes no difference in fuel economy between B20 and conventional diesel.

For a soya-based B20 blend, which is the most common biodiesel blend in the U.S., the EPA study estimated the following emission reduction potential, shown in Table 2-37. These results are highly dependent on the type of biodiesel (i.e., soyabean, rapeseed, or animal fats) and on the type of conventional diesel to which the biodiesel is added to. Additionally, these results came from data collected in 1997, so the impact of biodiesel in future fleets could vary from these estimates. A more recent study relied on tests of entire vehicles, in contrast to previous tests of engines, on a heavy-duty chassis dynamometer, which should provide a more realistic estimate of the emission impact of B20.³⁵ These results are also shown in Table 2-37, which includes an average scenario based on these two data sources.

³⁴ U.S. Department of Energy (2006a).

³⁵ National Renewable Energy Laboratory (2006).

Table 2-37: Emission Impacts from Soya-based B20

Pollutant	References		Scenario Evaluated
	EPA (2002)	NREL (2006)	
NO _x	+ 2.0%	-0.1% to +3.6%	+1.8%
PM	- 10.1%	-34.7% to -19.4%	-22.6%
CO	- 11.0%	-15.3% to -6.9%	-11.0%
HC	-21.1%	-16.8 to -12.4%	-16.6%

The emission benefits in Table 2-38 assume a participation rate of 10%, and it is evident that the emission benefits decrease substantially over time since the strategy is limited to pre-2007 heavy-duty trucks. Negative values indicate an increase in emissions.

Table 2-38: Emissions Reduction with B20 (10% participation)

Year	Affected Age Group	Affected Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)	
				NO _x	PM _{2.5}
2010	1994-2006	6,931	559,856	(70)	34
2020	1994-2006	3,802	145,903	(18)	10
2030	1994-2006	1,336	19,428	(2)	1

Cost

Table 2-39 presents the costs per truck associated with the use of B20 blend. Because engine modifications are not necessary for the use of a B20 blend, and the current fuel infrastructure is also adequate to handle B20, the only cost considered in this analysis is the price differential between a B20 blend and conventional diesel. Costs per truck decrease throughout time because daily mileage for pre-2007 trucks decrease throughout time. For example, pre-2007 trucks run an average of 80 miles a day in 2010, but just under 15 miles a day in 2030.

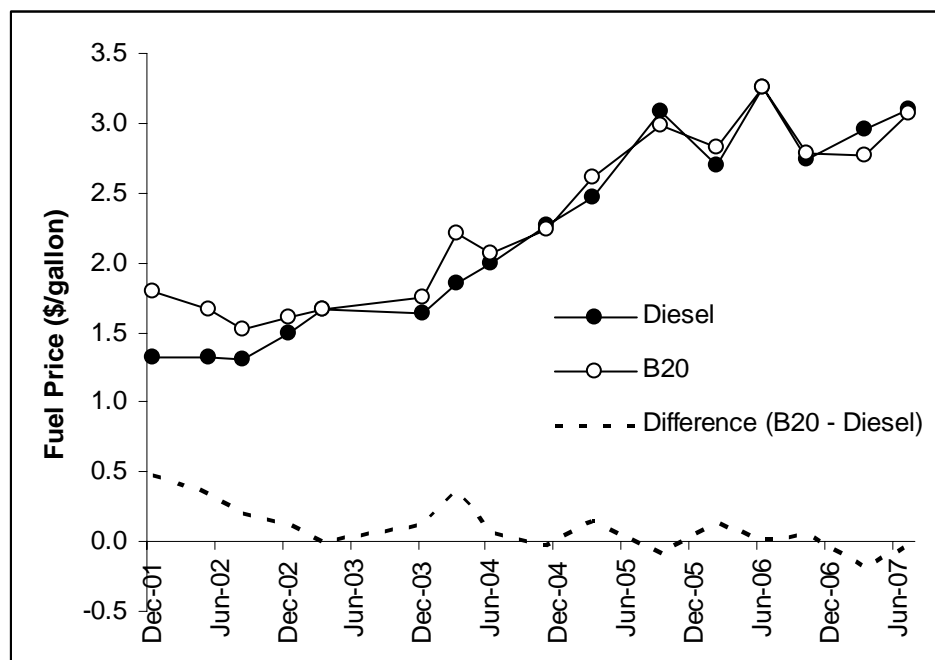
Table 2-39: Annual Costs per truck of B20 Strategy

2010	2020	2030
\$1,087	\$473	\$192

The wholesale cost of biodiesel (B100) is typically higher than conventional diesel fuel by \$1 to \$2 per gallon, depending on the size of the producer, feedstock cost, transportation cost, production and tax incentives, as well as other local variables. The cost of the B20 blend has been about 20 cents per gallon higher than conventional diesel (DOE).³⁶ However, more recent price statistics included in the Clean Cities Alternative Fuel Price Reports, also published by the DOE, indicate that the difference has narrowed in recent years.³⁷ Figure 2-3 illustrates the trends for the West Coast. Since 2004, a biodiesel tax incentive has lowered the prices of B20. This incentive is a federal excise tax credit equal to one penny per percent of biodiesel, which adds up to 20 cents per gallon for a B20 blend.

³⁶ U.S. Department of Energy (2006a).

³⁷ U.S. Department of Energy (2007).

Figure 2-3: Historical Trends in Diesel and B20 Prices on the West Coast

Source: U.S. Department of Energy (2007).

Because tax incentives are a type of cost, the analysis assumes that the price difference between B20 and conventional fuel is 20 cents per gallon. Based on EIA's Annual Energy Outlook, the average diesel price in 2005 was \$2.413 per gallon.³⁸ Therefore, the price difference between B20 and conventional diesel fuel without tax incentives is about 8.3%. There is substantial uncertainty associated with future prices of fuel, but this analysis assumes that the price difference (on a percentage basis) between both types of fuel remains constant in future years. Future diesel fuel prices are forecasted based on estimates from the Annual Energy Outlook.³⁹

Cost Effectiveness

The cost effectiveness of the B20 strategy is calculated as the cost per ton of emissions reduced. Table 2-40 provides estimated cost effectiveness for NO_x and PM_{2.5} which are the pollutants of greatest concern. The cost effectiveness for PM_{2.5} improves from 2010 to 2020 due to the lower fuel prices estimated for 2020. In 2030, diesel fuel prices are expected to rise again, which combined to cleaner diesel engines, explains the higher cost per ton of pollutant. For this study the cost effectiveness is calculated by both the ARB method and the SCAQMD method as explained in the introduction. Because all costs involved are recurring, both methods yield the same results. The cost effectiveness for NO_x is negative since there is an increase in NO_x emissions due to the use of B20 blend.

³⁸ Energy Information Administration (2007).

³⁹ Energy Information Administration (2007).

Table 2-40: Cost Effectiveness of the B20 Strategy

Year	ARB Annualized Method				SCAQMD BACT Method			
	Annual Benefits (tons/year)		Cost Effectiveness (\$/ton)		Lifetime Benefits (tons)		Cost Effectiveness (\$/ton)	
	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}
2010	(70)	34	(\$107,908)	\$222,872	(70)	34	(\$107,908)	\$222,872
2020	(18)	10	(\$99,944)	\$176,432	(18)	10	(\$99,944)	\$176,432
2030	(2)	1	(\$114,751)	\$250,768	(2)	1	(\$114,751)	\$250,768

2.10. Truck Replacement with LNG Heavy-Duty Trucks

This strategy considers the replacement of heavy-duty diesel trucks with liquefied natural gas heavy-duty trucks. Only pre-2007 model years were taken into account in the analysis because trucks complying with 2007 and 2010 emissions standards will be substantially cleaner, and the use of LNG would provide only marginal emissions benefits. Despite decreasing emission benefits throughout time, the use of natural gas in heavy-duty trucks is expected to increase due to the sustained energy policy supporting energy sources other than imported oil.⁴⁰

With commercially available low emission vehicles and fueling stations, natural gas is the leading alternative fuel in California. Based on 2002 data from the California Department of Motor Vehicles, over 30,000 natural gas vehicles are currently on the state's roads. The majority of the current natural gas powered heavy-duty vehicles are transit buses and garbage trucks. However, there are already a few options in the market place for heavy-duty trucks powered by natural gas.

In 2004, there were just over 2,400 natural gas heavy-duty vehicles in the U.S., with about two thirds in California.⁴¹ Gladstein, Neandross, and Associates, administrators of the Interstate Clean Transportation Corridor Program, believe that more than 120,000 heavy-duty trucks can be fueled by LNG nationwide every year.⁴² Such growth is certainly dependent on an accelerated development of fueling infrastructure, which could cost hundreds of millions of dollars over the next decade, as well as on the reduction of the share of imported natural gas, currently at 85%.⁴³

Monetary incentives for truck replacement can promote more rapid turnover of the truck fleet, accelerating retirement of older vehicles that have higher emission rates. However, since the cost of natural gas has been lower than diesel (Figure 2-4), there can be economic benefits involved in the replacement. This strategy assumes that the truck owner scraps his/her current truck and replaces it with a newer LNG truck. There must be proof of disposal of the older truck to ensure that it is not resold into the SCAG truck population.

Emissions Reduction Potential

Despite the fact that several automobile manufacturers have stopped producing light-duty natural gas vehicles, technology development activities have focused on heavy-duty natural gas engines. As a result, Cummins has recently released its ISL-G model, which complies with 2010 emission standards.⁴⁴ The ISL-G model has an 8.8 liter engine and falls into the medium heavy-duty truck category. The ISXG model, also from Cummins, has a 14.9 liter engine and is comparable to a heavy-heavy duty engine.

This analysis assumes that the ISL-G and the ISXG replace 10% of the pre-2007 medium and heavy heavy-duty truck fleet, respectively. The emission reduction potential was calculated by comparing the ISL-G and ISXG's emission factors (in grams/mile) with model-year specific emission factors.

ISL-G and ISXG's emission factors were calculated based on the following formula, assuming an energy consumption factor of 10.5 bhp-hr/gallon.⁴⁵ EMFAC2007 was used to estimate fuel economy (miles per gallon), an approach consistent with the other truck strategies included in this report. Fuel economy was

⁴⁰ National Renewable Energy Laboratory (2003)

⁴¹ California Energy Commission (2004)

⁴² California Energy Commission (2005).

⁴³ TIAX (2003)

⁴⁴ Cummins Westport (2007)

⁴⁵ South Coast Air Quality Management District (2005)

discounted by 20% to account for the fact that natural gas engines are less fuel efficient than diesel engines on a per gallon basis.

$$\text{Emission Factor (grams/mile)} = \frac{\text{Emission Factor (grams/bhp-hr)} \times \text{Energy Consumption Factor (bhp-hr/gallon)}}{\text{Fuel Economy (miles/gallon)}}$$

For medium-heavy duty trucks, the resulting LNG NO_x and PM emission factors are 0.41 and 0.02 grams per mile, respectively. For heavy-heavy duty trucks, the LNG NO_x and PM emission factors are 3.45 and 0.06 grams per mile, respectively.

EMFAC2007 was also used to determine the truck population, total daily VMT, and total daily emissions by model year. Emission factors for diesel trucks were estimated by dividing daily emissions by daily VMT. Table 2-41 shows the diesel emission factors by model year and the emission reduction from the LNG truck. The emission benefits of this strategy are included in Table 2-42.

Table 2-41: Emission Reduction for LNG Replacement

Model Year	MHDDT				HHDDT			
	NO _x		PM _{2.5}		NO _x		PM _{2.5}	
	Diesel EF (grams/mile)	Emission Reduction	Diesel EF (grams/mile)	Emission Reduction	Diesel EF (grams/mile)	Emission Reduction	Diesel EF (grams/mile)	Emission Reduction
1988	23.08	98.2%	0.7	97.1%	26.23	86.8%	3.04	98.1%
1989	23.02	98.2%	0.69	97.1%	26.02	86.7%	3.01	98.1%
1990	22.96	98.2%	0.69	97.0%	25.82	86.6%	2.97	98.1%
1991	21.81	98.1%	0.63	96.8%	30.32	88.6%	1.61	96.4%
1992	21.68	98.1%	0.62	96.7%	30.04	88.5%	1.58	96.4%
1993	21.54	98.1%	0.61	96.6%	29.75	88.4%	1.55	96.3%
1994	17.88	97.7%	0.44	95.4%	30.21	88.6%	1.11	94.8%
1995	17.78	97.7%	0.43	95.3%	29.87	88.4%	1.09	94.7%
1996	17.67	97.7%	0.42	95.1%	29.52	88.3%	1.06	94.6%
1997	17.56	97.7%	0.41	95.0%	29.16	88.2%	1.03	94.4%
1998	15.4	97.3%	0.29	93.0%	29.33	88.2%	0.96	94.0%
1999	15.32	97.3%	0.28	92.8%	28.89	88.1%	0.93	93.8%
2000	15.23	97.3%	0.27	92.5%	28.43	87.9%	0.9	93.6%
2001	15.14	97.3%	0.26	92.2%	27.95	87.6%	0.86	93.3%
2002	15.04	97.3%	0.25	91.8%	27.44	87.4%	0.82	93.0%
2003	8.27	95.0%	0.23	91.2%	14.07	75.5%	0.94	93.9%
2004	7.79	94.7%	0.22	90.7%	13.67	74.7%	0.89	93.5%
2005	7.73	94.7%	0.21	90.3%	13.24	73.9%	0.83	93.1%
2006	7.67	94.7%	0.2	89.8%	12.81	73.0%	0.77	92.6%

Table 2-42: Emissions Reduction with LNG Replacement (10% participation)

Year	Vehicle Class	Scrapped Age Group	Replaced Population	Total Daily VMT	Average Lifetime Emissions Reduction (tons/year)	
					NO _x	PM _{2.5}
2010	MHDDT	1988-2006	5,230	317,510	1,441	32
	HHDDT	1988-2006	3,006	527,362	3,718	188
2020	MHDDT	1988-2006	2,920	99,597	439	12
	HHDDT	1988-2006	1,312	116,998	877	51
2030	MHDDT	1988-2006	1,256	20,749	98	3
	HHDDT	1988-2006	274	10,025	84	5

Cost

There are three cost elements involved in the replacement of conventional diesel trucks with natural gas powered trucks. First, the capital costs associated with the purchase of the new equipment. Second, additional maintenance costs associated with the operation of a natural gas truck. Finally, any price differential between diesel and natural gas fuel that might occur in the future.

The analysis assumes that a new Cummins ISL-G truck costs \$90,000 and \$140,000 for a medium and heavy-heavy duty trucks, respectively^{46,47}, and that additional maintenance requirements include \$200/year for service checks on the LNG fuel system, and \$500/year for spark-plugs on the stoichiometric engines.⁴⁸ The new natural gas truck is estimated to be used for 10 years as specified in ARB's *Evaluation of Port Trucks and Possible Mitigation Strategies*.⁴⁹ In this analysis, no value is given to the scrapped truck. The largest uncertainty in terms of cost involves the price differential between conventional diesel and natural gas.

Since 2004, the price of natural gas has been about 20% lower than conventional diesel on a gallon equivalent basis (Figure 2-4). Data from the 2007 Annual Energy Outlook were used to estimate the future price of conventional diesel, as well as the price difference between both fuels (Table 2-43).⁵⁰ Three scenarios were assumed: conservative, moderate, and aggressive. The moderate and aggressive scenarios are consistent with the reference and high scenarios in the Annual Energy Outlook, respectively. The conservative scenario assumed that there is no price differential between natural gas and conventional diesel, in order to isolate the effects of capital and additional maintenance costs.

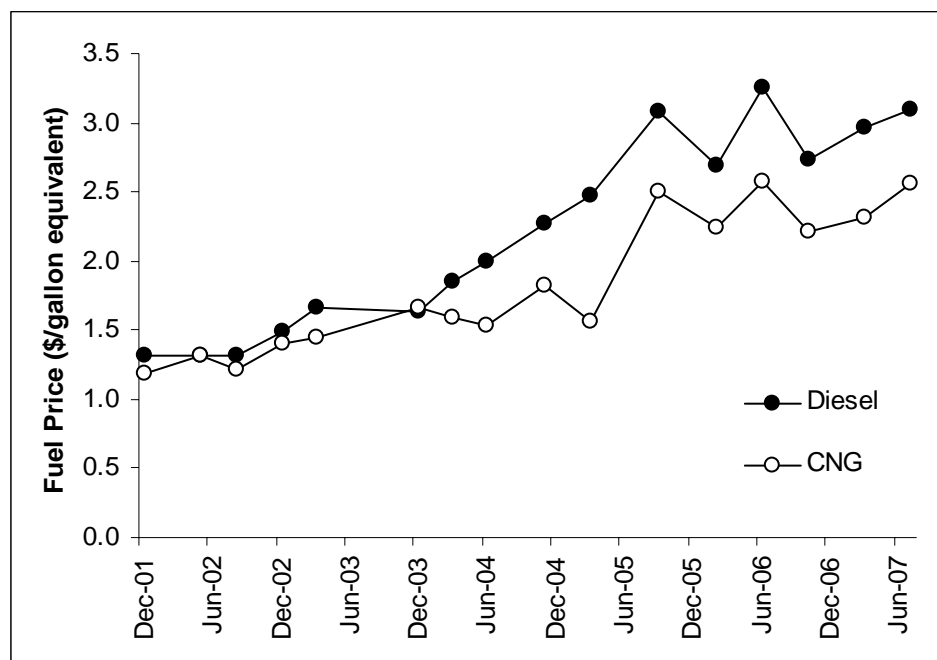
⁴⁶ U.S. Department of Energy (2000)

⁴⁷ California Air Resources Board (2006)

⁴⁸ TIAX (2005)

⁴⁹ California Air Resources Board (2006)

⁵⁰ Energy Information Administration (2007)

Figure 2-4: Historical Trends in Diesel and Natural Gas Prices on the West Coast

Source: U.S. Department of Energy (2007).

Table 2-43: Estimated Fuel Costs

	Price of Conventional Diesel (\$2005 per gallon)			Price Differential between Natural Gas and Conventional Diesel		
	2010	2020	2030	2010	2020	2030
Conservative	\$2.027	\$1.541	\$1.647	0%	0%	0%
Moderate	\$2.304	\$2.112	\$2.257	-16.9%	-15.8%	-18.3%
Aggressive	\$2.572	\$2.839	\$3.042	-20.6%	-27.7%	-25.5%

Table 2-44 summarizes the costs associated with this strategy. Annualized costs are calculated by adding the annualized capital costs (discounted by an annual rate of 4%), the additional maintenance costs, as well as the cost difference between fuels. The latter is calculated by multiplying total gallons of fuel equivalent consumed (daily VMT x 365 days / fuel efficiency) by the diesel price and the price differential between natural gas and diesel.

Table 2-44: Costs of LNG Replacement Strategy

Scenario	Vehicle Class	2010		2020		2030	
		Cost of New Truck	Annualized Cost per truck (\$/year)	Cost of New Truck	Annualized Cost per truck (\$/year)	Cost of New Truck	Annualized Cost per truck (\$/year)
Conservative	MHDDT	\$90,000	\$13,939	\$90,000	\$12,900	\$90,000	\$12,368
Moderate	MHDDT	\$90,000	\$12,129	\$90,000	\$12,027	\$90,000	\$11,844
Aggressive	MHDDT	\$90,000	\$11,734	\$90,000	\$11,371	\$90,000	\$11,640
Conservative	HHDDT	\$140,000	\$25,769	\$140,000	\$21,595	\$140,000	\$19,548
Moderate	HHDDT	\$140,000	\$19,173	\$140,000	\$18,720	\$140,000	\$18,093
Aggressive	HHDDT	\$140,000	\$17,736	\$140,000	\$16,561	\$140,000	\$17,528

Cost Effectiveness

The cost effectiveness of the LNG replacement strategy is calculated as the cost per ton of emissions reduced. Table 2-45 provides estimated cost effectiveness for NO_x and PM_{2.5} which are the pollutants of greatest concern. The cost effectiveness in the conservative scenario, which was designed to disregard the effects of fuel price, decreases with time since the pool of pre-2007 trucks is reduced.

Table 2-45: Cost Effectiveness of the Truck Replacement LNG Strategy

Year	Scenario	Vehicle Class	ARB Annualized Method				SCAQMD BACT Method			
			Annual Benefits (tons/year)		Cost Effectiveness (\$/ton)		Lifetime Benefits (tons)		Cost Effectiveness (\$/ton)	
			NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}
2010	Conservative	MHDDT	1,441	32	\$50,593	\$2,310,130	14,410	316	\$40,699	\$1,858,325
	Moderate	MHDDT	1,441	32	\$44,023	\$2,010,101	14,410	316	\$34,128	\$1,558,297
	Aggressive	MHDDT	1,441	32	\$42,591	\$1,944,732	14,410	316	\$32,696	\$1,492,927
	Conservative	HHDDT	3,718	188	\$20,829	\$411,532	37,184	1,882	\$17,684	\$349,397
	Moderate	HHDDT	3,718	188	\$15,497	\$306,194	37,184	1,882	\$12,353	\$244,059
	Aggressive	HHDDT	3,718	188	\$14,336	\$283,243	37,184	1,882	\$11,191	\$221,108
2020	Conservative	MHDDT	439	12	\$85,782	\$3,098,055	4,391	122	\$67,654	\$2,443,358
	Moderate	MHDDT	439	12	\$79,972	\$2,888,245	4,391	122	\$61,845	\$2,233,548
	Aggressive	MHDDT	439	12	\$75,611	\$2,730,736	4,391	122	\$57,483	\$2,076,039
	Conservative	HHDDT	877	51	\$32,321	\$557,198	8,767	509	\$26,498	\$456,808
	Moderate	HHDDT	877	51	\$28,018	\$483,009	8,767	509	\$22,195	\$382,619
	Aggressive	HHDDT	877	51	\$24,787	\$427,314	8,767	509	\$18,964	\$326,924
2030	Conservative	MHDDT	98	3	\$157,734	\$5,426,827	985	29	\$122,965	\$4,230,608
	Moderate	MHDDT	98	3	\$151,051	\$5,196,892	985	29	\$116,282	\$4,000,673
	Aggressive	MHDDT	98	3	\$148,458	\$5,107,683	985	29	\$113,689	\$3,911,464
	Conservative	HHDDT	84	5	\$63,789	\$1,030,805	841	52	\$51,093	\$825,642
	Moderate	HHDDT	84	5	\$59,040	\$954,055	841	52	\$46,344	\$748,892
	Aggressive	HHDDT	84	5	\$57,197	\$924,278	841	52	\$44,501	\$719,115

2.11. Longer Combination Vehicles

Description of Strategy

This analysis quantifies the environmental benefits associated with the operations of longer combination vehicles (LCVs) along future truck-only lanes in Southern California. LCVs are tractor-trailer combinations typically with two or three trailers that may exceed a gross vehicle weight of 80,000 pounds.

LCVs are currently not allowed on California Interstates or State routes. Due to a federal freeze on an increase in the weight and size of trucks, California cannot currently allow the operations of LCVs. States that permitted the operations of LCVs before June 1, 1991, can allow LCVs due to a grandfathering clause, including designated routes in Alaska, Arizona, Colorado, Florida, Idaho, Indiana, Iowa, Kansas, Massachusetts, Michigan, Missouri, Montana, Nebraska, Nevada, New York, North Dakota, Ohio, Oklahoma, Oregon, South Dakota, Utah, Washington, and Wyoming.

The advantages of LCVs rely on an increase in productivity, since higher cargo capacity could result in fewer trips, lower costs, fewer miles driven, less fuel consumed, and less emissions. Due to more efficient use of fuel on a ton-miles basis, as well as the need for fewer drivers, cost savings could be realized by consumers, shippers, and possibly carriers.

On the other hand, there is strong opposition to LCVs due to safety concerns. Large trucks are responsible for a disproportionate percentage of fatal accidents. Large trucks can also contribute to a higher infrastructure deterioration rate, although this can be mitigated by increasing the number of axles. Parking at rest areas can also be a problem, since current truck stops are not designed to accommodate LCVs. Finally, to the extent that LCVs can divert traffic from rail, some of the productivity advantages can be negated.

Our analysis assumes that a system of truck-only lanes will be in place by 2020. The Multi-County Goods Movement Action Plan evaluated different scenarios and configurations, and this analysis considers a system of four truck-only lanes (two in each direction) along I-710, along an east-west corridor (between I-710 and I-15), and along I-15 (out to Victorville).⁵¹ Note that current SCAG plans and modeling assumes that only the I-710 portion would be complete by 2020; other portions would be complete by 2030. Thus, the scenario envisioned in this report reflects a more aggressive implementation. Also note that our analysis does not take into account the need for staging areas if LCVs are not allowed to operate on local streets where shippers and receivers might be located.

Emissions Reduction Potential

The emission reduction from the use of LCVs is a result of fewer trucks necessary to carry the same amount of cargo, as well as less congestion. Consistent with the assumptions in the Multi-County Goods Movement Action Plan analysis, our analysis considers two scenarios:

- Baseline: use of standard 48-foot trailers;
- Double: use of “Double Long” trucks, consisting of two 48-foot trailers, with a total capacity of 100% more tonnage than a standard 48-foot trailer;

⁵¹ Wilbur Smith Associates (2007)

The evaluation of the potential market for LCVs was based on the Multi-County Goods Movement Action Plan analysis, and included two possible groups:

1. **Regional Market:** domestic commodity-specific shipments of more than 100 miles, which is a similar approach included in the I-15 Comprehensive Corridor Study⁵², and is based on the assumption that only a set of commodities would benefit from LCVs;
2. **Port Market:** container shipments to and from the Ports of Los Angeles and Long Beach, specifically the portion of these trips that stay within the SCAG region.

Table 2-46 presents the number of truckloads that are eligible for LCV conversion in 2020, as well as truck VMT. These values were adjusted from results included in the Multi-County Goods Movement Action Plan analysis, which provided truckloads and VMT eligible for conversion in 2030.⁵³ The values for the regional market were adjusted based on truck VMT forecasts in California⁵⁴, while values for the port market were adjusted based on port trip forecasts provided by SCAG. The number of double-long truckloads was calculated by applying a factor of 2.0 over the number of standard truckloads, respectively. VMT for the regional market assumed a distance of 98 miles, while port trips had an average of 38 miles.

Table 2-46: Number of Annual LCV-Eligible Truckloads and VMT along Designated Corridor (2020)

Market	Truckloads		VMT	
	Standard	Double-Long	Standard	Double-Long
Regional Market	1,876,158	938,079	183,863,512	91,931,756
Port Market	6,954,587	3,477,293	265,658,864	132,829,432

EMFAC2007 was used to estimate emission factors and fuel efficiency (miles per gallon) for standard port and regional trucks in 2020, an approach consistent with the other truck strategies included in this report. Based on previous research developed by ICF staff⁵⁵, correction factors were developed to account for the additional weight hauled by double-longs (Table 2-47). Particulate matter is highly sensitive to vehicle weight during transient states, but relatively insensitive in steady state conditions (i.e., constant speed). Because the level of congestion along the proposed truck-only lanes is uncertain, it is assumed that PM emissions increase proportionally with vehicle gross weight.

It is expected that the truck-only lanes will provide smoother traffic flows than mixed-use lanes. Vehicle per-mile emissions are generally higher in congested roadway conditions than in free flow traffic, since short bursts of acceleration generate per-mile emission rates that are higher than at free flow speeds. Therefore, correction factors that account for lower levels of congestion were also developed (Table 2-47). EMFAC2007 is not well suited to calculate the emissions impacts of changes in traffic congestion and speeds, since it does not directly estimate the impacts of acceleration and deceleration patterns. In order to compare emissions as a function of congestion, models that are based on micro-simulation theories can provide reasonable estimates. Since emissions are calculated on a second by second basis, acceleration and deceleration are accounted at any given speed. Researchers at West Virginia University have developed a predictive tool for emissions from heavy-duty diesel vehicles that produces reliable results when compared to actual measurements from chassis dynamometer tests.⁵⁶ We used the results of this tool for our analysis, including emission factors for NO_x, PM, and HC (in grams per second) from

⁵² Parsons Brickerhoff Quade & Douglas (2005)

⁵³ Wilbur Smith Associates (2007)

⁵⁴ California Department of Transportation (2005a)

⁵⁵ Facanha, C. (2006)

⁵⁶ Clark, N., Gajedran, P. (2003)

different models of heavy trucks, categorized in acceleration, deceleration, and cruise modes, and each associated with speed intervals.

The Multi-County Goods Movement Action Plan analysis estimated that there would be a reduction of 78,000 truck-hours on a daily basis with the operation of truck-only lanes along the designated corridor, which translate into an increase of the average speed from 30 mph to 50 mph (assumed to be the truck free-flow speed). Road capacity (in vehicles/hour) and jam density (in vehicles/mile) were used to determine the share of the time when trucks would be on steady state, acceleration, or deceleration modes at given speeds.

Table 2-47. Correction Factors (Compared to Standard Truck)

	Regional Market				Port Market			
	Fuel Efficiency	NO _x	PM _{2.5}	ROG	Fuel Efficiency	NO _x	PM _{2.5}	ROG
Weight (Double Long)	0.83	1.35	1.50	1.50	0.84	1.34	1.49	1.49
Congestion	1.60	0.74	0.32	0.53	1.60	0.74	0.32	0.53

Weight and congestion correction factors were applied on the baseline emission factors and fuel efficiency calculated with EMFAC2007 (Table 2-48).

Table 2-48. Corrected Fuel Efficiency (mpg) and Emission Factors (grams/mile), 2020

Truck Type	Regional Market				Port Market			
	Fuel Efficiency	NO _x	PM _{2.5}	ROG	Fuel Efficiency	NO _x	PM _{2.5}	ROG
Baseline (standard truck)	5.66	5.52	0.21	0.50	5.35	10.06	0.42	0.83
LCV (Double Long)	7.57	5.48	0.10	0.39	7.21	9.92	0.20	0.66

Total emissions were obtained by multiplying total annual VMT by corrected emission factors (Table 2-49).

Table 2-49. Emission Reduction from LCVs, 2020 (tons per year)

Truck Type	Regional Market			Port Market			Total		
	NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
Baseline (standard truck)	1,016	38	91	2,674	111	222	3,689	149	313
LCV (Double Long)	504	9	36	1,317	27	87	1,821	36	124
Reduction	512	29	55	1,357	84	134	1,868	114	189

Cost

The operation of LCVs is dependent on the construction and operation of truck-only lanes. The Multi-County Goods Movement Action Plan estimated that construction costs could range anywhere between \$6.43 million and \$32.44 million per lane-mile, including new construction, preliminary studies, and right-of-way acquisition. Due to high costs of land acquisition in Southern California, costs could be as high as \$50 million per lane-mile. Bonds are anticipated to be issued to fund construction costs, and toll revenue is expected to pay at least part of the construction costs. A toll of \$0.6 per mile for heavy-duty trucks is expected to maximize toll revenue.

Costs associated with the construction of truck-only lanes are not allocated to this strategy because this analysis evaluates the operation of LCVs versus the operations of standard trucks along truck-only lanes. A study of environmental benefits of truck-only lanes would also have to account for the fact that

emissions from standard trucks might also decline due to improved flows (see Section 2.15). In addition, roadway capacity could be improved for mixed-use lane, reducing congestion and emissions levels, at least in the short-term (over time, induced demand and diversion would likely use up remaining roadway capacity).

Because this analysis is limited to the environmental benefits of LCVs, toll costs are evaluated for the baseline scenario and for the LCV scenario. If we assume that toll costs per mile for LCVs would be twice as much the toll for a standard truck, there would be no difference in toll costs (there are half as many LCV truck trips as there are standard truck trips). The analysis also considers fuel savings associated with fewer truck loads and VMT, so this strategy brings net savings.

No equipment costs are considered in this analysis. Note that while double and triple truck trailers are commonly available equipment used in other states, there is currently no known operation of double container chassis. Thus, this equipment would need to be developed in order to implement this strategy for port truck trips. The incremental cost of this equipment is unknown.

Fuel costs are calculated by multiplying fuel efficiency (Table 2-50), VMT, and cost per gallon, which was estimated based on forecasts from the 2007 Annual Energy Outlook.

Table 2-50: Estimated Costs of LCV Strategy (2020)

Truck Type	Regional Market		Port Market		Total
	Fuel	Toll	Fuel	Toll	
Baseline (standard truck)	\$82,097,088	\$55,159,054	\$125,523,763	\$79,697,659	\$342,477,564
LCV (Double Long)	\$30,716,472	\$55,159,054	\$46,563,075	\$79,697,659	\$212,136,260
Difference	(\$51,380,616)	\$0	(\$78,960,688)	\$0	(\$130,341,304)

Cost Effectiveness

The cost effectiveness of the LCV strategy is calculated as the cost per ton of emissions reduced. Table 2-51 provides estimated cost effectiveness for NO_x and PM_{2.5} which are the pollutants of greatest concern. Because this strategy results in net savings, there is no cost per ton of pollutant.

Table 2-51: Cost Effectiveness of the LCV Strategy (2020)

Scenario	Annual Benefits (tons/year)			Cost Effectiveness (\$/ton)		
	NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
Regional Market	512	29	55	<0	<0	<0
Port Market	1,357	84	134	<0	<0	<0
Total	1,868	114	189	<0	<0	<0

2.12. Virtual Container Yard

Description of Strategy

This analysis evaluates the environmental benefits from an internet-based system (virtual container yard) that facilitates the coordination between shippers and receivers, so that containers can be filled with export cargo before returning empty to the ports. Matching empty containers with shippers can eliminate truck trips and associated emissions.

The flow imbalance on the transpacific market generates excessive demand for containers in Asia and excessive supply in North America. Since the ports of Los Angeles and Long Beach are responsible for a significant share of this market, empty container logistics imposes a strain on infrastructure without gains in productivity. According to the Port of Los Angeles, a study developed in 2000 indicated that of the 1.1 million import containers that are emptied in Southern California, almost all return empty to the ports of Los Angeles and Long Beach.⁵⁷ The study also estimates that 500,000 empty containers are trucked from the port terminals to locations throughout the region where they are loaded with export cargo. Currently, only about 2% of emptied import containers are matched with shippers needing an export container.⁵⁸ This strategy would increase the number of “street turns”, whereby empty containers are reloaded for export before returning to marine terminals. This strategy examines increases in the percent of container matching to 5% and 10%.

Another option to reduce empty-container truck trips is to implement an off-port depot where all trucks are directed to instead of the port. The depot could match incoming and outgoing loads to reduce the number of empty containers trips to the port. Although such an initiative would result in fewer empty-container trips, it might increase VMT for some trucks due to the additional distance from rerouting all containers to the off-port depot. This analysis does not address the implementation of an off-port depot.

Pollutants Reduced

This strategy eliminates truck trips and truck VMT, thereby eliminating emissions of all pollutants, including NO_x, PM, and ROG.

Emissions Impacts

Methodology

The most comprehensive study regarding the logistics of empty containers in Southern California was developed by the Tioga Group. This study mapped empty container flows and focused on how these flows can be improved to minimize the number of empty moves. A virtual container yard was one of the strategies proposed by the study.

There are two ways to reduce the number of empty moves into the ports. The first is to increase the number of street turns (i.e., when empty containers are reloaded for export before returning to marine terminals). The second alternative is by taking off-hired containers directly to off-dock depots instead of taking them first to marine terminals. A container is off-hired when its leasing term ends. Today, about 30% of off-hired containers are taken to off-dock depots, but the goal is to increase that percentage. Since a virtual container yard is not necessary for this process, this analysis focuses on an increase of street turns. There are a number of factors limiting the number of street turns:

⁵⁷ Port of Los Angeles (2006)

⁵⁸ Tioga Group (2002)

- Timing and location mismatch between import and export loads
- Ownership mismatch: import and export loads that belong to different shipping lines cannot share the same container due to a lack of agreements between shipping lines.
- Container mismatch (e.g., container size, container type, chassis type): most U.S. imports contain retail merchandise, food and beverages that generally come in 40-foot or 45-foot high-cube dry containers. Export loads on the other hand, carry chemical, paper, and forest products that are typically transported in 20-foot dry containers.
- Off-hiring of leased containers: since shipping lines are routinely trying to minimize the size of their container fleet for financial purposes, containers are off-hired back to container leasing companies. Therefore, it may be preferable to off-hire a container rather than to load it for export.
- Lack of shipping lines incentives: westbound export rates have deteriorated to a point that shipping lines might prefer shipping an empty container back east (where it is needed) than to wait for an export load.

Currently street turns represent about 2% of empty container trips to marine facilities, and previous research indicated that the potential for container reuse ranges from 5-10%, despite all limiting factors. A virtual container yard is key in improving the number of street turns, since it provides container information (e.g., location, type), facilitates communication between parties, and allows equipment interchange without the need to move the empty container to the marine terminal.

We obtained VMT for different scenarios from the Tioga study.⁵⁹ A baseline scenario assumed 2% of container reuse, while scenarios A and B took into consideration reuse rates of 5% and 10%, respectively. For each scenario, empty moves were divided into several types (e.g., local moves for export loading, repositioning of off-hired containers from depots to ports), and the number of trips for each type was estimated (Table 2-52). This is what differentiated scenarios A and B from the baseline. Each move type was associated with an average distance, which did not change across scenarios. Total VMT associated with empty moves was then calculated for each scenario. The three scenarios were evaluated in 5-year increments from 2010 to 2035. Since the Tioga study only included scenarios up to 2020, we used data from SCAG to forecast the growth in truck trips to and from the Ports of Los Angeles and Long Beach.

⁵⁹ Tioga Group (2002)

Table 2-52: Annual VMT by Scenario

	2010	2015	2020	2025	2030	2035
Baseline Scenario						
Eastbound	18,972,405	24,639,613	33,552,658	35,408,697	39,669,070	39,794,824
Westbound	43,296,778	65,101,392	98,802,722	104,268,210	116,813,759	117,184,068
Cross-town	1,771,089	2,633,113	3,966,935	4,186,375	4,690,079	4,704,947
Total	64,040,272	92,374,118	136,322,315	143,863,281	161,172,909	161,683,839
Scenario A						
Eastbound	17,862,022	23,003,801	31,102,279	32,822,769	36,772,004	36,888,574
Westbound	41,153,650	61,944,118	94,073,018	99,276,872	111,221,864	111,574,445
Cross-town	2,837,129	4,203,621	6,319,489	6,669,065	7,471,487	7,495,172
Total	61,852,801	89,151,540	131,494,786	138,768,707	155,465,355	155,958,192
Scenario B						
Eastbound	16,011,400	20,277,466	27,018,318	28,512,895	31,943,566	32,044,830
Westbound	37,581,796	56,681,996	86,190,176	97,727,411	103,071,372	103,418,450
Cross-town	4,613,876	6,821,124	10,240,416	10,806,887	12,107,171	12,145,552
Total	58,207,072	83,780,586	123,448,910	137,047,194	147,122,109	147,608,832

Total truck emissions were calculated by multiplying VMT by emission factors. The latter were developed using EMFAC2007 and reflect the fleet age distribution of all trucks in Southern California.

In this analysis, emissions are proportional to VMT. It could be argued that a reduction in empty moves could alleviate congestion along local roads and highways, and that emissions from personal automobiles and trucks could decrease due to smoother traffic flows. However, these benefits would be minimal, given that changes will be gradual, and an availability of road capacity could induce additional demand that would eventually bring traffic levels to its original values. For this reason, emissions reduction from alleviated traffic congestion is not taken into account in this analysis.

Results

The emissions reduction from a virtual container yard is the result of a reduction in empty moves. Table 2-53 includes the emissions reduction associated with the implementation and operations of a virtual container yard. The main reason for the decline in emissions reduction over time is the fact that improvements in emission factors outpace the increase in traffic levels.

Table 2-53: Emissions Reduction (tons/year)

	Scenario A (5% reuse)			Scenario B (10% reuse)		
	NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
2010	36	1.5	3.0	95	4.1	8.0
2015	29	1.2	2.6	78	3.2	6.9
2020	27	1.0	2.4	71	2.7	6.4
2025	21	0.7	1.8	28	1.0	2.4
2030	21	0.7	1.8	51	1.6	4.4
2035	20	0.6	1.7	48	1.5	4.2

Costs

If an independent party is responsible for the implementation and operation of such internet-based system, it is reasonable to assume that a fee will be charged for the service. Operational changes associated with the implementation of a virtual container yard also generate cost savings to shipping lines and carriers. Since carriers would only pay for such a service if it is economically effective, carriers should not incur in any net costs.

However, the costs of implementing a virtual container yard can be roughly estimated in order to compare its cost effectiveness with other strategies. Based on estimates from the Port of Long Beach, implementation costs for the first two years amounted to about \$1.2 million. Assuming that \$120,000 will be incurred annually to adapt and improve the tool over time, the total implementation cost is estimated at \$4.2 million (assuming 25 years of operations). Daily emissions were annualized by assuming 5-day (per week) port operations until 2024, 6-day operations from 2025 to 2029, and 7-day operations from 2030 on.

Cost Effectiveness

Tables 2-54 and 2-55 summarize the cost effectiveness of this strategy, based on calculations by both the ARB and the SCAQMD methods as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%. Since the project has a lifetime of 25 years, only the 2010 cost effectiveness is calculated. For the ARB method, annual costs (i.e., sum of annualized capital costs and operational costs) are divided by the emissions reduction in 2010. For the SCAQMD method, total costs (i.e., sum of capital costs and net present value of operational costs) are divided by total emissions reduction in the lifetime of the project. Total emissions reduction for the timeframe considered is estimated by interpolating the results for the calculated years. The ARB and SCAQMD methods give similar cost effectiveness estimates with the SCAQMD results being slightly lower for NO_x and ROG.

Table 2-54: Cost Effectiveness in 2010 (ARB Annualized Method)

	Annual Benefits (tons/year)			Cost Effectiveness (\$/ton)		
	NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
Scenario A (5%)	36	2	3	\$5,501	\$128,307	\$65,645
Scenario B (10%)	95	4	8	\$2,063	\$48,115	\$24,617

Table 2-55: Cost Effectiveness (SCAQMD BACT Method)

	Lifetime Benefits (tons/year)			Cost Effectiveness (\$/ton)		
	NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
Scenario A (5%)	640	24	56	\$4,643	\$123,308	\$53,063
Scenario B (10%)	1,547	59	135	\$1,922	\$50,610	\$21,978

2.13. Expanded Incident Management for Trucks

Description of Strategy

This analysis evaluates the environmental benefits from an expanded incident management program that addresses incidents involving heavy-duty trucks along the I-710 corridor. Since conventional tow trucks are not capable of clearing accidents involving heavy-duty trucks, this strategy relies on an incident management program that is able to detect and clear such incidents. We evaluate a case study involving traffic on the I-710 and quantify emissions reduction of NO_x, PM, and ROG due to smoother traffic flows and lower congestion.

Incident management programs seek to detect and clear roadway incidents quickly and effectively, thereby minimizing the congestion impacts of the incident. An incident management program can be applied region-wide or can be focused on a specific corridor. It has been estimated that roughly half of total roadway delay is caused by incidents, including delay caused by traffic incidents (crashes, vehicle disablements, cargo spills), non-traffic incidents (bridge collapse, emergency road work), or other unexpected activity (severe weather events, natural disasters).⁶⁰ Incident management programs can have a significant effect on traffic speeds and emissions. If fewer incidents occur or are cleared away more quickly, vehicles idle less and travel at higher speeds. Incident management projects also minimize drivers' need to seek alternate routes to avoid congestion due to incidents. The alternate routes can frequently be longer than the original route and the increased VMT would result in greater emissions.

Pollutants Reduced

This strategy can reduce NO_x, PM, and ROG emissions by improving traffic flows and reducing truck idling. The strategy would not have a significant affect on VMT or the number of truck trips, other than potentially reducing route diversion as described above.

Emissions Impacts

System Description

Freeway service patrol (FSP) is an incident management program that detects and removes incidents from congested freeway segments. A demonstration program has been proposed to extend FSP service to heavy-duty trucks along the I-710. A previous study has examined the operational benefits of such program, including a reduction in response time, traffic delay, as well as its cost effectiveness.⁶¹ Our analysis examines the emissions benefits associated with this program.

In Caltrans District 7, the Metro FSP program is jointly provided and funded by the Metropolitan Transportation Authority, Caltrans, and the California Highway Patrol. Today 147 tow trucks cover 425 miles of the busiest freeways in District 7 during peak periods on weekdays. The I-710 is a major freight corridor that has an incident rate that exceeds statewide averages for this type of freeway. Trucks make up 45-60% of total traffic on this facility and are involved in approximately one-third of the collisions. Since current FSP programs cannot handle heavy-duty trucks they take longer to clear and can block more lanes.

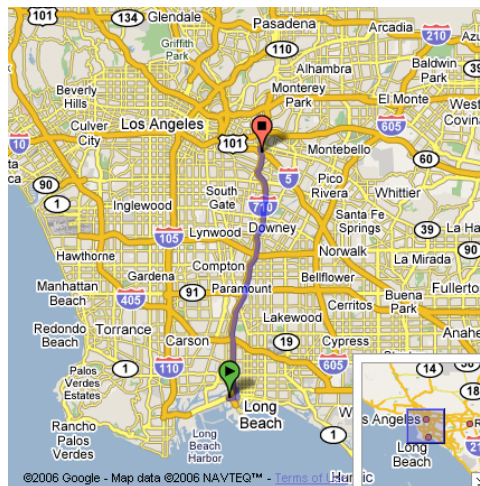
A 2-year demonstration program that includes two heavy-duty tow trucks is expected to alleviate congestion caused due to incidents involving heavy trucks (up to 80,000 GVWR). The selected segment

⁶⁰ Schrank, D., Lomax, T. (2004)

⁶¹ Mauch M., Ahn S., Chung K., Skabardonis A. (2005)

(18.3 miles long) runs from Ocean Boulevard in Long Beach to the I-5 interchange near downtown Los Angeles (Figure 2-5). This segment was chosen due to its high average daily traffic, and high percentage of truck traffic.

Figure 2-5: Study Corridor



Methodology

We modeled baseline traffic along the I-710 based on standard values for freeway capacity in terms of maximum vehicle flows (2,300 vehicles/lane-hour) and jam density (200 vehicles/lane-mile), which is the density where vehicle speed and flow are zero.⁶² Jam density is adjusted to account for the high share of truck traffic along the I-710. Free flow speed is assumed to be 70 mph for personal automobiles and 65 mph for heavy-duty trucks. The I-710 is modeled as a 4-lane freeway, implying a capacity of 9,200 vehicles per hour in each direction.

The Mauch study extracted data from the Freeway Performance Measurement System (PeMS), which collects historical and real-time traffic data for all freeways in California. The project is led by the Department of Electrical Engineering and Computer Sciences at the University of California, at Berkeley, with the cooperation of Caltrans. Data on incidents and traffic volumes were collected for the months of April and May in 2005, before the demonstration project. Incident data was complemented with information from the CHP Los Angeles Communication Center and the Metro FSP Program. During the study period, there were 69 lane blocking incidents involving heavy-duty trucks, and the response time (i.e., time from when incident is called in to when it is cleared) was 58 minutes, with traffic delays estimated at 1,050 vehicle-hours. With the introduction of two heavy-duty tow trucks, response time can be reduced to 28 minutes, with a corresponding drop in traffic delay.

Truck and passenger traffic forecasts are based on data from SCAG (Table 2-56), accounting for the time period from 6AM-6PM. Current traffic volume is calculated based on data extracted from PeMS. Truck share can be predicted based on truck and passenger forecast traffic volumes. Freeway capacity is predominantly determined by the number of lanes, but our analysis also assume that freeway capacity is improved at a rate of 1% every 5 years due to the implementation of intelligent transportation systems and better incident management programs. The analysis does not cover the period beyond 2015 due to the planned construction of truck-only lanes along the considered section of the I-710.

⁶² Transportation Research Board (2000)

Table 2-56: Volume and Capacity Forecast

	2005	2010	2015
Volume Forecast			
Daily Truck Traffic	22,208	29,610	34,498
Daily Passenger Traffic	80,726	107,634	99,627
Traffic Flow (vehicles/hour)	5,625	7,500	7,404
Number of Lanes	4	4	4
Freeway Capacity (vehicles/hour)	9,200	9,292	9,385

Our analysis is limited to lane blocking incidents. When a lane blocking incident occurs, one lane is blocked for a given amount of time, reducing freeway capacity temporarily. If traffic flows are close to capacity, the system will likely enter a congestion state, backing up traffic and causing delay to automobiles and trucks.

Response times and traffic delay for 2005 are taken from the Mauch study, which modeled two scenarios: a baseline scenario assumes no additional heavy-duty tow trucks, while the FSP scenario takes into consideration the introduction of two heavy-duty tow trucks. To estimate response times and traffic delay for future years, our analysis assumes that traffic flows (including truck share), and freeway capacity remain constant for both scenarios, while incident response time and traffic delays are differentiated (Table 2-57). Response times remain constant throughout time since tow trucks utilize shoulder lanes if freeways are congested. We assume that delay increases proportionally to the fraction of traffic demand and freeway capacity. No increase in the number of incidents is assumed. Both scenarios quantify the emissions resulted from congestion associated with a heavy-duty truck incident.

Table 2-57: Response Times and Traffic Delay

		2005	2010	2015	2020
Baseline	Response Time (min)	58	58	58	58
	Delay (veh-hours)	1,050	1,386	1,355	1,843
FSP	Response Time (min)	28	28	28	28
	Delay (veh-hours)	507	669	654	890

Results

An extended FSP program to incidents involving heavy-duty trucks can reduce emissions by improving traffic flows along freeways during peak times. Vehicle per-mile emissions are generally higher in congested roadway conditions than in free flow traffic, since short bursts of acceleration generate per-mile emission rates that are higher than at free flow speeds. EMFAC is not well suited to calculate the emissions impacts of changes in traffic congestion and speeds, since it does not directly estimate the impacts of acceleration and deceleration patterns. In order to compare emissions as a function of congestion, models that are based on micro-simulation theories can provide reasonable estimates. Since emissions are calculated on a second by second basis, acceleration and deceleration are accounted at any given speed. Researchers at West Virginia University have developed a predictive tool for emissions from heavy-duty diesel vehicles that produces reliable results when compared to actual measurements from chassis dynamometer tests.⁶³ We used the results of this tool for our analysis, including emission factors for NO_x, PM, and HC (in grams per second) from different models of heavy trucks, categorized in acceleration, deceleration, and cruise modes, and each associated with speed intervals. We calculated the

⁶³ Clark, N., Gajedran, P. (2003)

ROG emission factor as a function of HC emission factors. We used EMFAC2007 to estimate improvements in overall truck emission factors over time.

Since this analysis is limited to heavy-duty trucks, a potential reduction in automobile emissions due to less congestion is not taken into account. Although the difference between automobile emissions in congested and in free flow states is not expected to be as wide as for heavy-duty trucks, the emissions reduction calculated in this analysis is a conservative estimate because it ignores any reduction in automobile emissions.

Table 2-58 includes the emissions reduction for NO_x, PM, and ROG from heavy-duty trucks due to the introduction of the new program. The emission benefits from this strategy decrease from 2010 to 2015 due to improvements in the fleet average emission factors.

Table 2-58: Emissions Reduction

	Emissions Reduction in chosen segment (tons/year)		
	NO _x	PM _{2.5}	ROG
2010	132	32	17
2015	90	20	12
2020	-	-	-
2025	-	-	-
2030	-	-	-
2035	-	-	-

Costs

We assume that two heavy-duty tow trucks are used in the program from 6AM-6PM on weekdays, and that a truck-hour costs \$149.50.⁶⁴ This cost accounts for equipment, labor, fuel, and maintenance. The total program costs add up to \$933,000 annually.

Cost Effectiveness

Table 2-59 summarizes the cost effectiveness of this strategy, based on calculations by both the ARB and the SCAQMD methods as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%. Because there are no capital costs involved in this project, and its lifetime is one year, both methods result in the same cost effectiveness. Since fleet-average emission factors for heavy-duty trucks are expected to improve substantially, the cost effectiveness decreases by about 30% from 2010 to 2015.

Table 2-59: Cost Effectiveness (both methods)

	Annual Benefits (tons/year)			Cost Effectiveness (\$/ton)		
	NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
2010	132	32	17	\$6,260	\$26,313	\$47,613
2015	90	20	12	\$7,591	\$33,279	\$54,931

⁶⁴ Mauch M., Ahn S., Chung K., Skabardonis A. (2005)

2.14. Expanded Use of PierPass Program

Description of Strategy

This section evaluates the environmental benefits from expanded use of the Pierpass Program, and quantifies the emissions reduction of NO_x, PM, and ROG due to a shift in truck traffic along the I-110 and I-710 from peak to off-peak times. Shifting vehicles from congested to uncongested facilities or time periods reduces emissions. The benefits are two-fold: shifted trucks generate fewer emissions because they move to free flow conditions; and the remaining vehicles generate fewer emissions because traffic is improved. It is assumed that truck traffic will be shifted to periods when free flow conditions exist. This strategy would also reduce emissions from truck idling at port gates, but the analysis does not quantify this component due to lack of data.

Aside from the emissions benefits of congestion reduction, shifting emissions to evening and night periods would also likely result in less ozone formation as compared to daytime emissions. This effect is complex, and properly understanding any ozone impacts require regional air quality modeling, which is outside the scope of this study.

PierPass, Inc. is an association of terminal operators at the Ports of Los Angeles and Long Beach.⁶⁵ The organization implemented the OffPeak program in July 2005, which uses a fee/rebate system to encourage trucks to shift port access trips from peak-hours to off-peak night periods and weekends. A \$50 fee per TEU is charged for every container arriving at San Pedro Bay, and a refund is given to containers that utilize off-peak terminal gates. Since becoming operational, off-peak use has increased significantly. PierPass claims that, since establishment, more than 2 million truck trips have been diverted from daytime hours to off-peak hours and weekends. The Pierpass Program could potentially be extended by either raising user fees or by extending hours during which the fee is imposed.

Pollutants Reduced

Since the environmental benefits from this strategy come from improved traffic flows and less idling emissions from trucks (rather than a reduction in VMT or trips), this strategy affects the emissions of NO_x, PM, and ROG differently.

Emissions Impacts

Previous Studies

While this strategy does not reduce vehicle miles traveled, it has contributed to reduced congestion along the I-710 on weekdays by shifting traffic from peak to non-peak hours. Table 2-60 shows the impacts of the existing PierPass program on trucks volumes on the I-710.⁶⁶ Total weekday volume has declined due to a shift from weekdays to weekends. It also has reduced truck waiting times inside port terminals.

⁶⁵ Pierpass Inc. (2006)

⁶⁶ Fischer, M., Hicks, G., Cartwright, K. (2006)

Table 2-60: Impacts of PierPass on Weekday I-710 Volumes

AM Peak (6AM-9AM)	Midday (9AM-3PM)	PM Peak (3PM- 7PM)	Total Day	Night (7PM- 6AM)	Total Weekday
- 51-53%	- 29-33%	- 6-11%	- 28-31%	+ 147-163%	- 12-16%

Given the success of Pierpass, it is clear that shippers and carriers have some flexibility to shift travel time. Providing further incentives to shift traffic to off-peak periods, or penalties for keeping traffic during peak-hours, can encourage an additional shift from peak to off-peak hours. This analysis assumes that a further 10% of peak truck traffic can be diverted to off-peak hours.

System Description

The analysis is limited to the Interstates 110 and 710, which are the highway facilities whose capacities are most affected by port truck traffic. In order to better isolate the effects of port truck traffic, we selected the sections closest to the ports where data was available for the analysis (Table 2-61).

Table 2-61: Highway Sections Selected for Analysis

Interstate	Start post mile	End post mile
110S	8.58	13.45
110N	5.21	7.94
710S	6.03	9.00
710N	6.03	9.00

We modeled baseline traffic along the I-110 and the I-710 based on standard values for freeway capacity in terms of maximum vehicle flows (2,300 vehicles/lane-hour), and jam density (200 vehicles/lane-mile), which is the density where vehicle speed and flow are zero.⁶⁷ Jam density is adjusted to account for the high share of truck traffic along the I-710 and I-110. We assumed free flow speed to be 70 mph for personal automobiles and 65 mph for heavy-duty trucks. The I-710 and I-110 are modeled as 4-lane freeways (in each direction), implying a capacity of 9,200 vehicles per hour in each direction.

Freeway capacity depends on the number of lanes, but our analysis also assumes that freeway capacity is improved at a rate of 1% every 5 years due to the implementation of intelligent transportation systems, and better incident management programs (i.e., accident removal). The analysis does not cover the I-710 beyond 2015, since truck-only lanes will provide enough capacity to guarantee free flow conditions to heavy-duty diesel trucks until 2035.

Methodology

A shift of truck traffic from peak periods to off-peak hours can reduce emissions by:

1. Improving traffic flows along freeways during peak times. It is assumed that the shifted truck traffic will move to off-peak hours, which have enough capacity to sustain free flow conditions even with the additional traffic. This analysis quantifies emissions benefits from reduced congestion along the I-710 and I-110 freeways during peak time. Emissions reduction from personal automobiles was not quantified.
2. Reducing idling at port gates. It is possible to reduce the time trucks spend on queues at port gates by shifting truck traffic to off-peak times. Based on discussions with the Port of Long Beach, the

⁶⁷ Transportation Research Board (2000)

recent implementation of optical character recognition (OCR) devices at port gates has eliminated gate queues. Therefore this analysis does not take into account reduced idling at the gates.

Vehicle per-mile emissions are generally higher in congested roadway conditions than in free flow traffic, since short bursts of acceleration generate per-mile emission rates that are higher than at free flow speeds. EMFAC is not well suited to calculate the emissions impacts of changes in traffic congestion and speeds, since it does not directly estimate the impacts of acceleration and deceleration patterns. In order to compare emissions as a function of congestion, models that are based on micro-simulation theories can provide reasonable estimates. Since emissions are calculated on a second by second basis, acceleration and deceleration are accounted at any given speed. Researchers at West Virginia University have developed a predictive tool for emissions from heavy-duty diesel vehicles that produces reliable results when compared to actual measurements from chassis dynamometer tests.⁶⁸ We used the results of this tool for our analysis, including emission factors for NO_x, PM, and HC (in grams per second) from different models of heavy trucks, categorized in acceleration, deceleration, and cruise modes, and each associated with speed intervals. We calculated the ROG emission factor as a function of HC emission factors. We used EMFAC2007 to estimate improvements in overall truck emission factors over time.

We obtained data from the Freeway Performance Measurement System (PeMS) website, which collects historical and real-time traffic data for all freeways in California. The project is led by the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley, with the cooperation of Caltrans. Vehicle miles traveled, truck miles traveled, and average speed were collected for the selected sections along the I-710 and I-110, from August 1st, 2005 to July 31st, 2006. We collected data for different time periods (e.g., 6AM-9AM, 3PM-6PM) to assess the impacts of shifting truck traffic from peak to off-peak periods. Based on these variables, it was possible to determine vehicle flows, vehicle densities, and truck traffic share of total traffic.

Truck and passenger traffic forecasts were based on data provided by SCAG, which included traffic volumes by time period (e.g., morning peak, midday, afternoon peak, and night) and by vehicle type along the selected sections of I-110 and I-710 for the considered years in this analysis.

Results

Table 2-62 shows the emissions reduction for NO_x, PM, and ROG from heavy-duty trucks. The effectiveness of the strategy declines significantly over time due to improving truck emission factors. Emissions reduction in 2010 and 2015 are significantly higher than the remaining years because they include benefits on both the I-110 and the I-710. By 2020, truck-only lanes are planned along the I-710, which will ensure free-flow conditions, so the analysis is limited to the I-110 for the years 2020 and beyond.

⁶⁸ Clark, N., Gajedran, P. (2003)

Table 2-62: Emissions Reduction

	Emissions Reduction in chosen segment (tons/year)		
	NO _x	PM _{2.5}	ROG
2010	19.97	1.08	1.74
2015	4.60	0.36	0.28
2020	0.57	0.02	0.05
2025	0.45	0.01	0.04
2030	0.47	0.01	0.04
2035	0.43	0.01	0.04

Due to lack of data, we did not incorporate the benefits resulting from fewer emissions from personal automobiles. Although the difference between automobile emissions in congested and in free flow states is not expected to be as wide as for heavy-duty trucks, this analysis is a conservative estimate because it ignores any emissions benefit associated with passenger vehicles.

Costs

The costs associated with operating the gates during off-peak hours are covered by the additional PierPass container fees. Although drivers' wages are generally independent from time of travel, carrier costs can increase if they call the ports during off-peak hours but are forced to pick up and drop the cargo during business hours only. In that case, a waiting time might be associated either at the beginning or at the end of their trips. For example, if a driver picks up a load at the port during the night, he/she may have to wait until regular business hours to drop it at the receiving location. This increases the number of hours drivers need to be paid, and reduces equipment utilization. If shippers are flexible enough to enable pick ups and deliveries during off-peak hours, carrier costs can remain constant, but shippers' costs might increase due to personnel and facility overtime costs.

This analysis assumes that shippers do not have the flexibility to ship and receive goods during off-peak hours, and shippers assume the responsibility for the additional costs imposed on carriers. Inventory costs are not taken into consideration for simplification purposes.

From a carrier's perspective, Pierpass would only impose an additional cost for trips that were previously performed during peak hours. If carriers decide to switch to off-peak hours, it means their additional costs for doing so will be less than the container fee. This would be the case if shippers are open during off-peak hours, if they can perform the pickup in the late part of the afternoon (arriving at the port after 6PM), or if they can perform a delivery in the early part of the morning (leaving the port before 6AM). If any of these conditions hold true, carriers might not incur in any additional costs. If switching to off-peak hours implies costs beyond the container fee, it is assumed that carriers will keep their moves during peak hours. Therefore, maximum costs to carriers due to Pierpass are equal to the container fee.

If carriers incur in additional costs, they will likely pass these costs to shippers. Shippers can either pay the additional costs, or extend their opening hours if that is a more inexpensive alternative. In either case, costs to shippers will remain less than the container fee.

Independently of who incurs in additional costs, it is reasonable to assume that such costs will remain less than the container fee. Over the period from 2010 to 2035, total costs will remain less than \$2.8 million. This is calculated by multiplying a \$50 container fee by the number of trucks diverted (10% of total port traffic) from peak hours to off-peak hours.

Cost Effectiveness

Table 2-63 summarizes the cost effectiveness of this strategy, based on calculations by both the ARB and the SCAQMD methods as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%. Because there are no capital costs involved in this project, and its lifetime is one year, both methods result in the same cost effectiveness. Since fleet-average emission factors for heavy-duty trucks are expected to improve substantially, the cost effectiveness decreases over time.

Table 2-63: Cost Effectiveness (both methods)

	Annual/Lifetime Benefits (tons/year)			Cost Effectiveness (\$/ton)		
	NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
2010	19.97	1.18	1.74	\$7,799	\$132,110	\$89,364
2015	4.60	0.39	0.28	\$31,230	\$366,776	\$515,717
2020	0.57	0.02	0.05	\$69,203	\$1,822,697	\$779,465
2025	0.45	0.02	0.04	\$75,831	\$2,156,870	\$870,905
2030	0.47	0.02	0.04	\$67,060	\$2,063,927	\$780,785
2035	0.43	0.01	0.04	\$59,909	\$1,933,394	\$692,996

2.15. Dedicated Truckways

Description of Strategy

A system of dedicated toll truckways has been proposed for the SCAG region to increase freight capacity, alleviate congestion, and reduce emissions. Four truck-only lanes would be installed on the I-710, an east-west corridor, and I-15, and trucks would be charged electronically on a per-mile basis. Depending on the fee charged, the system could not only finance itself but also potentially subsidize environmental mitigation projects. We are not able to quantify the emissions impacts of this strategy at this time. Such an analysis requires regional network modeling, which is being undertaken as part of a different project and is outside the scope of our study.

Pollutants Reduced

Due to the uncertainties described below, it is not known which pollutants would be reduced.

Emissions Impacts

Due to the forecast growth in freight traffic, this system is being proposed to maintain and leverage Southern California's competitiveness as a hub for international trade. The most important benefit is a reduction in highway congestion, which would yield travel time savings and cost savings for freight shippers and carriers. The project might also generate safety improvements by reducing interactions between trucks and passenger vehicles. The emissions impacts of this strategy are unclear, since truck emissions depend on a combination of traffic flows (i.e., congestion patterns), truck speed, VMT, and mode shift. The following section provides a brief discussion about the effects of traffic flow characteristics and speed on truck emissions.

It is possible that designated truckways could increase truck VMT, although such an increase would likely be small. Depending on the location of access points, trucks might have to drive further to access or get off the dedicated lanes.

Potential mode shift needs to be taken into account in the assessment of emissions benefits from this strategy. If implemented alone, the system could potentially shift traffic from rail to road, which might increase emissions, or at least affect some of the benefits of congestion reduction. If the system is implemented concurrently with rail improvements however, the strategy could maintain or even increase rail market share.

If larger and heavier trucks are allowed on these lanes (e.g., longer combination vehicles), system capacity would increase, and VMT would likely be reduced. Infrastructure considerations need to be taken into account. Heavier trucks would also be more competitive with rail, and a shift from rail to road would also be more likely.

The emissions benefits of this strategy would likely dissipate in the long term, as traffic reaches congested levels again. However, pricing mechanisms are anticipated to manage traffic demand.

Congestion and Emissions

The environmental impacts of this strategy depend heavily on the relationship between truck emissions and traffic flow characteristics. This relationship is a subject of substantial uncertainty and is worthy of a brief discussion.

In general, it can be assumed that vehicle per-mile emissions are higher in congested roadway conditions than in free flow traffic. Vehicles traveling in congested conditions experience more frequent short bursts of acceleration, when per-mile emission rates are higher than at free flow speeds. In heavy congestion, vehicles may idle, emitting pollutants without any travel.

A simple quantitative analysis confirms that free flow traffic conditions are indeed associated with fewer emissions. Models that are based on micro-simulation theories can provide reasonably accurate predictions of emissions associated with congested states. This is due to the fact that emissions are calculated on a second by second basis, and account for acceleration and deceleration at any given speed. Researchers at West Virginia University have developed a predictive tool for emissions from heavy-duty diesel vehicles that produces reliable results when compared to actual measurements from chassis dynamometer tests.⁶⁹ The tool includes emission factors for NO_x, PM, and HC (in grams per second) from different models of heavy trucks, categorized in acceleration, deceleration, and cruise modes, and each associated with speed intervals. These emission factors are used to quantify emissions associated with four traffic scenarios:

1. Level of Service A: this scenario describes free-flow operations, and assumes steady state at 50mph.
2. Level of Service C: this scenario consists of free-flow operations for 80% of the time (at 35 mph), with the remaining 20% of the time in acceleration and deceleration modes.
3. Level of Service F: this scenario describes roadway operations at capacity. Vehicles drive in cruise mode for 50% of the time (at 15 mph), while the remaining time is spent in acceleration and deceleration modes.
4. Queuing: this scenario assumes that vehicles spend 100% of the time in acceleration and deceleration modes. It represents situations where trucks are lined up in queues (e.g., terminal gates).

Table 2-64 presents emissions associated with each of the four scenarios, assuming a heavy-duty diesel truck of model 1998 and newer.

Table 2-64: Congestion Effects on Truck Emissions (grams/mile)

	NO _x	HC	CO	PM	CO ₂
LOS A	11.89	0.55	1.25	0.16	1,053
LOS C	15.28	0.85	2.66	0.34	1,390
LOS F	26.08	1.85	8.18	1.21	3,296
Queuing	51.01	4.07	27.00	5.00	5,421

Travel Speed and Emissions

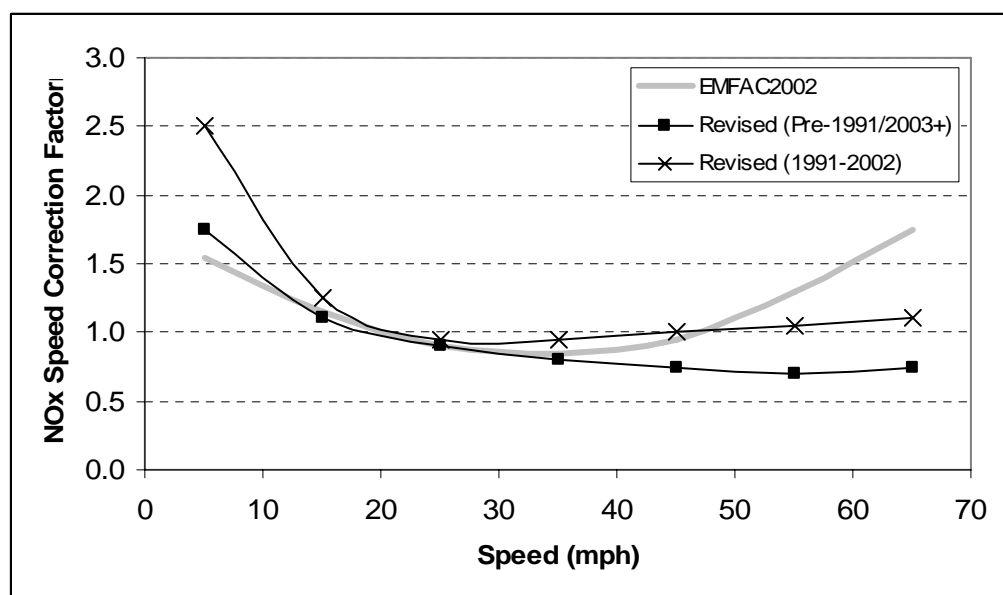
There is significant uncertainty with respect to how emission rates vary as a function of travel speeds, and a number of researchers have documented significant discrepancies between actual emissions and those modeled using MOBILE and EMFAC. These existing emissions models are not well suited to calculate the emissions impacts of changes in traffic congestion and speeds. These models do not directly estimate the impacts of acceleration and deceleration patterns. Rather, emission factors are developed for average travel speeds based on a standardized driving cycle, which includes stops, accelerations, decelerations, and steady speeds. For example, the EPA and CARB models would show the same emissions results for a

⁶⁹ Clark, N., Gajedran, P. (2003)

roadway segment on which all vehicles travel at a constant free flow of 40 mph, and a congested roadway segment on which vehicles travel partly at 20 mph and partly at 60 mph but average 40 mph. Actual emissions would likely be higher in the latter case.

CARB's EMFAC2002 model predicts that NO_x emissions from heavy-duty trucks are lowest around 35 mph, increasing as speeds drop below 35 mph and rise above 35 mph. CARB has just issued an updated version of the model, EMFAC2007, including the speed correction factors that define how emission factors vary with average speed.⁷⁰ Figure 2-6 provides a comparison between current speed correction factors and the new factors (for EMFAC2007). The latter are subdivided into two model year groups. In the new model, NO_x emissions remain fairly constant as speeds increase past 30 mph. For pre-1991 and 2003+ model year trucks, NO_x emission factors actually decline slightly with speed until 55 mph. This represents a significant departure from past practice, and it will have the effect of making highway capacity improvement projects more beneficial from a NO_x standpoint.

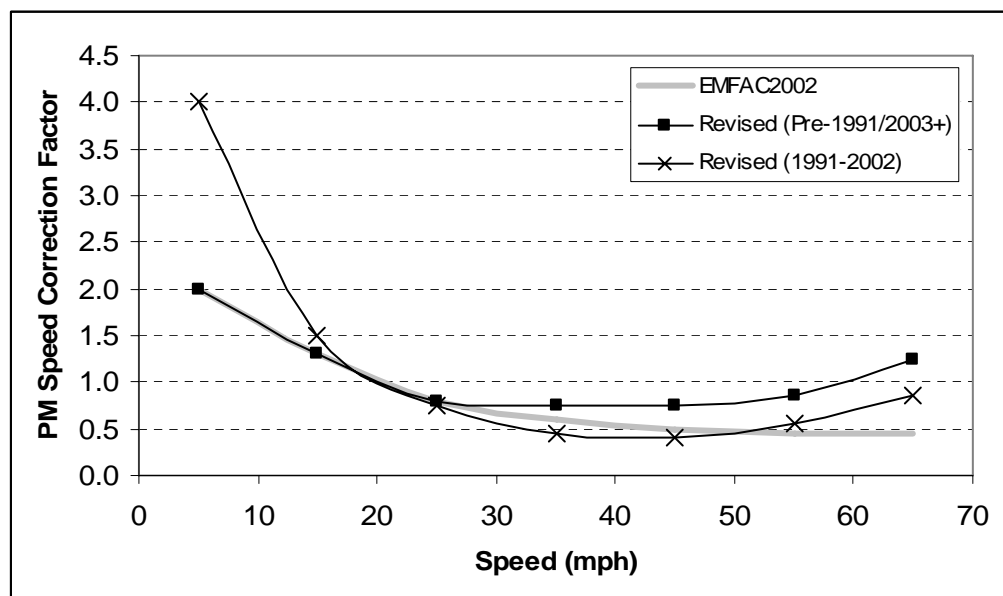
Figure 2-6: Heavy-Duty Truck NO_x Speed Correction Factors (EMFAC2002 vs. EMFAC 2007)



Source: Zhou, L. (2006)

The EMFAC2007 model revisions have the opposite effect on PM emissions from heavy-duty trucks. As shown in Figure 2-7, PM emissions decline with speed using EMFAC2002, leveling off at speeds over 50 mph. With the changes to EMFAC2007, PM emissions rise as speeds increase past 45 or 50 mph. As a result, highway capacity improvement projects will appear less beneficial from a PM standpoint.

⁷⁰ Zhou, L. (2006)

Figure 2-7: Heavy-Duty Truck PM Speed Correction Factors (EMFAC2002 vs. EMFAC 2007)

Source: Zhou, L. (2006)

In order to determine emissions impacts, regional network modeling is required to estimate traffic volumes and speeds on every facility that would be affected by the additional of dedicated truckways. This modeling is being conducted as part of the development of Multi-County Goods Movement Action Plan, led by MTA. If those results become available, we will include estimates of emissions impacts in a future version of this report.

Costs

The estimated project costs are summarized in Table 2-65. A proposal suggests that the system be financed through bonds to be repaid with fees collected electronically. SCAG reckons that a user fee of \$0.86/mile in combination with a container fee of \$160-170 is sufficient to finance this system of dedicated truckways and \$10 billion worth of other environmental mitigation projects. SCAG's 2005 Port and Modal Elasticity Study determined that traffic will not be diverted from the region if an additional fee charged per container remains under \$200. Even though this fee was originally planned as an import charge, alternative collection mechanisms can be developed.

Table 2-65: Estimate Cost of SCAG's Truckway System

Segment	Length (miles)	Lane Miles	Total Cost (million)
I-710	18	86	\$2,166
East-west corridor	38	151	\$4,300
I-15	86	344	\$10,066
Total	142	581	\$16,533

Cost-Effectiveness

Because we are unable to determine the emissions impacts of this strategy, we cannot estimate cost-effectiveness at this time.

2.16. Chassis Pools

Description of Strategy

Chassis pools are a relatively new concept implemented by ports and intermodal terminals to reduce the number of necessary chassis, free up space requirements for chassis, as well as to improve chassis maintenance. The term chassis refers to the wheeled frame that connects to the tractor and is used to transport ocean containers. Truck chassis for moving containers are generally owned by the ocean carriers, who maintain a fleet of chassis sufficient to handle their peak demand. Because of demand fluctuations, utilization of chassis can be relatively low, increasing land and capital requirements. In a chassis pool, different ocean carriers combine resources and utilize the same pool of equipment, alleviating demand fluctuations, and increasing chassis utilization. Ocean carriers benefit because they don't need to own as many chassis. The port benefits because it frees up land for other productive activities. Truckers benefit because they can go to one central location for their chassis, rather than different storage locations for each ocean carrier. This strategy could reduce emissions if it reduces truck VMT or idling. The implementation of chassis pool has been limited so far, but the ports of New Jersey and Norfolk have both reported positive results from such a program. Due to lack of data from the ports, it was not possible to quantify emissions reduction from this strategy.

Pollutants Reduced

Emissions of NO_x, PM, and ROG can possibly be reduced due to lower VMT and less idling.

Emissions Impacts

There has been no analysis to date of the effects of this strategy on truck VMT, idling, or emissions. The Port of Norfolk implemented the Hampton Roads Chassis Pool (HRCP II) in October 2004, becoming the first U.S. port to achieve 100% participation from the port's shipping lines. The pool has reduced the number of chassis from 23,000 in 2004 to less than 15,000 today, resulting in up to 60 acres of land recaptured for other activities. Turn times, which ranged from 65 to 70 minutes before the program's implementation, now stay within 45-60 minutes.

We were unable to obtain data necessary to quantify emissions impacts from a chassis pool in the ports of Los Angeles and Long Beach. Due to the lack of previous emissions analyses and a wide range of operational parameters, it is impossible to determine whether a chassis pool at the ports of Los Angeles and Long Beach would reduce emissions. A chassis pool is likely to reduce emissions if it succeeds in reducing distance traveled and improves turn times, since the latter is directly correlated with idling times. Depending on the location of the chassis inside the terminals, a chassis pool might be beneficial not only for cases when truckers need to switch chassis but also when they only need to pick or drop a chassis. For example, if the chassis pool location is closer to the gate, or if it is operated by a party who is able to make chassis assignments faster, truckers picking up or dropping a chassis could save time and possibly reduce VMT and/or idling.

Despite the lack of data, it is possible to provide a framework for an analysis that quantifies emissions reduction from a chassis pool. The first step is to categorize port truck movements. Any incoming tractor can drop one of the following: chassis, chassis/container, container, or nothing. The same is true for pick ups from outgoing tractors. There are 11 possible combinations (Table 2-66).

Table 2-66: Movement Types

Trip ID	Incoming Tractor Drops	Outgoing Tractor Picks up
1	None	Chassis
2	None	Container
3	None	Chassis/Container
4	Chassis	None
5	Chassis	Chassis
6	Chassis	Chassis/Container
7	Container	None
8	Container	Container
9	Chassis/Container	None
10	Chassis/Container	Chassis
11	Chassis/Container	Chassis/Container

For each type of movement, a tractor might need to pick, switch, and/or drop a chassis. Distances and times can be associated with each of these 3 operations (pick, switch, or drop chassis). Idling times can be calculated from these two variables. Distances and idling times can then be multiplied by emission factors to obtain total emissions.

Costs

The costs of this strategy are unknown. After an initial investment associated with establishing a program, this strategy would likely reduce long-term overall operating costs because it would allow ocean carriers to maintain smaller chassis fleets and would reduce space requirements in terminals.

Cost-Effectiveness

We are unable to estimate the cost-effectiveness of this strategy.

3. Railroad Strategies

3.1. Introduction

Goods movement railroad emissions in the SCAG region are primarily from the activities of the Burlington Northern Santa Fe Railway (BNSF) and the Union Pacific Railroad (UP), which own and operate rail lines and rail yards in the region. Pacific Harbor Lines is a short-line railroad, moving cars and equipment in and between the San Pedro ports and intermodal rail yards. Another short-line railroad, Ventura Railway, serves the Port of Hueneme in Ventura County. There are three main locomotive types operating in this region: line-haul freight locomotives, yard or switching locomotives, and passenger locomotives. This analysis focuses primarily on switching and line-haul locomotives because they are involved in goods movement and collectively represent the majority of locomotive emissions in the region.

Trains are currently responsible for approximately 9% of goods movement NO_x emission and 5% of goods movement PM_{2.5} emissions in the South Coast Air Basin. Absent any additional regulations or control strategies, the 2007 Air Quality Management Plan projects train emissions to drop significantly by 2010, then increase gradually over the next two decades such that by 2030, train emissions will exceed 2005 levels. More detail on the emissions inventory and baseline forecasts are presented below.

Overview of Emission Reduction Strategies

Strategies to reduce railroad emissions include operational/infrastructure improvements to reduce idling and braking events, electrification, retrofit controls, new engine technologies, alternative fuels, diesel replacement fuels, and new engine emission standards. There are numerous technological challenges to reducing emissions from locomotives, including space constraints for packaging control equipment, low exhaust temperatures at lower throttle notches that affect after-treatment performance, and limited experience by emission control manufacturers with after-treatment for very large diesel engines. The impacts of proposed technologies on railroad operations also need to be considered.⁷¹

One of the most effective long-term strategies for reducing railroad emissions is to adopt more stringent national emissions standards for new locomotive engines. EPA recently announced proposed new emission standards for locomotives, including Tier 3 and Tier 4 standards for new engines (more details below).⁷² Significant emission reductions are expected by having a national standard and allowing fleet turnover or by dedicating these new engines to the South Coast. Assuming these standards are adopted as proposed, we analyze several strategies that would increase the market penetration of locomotives meeting these new standards.

Emissions can also be reduced through infrastructure improvements that allow diversion of freight from truck to rail, or grade separation projects that reduce vehicle idling at railroad grade crossings. These types of projects do not reduce railroad emissions per se; we include them in this section rather than the truck section because the investments focus on railroad infrastructure.

In total, 13 strategies are analyzed in this section, as follows:

- Replacing switching locomotives with hybrid diesel-electric locomotives
- Retrofitting switching and line-haul locomotives with a diesel oxidation catalyst (DOC)

⁷¹ U.S. Environmental Protection Agency (2007)

⁷² U.S. Environmental Protection Agency (2007a)

- Retrofitting switching and line-haul locomotives with a diesel particulate filter (DPF)
- Retrofitting switching and line-haul locomotives with selective catalytic reduction system (SCR)
- Accelerated locomotive rebuilds
- Accelerated replacement with Tier 3 or Tier 4 locomotives
- Reducing idling emissions from locomotives
- Electrification of the Alameda Corridor
- Electrification of the entire railroad mainline system
- Expansion of on-dock rail service
- Expansion of near-dock rail service
- Inland rail improvements
- Grade crossing separation

Note that there are numerous other strategies for reducing railroad emissions, some of which appear to be promising. Two such strategies are described below.

- ***LNG locomotives for switch applications*** – LNG switch locomotives have been shown to significantly reduce NO_x and PM emissions compared to a Tier 2 diesel locomotive. Pacific Harbor Line has a LNG locomotive demonstration currently underway within the San Pedro Bay Ports. BNSF has been operating four LNG switch locomotives in the Los Angeles area for 10 years. BNSF has not expanded the use of LNG locomotives due to operational and economic challenges. For example, separate LNG centralized fueling is necessary, the fueling range of LNG switch locomotives is limited, and there are additional handling and safety requirements associated with the use of LNG. Additionally, LNG switch locomotives are about 30% less fuel efficient than conventional diesel switch locomotives.⁷³
- ***Advanced Locomotive Emission Control System (ALECS)*** – ALECS involves stationary air pollution control equipment (exhaust hood) to capture and treat emissions from locomotives while refueling or undergoing engine diagnostics or load tests after being serviced. UP recently completed a demonstration of this technology at the Roseville yard. ALECS has the potential to reduce NO_x and PM emissions by up to 98%.⁷⁴ However, its application is limited and only addresses a fraction of idling emissions.

Aside from regulatory and enforceable actions (discussed below), there are several initiatives to evaluate and reduce emissions from locomotives in California. The AB 1222 Remote Sensing Pilot Program will determine the feasibility of using remote sensing to quantify emissions from locomotives, potentially improving the measurement of emissions. The “California Emissions Program” is a joint effort between ARB and the major railroads that aims to 1) to reduce lubricating oil consumption in a typical EMD engine to prepare for after-treatment technologies, and 2) to test after-treatment systems for their emissions reduction capabilities and durability. Future phases will certainly shed light to the effectiveness of after-treatment technologies for switch locomotives.

⁷³ California Air Resources Board (2006d)

⁷⁴ TIAX (2007)

Emission Standards and Emission Factors

The U.S. EPA finalized emission standards for locomotives in April 1998, which took effect in 2000. These standards involve three tiers, based on the year of original locomotive engine manufacture. The Tier 0 emission standards apply to locomotives and engines originally manufactured from 1973 through 2001, any time the engine is manufactured or remanufactured. Tier 1 standards apply to original model years between 2002 through 2004. Tier 2 standards apply to original model years of 2005 and later. In July 1998, BNSF and UP signed a Memorandum of Understanding with ARB that requires early introduction of Tier 2 locomotives into the South Coast Air Basin, such that both railroads must achieve a fleet average Tier 2 standard in the basin by 2010.

In 2005, ARB established a Rail Yard Agreement with UP and BNSF that obligates the railroads to significantly reduce diesel emissions in and around rail yards in California. Among other provisions, the agreement includes a statewide idling-reduction program and health risk assessments for all major rail yards.

We calculated average emissions rates for Tier 2 locomotives and divided by a weighted average power to derive brake-specific emissions factors. This data was gathered as part of the Rail Yard Agreement health risk evaluation conducted on actual Tier 2 locomotives (on line-haul and switcher duty cycles).⁷⁵ The per engine Tier 2 baseline emissions factors are summarized below in Table 3-1.

Table 3-1: Baseline emissions factors for Tier 2 locomotives

	NO _x		PM		HC		CO	
	[g/bhp-hr]	[g/hr]	[g/bhp-hr]	[g/hr]	[g/bhp-hr]	[g/hr]	[g/bhp-hr]	[g/hr]
Line-Haul	4.60	5789	0.15	183	0.13	159	0.38	479
Switcher	5.48	2268	0.20	85	0.21	89	0.70	288
Passenger	5.09	2432	0.19	91	0.18	87	0.58	280

EPA recently announced proposed new emission standards for locomotives.⁷⁶ The proposed emission standards include a retrofit of existing equipment as well as new engine emission standards (Tier 3 and Tier 4). Existing Tier 0, 1, and 2 engines will be subject to retrofit at the time of rebuild, so the engines will be rebuilt gradually throughout their remaining useful life.

The emissions standards and projected EPA emission factors are shown in Tables 3-2 and 3-3, and depend on the duty cycle chosen to certify the engines – either line-haul or switching engine duty cycles. The duty cycle for line-haul engines typically leads to lower emission on a gram per horsepower-hour (hp-hr) basis because there is considerable idling time in the switching engine duty cycle. In some cases the uncontrolled emissions are much lower than some of the emission standards, so no emission reduction would be expected from those standards especially for HC and CO emissions.

⁷⁵ ENVIRON (2006)

⁷⁶ U.S. Environmental Protection Agency (2007a)

Table 3-2: Emission standards (g/hp-hr) for line-haul (duty cycle) locomotive engines

Emission Standard	Applicable Year	HC (g/hp-hr)	CO (g/hp-hr)	NO_x (g/hp-hr)	PM (g/hp-hr)
Uncontrolled Emissions	Pre-1973	0.48	1.28	13.0	0.32
Tier 0	1973 – 2001	1.00	5.0	9.50	0.60
Tier 0 proposed ^a	2008 / 2010	0.30	5.0	7.40	0.22
Tier 1	2002 – 2004	0.55	2.2	7.40	0.45
Tier 1 proposed ^a	2008 / 2010	0.55	5.0	7.40	0.22
Tier 2	2005	0.30	1.5	5.50	0.20
Tier 2 proposed ^a	2008 / 2013	0.30	1.5	5.50	0.10
Tier 3 proposed	2012 – 2014	0.30	1.5	5.50	0.10
Tier 4 proposed ^b	2015 / 2017	0.14	1.5	1.30	0.03

Note a: These are retrofit standards at the time of rebuild and phased in as retrofit kit availability allows.

Note b: The Tier 4 NO_x standard would not apply until 2017, while the other standards would apply starting in 2015. The Tier 4 NO_x standard would apply, however, at remanufacture for model year 2015 and 2016 locomotives.

Table 3-3: EPA projected emissions factors (g/hp-hr) for line-haul locomotive engines

Emission Standard	Applicable Year	HC (g/hp-hr)	CO (g/hp-hr)	NO_x (g/hp-hr)	PM (g/hp-hr)
Uncontrolled Emissions	Pre-1973	0.48	1.28	13.0	0.32
Tier 0	1973 – 2001	0.48	1.28	8.60	0.32
Tier 0 proposed ^a	2008 / 2010	0.30	1.28	8.60	0.20
Tier 1	2002 – 2004	0.47	1.28	6.70	0.32
Tier 1 proposed ^a	2008 / 2010	0.29	1.28	6.70	0.20
Tier 2	2005	0.26	1.28	5.50	0.18
Tier 2 proposed ^a	2008 / 2013	0.13	1.28	4.95	0.09
Tier 3 proposed	2012 – 2014	0.13	1.28	4.95	0.09
Tier 4 proposed ^b	2015 / 2017	0.04	1.28	1.00	0.027

Note a: These are estimated emissions with retrofit with some exceptions for older Tier 0 engines.

Note b: The Tier 4 NO_x standard would not apply until 2017, while the other standards would apply starting in 2015. The Tier 4 NO_x standard would apply, however, at remanufacture for model year 2015 and 2016 locomotives.

Table 3-4: Emission standards for switching (duty cycle) locomotive engines

Emission Standard	Applicable Year	HC (g/hp-hr)	CO (g/hp-hr)	NO_x (g/hp-hr)	PM (g/hp-hr)
Uncontrolled Emissions	Pre-1973	1.01	1.83	17.4	0.44
Tier 0	1973 – 2001	2.10	8.0	14.00	0.72
Tier 0 proposed ^a	2008 / 2010	2.10	8.0	11.80	0.26
Tier 1	2002 – 2004	1.20	2.5	11.00	0.54
Tier 1 proposed ^a	2008 / 2010	1.20	2.5	11.00	0.26
Tier 2	2005	0.60	2.4	8.10	0.24
Tier 2 proposed ^a	2008 / 2013	0.60	2.4	8.10	0.13
Tier 3 proposed	2011 - 2015	0.60	2.4	5.00	0.10
Tier 4 proposed ^b	2015 / 2017	0.14	2.4	1.30	0.03

Note a: These are retrofit standards at the time of rebuild and phased in as retrofit kit availability allows.

Note b: The Tier 4 NO_x standard would not apply until 2017, while the other standards would apply starting in 2015. The Tier 4 NO_x standard would apply, however, at remanufacture for model year 2015 and 2016 locomotives.

Table 3-5: EPA projected emission factors for switching (duty cycle) locomotive engines

Emission Standard	Applicable Year	HC (g/hp-hr)	CO (g/hp-hr)	NO_x (g/hp-hr)	PM (g/hp-hr)
Uncontrolled Emissions	Pre-1973	1.01	1.83	17.4	0.44
Tier 0	1973 – 2001	1.01	1.83	14.00	0.44
Tier 0 proposed ^a	2008 / 2010	0.57	1.83	12.60	0.25
Tier 1	2002 – 2004	1.01	1.83	11.00	0.43
Tier 1 proposed ^a	2008 / 2010	0.57	1.83	9.90	0.25
Tier 2	2005	0.51	1.83	8.10	0.19
Tier 2 proposed ^a	2008 / 2013	0.26	1.83	7.30	0.09
Tier 3 proposed	2011 – 2015	0.26	1.83	5.40	0.09
Tier 4 proposed ^b	2015 / 2017	0.08	1.83	1.00	0.02

Note a: These are estimated emissions with retrofit with some exceptions for older Tier 0 engines.

Note b: The Tier 4 NO_x standard would not apply until 2017, while the other standards would apply starting in 2015. The Tier 4 NO_x standard would apply, however, at remanufacture for model year 2015 and 2016 locomotives.

Emission Inventory

For a number of the emission reduction strategies analyzed in this document, the analysis relies on the current and forecast inventory of locomotive emissions. The 2007 Air Quality Management Plan (AQMP) presents an inventory of total locomotive emissions in the South Coast Air Basin, as shown in Table 3-6.

Table 3-6: South Coast locomotive emission inventory by pollutant (tons per day)

	2005	2010	2014	2020	2023	2030
NO _x	32.26	19.69	22.75	25.82	27.63	32.86
Total PM	0.94	0.85	0.85	0.88	0.90	0.95
PM ₁₀	0.94	0.84	0.84	0.87	0.89	0.95
PM _{2.5}	0.86	0.77	0.77	0.80	0.82	0.87
VOC	2.55	2.45	2.50	2.60	2.66	2.85

Source: 2007 Air Quality Management Plan

Our analysis of most strategies depends on estimates of locomotive emissions by train or locomotive type. ARB has developed a locomotive emission inventory for the South Coast Air Basin for 2010 and 2020 that provides emissions by train type, shown in Table 3-7. For 2030 and other analysis years, we used the distribution of emissions by train type in Table 3-7 in order to allocate total locomotive emissions in Table 3-6.

Table 3-7: South Coast locomotive emission inventory by train type (tons per day)

Train Type	2010		2020		2030	
	NO_x	PM_{2.5}	NO_x	PM_{2.5}	NO_x	PM_{2.5}
Intermodal	8.16	0.35	11.87	0.43	15.11	0.46
Local Short Haul	1.63	0.06	1.63	0.05	2.07	0.06
Mixed Bulk	4.46	0.20	4.89	0.18	6.22	0.20
Yard/Switch	2.6	0.07	2.59	0.07	3.30	0.08
Passenger	2.85	0.07	4.84	0.06	6.16	0.07
Total	19.7	0.76	25.8	0.80	32.9	0.87

Source: For 2010 and 2020, Walter Wong, ARB; for 2030, total locomotive emissions allocated to train type based on 2020 distribution.

The inventories presented above do not reflect the proposed new EPA locomotive emissions standards. Although the level of standards that will be specified in the final EPA rule is unknown, it is likely that

standards similar to those proposed will be adopted in the near future. This will have the effect of reducing the forecast emissions baseline, particularly in the years 2020 and beyond. To estimate the effects of the proposed new EPA standards, we calculated the percent reduction in national locomotive emissions (by locomotive type) based on data presented in EPA's Draft Regulatory Impact Analysis (RIA).⁷⁷ The percent reductions in shown in Table 3-8.

Table 3-8: Impact of proposed EPA standards on U.S. locomotive emissions

	2020			2030		
	NO _x	PM _{2.5}	VOC	NO _x	PM _{2.5}	VOC
Line-haul	19.2%	40.8%	48.8%	52.1%	62.7%	68.5%
Switcher	9.6%	23.9%	26.5%	27.8%	44.5%	50.0%
Passenger	19.1%	43.5%	51.5%	52.9%	66.4%	72.3%
Total	17.2%	37.8%	42.7%	46.9%	58.1%	60.7%

Source: Calculated based on data in U.S. EPA Draft Regulatory Impact Analysis

We applied these percentage reductions to the baseline inventory in Table 3-7 to estimate the inventory under the proposed reductions, shown in Table 3-9.

Table 3-9: Estimated South Coast locomotive emission inventory under proposed EPA standards (tons per day)

Train Type	2020		2030	
	NO _x	PM _{2.5}	NO _x	PM _{2.5}
Intermodal	9.59	0.25	7.23	0.19
Local Short Haul	1.32	0.03	0.99	0.02
Mixed Bulk	3.95	0.11	2.98	0.08
Yard/Switch	2.34	0.06	2.38	0.05
Passenger	3.91	0.04	2.90	0.03
Total	21.1	0.48	16.5	0.37

⁷⁷ U.S. Environmental Protection Agency (2007a)

3.2. Clean Switching Locomotive (Green Goat or Gen Set)

Description of Strategy

This strategy involves replacing a fraction of locomotive yard/switching engines with a hybrid-electric or generator set switching engine. Hybrid-electric engines use a combination of a heavy-duty battery rack to supply electrical power, and a small diesel generator to provide some prime power, and to provide a trickle charge to the battery rack. This would reduce emissions by operating the small diesel generator at optimized conditions and eliminating emissions from a standard Tier 2 diesel switching engine over much of its cycle. A hybrid electric locomotive can also reduce fuel consumption by operating the engine in its most efficient mode, eliminating idle, and recovering braking energy. An example of such an engine is the Green Goat engine manufactured by RailPower Technologies Corp., which uses lead-acid batteries and a 290 HP diesel generator to provide a total brake horsepower of 2000.⁷⁸ The Green Goat has been estimated to reduce fuel consumption by 40-60% and reduce emissions of PM and NO_x by 80% to 90%, respectively.

A generator set switching locomotive is similar to the Green Goat, but is entirely powered by two, three, or perhaps four smaller diesel generator engines meeting lower emission standards than the current locomotive standards. Generator set locomotives do not recover braking energy as the Green Goat was designed to do, and so forfeit some incremental emission reduction when the batteries would be supplying power in the Green Goat.

This strategy would apply to yard or switching engines, but not to passenger train engines or to line haul engines. Passenger train or line haul engines see more substantial use at high load and a high notch setting, whereas switching engines operate at lower notch settings or frequently idle over much of their duty cycle. It is not expected that this measure would apply to all switching engines in the SCAG region because not all of these engines can be replaced by the hybrid electric or generator set locomotives due to power requirements.⁷⁹ This section evaluates the potential emissions impact, costs, and cost-effectiveness of replacing 10%, 25%, and 50% of Tier 2 switching engines in the South Coast region with a hybrid-electric locomotive. The base case year for this analysis is 2010, and it is assumed that the baseline emissions in 2010 and all subsequent years are those of a Tier 2 locomotive engine.

Pollutants Reduced

This measure would reduce emissions of all pollutants, including NO_x, ROG, and PM_{2.5}, by replacing some Tier 2 locomotive switching engines with hybrid-electric engines.

Emissions Reductions

Emission reductions from this measure are primarily due to the offroad generator engines meeting lower emission standards than locomotives for the same model year. Offroad engines meet lower emission standards earlier than EPA has proposed for locomotives.

We assumed baseline emissions to be those of a Tier 2 locomotive switching engine based on EPA switching engine cycle emissions tests for two locomotive engines. The weighted average emissions rates were calculated and divided by a weighted average power to derive brake-specific emissions factors. This data was gathered as part of the Rail Yard Agreement Health Risk Evaluation conducted on actual Tier 2

⁷⁸ RailPower Technologies Corporation (2006)

⁷⁹ ENVIRON (2006a)

locomotives (on line-haul and switcher duty cycles).⁸⁰ The emissions of the hybrid-electric engine were assumed to be those of a small (130 HP) diesel generator and were obtained from the EPA standards for Tier 4 nonroad engines. The nonroad engine standards are shown below in Table 3-10.

Table 3-10: EPA emission standards for nonroad engines to 560 kW, g/kWh (g/bhp-hr)

Engine Power	Year	CO	NMHC	NMHC+NO _x	NO _x	PM
kW < 8 (hp < 11)	2008	8.0 (6.0)	-	7.5 (5.6)	-	0.4 ^a (0.3)
8 ≤ kW < 19 (11 ≤ hp < 25)	2008	6.6 (4.9)	-	7.5 (5.6)	-	0.4 (0.3)
19 ≤ kW < 37 (25 ≤ hp < 50)	2008	5.5 (4.1)	-	7.5 (5.6)	-	0.3 (0.22)
	2013	5.5 (4.1)	-	4.7 (3.5)	-	0.03 (0.022)
37 ≤ kW < 56 (50 ≤ hp < 75)	2008	5.0 (3.7)	-	4.7 (3.5)	-	0.3 ^b (0.22)
	2013	5.0 (3.7)	-	4.7 (3.5)	-	0.03 (0.022)
56 ≤ kW < 130 (75 ≤ hp < 175)	2012-2014 ^c	5.0 (3.7)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)
130 ≤ kW < 560 (175 ≤ hp < 750)	2011-2014 ^d	3.5 (2.6)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)

Note a: Hand-startable, air-cooled, DI engines may be certified to Tier 2 standards through 2009 and to an optional PM standard of 0.6 g/kWh starting in 2010

Note b: 0.4 g/kWh (Tier 2) if manufacturer complies with the 0.03 g/kWh standard from 2012

Note c: PM/CO: full compliance from 2012; NO_x/HC: Option 1 (if banked Tier 2 credits used) – 50% engines must comply in 2012-2013; Option 2 (if no Tier 2 credits claimed) – 25% engines must comply in 2012-2014, with full compliance from 2014.12.31

Note d: PM/CO: full compliance from 2011; NO_x/HC: 50% engines must comply in 2011-2013

Whether a hybrid-electric (Green Goat) or generator set design is used for low emissions locomotives, the primary difference in emission is due to the lower offroad emission standards. There are several special demonstration designs for low emission switching engines using a bank of smaller off-road generator engines. Currently these engines are available in limited quantities, and would likely meet an emission standard significantly below the Tier 3 proposed standard, shown in Table 3-4, but are not yet compliant with Tier 4. BNSF and UP provided preliminary emissions test results for example demonstration engines in order to determine emissions for the switching engine. The demonstration engines currently are rated at up to 2000 hp instead of the maximum power 3800 hp necessary for general purpose switching engines that may also pull local short-haul trains. Using the data supplied by UP and BNSF shown in Table 3-11, a generator set locomotive could be expected to produce NO_x and PM reductions beyond current Tier 2 switching engines more than 60% for NO_x and 70% for PM, and compared to the EPA proposed Tier 2 retrofit of 60% for NO_x and 40% for PM. This is less than the projected benefit of the Green Goat, but reduces the design complexities and cost of the hybrid electric system inherent in the Green Goat.

Table 3-11: Emission rates for generator set locomotives (g/hp-hr)

Switch Engine	HC	CO	NO _x	PM
BNSF Demonstration Model Results	0.10	1.09	2.67	0.05
UP Demonstration Model	0.04	1.51	3.40	0.06

Source for BNSF results: personal communication with ENVIRON

Source for UP results: <http://www.ffca2006.com/documents/presentations/rail/Mike%20Iden.pdf>

By 2011, off-road generator sets will also need to meet more stringent standards likely necessitating the use of diesel particulate filters lowering the emissions in the Table 3-11 above by an order of magnitude. Therefore, Tier 4 compliant generator set switching engines could be available starting as early as 2011.

⁸⁰ ENVIRON (2006)

The brake-specific fuel consumption (BSFC) of the Tier 2 locomotive switching engines was obtained from emissions testing data on two locomotive engines, which included a measurement of fuel flow rate. The BSFC of the Green Goat hybrid-electric engine was assumed to be that of a Tier 4 nonroad engine using the ARB's OFFROAD model, which gives a BSFC of 0.49 lb/bhp-hr for a 130 HP diesel generator engine.⁸¹

Based on information from RailPower Technologies Corporation, the useful life of the hybrid-electric engines was assumed to be 10 years, and calculations of overall emissions reductions and cost-effectiveness are based on this useful life.⁸²

The per engine emissions from Tier 2 locomotive switching engines and from the hybrid-electric engines was calculated using the following equation:

$$E_{engine} = \left(EF / BSFC \right) \rho_{fuel} \dot{Q}_{fuel} \quad [\text{ton/yr}]$$

where E_{engine} is the per engine emissions, EF is the brake-specific emissions factor for each pollutant, $BSFC$ is the brake specific fuel consumption for each engine, ρ_{fuel} is the diesel fuel density taken to be 7.1 lb/gal, and \dot{Q}_{fuel} is the annual fuel usage of locomotive switching engines, assumed to be 25,000 gal/yr based on experience.

To estimate the impact of this strategy, we assume that APU hybrid locomotives would be substituted for existing switcher locomotives and not those that would be subject to new EPA emission standards. The emission reductions calculated in this analysis are shown in Tables 3-12, 3-13, and 3-14. Because the uncertainty associated with the maximum feasible level of penetration of APU hybrid switcher locomotives, we present results for three different penetration levels – 10%, 25%, and 50%.

Table 3-12: NO_x Emissions Reductions from Hybrid-Electric Switching Engine Strategy (tons/yr)

	Tier 2	2010	2015	2020	2025	2035
Emission Rate (per engine)	2.715	0.078	0.078	0.078	0.078	0.078
Emission Reduction (per engine)		2.637	2.637	2.637	2.637	2.637
		[97.1%]	[97.1%]	[97.1%]	[97.1%]	[97.1%]
Overall Emissions Reduction (10% penetration rate)		93.5	93.3	93.2	105.9	131.3
Overall Emissions Reduction (25% penetration rate)		233.7	233.3	232.9	264.7	328.3
Overall Emissions Reduction (50% penetration rate)		467.4	466.6	465.9	529.4	656.5

⁸¹ California Air Resources Board (2007)

⁸² RailPower Technologies Corporation (2006)

Table 3-13: PM_{2.5} Emissions Reductions from Hybrid-Electric Switching Engine Strategy (tons/yr)

	Tier 2	2010	2015	2020	2025	2035
Emission Rate (per engine)	0.092	0.004	0.004	0.004	0.004	0.004
Emission Reduction (per engine)		0.089	0.089	0.089	0.089	0.089
		[96.0%]	[96.0%]	[96.0%]	[96.0%]	[96.0%]
Overall Emissions Reduction (10% penetration rate)		3.2	3.1	3.1	3.6	4.5
Overall Emissions Reduction (25% penetration rate)		7.9	7.9	7.9	9.0	11.1
Overall Emissions Reduction (50% penetration rate)		15.8	15.7	15.7	17.9	22.2

Table 3-14: VOC Emissions Reductions from Hybrid-Electric Switching Engine Strategy (tons/yr)

	Tier 2	2010	2015	2020	2025	2035
Emissions Rate (per engine)	0.134	0.046	0.046	0.046	0.046	0.046
Emissions Reduction (per engine)		0.088	0.088	0.088	0.088	0.088
		[65.7%]	[65.7%]	[65.7%]	[65.7%]	[65.7%]
Overall Emissions Reduction (10% penetration rate)		3.1	3.1	3.1	3.5	4.4
Overall Emissions Reduction (25% penetration rate)		7.8	7.8	7.8	8.9	11.0
Overall Emissions Reduction (50% penetration rate)		15.7	15.6	15.6	17.7	22.0

Costs

The initial capital cost of purchasing each hybrid-electric engine is \$750,000 per engine. This cost was obtained from the average cost of a 1000 HP Green Goat engine from RailPower.⁸³ It should be noted that this is a present value cost but it is expected that if there is future greater demand for the technology and a production increase, the initial capital cost could fall substantially. A conservative estimate for the cost of a conventional Tier 2 locomotive switching engine is \$1.5M. This cost is not expected to decrease in coming years due to volume demand since the locomotive engine industry is a relatively low-volume industry.⁸⁴

In addition to the initial capital cost, we have estimated a maintenance and operational yearly cost of \$3,150 which includes routine maintenance of the batteries, diesel generator, and other components, as well as replacement of any batteries that fail during routine operation. We have calculated a fuel savings benefit based on the annual fuel consumption rate of a typical Tier 2 locomotive switching engine and the ratio of BSFC of the Tier 2 engine to the hybrid-electric engine. The fuel savings benefit was calculated to be approximately \$23,100 per year of operation.

Cost-Effectiveness

The NO_x, PM, and ROG cost effectiveness calculations are based on the SCAQMD BACT methodology reported in MSBACT Guidelines and described in Section 1.⁸⁵ The BACT guidelines give the following equation for calculating the cost-effectiveness for each pollutant:

⁸³ RailPower Technologies Corporation (2004)

⁸⁴ EMD Corporation (2006)

⁸⁵ South Coast Air Quality Management District (2006a)

$$\text{CE Value (\$/ton)} = \frac{\text{Project Life Cost (\$)}}{\text{Pollutant reduction (10-Year)}}$$

The project life cost is the sum of the initial capital costs and the sum of the net present value of the maintenance and operational costs over the 10-year lifetime of the project. In addition to the BACT methodology, we have also calculated a cost-effectiveness per pollutant using the annualized capital cost, similar to the Carl Moyer method, incorporating annual operational costs. This annual cost-effectiveness uses the following methodology:

$$\text{Annual CE Value (\$/ton)} = \frac{\text{Annualized Capital Cost (\$/yr)} + \text{Annual Operational Costs (\$/yr)}}{\text{Pollutant Reduction (ton/yr)}}$$

The cost-effectiveness calculations for each of these three methodologies are summarized in Table 3-15. The Green Goat switcher costs less initially and generates additional fuel savings, which more than outweigh the Green Goat's relatively high maintenance costs relative to the Tier 2 engine over the 10-year lifetime of the project. Thus the cost-effectiveness values for this measure are all calculated to be negative, meaning that the capital and operating cost savings outweigh the costs of this strategy.

Table 3-15: Cost-effectiveness of Replacing Tier 2 Switchers with Hybrid-Electric Switchers

	NO _x				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$/ton]	< 0*	< 0*	< 0*	< 0*	< 0*
Annual Cost Effectiveness (per pollutant) [\$/ton]	< 0*	< 0*	< 0*	< 0*	< 0*
	PM				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$/ton]	< 0*	< 0*	< 0*	< 0*	< 0*
Annual Cost Effectiveness (per pollutant) [\$/ton]	< 0*	< 0*	< 0*	< 0*	< 0*
	ROG				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$/ton]	< 0*	< 0*	< 0*	< 0*	< 0*
Annual Cost Effectiveness (per pollutant) [\$/ton]	< 0*	< 0*	< 0*	< 0*	< 0*

* An entry of "< 0" indicates a negative cost-effectiveness value – the fuel costs and initial capital costs of the Green Goat are lower than a Tier 2 engine over the 10-year lifetime of the project.

3.3. Retrofit Locomotive Engines with DOC

Description of Strategy

This strategy involves retrofitting locomotive switching and line haul engines with diesel oxidation catalysts (DOCs). DOCs use a chemical process to convert PM into less harmful components through oxidation with the excess air inherent in diesel exhaust. They have been used for over 20 years and are perhaps the most proven after-treatment device for diesel engines, although there is less experience using them on locomotives.⁸⁶ DOCs can lower emissions of PM by 20% to 40% and ROG emissions by up to 60%, but do not affect NO_x emissions. DOCs must be used with ultra-low sulfur diesel fuel (ULSD) which is scheduled to be phased in for locomotives by the years that these emissions reduction scenarios are evaluated.

An EMD SD-60M line-haul locomotive has been equipped with an experimental DOC, and has been undergoing in-use durability and emissions testing. Results have been mixed but are leading to design improvements. DOCs are also being demonstrated on an EMD passenger locomotive for LACMTA. Problems with DOC plugging and getting full engine power have caused significant delays for this demonstration.⁸⁷

The emissions reduction calculations for this measure are applied to line haul and switching engines. This section evaluates the potential emissions impact, costs, and cost-effectiveness of retrofitting 10%, 25%, and 50% of Tier 2 switching and line haul engines in the South Coast region with DOCs. The analysis is conducted for 2010, 2015, 2020, 2025 and 2035 by which time it is expected that all switching and line haul locomotives will use Tier 2 engines. Thus the emissions reductions analysis is conducted relative to Tier 2 locomotive switching and line haul engines.

Pollutants Reduced

DOCs typically reduce PM and ROG emissions but do not affect NO_x emissions.

Emissions Reductions

Baseline emissions were assumed to be those of Tier 2 locomotive switching and line haul engines. Emissions data for typical switching and line haul engines were used to derive brake-specific emissions factors. This data was gathered from the Rail Yard Agreement Health Risk Evaluation conducted on actual Tier 2 locomotives (on line-haul and switcher duty cycles).⁸⁸

The per engine emissions from Tier 2 locomotive switching and line haul engines and from these engines retrofitted with a DOC were calculated using the following equation:

$$E_{engine} = \left(EF / BSFC \right) \rho_{fuel} \dot{Q}_{fuel} \quad [\text{ton/yr}]$$

where E_{engine} is the per engine emissions, EF is the brake-specific emissions factor for each pollutant with and without the DOC retrofit, $BSFC$ is the brake specific fuel consumption for each engine, ρ_{fuel} is the

⁸⁶ MECA (2006)

⁸⁷ Southwest Research Institute (2007)

⁸⁸ ENVIRON (2006)

diesel fuel density taken to be 7.1 lb/gal, and \dot{Q}_{fuel} is the annual fuel usage of locomotive switching engines, assumed to be 25,000 gal/yr based on experience. The overall emissions reductions were generated by multiplying the per engine emissions reduction by the estimated engine inventory for each scenario year. The estimated emissions inventory was generated from the emissions inventory projection analysis conducted by ARB.⁸⁹

The PM_{2.5} emissions reductions calculated in this analysis for switching engines are shown below in Table 3-16. SCAG region-wide PM_{2.5} emissions reductions in 2010 range from 1.3 – 6.3 tons/yr for a penetration rate ranging from 10% – 50%. By 2035, SCAG region-wide PM emissions reductions range from 1.8 – 9.0 tons/yr for a penetration rate ranging from 10% – 50%.

Table 3-16: PM_{2.5} Emission Reductions from Locomotive Switching Engine DOC Retrofits (tons/yr)

	Tier 2	2010	2015	2020	2025	2035
Emissions Rate (per engine)	0.092	0.057	0.057	0.057	0.057	0.057
Emissions Reduction (per engine)		0.036	0.036	0.036	0.036	0.036
		[38.6%]	[38.6%]	[38.6%]	[38.6%]	[38.6%]
Overall Emissions Reduction (10% penetration rate)		1.3	1.3	1.3	1.5	1.8
Overall Emissions Reduction (25% penetration rate)		3.2	3.2	3.2	3.6	4.5
Overall Emissions Reduction (50% penetration rate)		6.3	6.3	6.3	7.2	9.0

Table 3-17 shows ROG emissions reductions from Tier 2 switching engines. SCAG region-wide ROG emissions reductions in 2010 range from 2.7 – 13.6 tons/yr for a penetration rate ranging from 10% – 50%. By 2035, SCAG region-wide ROG emissions reductions range from 3.8 – 19.1 tons/yr for a penetration rate ranging from 10% – 50%.

Table 3-17: ROG Emission Reductions from Locomotive Switching Engine DOC Retrofits (tons/yr)

	Tier 2	2010	2015	2020	2025	2035
Emissions Rate (per engine)	0.134	0.058	0.058	0.058	0.058	0.058
Emissions Reduction (per engine)		0.077	0.077	0.077	0.077	0.077
		[57.5%]	[57.5%]	[57.5%]	[57.5%]	[57.5%]
Overall Emissions Reduction (10% penetration rate)		2.7	2.7	2.7	3.1	3.8
Overall Emissions Reduction (25% penetration rate)		6.8	6.8	6.8	7.7	9.6
Overall Emissions Reduction (50% penetration rate)		13.6	13.6	13.6	15.4	19.1

Table 3-18 shows PM_{2.5} emissions reductions from Tier 2 line haul engines. SCAG region-wide PM emissions reductions in 2010 range from 5.8 – 29.0 tons/yr for a penetration rate ranging from 10% – 50%. By 2035, SCAG region-wide PM emissions reductions range from 10.5 – 52.8 tons/yr for a penetration rate ranging from 10% – 50%.

⁸⁹ California Air Resources Board (2006f)

Table 3-18: PM_{2.5} Emission Reductions from Locomotive Line-Haul Engine DOC Retrofits (tons/yr)

	Tier 2	2010	2015	2020	2025	2035
Emissions Rate (per engine)	0.803	0.49	0.49	0.49	0.49	0.49
Emissions Reduction (per engine)		0.31	0.31	0.31	0.31	0.31
		[38.9%]	[38.9%]	[38.9%]	[38.9%]	[38.9%]
Overall Emissions Reduction (10% penetration rate)		5.8	6.7	7.5	8.5	10.5
Overall Emissions Reduction (25% penetration rate)		14.5	16.6	18.8	21.2	26.3
Overall Emissions Reduction (50% penetration rate)		29.0	33.2	37.4	42.5	52.8

Table 3-19 shows ROG emissions reductions from Tier 2 line haul engines. SCAG region-wide ROG emissions reductions in 2010 range from 10.3 – 51.5 tons/yr for a penetration rate ranging from 10% - 50%. By 2035, SCAG region-wide ROG emissions reductions range from 18.7 – 93.7 tons/yr for a penetration rate ranging from 10% - 50%.

Table 3-19: ROG Emission Reductions from Locomotive Line-Haul Engine DOC Retrofits (tons/yr)

	Tier 2	2010	2015	2020	2025	2035
Emissions Rate (per engine)	0.969	0.415	0.415	0.415	0.415	0.415
Emissions Reduction (per engine)		0.554	0.554	0.554	0.554	0.554
		[57.2%]	[57.2%]	[57.2%]	[57.2%]	[57.2%]
Overall Emissions Reduction (10% penetration rate)		10.3	11.8	13.3	15.1	18.7
Overall Emissions Reduction (25% penetration rate)		25.8	29.5	33.3	37.8	46.9
Overall Emissions Reduction (50% penetration rate)		51.5	59.0	66.5	75.6	93.7

Costs

The cost of a DOC retrofit was estimated at \$8/hp, similar to nonroad engines. Thus, the cost is \$16,800 for a switching engine and \$33,600 for a line haul engine. It should be noted that this is a present value cost, but it is expected that if there is future greater demand for the technology and a production increase, the initial capital cost could be substantially decreased. The maintenance and operational costs associated with this device are negligible. However, we have estimated a fuel consumption penalty resulting from the backpressure associated with retrofitting a DOC that is 2% greater than the annual fuel costs of a Tier 2 engine without the retrofit.

Cost-Effectiveness

The PM_{2.5} and ROG cost effectiveness calculations are based on the SCAQMD BACT methodology reported in MSBACT Guidelines, as described in Section 1.⁹⁰ This strategy was assumed to have a 10-year effective life. In addition to the BACT methodology, we have also calculated a cost-effectiveness per pollutant using the annualized capital cost, similar to the Carl Moyer method, and incorporating annual operational costs. The cost-effectiveness of pollutant calculations for both of these methodologies for switching engines are summarized below in Table 3-20.

⁹⁰ South Coast Air Quality Management District (2006a)

Table 3-20: Cost-effectiveness of Switching Locomotive DOC Retrofits

	PM_{2.5}				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$ /ton]	\$70,469	\$74,563	\$76,556	\$76,556	\$76,556
Annual Cost Effectiveness (per pollutant) [\$ /ton]	\$90,048	\$95,640	\$98,363	\$99,256	\$99,978
	ROG				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$ /ton]	\$33,006	\$34,923	\$35,857	\$35,857	\$35,857
Annual Cost Effectiveness (per pollutant) [\$ /ton]	\$42,176	\$44,795	\$46,070	\$46,489	\$46,826

By 2020, the BACT cost-effectiveness for PM_{2.5} reduction in switching engines is approximately \$80,000/ton of PM_{2.5}, and the annual cost-effectiveness is approximately \$100,000/ton of PM_{2.5}. The BACT cost-effectiveness for ROG reduction in switching engines is approximately \$35,000/ton of ROG, and the annual cost-effectiveness is approximately \$45,000/ton of ROG.

The cost-effectiveness calculations for PM_{2.5} and ROG emissions reductions for line haul engines are summarized below in Table 3-21.

Table 3-21: Cost-effectiveness of Line Haul Locomotive DOC Retrofits

	PM_{2.5}				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$ /ton]	\$41,710	\$47,034	\$49,627	\$50,477	\$51,163
Annual Cost Effectiveness (per pollutant) [\$ /ton]	\$55,541	\$62,814	\$66,355	\$67,518	\$68,455
	ROG				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$ /ton]	\$23,468	\$26,464	\$27,923	\$28,402	\$28,788
Annual Cost Effectiveness (per pollutant) [\$ /ton]	\$31,251	\$35,343	\$37,336	\$37,990	\$38,517

By 2020, the BACT cost-effectiveness for PM_{2.5} reduction in line haul engines is approximately \$50,000/ton of PM, and the annual cost-effectiveness is approximately \$65,000/ton of PM. The BACT cost-effectiveness for ROG reduction in line haul engines is approximately \$28,000/ton of ROG, and the annual cost-effectiveness is approximately \$37,000/ton of ROG.

Because the emissions reductions of NO_x from a DOC system are negligible, calculations of cost-effectiveness for NO_x have not been included.

3.4. Retrofit Locomotive Engines with DPF

Description of Strategy

This strategy involves retrofitting locomotive switching engines and line haul engines with a diesel particulate filter (DPF). DPFs are typically ceramic filters that collect particulate matter in the exhaust stream of the engine – catalyzed DPFs then use the high temperature of the exhaust and a catalytic substrate to react the PM into carbon dioxide and water. DPFs require that the engine operate such that exhaust temperatures are sufficiently high to “light off” the catalyzed DPF. In addition, at some point during the engine’s cycle, the exhaust temperature must be raised to a temperature sufficient to regenerate the DPF to prevent saturation and clogging. This latter requirement presents some difficulty with locomotive switching engines, which typically see low load in their duty cycle.⁹¹ In this case the DPF may need to be actively regenerated using an electric heating component. This presents a power draw (and hence fuel consumption penalty) as well as additional technical complication.

Long-term durability, performance, and maintenance requirements have yet to be established for DPFs on locomotives. There are also significant space constraints on locomotives, which the railroads regard as an additional limitation to installing DPF systems. It is anticipated that by the scenario years considered in this analysis, some of these technical issues will be overcome. Indeed, UP is already testing a pilot project to install an experimental DPF system on a switching engine in a yard near the Port of Oakland.⁹² Well-functioning DPFs can reduce PM emissions by 70% to 95% and catalyzed DPFs can also reduce ROG emissions by up to 80%. DPFs are currently the most effective technology for PM emissions reduction in diesel engines.⁹³

We evaluate this strategy for switching and line haul locomotives. This section evaluates the potential emissions impact, costs, and cost-effectiveness of replacing 10%, 25%, and 50% of Tier 2 switching and line haul engines in the South Coast region with DPFs. The analysis is conducted for 2010, 2015, 2020, 2025 and 2035 by which time it is expected that all switching and line haul locomotives will use Tier 2 engines. Thus the emissions reductions analysis is conducted relative to Tier 2 locomotive switching and line haul engines.

Pollutants Reduced

DPFs can reduce PM emissions and catalyzed DPFs can also reduce ROG emissions. NO_x emissions will be unaffected by a DPF.

Emissions Reductions

Baseline emissions were assumed to be those of Tier 2 switching and line haul locomotive engines. Emissions data for typical switching and line haul engines were used to derive brake-specific emissions factors. This data was gathered from the Rail Yard Agreement Health Risk Evaluation conducted on actual Tier 2 locomotives (on line-haul and switcher duty cycles).⁹⁴

The per engine emissions from Tier 2 locomotive switching engines and from these engines retrofitted with a DPF were calculated using the following equation:

⁹¹ Southwest Research Institute (2006)

⁹² Union Pacific Railroad (2006)

⁹³ MECA (2006)

⁹⁴ ENVIRON (2006)

$$E_{engine} = \left(\frac{EF}{BSFC} \right) \rho_{fuel} \dot{Q}_{fuel} \quad [\text{ton/yr}]$$

where E_{engine} is the per engine emissions, EF is the brake-specific emissions factor for each pollutant with and without the DPF retrofit, $BSFC$ is the brake specific fuel consumption for each engine, ρ_{fuel} is the diesel fuel density taken to be 7.1 lb/gal, and \dot{Q}_{fuel} is the annual fuel usage of locomotive switching engines, assumed to be 25,000 gal/yr based on experience. The overall emissions reductions were generated by multiplying the per engine emissions reduction by the estimated engine inventory for each scenario year. The estimated emissions inventory was generated from the emissions inventory projection analysis conducted by ARB.⁹⁵

The PM_{2.5} and ROG emissions reductions calculated in this analysis for switching engines are shown below in Tables 3-22 and 3-23. As noted above, a DPF has a negligible effect on NO_x emissions. For 2010, switching engine PM_{2.5} emissions reductions range from 2.7 – 13.9 tons/yr in the SCAG region for a penetration rate ranging from 10% – 50%. For 2035, switching engine PM_{2.5} emissions reductions range from 3.9 – 19.6 tons/yr in the SCAG region for a penetration rate ranging from 10% – 50%.

Table 3-22: PM_{2.5} Emission Reductions from Locomotive Switching Engine DPF Retrofits (tons/yr)

	Tier 2	2010	2015	2020	2025	2035
Emissions Rate (per engine)	0.092	0.015	0.015	0.015	0.015	0.015
Emissions Reduction (per engine)		0.079	0.079	0.079	0.079	0.079
		[85.2%]	[85.2%]	[85.2%]	[85.2%]	[85.2%]
Overall Emissions Reduction (10% penetration rate)		2.7	2.7	2.7	3.1	3.9
Overall Emissions Reduction (25% penetration rate)		7.0	7.0	7.0	7.9	9.8
Overall Emissions Reduction (50% penetration rate)		13.9	13.9	13.9	15.7	19.6

For 2010 switching engine ROG emissions reductions range from 3.8 – 19.0 tons/yr in the SCAG region for a penetration rate ranging from 10% – 50%. For 2035, switching engine ROG emissions reductions range from 5.3 – 26.6 tons/yr in the SCAG region for a penetration rate ranging from 10% – 50%.

Table 3-23: ROG Emission Reductions from Locomotive Switching Engine DPF Retrofits (tons/yr)

	Tier 2	2010	2015	2020	2025	2035
Emissions Rate (per engine)	0.134	0.027	0.027	0.027	0.027	0.027
Emissions Reduction (per engine)		0.107	0.107	0.107	0.107	0.107
		[79.9%]	[79.9%]	[79.9%]	[79.9%]	[79.9%]
Overall Emissions Reduction (10% penetration rate)		3.8	3.8	3.8	4.3	5.3
Overall Emissions Reduction (25% penetration rate)		9.5	9.5	9.5	10.7	13.3
Overall Emissions Reduction (50% penetration rate)		19.0	18.9	18.9	21.5	26.6

Table 3-24 shows PM_{2.5} emissions reductions from Tier 2 line haul engines. SCAG region-wide PM_{2.5} emissions reductions in 2010 range from 12.6 – 63.3 tons/yr for a penetration rate ranging from 10% –

⁹⁵ California Air Resources Board (2006f)

50%. SCAG region-wide PM_{2.5} emissions reductions in 2035 range from 23.1 – 115.2 tons/yr for a penetration rate ranging from 10% – 50%.

Table 3-24: PM_{2.5} Emission Reductions from Locomotive Line-Haul Engine DPF Retrofits (tons/yr)

	Tier 2	2010	2015	2020	2025	2035
Emissions Rate (per engine)	0.803	0.123	0.123	0.123	0.123	0.123
Emissions Reduction (per engine)		0.681	0.681	0.681	0.681	0.681
		[84.74%]	[84.74%]	[84.74%]	[84.74%]	[84.74%]
Overall Emissions Reduction (10% penetration rate)		12.6	14.5	16.4	18.6	23.1
Overall Emissions Reduction (25% penetration rate)		31.7	36.2	40.9	46.4	57.5
Overall Emissions Reduction (50% penetration rate)		63.3	72.5	81.7	92.9	115.2

Table 3-25 shows ROG emissions reductions from Tier 2 line haul engines. SCAG region-wide ROG emissions reductions in 2010 range from 14.3 – 71.7 tons/yr for a penetration rate ranging from 10% – 50%. SCAG region-wide ROG emissions reductions in 2035 range from 26.1 – 130.5 tons/yr for a penetration rate ranging from 10% – 50%.

Table 3-25: ROG Emission Reductions from Locomotive Line-Haul Engine DPF Retrofits (tons/yr)

	Tier 2	2010	2015	2020	2025	2035
Emissions Rate (per engine)	0.969	0.198	0.198	0.198	0.198	0.198
Emissions Reduction (per engine)		0.771	0.771	0.771	0.771	0.771
		[79.6%]	[79.6%]	[79.6%]	[79.6%]	[79.6%]
Overall Emissions Reduction (10% penetration rate)		14.3	16.4	18.5	21.1	26.1
Overall Emissions Reduction (25% penetration rate)		35.9	41.1	46.3	52.6	65.3
Overall Emissions Reduction (50% penetration rate)		71.7	82.2	92.6	105.3	130.5

Costs

The cost of a DPF retrofit was estimated at \$38/hp, similar to nonroad engines. It should be noted that this is only an estimate because active regeneration requirements may necessitate the use of electrical heaters which could add to the cost of the device. Such costs have not been included in this analysis. Thus, we estimate the cost to be \$75,000 for a switching engine and \$150,000 for a line haul engine. This is a present value cost, but it is expected that if there is future greater demand for the technology and a production increase, the initial capital cost could drop substantially. The maintenance and operational costs associated with this device are negligible. However, we have estimated a fuel consumption penalty resulting from the backpressure associated with retrofitting a DPF that is 2% greater than the annual fuel costs of a Tier 2 engine without the retrofit.

Cost-Effectiveness

The PM_{2.5} and ROG cost effectiveness calculations are based on the SCAQMD BACT methodology reported in MSBACT Guidelines, as described in Section 1.⁹⁶ This strategy was assumed to have a 10-

⁹⁶ South Coast Air Quality Management District (2006a)

year effective life. In addition to the BACT methodology, we have also calculated a cost-effectiveness per pollutant using the annualized capital cost, similar to the Carl Moyer method, and incorporating annual operational costs.

The cost-effectiveness of pollutant calculations for both of these methodologies for switching engines are summarized below in Table 3-26.

Table 3-26: Cost-effectiveness of Switching Locomotive DPF Retrofits

	PM_{2.5}				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$ /ton]	\$106,373	\$108,249	\$109,161	\$109,161	\$109,161
Annual Cost Effectiveness (per pollutant) [\$ /ton]	\$132,598	\$135,160	\$136,407	\$136,817	\$137,147
	ROG				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$ /ton]	\$78,100	\$79,477	\$80,147	\$80,147	\$80,147
Annual Cost Effectiveness (per pollutant) [\$ /ton]	\$97,355	\$99,236	\$100,151	\$100,452	\$100,694

In 2020, the BACT cost-effectiveness for PM_{2.5} reduction in switching engines is approximately \$110,000/ton of PM_{2.5}, and the annual cost-effectiveness is approximately \$135,000/ton of PM_{2.5}. The BACT cost-effectiveness for ROG reduction in switching engines is approximately \$80,000/ton of ROG, and the annual cost-effectiveness is approximately \$100,000/ton of ROG.

The cost-effectiveness calculations for PM_{2.5} and ROG emissions reductions for line haul engines are summarized below in Table 3-27.

Table 3-27: Cost-effectiveness of Line Haul Locomotive DPF Retrofits

	PM_{2.5}				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$ /ton]	\$36,212	\$38,651	\$39,839	\$40,229	\$40,542
Annual Cost Effectiveness (per pollutant) [\$ /ton]	\$46,532	\$49,864	\$51,487	\$52,019	\$52,448
	ROG				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$ /ton]	\$31,940	\$34,091	\$35,139	\$35,483	\$35,760
Annual Cost Effectiveness (per pollutant) [\$ /ton]	\$41,043	\$43,981	\$45,412	\$45,882	\$46,261

In 2020, the BACT cost-effectiveness for PM_{2.5} reduction in line haul engines is approximately \$40,000/ton of PM_{2.5}, and the annual cost-effectiveness is approximately \$50,000/ton of PM_{2.5}. The BACT cost-effectiveness for ROG reduction in switching engines is approximately \$35,000/ton of ROG, and the annual cost-effectiveness is approximately \$45,000/ton of ROG. Because the emissions reductions of NO_x from a DPF system are negligible, calculations of cost-effectiveness for NO_x have not been included.

3.5. Retrofit Locomotive Engines with SCR

Description of Strategy

This strategy involves retrofitting locomotive switching engines and line haul engines with an SCR system. The SCR system requires a reducing agent (ammonia or urea) to be injected into the exhaust stream and uses the ammonia or urea in conjunction with a catalyst to reduce NO_x to N₂ and water. SCR has the potential to reduce NO_x emissions by 75 to 90% but has a relatively smaller effect on PM emissions. An SCR system in combination with a diesel particulate filter helps to achieve significant PM and NO_x reduction.

ARB is currently funding pilot projects to install an SCR system aboard a passenger locomotive (model EMD F59PH), with expected NO_x emissions reduction of 90%.⁹⁷ Five 1200 HP “Euro Tunnel” switchers have been equipped with SCR systems. Problems have included high engine-out NO_x levels leading to excessive urea consumption rates, which is expensive and impacts cost effectiveness.⁹⁸

We evaluate this strategy for both switching and line haul locomotives. This section evaluates the potential emissions impacts, costs, and cost-effectiveness of retrofitting 10%, 25%, and 50% of Tier 2 switching and line haul engines in the South Coast region with an SCR system. The emissions reduction scenario is evaluated for calendar years 2010, 2015, 2020, 2025 and 2035. By 2010 it is expected that all switching and line haul locomotives will use Tier 2 engines, thus the emissions reductions analysis is conducted relative to Tier 2 locomotive switching and line haul engines.

Pollutants Reduced

SCR converts NO_x into nitrogen and water, thereby reducing NO_x emissions. It is not expected to have any effect on PM or ROG emissions.

Emissions Reductions

Baseline emissions were assumed to be those of Tier 2 switching and line haul locomotive engines. Emissions data for typical switching and line haul engines were used to derive brake-specific emissions factors. This data was gathered from the Rail Yard Agreement Health Risk Evaluation conducted on actual Tier 2 locomotives (on line-haul and switcher duty cycles).⁹⁹

The per engine emissions from Tier 2 locomotive switching engines and from these engines retrofitted with an SCR were calculated using the following equation:

$$E_{engine} = \left(EF / BSFC \right) \rho_{fuel} \dot{Q}_{fuel} \quad [\text{ton/yr}]$$

where E_{engine} is the per engine emissions, EF is the brake-specific emissions factor for each pollutant with and without the SCR retrofit, $BSFC$ is the brake specific fuel consumption for each engine, ρ_{fuel} is the diesel fuel density taken to be 7.1 lb/gal, and \dot{Q}_{fuel} is the annual fuel usage of locomotive switching engines, assumed to be 25,000 gal/yr based on experience. Overall emissions reductions for the SCAG

⁹⁷ Bogdanoff M (2006)

⁹⁸ Southwest Research Institute (2007)

⁹⁹ ENVIRON (2006)

region are generated by multiplying the per engine emissions reductions by the engine inventory for each engine type. The engine inventory was estimated based on an emissions inventory projection analysis conducted by ARB.¹⁰⁰

The NO_x emissions reductions calculated in this analysis for switching engines are shown in Table 3-28. As noted above, SCR has a negligible effect on ROG and PM emissions. For 2010 switching engine NO_x emissions reductions range from 86.4 – 432.1 tons/yr in the SCAG region for a penetration rate ranging from 10% - 50%. For 2035 switching engine NO_x emissions reductions range from 121.4 – 607.0 tons/yr in the SCAG region for a penetration rate ranging from 10% - 50%.

Table 3-28: NO_x Emission Reductions from Switching Engine SCR Retrofits

	Tier 2	2010	2015	2020	2025	2035
Emissions Rate (per engine)	2.715	0.277	0.277	0.277	0.277	0.277
Emissions Reduction (per engine)		2.44	2.44	2.4	2.44	2.44
		[89.8%]	[89.8%]	[89.8%]	[89.8%]	[89.8%]
Overall Emissions Reduction (10% penetration rate)		86	86	86	98	121
Overall Emissions Reduction (25% penetration rate)		216	216	215	245	304
Overall Emissions Reduction (50% penetration rate)		432	431	431	490	607

Table 3-29 shows the NO_x emissions reductions calculated for line haul locomotive engines in the SCAG region. For 2010 line haul engine NO_x emissions reductions range from 465 – 2323 tons/yr in the SCAG region for a penetration rate ranging from 10% - 50%. For 2035 line haul engine NO_x emissions reductions range from 845 – 4226 tons/yr in the SCAG region for a penetration rate ranging from 10% - 50%. Line haul locomotives have a much heavier annual usage and thus the potential emissions reductions of the scenario in Table 3-29 are greater than those for switching engines shown in Table 3-28.

Table 3-29: NO_x Emission Reductions from Line-Haul Engine SCR Retrofits

	Tier 2	2010	2015	2020	2025	2035
Emissions Rate (per engine)	27.813	2.84	2.84	2.84	2.84	2.84
Emissions Reduction (per engine)		24.98	24.98	24.98	24.98	24.98
		[89.8%]	[89.8%]	[89.8%]	[89.8%]	[89.8%]
Overall Emissions Reduction (10% penetration rate)		465	532	600	682	845
Overall Emissions Reduction (25% penetration rate)		1161	1330	1500	1704	2113
Overall Emissions Reduction (50% penetration rate)		2323	2661	2999	3408	4226

Costs

The cost of an SCR retrofit was estimated at \$100/hp, similar to nonroad engines. Thus, we estimate the cost to be \$200,000 for a switching engine and \$400,000 for a line haul engine. It should be noted that this is a present value cost – it is expected that if there is future greater demand for the technology and a production increase, the initial capital cost could decline substantially. The maintenance costs associated with this device were assumed to be negligible. However, we have estimated a fuel consumption penalty

¹⁰⁰ California Air Resources Board (2006f)

resulting from the SCR retrofit and an additional cost associated with the usage of ammonia or urea. These costs are estimated at 2% greater than the annual fuel costs of a Tier 2 engine.

Cost-Effectiveness

The NO_x cost effectiveness calculations are based on the SCAQMD BACT methodology reported in MSBACT Guidelines, as described in Section 1.¹⁰¹ This strategy was assumed to have a 10-year effective life. In addition to the BACT methodology, we have also calculated a cost-effectiveness per pollutant using the annualized capital cost, similar to the Carl Moyer method, and incorporating annual operational costs.

The cost-effectiveness of pollutant calculations for both of these methodologies for switching and line haul engines are summarized below in Table 3-30.

Table 3-30: Cost-Effectiveness of Switching Engine SCR Retrofits

	NO _x				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$/ton]	\$8,555	\$8,615	\$8,645	\$8,645	\$8,645
Annual Cost Effectiveness (per pollutant) [\$/ton]	\$10,594	\$10,677	\$10,717	\$10,730	\$10,741

The cost-effectiveness values for NO_x emissions reductions from line haul locomotives are shown in Table 3-31.

Table 3-31: Cost-Effectiveness of Line-Haul Engine SCR Retrofits

	NO _x				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$/ton]	\$1,988	\$2,054	\$2,086	\$2,097	\$2,106
Annual Cost Effectiveness (per pollutant) [\$/ton]	\$2,502	\$2,593	\$2,637	\$2,651	\$2,663

Because the emissions reductions of PM and ROG from an SCR system are negligible, calculations of cost-effectiveness for PM and ROG have not been included.

¹⁰¹ South Coast Air Quality Management District (2006a)

3.6. Accelerated Locomotive Rebuilds

Description of Strategy

The proposed new EPA emission standards for locomotives include more stringent Tier 2 standards that apply upon normal rebuild of Tier 2 engines.¹⁰² As shown in Tables 3-2 through 3-5, the Tier 2 rebuild standards will result in significantly lower PM emissions for both line-haul and switching engines, as compared to the current Tier 2 standards. The proposed Tier 2 rebuild standards would take effect beginning in 2008 as available, required by 2013. EPA estimates the cost of achieving these lower emission rates upon rebuild will be relatively small. This strategy would accelerate the rebuilding of Tier 2 engines, beyond what would occur due to normal rebuild frequency. This strategy assumes the new EPA standards are enacted as proposed.

Pollutants Reduced

This strategy primarily reduces PM emission. Reductions in ROG and NO_x emission would also occur.

Emissions Reductions

Table 3-32 shows the emission reductions resulting from this strategy for line-haul engines, and Table 3-33 shows emissions impacts for switch engines. Results are presented for two levels of penetration – 25% and 50%. Assuming the proposed EPA standards are adopted as proposed, some rebuilding of Tier 2 locomotives will occur regardless of this strategy. This strategy would target any remaining Tier 2 engines that would not be rebuilt by 2020.

Due to normal locomotive fleet turnover and rebuilding, a large portion of engines in service beyond 2020 would be Tier 2 rebuilds, Tier 3, or Tier 4 engines (assuming the proposed EPA standards are enacted). Thus, we do not calculate any benefits from this strategy after 2020.

Table 3-32: Impact of Accelerated Tier 2 Locomotive Rebuilds, Line-Haul Engines (tpy)

	NO _x			PM _{2.5}			ROG		
	2010	2015	2020	2010	2015	2020	2010	2015	2020
Baseline Tier 2 Emissions (per engine)	27.81	27.81	27.81	0.799	0.799	0.799	0.969	0.969	0.969
Emission Reduction (per engine)	10%	10%	10%	50%	50%	50%	50%	50%	50%
Overall Emission Reduction (25% penetration rate)	130.0	153.5	167.8	28.4	28.6	30.3	90.5	93.0	98.4
Overall Emission Reduction (50% penetration rate)	260.1	307.1	335.6	56.9	57.2	60.6	181.0	185.9	196.8

¹⁰² U.S. Environmental Protection Agency (2007a)

Table 3-33: Impact of Accelerated Tier 2 Locomotive Rebuilds, Switch Engines (tpy)

	NO _x			PM _{2.5}			ROG		
	2010	2015	2020	2010	2015	2020	2010	2015	2020
Baseline Tier 2 Emissions (per engine)	2.715	2.715	2.715	0.092	0.092	0.092	0.134	0.134	0.134
Emission Reduction (per engine)	10%	10%	10%	53%	53%	53%	49%	49%	49%
Overall Emission Reduction (25% penetration rate)	23.4	27.7	23.3	3.5	3.5	3.5	10.4	10.7	10.6
Overall Emission Reduction (50% penetration rate)	46.9	55.3	46.7	7.0	7.1	7.0	20.9	21.4	21.1

Costs

EPA has estimated the cost for rebuilding Tier 2 locomotives will range from \$9,000 to \$34,000 for switching engines and \$12,000 to \$34,000 for line-haul engines. We conservatively assume the high end of this range (\$34,000) for both types of engines. We assume no change in operating costs.

Cost-Effectiveness

Table 3-34 shows cost effectiveness calculated according to the SCAQMD BACT method and the CARB annualized cost effectiveness method. For both methods, we assumed this strategy has a 10 year life, based on the estimated average remaining useful life of the Tier 2 locomotives that are rebuilt. For the BACT method, we calculated 10 years of emission reduction benefits and divided this sum by the net present value of investment spread over 10 years. For the CARB method, we divided the annual emission reduction per engine by the annualized capital cost, calculated according to the formula provided in Section 1.

This strategy is highly cost effective, particularly for line-haul locomotives.

Table 3-34: Cost Effectiveness of Accelerated Tier 2 Rebuilds (\$ per ton)

	NO _x	PM _{2.5}	ROG
Line Haul Locomotives			
BACT Cost-Effectiveness	\$992	\$6,903	\$5,692
Annual Cost Effectiveness	\$900	\$6,262	\$5,164
Switcher Locomotives			
BACT Cost-Effectiveness	\$10,284	\$57,008	\$41,983
Annual Cost Effectiveness	\$9,330	\$51,718	\$38,087

3.7. Accelerated Replacement with Tier 3 or Tier 4 Locomotives

Description of Strategy

This strategy would accelerate the replacement of Tier 2 locomotives with those meeting the proposed new EPA emission standards.¹⁰³ As shown in Tables 3-2 through 3-5, the proposed Tier 4 standards will result in emission rates that are 80 – 90% lower than current Tier 2 engines.

The proposed Tier 3 emission standards are identical to the proposed Tier 2 rebuild standards for line-haul locomotives. Because the Tier 2 rebuilds can be performed at a fraction of the cost of a new Tier 3 locomotive, replacement of line-haul engines with Tier 3 locomotives will be much less cost effective than rebuilding to Tier 2. For switcher locomotives, the proposed Tier 3 standards offer a larger NO_x benefit than the Tier 2 rebuilds, but identical reductions of PM and ROG.

Pollutants Reduced

Replacement with Tier 4 locomotives would result in large reductions of all pollutants.

Emissions Reductions

Table 3-35 shows the date of the proposed Tier 3 and Tier 4 standards. The Tier 3 standards would take full effect in 2012, so we analyze the impact of this strategy in 2015 and 2020. The Tier 4 standards would not take full effect until 2017, so we analyze this strategy for 2020. Beyond 2020, there may be few Tier 2 locomotives remaining that have not been subject to the proposed rebuild requirements or replace through normal turnover, so we do not analyze this strategy for additional out years.

Table 3-35: Date of Proposed EPA Locomotive Emission Standards

		NO _x	PM	HC
Tier 3	Line Haul	2012	2012	2012
	Switcher	2011	2011	2011
Tier 4	Line Haul	2017	2015	2015
	Switcher	2015	2015	2015

Tables 3-36 and 3-37 show the emissions impact of accelerated replacement with Tier 3 locomotives. As noted above, with the exception of switcher NO_x emissions, the emission reductions are identical to those shown in the previous section for Tier 2 rebuilds.

¹⁰³ U.S. Environmental Protection Agency (2007a)

Table 3-36: Impact of Accelerated Replacement with Tier 3 Locomotives, Line-Haul Engines (tpy)

	NO _x			PM _{2.5}			ROG		
	2010	2015	2020	2010	2015	2020	2010	2015	2020
Baseline Tier 2 Emissions (per engine)	27.81	27.81	27.81	0.799	0.799	0.799	0.969	0.969	0.969
Emission Reduction (per engine)	N/A	10%	10%	N/A	50%	50%	N/A	50%	50%
Overall Emission Reduction (25% penetration rate)	N/A	153.5	167.8	N/A	28.6	30.3	N/A	93.0	98.4
Overall Emission Reduction (50% penetration rate)	N/A	307.1	335.6	N/A	57.2	60.6	N/A	185.9	196.8

Table 3-37: Impact of Accelerated Replacement with Tier 3 Locomotives, Switch Engines (tpy)

	NO _x			PM _{2.5}			ROG		
	2010	2015	2020	2010	2015	2020	2010	2015	2020
Baseline Tier 2 Emissions (per engine)	2.715	2.715	2.715	0.092	0.092	0.092	0.134	0.134	0.134
Emission Reduction (per engine)	N/A	33%	33%	N/A	53%	53%	N/A	49%	49%
Overall Emission Reduction (25% penetration rate)	N/A	93.4	78.8	N/A	3.5	3.5	N/A	10.7	10.6
Overall Emission Reduction (50% penetration rate)	N/A	186.8	157.6	N/A	7.1	7.0	N/A	21.4	21.1

Tables 3-38 and 3-39 show the show the emissions impact of accelerated replacement with Tier 4 locomotives.

Table 3-38: Impact of Accelerated Replacement with Tier 4 Locomotives, Line-Haul Engines (tpy)

	NO _x			PM _{2.5}			ROG		
	2010	2015	2020	2010	2015	2020	2010	2015	2020
Baseline Tier 2 Emissions (per engine)	27.81	27.81	27.81	0.799	0.799	0.799	0.969	0.969	0.969
Emission Reduction (per engine)	N/A	N/A	82%	N/A	N/A	85%	N/A	N/A	85%
Overall Emission Reduction (25% penetration rate)	N/A	N/A	1373.0	N/A	N/A	51.5	N/A	N/A	166.5
Overall Emission Reduction (50% penetration rate)	N/A	N/A	2746.0	N/A	N/A	102.9	N/A	N/A	333.1

Table 3-39: Impact of Accelerated Replacement with Tier 4 Locomotives, Switcher Engines (tpy)

	NO _x			PM _{2.5}			ROG		
	2010	2015	2020	2010	2015	2020	2010	2015	2020
Baseline Tier 2 Emissions (per engine)	2.715	2.715	2.715	0.092	0.092	0.092	0.134	0.134	0.134
Emission Reduction (per engine)	N/A	N/A	88%	N/A	N/A	89%	N/A	N/A	84%
Overall Emission Reduction (25% penetration rate)	N/A	N/A	207.2	N/A	N/A	5.9	N/A	N/A	18.2
Overall Emission Reduction (50% penetration rate)	N/A	N/A	414.3	N/A	N/A	11.9	N/A	N/A	36.4

Costs

It is difficult to estimate the cost of new Tier 3 and Tier 4 locomotives, since the two major U.S. locomotive manufacturers do not typically divulge the price of their locomotives and there is some uncertainty as to how much it will cost the manufacturers to comply with the proposed EPA standards. EPA estimates that a new Tier 4 locomotive will cost approximately \$100,000 more than a Tier 3 locomotive. We estimate the cost of a new Tier 3 locomotive to be \$1.4 million for a switcher and \$2.3 million for a line-haul engine. Thus, we assume Tier 4 switcher and line-haul locomotives would cost \$1.5 million and \$2.4 million, respectively.

Cost Effectiveness

Tables 3-40 and 3-41 show the cost effectiveness of accelerated replacement with Tier 3 and Tier 4 locomotives, calculated according to the SCAQMD BACT method and the CARB annualized cost effectiveness method. For both methods, we assumed this strategy has a 10 year life, based on the estimated average remaining useful life of the Tier 2 locomotives that are rebuilt. For the BACT method, we calculated 10 years of emission reduction benefits and divided this sum by the net present value of investment spread over 10 years. For the CARB method, we divided the annual emission reduction per engine by the annualized capital cost, calculated according to the formula provided in Section 1.

The Tier 3 strategy has poor cost effectiveness. The Tier 4 strategy has significantly better cost effectiveness, particularly for line haul engines.

Table 3-40: Cost Effectiveness of Accelerated Replacement with Tier 3 Locomotives (\$ per ton)

	NO _x	PM _{2.5}	ROG
Line Haul Locomotives			
BACT Cost-Effectiveness	\$67,080	\$466,972	\$385,037
Annual Cost Effectiveness	\$60,855	\$423,635	\$349,304
Switcher Locomotives			
BACT Cost-Effectiveness	\$125,472	\$2,347,403	\$1,728,710
Annual Cost Effectiveness	\$113,828	\$2,129,556	\$1,568,280

Table 3-41: Cost Effectiveness of Accelerated Replacement with Tier 4 Locomotives (\$ per ton)

	NO _x	PM _{2.5}	ROG
Line Haul Locomotives			
BACT Cost-Effectiveness	\$8,555	\$286,632	\$237,414
Annual Cost Effectiveness	\$7,761	\$260,032	\$215,381
Switcher Locomotives			
BACT Cost-Effectiveness	\$51,123	\$1,479,456	\$1,076,854
Annual Cost Effectiveness	\$46,379	\$1,342,157	\$976,918

3.8. Locomotive Idle Reduction

Description of Strategy

This strategy involves implementing a locomotive idling reduction technology or operational strategy. Idling reduction operational strategies focus on training operators or other supervisors to reduce idling times of locomotive line-haul and switching engines when there is no operational need for the engine to idle. One potential idling technology is an auxiliary power unit (APU), which allows the engine to shut down during idling by providing power to keep the engine or fuel heated in cold conditions, providing power to air compressors for brakes, keeping batteries charged, providing air-conditioning in hot or cold climates, and powering other appliances such as communication devices. An APU is typically a small diesel generator, and one example of such a device is the Kim Hotstart Diesel Driven Heating System (DDHS).¹⁰⁴ This device is not ideally suited for use in the SCAG region because the APU is used most often for heating when the outside temperature is below freezing, such as in Alaska.¹⁰⁵ It is not used as frequently for idle reduction in warmer climates.

A second potential idling technology is an automatic engine start-stop (AESS) device, which consists of a controller on the ignition of the locomotive engine which uses sensors to determine if the engine has been idling under appropriate conditions to initiate a shutdown. The AESS will shut down the engine unless conditions indicate otherwise, or unless manually overridden by the operator. One example of such a device is the Smartstart AESS manufactured by ZTR Control Systems.¹⁰⁶ This device has greater potential use for idling reduction in the SCAG region because it is significantly less expensive than the DDHS/APU technology option and has benefits for shutdown in a wide range of conditions, not just cold weather.

The 2005 Rail Yard Agreement with ARB for training programs by the railroads to reduce idling, and both UP and BNSF have adopted policies and procedures to reduce locomotive idling.

We estimate the impacts of this strategy for both switching and line-haul engines because both engine types frequently idle. Potential emissions reductions can be determined on the basis of the potential idling percentages of emissions that can be affected. For purposes of estimating costs, we use the cost information of the ZTR Smartstart system. We evaluate the effectiveness of idling reduction for a range of percentages of the idling emissions – 25% effectiveness, 50% effectiveness, and 75% effectiveness. This is in agreement with the observation that fewer idling stops by line-haul locomotive engines would allow for a greater effectiveness in reducing idle times. Switching engines typically make more short-duration idling stops than line-haul engines and thus a smaller fraction of idling emissions could be affected by this measure. We compare the idling emission reduction to baseline emissions from Tier 2 switching and line-haul engines operating on a standard EPA cycle for each locomotive type.

Pollutants Reduced

This measure would reduce emissions of all pollutants from locomotive engines – including NO_x, ROG, and PM emissions – that occur as a result of engine idling.

¹⁰⁴ Kim Hotstart Manufacturing Company (2006)

¹⁰⁵ North Carolina Department of Environment and Natural Resources (2006)

¹⁰⁶ See <http://ztr.com/smartstart.htm>

Emissions Reductions

Baseline emissions were assumed to be those of Tier 2 locomotive switching and line-haul engines based on EPA switching and line-haul engine cycle emissions tests for two locomotive engines. The weighted average emissions rates were calculated and divided by a weighted average power to derive brake-specific emissions factors. This data was gathered from the Rail Yard Agreement Health Risk Evaluation conducted on actual Tier 2 locomotives (on line-haul and switcher duty cycles).¹⁰⁷ The fraction of these emissions generated during the “idle” and “low idle” engine settings in the EPA test cycles were calculated and summed, and these represent the fractions of total emissions that could be reduced by this idle reduction measure. The brake-specific fuel consumption (BSFC) of the Tier 2 locomotive switching and line-haul engines were obtained from emissions testing data on two locomotive engines, which included a measurement of fuel flow rate. The fuel usage of the switching and line-haul engines is determined from the EPA cycle and a fraction of the fuel usage during idle and low-idle is calculated to be 10.3% for switching engines and 2.4% for line-haul engines. This information is combined in the following equation to determine per engine idle emissions:

$$E_{engine, idling} = \left(EF / BSFC \right) \rho_{fuel} F_{idle} \dot{Q}_{fuel} \quad [\text{ton/yr}]$$

where $E_{engine, idling}$ is the per engine idling emissions, EF is the brake-specific emissions factor for each pollutant, $BSFC$ is the brake specific fuel consumption for each engine, ρ_{fuel} is the diesel fuel density taken to be 7.1 lb/gal, and $F_{idle} \dot{Q}_{fuel}$ is the fraction of the annual fuel usage of locomotive switching and line-haul engines during idling, taken to be 2,585 gal/yr for switching engines and 6,732 gal/yr for line-haul engines. The final per engine idling emissions reductions are calculated as:

$$E_{idling, reduction} = E_{engine, idling} EFF$$

where EFF is the idling reduction effectiveness, evaluated at 25%, 50%, and 75%. Overall emissions reductions for the SCAG region are generated by multiplying the per engine emissions reductions by the engine inventory for each engine type. The engine inventory was estimated based on an emissions inventory projection analysis conducted by ARB.¹⁰⁸

The idling emissions reductions for switching engines are summarized below in Tables 3-42, 3-43, and 3-44 for scenario years 2010, 2015, 2020, 2025, and 2035.

A wide range of idling reduction effectiveness (from 25% to 75%) is given in this analysis because in practice it is difficult to determine what fraction of all idling activities could be reduced in operational or device-driven anti-idling strategies. Certain types of idling activity are not subject to reduction by this measure, and this also greatly depends on the type of technology used and the on the mechanical maintenance condition of the trains themselves. For example some trains that have an AESS device installed see frequent engine restart due to air pressure leakage in the dynamic braking system, which could be resolved through maintenance of that component. Some idling activity is necessary operationally or mechanically for the engine and thus is also not subject to idling restriction. Only by calculating a wide range of idling reduction effectiveness can all of these variations be accounted for.

¹⁰⁷ ENVIRON (2006)

¹⁰⁸ California Air Resources Board (2006f)

Table 3-42: NO_x Idling Emission Reductions from Switching Engines (tons/year)

	NO _x				
	2010	2015	2020	2025	2035
Average Idle Percentage	15.2%	15.2%	15.2%	15.2%	15.2%
Idling Emissions Rate (per engine)	0.042	0.042	0.042	0.042	0.042
Per Engine Idling Emissions Reduction (25% effectiveness)	0.0105	0.0105	0.0105	0.0105	0.0105
Per Engine Idling Emissions Reduction (50% effectiveness)	0.0210	0.0210	0.0210	0.0210	0.0210
Per Engine Idling Emissions Reduction (75% effectiveness)	0.0315	0.0315	0.0315	0.0315	0.0315
Overall Emissions Reduction (25% effectiveness)	35.9	35.9	35.8	40.7	50.5
Overall Emissions Reduction (50% effectiveness)	71.9	71.7	71.6	81.4	100.9
Overall Emissions Reduction (75% effectiveness)	107.8	107.6	107.4	122.1	151.4

Table 3-43: PM_{2.5} Idling Emission Reductions from Switching Engines (tons/year)

	PM _{2.5}				
	2010	2015	2020	2025	2035
Average Idle Percentage	14.0%	14.0%	14.0%	14.0%	14.0%
Idling Emissions Rate (per engine)	0.001	0.001	0.001	0.001	0.001
Per Engine Idling Emissions Reduction (25% effectiveness)	0.0004	0.0004	0.0004	0.0004	0.0004
Per Engine Idling Emissions Reduction (50% effectiveness)	0.0006	0.0006	0.0006	0.0006	0.0006
Per Engine Idling Emissions Reduction (75% effectiveness)	0.0010	0.0010	0.0010	0.0010	0.0010
Overall Emissions Reduction (25% effectiveness)	0.9	0.9	0.9	0.9	1.0
Overall Emissions Reduction (50% effectiveness)	1.9	1.8	1.7	1.8	2.0
Overall Emissions Reduction (75% effectiveness)	2.8	2.7	2.7	2.7	3.0

Table 3-44: ROG Idling Emission Reductions from Switching Engines (tons/year)

	ROG				
	2010	2015	2020	2025	2035
Average Idle Percentage	36.7%	36.7%	36.7%	36.7%	36.7%
Idling Emissions Rate (per engine)	0.005	0.005	0.005	0.005	0.005
Per Engine Idling Emissions Reduction (25% effectiveness)	0.0013	0.0013	0.0013	0.0013	0.0013
Per Engine Idling Emissions Reduction (50% effectiveness)	0.0025	0.0025	0.0025	0.0025	0.0025
Per Engine Idling Emissions Reduction (75% effectiveness)	0.0038	0.0038	0.0038	0.0038	0.0038
Overall Emissions Reduction (25% effectiveness)	9.2	8.9	8.6	N/A *	N/A *
Overall Emissions Reduction (50% effectiveness)	18.4	17.8	17.2	N/A *	N/A *
Overall Emissions Reduction (75% effectiveness)	27.6	26.7	25.8	N/A *	N/A *

* ROG emissions inventories for 2025 and 2035 are not available.

The idling emissions reductions for line-haul engines are summarized below in Tables 3-45, 3-46, and 3-47 for scenario years 2010, 2015, 2020, 2025, and 2035.

Table 3-45: NO_x Idling Emission Reductions from Line-Haul Engines (tons/year)

	NO _x				
	2010	2015	2020	2025	2035
Average Idle Percentage	3.8%	3.8%	3.8%	3.8%	3.8%
Idling Emissions Rate (per engine)	0.025	0.025	0.025	0.025	0.025
Per Engine Idling Emissions Reduction (25% effectiveness)	0.0064	0.0064	0.0064	0.0064	0.0064
Per Engine Idling Emissions Reduction (50% effectiveness)	0.0127	0.0127	0.0127	0.0127	0.0127
Per Engine Idling Emissions Reduction (75% effectiveness)	0.0191	0.0191	0.0191	0.0191	0.0191
Overall Emissions Reduction (25% effectiveness)	49.8	57.1	64.4	73.1	90.7
Overall Emissions Reduction (50% effectiveness)	99.7	114.2	128.7	146.3	181.4
Overall Emissions Reduction (75% effectiveness)	149.5	171.3	193.1	219.4	272.1

Table 3-46: PM_{2.5} Idling Emission Reductions from Line-Haul Engines (tons/year)

	PM _{2.5}				
	2010	2015	2020	2025	2035
Average Idle Percentage	4.0%	4.0%	4.0%	4.0%	4.0%
Idling Emissions Rate (per engine)	0.001	0.001	0.001	0.001	0.001
Per Engine Idling Emissions Reduction (25% effectiveness)	0.0002	0.0002	0.0002	0.0002	0.0002
Per Engine Idling Emissions Reduction (50% effectiveness)	0.0004	0.0004	0.0004	0.0004	0.0004
Per Engine Idling Emissions Reduction (75% effectiveness)	0.0005	0.0005	0.0005	0.0005	0.0005
Overall Emissions Reduction (25% effectiveness)	2.3	2.4	2.5	2.6	2.7
Overall Emissions Reduction (50% effectiveness)	4.6	4.7	4.8	5.0	5.5
Overall Emissions Reduction (75% effectiveness)	6.8	7.0	7.3	7.6	8.1

Table 3-47: ROG Idling Emission Reductions from Line-Haul Engines (tons/year)

	ROG				
	2010	2015	2020	2025	2035
Average Idle Percentage	16.2%	16.2%	16.2%	16.2%	16.2%
Idling Emissions Rate (per engine)	0.004	0.004	0.004	0.004	0.004
Per Engine Idling Emissions Reduction (25% effectiveness)	0.0009	0.0009	0.0009	0.0009	0.0009
Per Engine Idling Emissions Reduction (50% effectiveness)	0.0019	0.0019	0.0019	0.0019	0.0019
Per Engine Idling Emissions Reduction (75% effectiveness)	0.0028	0.0028	0.0028	0.0028	0.0028
Overall Emissions Reduction (25% effectiveness)	30.6	32.1	33.5	N/A *	N/A *
Overall Emissions Reduction (50% effectiveness)	61.2	64.1	67.0	N/A *	N/A *
Overall Emissions Reduction (75% effectiveness)	91.8	96.2	100.5	N/A *	N/A *

* ROG emissions inventories for 2025 and 2035 are not available

Line-haul engine idling emissions reductions for all pollutants are greater than those of switching engines, despite lower idling percentages in the EPA duty cycle because their annual activity – in terms of annual fuel consumption – is much greater than those of switching engines. However, significant idling emissions reductions can be made for both line-haul and switching engines.

Costs

For purposes of calculating the cost and cost-effectiveness of this measure, we assumed that the ZTR Smartstart AESS system would be installed. The initial capital cost of the ZTR Smartstart system was estimated to be \$9,000 with an additional cost of \$2,500 for installation and operator training, resulting in a total cost of \$11,500 per unit.¹⁰⁹ We did not calculate any additional maintenance and operational costs associated with this device. Note that there are maintenance costs associated with not installing idle reduction technology. UP has estimated that the maintenance cost savings associated with installing idle reduction systems on locomotives of about \$1 per hour of idling. Due to the uncertainty associated with this component, we do not take maintenance savings into account. We have also estimated a fuel savings resulting from idle reduction in line-haul and switching locomotives. This fuel savings is dependent on the effectiveness of the idle reduction and ranges from \$1,706 – \$5,118 for switching engines and \$4,443 – \$13,329 for line-haul engines per year.

Cost-Effectiveness

The NO_x, PM_{2.5} and ROG cost effectiveness calculations are based on the SCAQMD BACT methodology reported in MSBACT Guidelines, as described in Section 1.¹¹⁰ In addition to the BACT methodology, we have also calculated a cost-effectiveness per pollutant using the annualized capital cost, similar to the Carl Moyer method, and incorporating annual operational costs.

Given the low cost of the AESS device, the fuel savings benefits are greater than the cost of the device both in a one-year time period and over the 10-year lifetime of the project. Thus, in all cases, the cost-

¹⁰⁹ <http://ztr.com/smartstart.htm>

¹¹⁰ South Coast Air Quality Management District (2006a)

effectiveness values for switching and line-haul locomotives for all pollutants, for all scenario years, and for all penetration rates will be negative values, as shown in Table 3-48.

Table 3-48: Cost-Effectiveness of Locomotive Idle Reduction Strategy

	NO _x , ROG, or PM _{2.5}				
	2010	2015	2020	2025	2035
BACT Cost-Effectiveness [\$ /ton]	< 0*	< 0*	< 0*	< 0*	< 0*
Annual Cost Effectiveness (per pollutant) [\$ /ton]	< 0*	< 0*	< 0*	< 0*	< 0*

* An entry of “< 0” indicates a negative cost-effectiveness value – the fuel savings benefits are greater than the cost of the idle reduction device over both a one-year time period and over the 10-year life of the project.

3.9. Alameda Corridor Electrification

Description of Strategy

This strategy involves electrification of the Alameda Corridor. The Alameda Corridor is a dedicated freight rail corridor running 22 miles directly between the Ports of Los Angeles and Long Beach and the Redondo Junction, near the major rail yards just east of downtown Los Angeles. The corridor currently carries more than 50 trains per day.

Electrification of the corridor would involve installation of catenary power lines and use of electric locomotives to pull trains. There has been particular interest in electrifying the Alameda Corridor because it has no interaction with adjacent or coincident commuter lines that would potentially have different infrastructure requirements. Also, much if not all of the Alameda Corridor was constructed with more vertical clearance than other parts of the region's mainline freight lines, and so may be better able to adapt to electrification. However, such a strategy is not without some major operational challenges, most notably the need to switch diesel locomotives for electric locomotives where the electrification ends.

Pollutants Reduced

This measure would reduce emissions of all pollutants from locomotive engines, including NO_x, ROG, and PM emissions.

Emissions Reductions

Electric locomotives emit no (local) emissions, although they do cause emissions from any necessary incremental power generation. To estimate the emission reduction from this strategy, we determined the fraction of regional locomotive activity that occurs on the Alameda Corridor and assumed that regional baseline locomotive emissions would be reduced by this fraction. We then estimated the emissions associated with the power generation to supply the necessary additional electricity.

We obtained data on current and forecast train volumes by train type for every segment of railroad mainline in the South Coast Air Basin.¹¹¹ From this same source, we also obtained information on the number of locomotives for each train type (8,000 ft intermodal, 6,000 ft intermodal, 5,000 ft unit bulk, 6,000 ft unit auto, 6,500 ft carload, 500 ft commuter passenger, and 1,000 ft intercity passenger). And we obtained data on the length of each railroad mainline segment.¹¹² Using this data, we calculated the number of locomotive-miles on each railroad segment. The Alameda Corridor accounts for 10.9% of total railroad mainline activity in the region in 2020. We applied a 10.9% reduction to the regional baseline emissions from all mainline freight and passenger rail activity.

To estimate power generation emissions, we first calculated the total annual train miles and ton-miles in the Alameda Corridor. Using national data on railroad fuel consumption, we estimated train fuel efficiency per ton-mile for intermodal trains (385 ton-miles per gallons). We estimated train electricity demand by assuming a conversion of 13.75 kilowatt-hours per gallon. We obtained power generation emission factors appropriate for Southern California using EPA's eGrid model.¹¹³

¹¹¹ Leachman (2005).

¹¹² Personal communication with George Fetty, consultant.

¹¹³ eGRID2006 Version 2.1, Summary Tables, Year 2004 eGRID Subregion Emission Rates.

There is considerable uncertainty regarding the location of the power generation needed to supply an electrified rail system in Southern California. Much of the region's power is generated outside the South Coast Air Basin (in regions with less serious air quality problems), and that would likely be the case for an electrified rail system. However, in order to conservatively estimate the potential emission benefits of this strategy, we assumed all incremental power generation would occur within the basin.

Table 3-49 presents annual emission reduction from the electrification of the Alameda Corridor, which equates to rail emissions associated with trains along the Alameda Corridor minus the power generation emissions.

Table 3-49: Emission Reduction from Alameda Corridor Electrification (tons/year)

	2010		2015		2020		2025		2030		2035	
	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}
Baseline Railroad Emission (All activity)	7,185	278	8,306	279	9,423	292	10,708	319	11,994	347	13,434	376
Alameda Corridor Emissions (eliminated)	565	23	674	23	860	27	1,017	30	1,139	33	1,276	36
Power Generation Emissions	19	1	23	1	29	1	34	1	38	1	43	1
Emission Reduction	546	22	651	22	831	26	983	29	1,101	32	1,233	35

Costs

The cost of the electrification would include the infrastructure cost as well as purchase of a dedicated fleet of electric locomotives for the corridor activity. In addition, there may be different electric and fuel costs and other operational costs such as added time and personnel to change power from electric to diesel at the north end of the corridor. Because of lack of information, we do not estimate any change in operation and maintenance costs, although we recognize that this strategy could require significant and costly operational changes for the railroads.

The cost of the infrastructure was estimated to be \$233 million, based on a per-mile cost of \$10.6 million that was derived from a prior study and adjusted for inflation at 6% per year.¹¹⁴ The cost was adjusted to 2006 dollars using the California Construction Cost Index¹¹⁵ from 1996 to 2006 using a factor of 1.403, and the Highway Construction Price Index¹¹⁶ to adjust from 1992 to 1996 dollars using a factor of 1.116. This work estimated a combined adjustment at 1.566 applied to the 1992 cost to adjust to 2006 dollars.

Another potentially significant cost would be the purchase of a dedicated fleet of electric engines to transport cargo along the corridor. Weston estimated that the corridor handles 47 trains a day or about 2 an hour.¹¹⁷ This level of activity could require that 2 or 3 engines (one in transit and two available) be available at both ends of the corridor, so that train building can be underway while a train is in transit within the corridor and to have flexibility for peak traffic or maintenance. Also because Union Pacific and BNSF would require 6 engines at a minimum, at least 12 engines would likely be required. We assumed that the 12 engines would likely be required at \$2 million each, or \$24 million. Thus, the total cost would be \$257 million.

¹¹⁴ Electrification Task Force (1992).

¹¹⁵ State of California (2007)

¹¹⁶ California Department of Transportation (2007)

¹¹⁷ Weston (2005)

Cost-Effectiveness

The cost effectiveness of this strategy is calculated as the cost per ton of emissions reduced. Table 3-50 provides estimated cost effectiveness for NO_x and PM_{2.5} which are the pollutants of greatest concern. For this study the cost effectiveness is calculated by both the ARB method and the SCAQMD method as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%, and the project life is assumed to be 30 years.

Table 3-50: Estimated Cost Effectiveness of Alameda Corridor Electrification

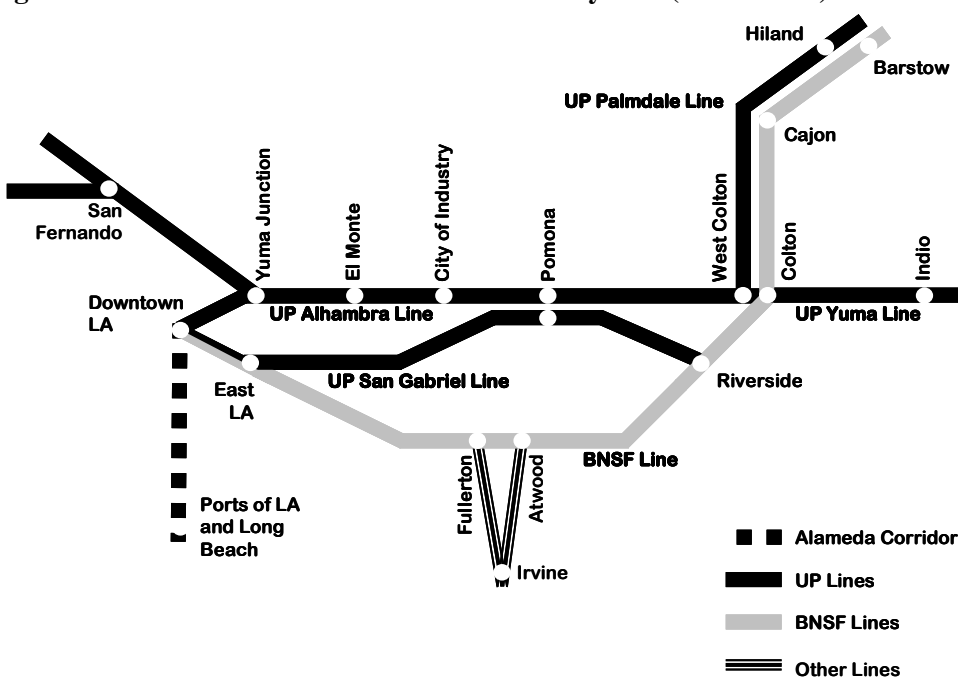
	ARB Annualized Method				SCAQMD BACT Method			
	Annual Benefits (tons/year)		Cost Effectiveness (\$/ton)		Lifetime Benefits (tons)		Cost Effectiveness (\$/ton)	
	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}
2010	546	22	\$27,256	\$674,519	28,411	846	\$9,053	\$303,953
2015	651	22	\$22,840	\$662,624	28,411	846	\$9,053	\$303,953
2020	831	26	\$17,908	\$575,228	28,411	846	\$9,053	\$303,953
2025	983	29	\$15,136	\$505,169	28,411	846	\$9,053	\$303,953
2030	1,101	32	\$13,513	\$465,287	28,411	846	\$9,053	\$303,953
2035	1,355	32	\$10,976	\$459,012	28,411	846	\$9,053	\$303,953

3.10. Full Railroad Mainline Electrification

Description of Strategy

This strategy would involve electrification of virtually the entire railroad mainline system in the South Coast Air Basin. This involves the heavily traveled UP and BNSF east-west mainlines, the Alameda Corridor, plus the UP lines heading northwest from the downtown area and county-owned lines between the BNSF mainline and Irvine in Orange County. The entire system to be electrified is shown schematically in Figure 3-1.

Figure 3-1: Southern California Mainline Rail System (not to scale)



Electrification of the corridor would involve installation of catenary power lines and use of electric locomotives to pull trains. Nearly all segments of this system carry both passenger and freight trains (the primary exception being the Alameda Corridor). Electrification would therefore allow use of electric locomotives on both passenger and freight trains.

In addition to cost, a major challenge to implementation of this strategy is the transition between diesel and electric locomotives on the periphery of the region. Most likely, electric locomotives would be added to incoming trains at yards or sidings outside the region, to be pulled by diesel locomotives until the electrified system begins.

Pollutants Reduced

This measure would reduce emissions of all pollutants from locomotive engines, including NO_x, ROG, and PM emissions.

Emissions Reductions

As with the Alameda Corridor electrification strategy, we calculated emission reductions by determining the portion of regional mainline railroad activity that would be subject to electrification (in terms of locomotive miles) and applied this percentage to the baseline forecast of mainline railroad emissions. The emission reduction benefit is offset by an increase in power generation emissions.

As described in Section 3.9, we obtained data on current and forecast train volumes by train type for every segment of railroad mainline in the South Coast Air Basin, the length of each segment, and the number of locomotives for each train type.¹¹⁸ Using this data, we calculated the number of locomotive-miles on each railroad segment. Under this scenario, 99% of mainline locomotive-miles would be subject to electrification (with the 1% coming from passenger trains running between Irvine and San Juan Capistrano). Thus, essentially the only remaining railroad emissions in the region would be those coming from switch yards and local spur lines (low-volume spurs and sidings serving industrial facilities).

To estimate power generation emissions, we use an approach similar to that described for the Alameda Corridor. We first calculated the total annual train miles and ton-miles in the region (by train type). Using national data on railroad fuel consumption, we estimated train fuel efficiency per ton-mile (385 ton-miles per gallons for intermodal and passenger trains, 715 ton-miles per gallon for bulk trains). We estimated train electricity demand by assuming a conversion of 13.75 kilowatt-hours per gallon. We obtained power generation emission factors appropriate for Southern California using EPA's eGrid model.¹¹⁹ We assumed (conservatively) that all power generation would occur in the South Coast Air Basin.

Table 3-51 presents annual emission reduction from the electrification of the full railroad mainline.

Table 3-51: Emission Reduction of Full Railroad Mainline Electrification (tons/year)

	2010		2015		2020		2025		2030		2035	
	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}
Baseline Railroad Emission (All activity)	7,185	278	8,306	279	9,423	292	10,708	319	11,994	347	13,434	376
Full Railroad Mainline Emissions (eliminated)	5,589	226	6,673	230	7,820	244	8,894	267	9,962	289	11,157	314
Power Generation Emissions	188	8	225	8	263	8	299	9	335	10	375	11
Emission Reduction	5,401	218	6,449	222	7,557	235	8,595	258	9,626	280	10,782	304

Costs

As with the previous strategy, this strategy would involve large infrastructure costs as well as costs for purchase of electric locomotives. Because of lack of information, we do not estimate any change in operation and maintenance costs, although we recognize that this strategy could require significant and costly operational changes for the railroads.

The total cost of this strategy is estimated to be \$6.5 billion, which reflects electrification of 460 miles of rail line (at \$10.6 million per mile) and purchase of 775 electric locomotives (at \$2 million each).

¹¹⁸ Leachman (2005).

¹¹⁹ eGRID2006 Version 2.1, Summary Tables, Year 2004 eGRID Subregion Emission Rates.

The cost of the infrastructure was estimated to be \$4.88 billion, based on 460 miles of rail line, and a per-mile cost of \$10.6 million that was derived from a prior study and adjusted for inflation at 6% per year.¹²⁰ The cost was adjusted to 2006 dollars using the California Construction Cost Index¹²¹ from 1996 to 2006 using a factor of 1.403, and the Highway Construction Price Index¹²² to adjust from 1992 to 1996 dollars using a factor of 1.116. This work estimated a combined adjustment at 1.566 applied to the 1992 cost to adjust to 2006 dollars.

Another significant cost would be the purchase of a dedicated fleet of electric engines to transport cargo along the rail line. Based on an estimate of 775 necessary electric locomotives, at \$2 million each, total equipment costs amount to \$1.55 billion.

Cost-Effectiveness

The cost effectiveness of this strategy is calculated as the cost per ton of emissions reduced. Table 3-52 provides estimated cost effectiveness for NO_x and PM_{2.5} which are the pollutants of greatest concern. For this study the cost effectiveness is calculated by both the ARB method and the SCAQMD method as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%, and the project life is assumed to be 30 years.

Table 3-52: Estimated Cost Effectiveness of the Full Railroad Mainline Electrification

	ARB Annualized Method				SCAQMD BACT Method			
	Annual Benefits (tons/year)		Cost Effectiveness (\$/ton)		Lifetime Benefits (tons)		Cost Effectiveness (\$/ton)	
	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}
2010	5,401	218	\$68,811	\$1,702,914	254,945	7,590	\$25,205	\$846,587
2015	6,449	222	\$57,625	\$1,671,800	254,945	7,590	\$25,205	\$846,587
2020	7,557	235	\$49,178	\$1,579,687	254,945	7,590	\$25,205	\$846,587
2025	8,595	258	\$43,239	\$1,443,118	254,945	7,590	\$25,205	\$846,587
2030	9,626	280	\$38,604	\$1,329,188	254,945	7,590	\$25,205	\$846,587
2035	11,640	266	\$31,927	\$1,399,328	254,945	7,590	\$25,205	\$846,587

¹²⁰ Electrification Task Force (1992).

¹²¹ State of California (2007)

¹²² California Department of Transportation (2007)

3.11. Expansion of On-Dock Rail Service

Description of Strategy

This strategy considers an increase in capacity and utilization of on-dock rail ramps at the San Pedro Bay ports. The analysis quantifies emission reductions resulting from the elimination of drayage truck trips due to a shift from off-dock to on-dock rail. Operational improvements to support the continuous increase in on-dock rail usage are taken into account. Specific elements of this strategy include increased availability of intermodal equipment and rail crew, improved productivity in loading and unloading of rail cars, use of “block swap” (i.e., sorting rail cars by blocks of cars instead of individual cars), and prevention of container storage at on-dock terminals.¹²³ In the long-run, additional on-dock terminals, rail tracks, and improved signaling and control systems are necessary to satisfy the increasing demand for on-dock rail terminals. The Port of Los Angeles is planning to add an on-dock rail facility in the TraPac terminal, which is the only container terminal currently without on-dock rail accessibility. This new facility, with completion scheduled for 2009, is expected to eliminate more than 200,000 truck trips per year.¹²⁴

Even though approximately 50% of freight from and to the ports is intermodal, only 21% is loaded directly to/from the rail docks.¹²⁵ The remaining cargo utilizes off-dock rail terminals, and requires the use of drayage trucks for transportation from the terminals to the intermodal ramps. Because drayage trucks tend to be older and have higher emission rates, elimination of drayage trips can result in significant emissions benefits.

Pollutants Reduced

This strategy reduces emissions of all pollutants, including NO_x, PM, and ROG, because it reduces truck trips and truck VMT. The reduction in truck emissions is partially offset by an increase in locomotive emissions.

Emissions Impacts

Methodology

We estimated on-dock rail capacity according to results included in the Portwide Rail Synopsis study, which considers both operational and physical improvements of rail capacity to meet future demand for rail transportation at the ports of LA and Long Beach.¹²⁶ This analysis assumes that on-dock rail improvements will result in a shift from off-dock rail to on-dock rail. Although volume could also be transferred from all-truck movements to on-dock rail, a shift is more likely to involve cargo that is already moving by rail. Since additional on-dock traffic is assumed to come from off-dock rail, emissions are reduced due to the elimination of drayage truck trips from port terminals to off-dock rail yards. This analysis does not account for the environmental benefits (e.g., reduced idling) from reduced congestion on highways, which would likely be very small.

By simulating additional eastbound trains, we calculated the number of reduced truck trips and vehicle miles traveled (VMT), accounting for trips to and from the port, as well as trips within the port (e.g., bobtail and chassis moves). We reviewed two studies of future capacity of on-dock rail terminals at the

¹²³ SCAG (2005)

¹²⁴ Port of Los Angeles (2006)

¹²⁵ Fischer, M., Hicks, G., Cartwright, K. (2006)

¹²⁶ Jones & Stokes (2004)

ports of Los Angeles and Long Beach, using results from the most conservative estimate (Jones & Stokes).^{127 128} We determined the number of additional daily trains (in comparison with 2005 volumes), as shown in Table 3-53. We assumed that on-dock rail capacity remains constant after 2020.

Our methodology is based on assumptions about how many truck trips would be eliminated by the addition of a rail car. This calculation was based on the QuickTrip model, which is part of the port travel demand model. Developed by Moffatt & Nichol Engineers, the QuickTrip model estimates the number of container truck trips generated at each terminal as a function of container throughput and various terminal operating parameters. The QuickTrip model evaluated two scenarios for each terminal with on-dock rail availability (Pier 300, 400, S, T, TI East, and TI West). Both scenarios had the same share of rail trips (as a percentage of total TEUs), but they were differentiated by the use of on-dock and near-dock rail. In other words, the difference between both scenarios is associated with a shift from near-dock to on-dock rail. By evaluating the difference in the number of truck trips and the share of near-dock trips that was converted into on-dock trips, it was possible to determine the number of truck trips per TEU shifted from near-dock to on-dock rail. On average, each TEU shifted from near-dock to on-dock rail eliminated about 1.5 truck trips. Because a double-stack container rail car is composed of 5 platforms and each platform can hold 4 TEUs, each rail car has a capacity of 20 TEUs. Assuming 90% utilization, 27 truck trips are eliminated per rail car. This number is very similar to a previous study, which estimated that 28 truck trips were eliminated per rail car.¹²⁹

Truck trips associated with container movement include container truck trips, empty returns, repositioning of empty chassis, and bobtail truck movements. Of 27 truck trips eliminated, 60% are trips to off-dock terminals and 40% are trips within terminals. It was assumed that each train holds 25 rail cars. It was then possible to estimate the number of truck trips reduced to and from the port based on a number of additional trains per weekday, shown in Table 3-53.

Table 3-53: Reduced Weekday Truck Trips

	2010	2015	2020	2025	2030	2035
Number of added trains	13	45	72	72	72	72
Number of railcars per train	25	25	25	25	25	25
Number of necessary railcars	325	1,125	1,800	1,800	1,800	1,800
Trips eliminated per railcar	27	27	27	27	27	27
Reduced Trips - To/From Port	5,265	18,225	29,160	29,160	29,160	29,160
Reduced Trips - Within Port	3,510	12,150	19,440	19,440	19,440	19,440

By assuming an average distance for truck trips to off-dock rail terminals (14 miles) and trips within terminals (1.5 miles), we calculated VMT reduced for the two types of trips, shown in Table 3-54.

¹²⁷ Jones & Stokes (2004)

¹²⁸ Parsons Transportation Group (2004)

¹²⁹ Fischer, M., Hicks, G., Cartwright, K. (2006)

Table 3-54: Weekday VMT Reduced

	2010	2015	2020	2025	2030	2035
To/From Port	73,710	255,150	408,240	408,240	408,240	408,240
Within Port	5,265	18,225	29,160	29,160	29,160	29,160

We calculated total truck emissions by multiplying VMT by emission factors. We developed emission factors for port-serving trucks using EMFAC2007. We used current the truck age distribution as presented in the ports' *Clean Air Action Plan* (CAAP). Our estimation of port truck emission factors does not take into account CAAP scenarios for early retirement (replacement) of pre-1994 trucks and retrofitting of eligible pre-2007 trucks (described in Section 1). Because of the uncertainty in the funding of the CAAP, it is possible the port truck emission reductions will not occur as described in the CAAP, and this strategy is intended to illustrate alternative options for reducing port truck emissions. If port truck replacements and retrofits occur as planned, the emissions benefits of this strategy would be significantly lower. Table 3-55 shows the estimated port truck emission factors by analysis year.

Table 3-55: Port Truck Emission Factors (grams/mile)

	NO _x	PM _{2.5}	ROG
2010	22.07	0.88	1.79
2015	14.14	0.64	1.09
2020	7.75	0.30	0.63
2025	5.05	0.17	0.41
2030	4.36	0.14	0.36
2035	4.27	0.13	0.36

Source: Calculated by ICF using EMFAC2007, assuming port truck age distributions as presented in CAAP.

We estimate the increase in train miles as the product of the number of additional daily trains and the average distance to off-dock rail terminals. As discussed in Section 3.1, all locomotives in the considered system are assumed to meet EPA Tier 2 standards by 2010. Note that the U.S. EPA has announced its intention to adopt much more stringent emission standards for locomotives (Tier 3 and 4 standards). Because of the uncertainty in the timing and market penetration of Tier 3 and 4 locomotives, our analysis assumes that affected locomotives would meet Tier 2 standards. If cleaner locomotives are used for on-dock service, the emissions benefits of this strategy would be greater.

Section 3.1 presented baseline emission factors (g/bhp-h) for line-haul locomotives. The following formula was used to convert emission factors from g/bhp-h to g/mile. Assuming 15 tons per TEU and 450 TEUs per train, total train cargo weight is approximately 7,000 tons. We used an estimate of locomotive fuel efficiency for intermodal traffic in a flat section in Southern California (486 ton-miles/gallon) to convert locomotive emission factors to grams per mile (Table 3-56).¹³⁰ Total train emissions were calculated by multiplying train miles added by emission factors.

$$\text{EF (g/mile)} = \frac{\text{EF (g/bhp-h)} \times \frac{20.8 \text{ bhp-h}}{\text{gallon}} \times \text{Train Weight (tons)}}{\text{Train Fuel Efficiency (ton-miles/gallon)}}$$

¹³⁰ Sierra Research (2004)

Table 3-56: Tier 2 Line-haul Emission Factors

	NO_x	PM_{2.5}	ROG
Grams/bhp-h	4.60	0.14	0.16
Grams/mile	1,394	41.81	48.54

Results

The emissions reduction from a mode shift is the difference between the emissions from eliminated truck trips and emissions from added trains. Table 3-57 includes the emission reduction associated with a higher usage of on-dock rail.

The potential for environmental gains increases until 2015, when emissions reduction reaches a maximum level. During this time, the increase in on-dock rail capacity and utilization outweighs the improvement in truck emission factors. After 2020, because of the assumption of no additional increase in on-dock usage, the potential for emissions reduction starts to decrease.

Table 3-57: Emission Reduction from Expansion of On-Dock Rail (tons/year)

	NO_x	PM_{2.5}	ROG
2010	387	16	34
2015	777	38	69
2020	516	23	59
2025	250	11	41
2030	183	7	40
2035	168	6	39

Costs

The Ports of Los Angeles and Long Beach have developed a series of rail infrastructure improvement projects at terminals and connecting facilities (Table 3-58). We selected the projects that will support an increase in on-dock rail capacity and utilization in order to calculate the total capital costs associated with a higher on-dock rail usage.

In our calculations of rail capacity and utilization, we took into account the estimated completion date of these projects. Since some projects are scheduled to be completed before 2010, benefits due to higher on-dock rail capacity and utilization are assumed to start in 2010. All costs are in 2006 dollars.

Table 3-58: Projects Supporting an Increase in On-dock Rail Capacity

Project	Sponsor	Estimated Completion Date	Project Cost (\$millions)
Very Short-Term			
Closure of Edison Avenue Grade Crossing	POLB	12/31/2007	0.3
Short-Term			
Pier A On-dock Rail Yard Expansion to Carrack	POLB	12/31/2009	19.6
Terminal Island Wye Track Realignment	POLB	8/31/2009	3.6
Pier S On-dock Rail Yard	POLB	8/31/2009	34.3
Pier B Street Realignment	POLB	6/30/2010	12.6
Constrain Badger Bridge Lifts	POLB/LA	6/30/2010	1.0
Track Realignment at Ocean Boulevard/ Harbor Scenic Drive	POLB	6/30/2010	20.0
Pier F Support Yard	POLB	6/30/2010	3.4
Pier G-New North Working Yard	POLB	7/31/2009	14.1
Pier G-South Working Yard Rehabilitation	POLB	6/30/2010	40.7
Double Track Access from Pier G to Pier J	POLB	6/30/2010	1.7
West Basin Rail Access Improvements	POLA	12/31/2009	150.0
West Basin East-New ICTF (Phase I)	POLA	12/31/2009	45.4
Near-Term			
Pier B Rail Yard Expansion (Phase I)	POLB	6/30/2013	85.4
Pier B Rail Yard Expansion (Phase II)	POLB	6/30/2015	159.9
Navy Mole Road Storage Rail Yard	POLB	12/31/2013	10.0
Pier 400 Second Lead Track	POLA	12/31/2011	7.7
Middle Harbor Terminal Rail Yard	POLB	11/30/2013	68.9
Pier J On-dock Rail Yard Reconfiguration	POLB	8/31/2015	100.0
Pier 400 On-dock Rail Yard Expansion (Phase I)	POLA	6/30/2015	33.4
Pier 300 On-dock Rail Yard Expansion	POLA	12/31/2015	23.4
Terminal Island ICTF Rail Yard Expansion	POLA	12/31/2011	18.9
West Basin ICTF Rail Yard Expansion (Phase I)	POLA	12/31/2014	6.2
Long-Term			
Triple Track Badger Bridge	ACTA	12/31/2019	91.0
Pier A On-dock Rail Yard East of Carrack	POLB	3/31/2021	31.4
Pier 400 On-dock Rail Yard Expansion (Phase II)	POLA	12/31/2020	16.3
West Basin ICTF Rail Yard Expansion (Phase II)	POLA	12/31/2020	12.5
West Basin East-ICTF Expansion (Phase II)	POLA	12/31/2020	7.8
Total:			1,019.5

Source: Port of Long Beach (2006)

Cost Effectiveness

Table 3-59 summarizes the cost effectiveness of this strategy, based on calculations by the SCAQMD method as explained in the introduction. The ARB method is not applied to this strategy since the method does not work well when large capital investments are spread across multiple years. For all cost effectiveness calculations the discount rate is assumed to be 4%. For the SCAQMD method, total costs

(i.e., capital costs) are divided by total emissions reduction in the lifetime of the project. Operational costs are not taken into account due to lack of data. Total emissions reduction for the timeframe considered is estimated by interpolating the results for the calculated years. Daily emissions were annualized by assuming 5-day (per week) port operations until 2024, 6-day operations from 2025 to 2029, and 7-day operations from 2030 on.

Table 3-59: Cost Effectiveness (SCAQMD BACT Method)

Lifetime Benefits (tons)			Cost Effectiveness (\$/ton)		
NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
10,158	454	1,243	\$100,361	\$2,243,141	\$820,353

3.12. Expansion of Near-Dock Rail Service

Description of Strategy

Near-dock rail terminals provide rail accessibility to import and export cargo, but rely on drayage trucks for the additional movement to port terminals. They can reduce emissions to the extent that they divert truck traffic from congested freeways or from intermodal terminals that are further away from ports. BNSF has proposed a new near-dock intermodal facility, the Southern California International Gateway (SCIG), to handle containers moving through the Ports of Los Angeles and Long Beach. The facility would be located north of Pacific Coast Highway, south of Sepulveda Boulevard, and west of SR-103, with easy access to the Alameda Corridor (Figure 3-2).¹³¹ The facility is expected to eliminate one million drayage trucks from the I-710 per year when completed in 2009.

This strategy involves an expansion of near-dock rail service through development of the SCIG. Emissions are reduced because of the diversion of trips from the Hobart intermodal terminal near downtown Los Angeles to the SCIG. This strategy also brings economic advantages, since near-dock terminals are currently operating near capacity. SCAG has forecast a region-wide shortage of intermodal capacity equal to 9 million lifts per year by 2020.¹³²

Figure 3-2: Location of SCIG Intermodal Terminal



Source: Port of Los Angeles

Pollutants Reduced

This strategy reduces emissions of all pollutants, including NO_x, PM, and ROG, because it reduces truck VMT. The reduction in truck emissions is partially offset by an increase in locomotive emissions.

¹³¹ Port of Los Angeles (2006)

¹³² SCAG (2005)

Emissions Impacts

Methodology

A previous study estimated the reduction in NO_x emissions due to an increase in near-dock capacity when the SCIG terminal is in operation.¹³³ The analysis included a baseline number of truck trips and VMT for 2005, 2010, and 2030, and figures for the remaining years were interpolated. It was assumed that all trips involving the new SCIG terminal are diverted trips from the Hobart intermodal terminal in downtown Los Angeles. Because the use of a near-dock terminal also requires a drayage move, the number of truck trips remained unaltered on the adjusted scenario. VMT however, was reduced due to the shorter distance from the ports to the SCIG terminal (3 miles), versus the distance to the Hobart terminal (20 miles). Table 3-60 summarizes the number of truck trips and VMT for both scenarios.

Table 3-60: Weekday Truck Trips and VMT

	2010	2015	2020	2025	2030	2035
Truck Trips - Baseline	78,638	100,917	123,195	145,474	167,752	193,442
Truck Trips - Near-dock	78,638	100,917	123,195	145,474	167,752	193,442
VMT - Baseline	1,205,617	1,547,177	1,888,736	2,230,296	2,571,855	2,965,723
VMT - Near-dock	1,147,665	1,468,312	1,788,959	2,109,606	2,430,253	2,799,636
Reduced VMT	57,952	78,865	99,777	120,690	141,602	166,086

Source: Fischer, M., Hicks, G., Cartwright, K. (2006)

As in the previous strategy (on-dock rail expansion), analysis of this strategy is based on assumptions about how many truck trips would be eliminated by the addition of a near-dock rail car. This calculation was based on the QuickTrip model, which is part of the port travel demand model. Developed by Moffatt & Nichol Engineers, the QuickTrip model estimates the number of container truck trips generated at each terminal as a function of container throughput and various terminal operating parameters. The QuickTrip model evaluated two scenarios for each terminal with on-dock rail availability (Pier 300, 400, S, T, TI East, and TI West). Both scenarios had the same share of rail trips (as a percentage of total TEUs), but they were differentiated by the use of on-dock and near-dock rail. In other words, the difference between both scenarios is associated with a shift from near-dock to on-dock rail. By evaluating the difference in the number of truck trips and the share of near-dock trips that was converted into on-dock trips, it was possible to determine the number of truck trips per TEU shifted eliminated about 1.5 truck trips. Because a double stack rail car is composed of 5 platforms and each platform can hold 4 TEUs, each rail car has a capacity of 20 TEUs. Assuming 90% utilization, 27 truck trips are eliminated per rail car. This number is very similar to a previous study that estimated that 28 truck trips were eliminated per rail car.¹³⁴

Container related truck trips include container truck trips, empty returns, repositioning of empty chassis, and bobtail truck movements. Of 27 truck trips eliminated, 60% are trips to off-dock terminals and 40% are trips within terminals. Because this strategy considers near-dock rail service, it was necessary to deduct the 40% of trips that occur within ports (e.g., bobtail and chassis moves). Thus, we assumed that one rail car eliminates roughly 16 truck trips. We also assumed that each train holds 25 rail cars. We then estimated the number of added daily trains between the SCIG and Hobart terminals (Table 3-61).

¹³³ Fischer, M., Hicks, G., Cartwright, K. (2006)

¹³⁴ Fischer, M., Hicks, G., Cartwright, K. (2006)

Table 3-61: Calculation of Number of Added Weekday Trains

	2010	2015	2020	2025	2030	2035
Number of truck trips affected	3,409	4,639	5,869	7,099	8,330	9,770
Trips eliminated per railcar	16	16	16	16	16	16
Number of necessary railcars	210	286	362	438	514	603
Number of railcars per train	25	25	25	25	25	25
Number of added trains between SCIG and Hobart	8	11	14	18	21	23

We calculated total truck emissions by multiplying VMT by emission factors. We developed emission factors for port-serving truck using EMFAC2007. We used current the truck age distribution as presented in the ports' *Clean Air Action Plan* (CAAP). Our estimation of port truck emission factors does not take into account CAAP scenarios for early retirement (replacement) of pre-1994 trucks and retrofitting of eligible pre-2007 trucks (described in Section 1). Because of the uncertainty in the funding of the CAAP, it is possible the port truck emission reductions will not occur as described in the CAAP, and this strategy is intended to illustrate alternative options for reducing port truck emissions. If port truck replacements and retrofits occur as planned, the emissions benefits of this strategy would be significantly lower. Table 3-62 shows the estimated port truck emission factors by analysis year.

Table 3-62: Port Truck Emission Factors (grams/mile)

	NO _x	PM _{2.5}	ROG
2010	22.07	0.88	1.79
2015	14.14	0.64	1.09
2020	7.75	0.30	0.63
2025	5.05	0.17	0.41
2030	4.36	0.14	0.36
2035	4.27	0.13	0.36

Source: Calculated by ICF using EMFAC2007, assuming port truck age distributions as presented in CAAP.

We estimate the increase in train miles as the product of the number of additional daily trains and the distance between the SCIG and the Hobart terminals (17 miles). As discussed in Section 3.1, all locomotives in the considered system are assumed to meet EPA Tier 2 standards by 2010. Note that the U.S. EPA has announced its intention to adopt much more stringent emission standards for locomotives (Tier 3 and 4 standards). Because of the uncertainty in the timing and market penetration of Tier 3 and 4 locomotives, our analysis assumes that affected locomotives would meet Tier 2 standards. If cleaner locomotives are used for near-dock service, the emissions benefits of this strategy would be greater.

Section 3.1 presented baseline emission factors (g/bhp-h) for line-haul locomotives. The following formula was used to convert emission factors from g/bhp-h to g/mile. Assuming 15 tons per TEU, and 450 TEUs per train, total train cargo weight is approximately 7,000 tons. We used an estimate of locomotive fuel efficiency for intermodal traffic in a flat section in Southern California (486 ton-miles/gallon) to convert locomotive emission factors to grams per mile (Table 3-63).¹³⁵ Total train emissions were calculated by multiplying train miles added by emission factors.

$$\text{EF (g/mile)} = \frac{\text{EF (g/bhp-h)} \times \frac{20.8 \text{ bhp-h}}{\text{gallon}} \times \text{Train Weight (tons)}}{\text{Train Fuel Efficiency (ton-miles/gallon)}}$$

¹³⁵ Sierra Research (2004)

Table 3-63: Tier 2 Line-haul Emission Factors

	NO_x	PM_{2.5}	ROG
Grams/bhp.h	4.60	0.14	0.16
Grams/mile	1,394	41.81	48.54

This analysis does not account for any environmental benefits from reduced congestion on highways.

Results

The emission reduction is the difference between the emissions from eliminated truck trips and emissions from added trains between the SCIG and Hobart intermodal terminals. Table 3-64 shows the emission reduction associated with a higher usage of near-dock rail.

Near-dock capacity and utilization remain constant after 2010 since the construction of the SCIG terminal is scheduled for 2009.¹³⁶ The potential for environmental gains declines after 2010 because improvements in fleet average truck emission factors (while locomotive emission factors remain constant) narrow the gap between truck and locomotive emission factors.

Table 3-64: Emissions Reduction from Expansion of Near-Dock Rail (tons/year)

	NO_x	PM_{2.5}	ROG
2010	281	12	25
2015	219	11	20
2020	112	5	13
2025	60	3	11
2030	47	2	12
2035	50	2	14

Costs

The projected costs for the SCIG terminal are \$200 million.¹³⁷ Since the completion for the SCIG terminal is scheduled for 2009, benefits are assumed to start in 2010.

Cost Effectiveness

Table 3-65 summarizes the cost effectiveness of this strategy, based on calculations by both the ARB and the SCAQMD methods as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%. The project is assumed to have a lifetime of 25 years. For the ARB method, annual costs (i.e., annualized capital costs) are divided by the emissions reduction in 2010. For the SCAQMD method, total costs (i.e., capital costs) are divided by total emissions reduction in the lifetime of the project. Operational costs are not taken into account due to lack of data. Total emissions reduction for the timeframe considered is estimated by interpolating the results for the calculated years. Daily emissions were annualized by assuming 5-day (per week) port operations until 2024, 6-day operations from 2025 to 2029, and 7-day operations from 2030 on.

¹³⁶ Port of Los Angeles (2006)

¹³⁷ CALMITSAC (2006)

Table 3-65: Cost Effectiveness

ARB Annualized Method	Annual Benefits (tons/year)			Cost Effectiveness (\$/ton)		
	NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
	281	12	25	\$45,613	\$1,097,349	\$509,267
SCAQMD BACT Method	Lifetime Benefits (tons)			Cost Effectiveness (\$/ton)		
	NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
	3,152	142	395	\$63,443	\$1,412,798	\$506,939

3.13. Inland Rail Improvements

Description of Strategy

This analysis evaluates the environmental benefits from an improved rail service to the Inland Empire. It involves improvements to railroad capacity along the UP and BNSF networks from near downtown Los Angeles to Indio and Barstow. It includes the construction of additional tracks, as well as grade separation projects. These rail upgrades will improve connectivity from the ports to the Inland Empire, which receives two million TEUs per year.¹³⁸

This analysis quantifies emissions reduction associated with smoother rail flows due to less congestion along the rail lines. This strategy could also result in some mode shift from trucking to rail, but we have not quantified any emission reduction from such a shift. This strategy could also create emissions benefits through a reduction in congestion along the heavily traveled I-710, I-10, and other freeways, although we do not attempt to quantify this component.

Pollutants Reduced

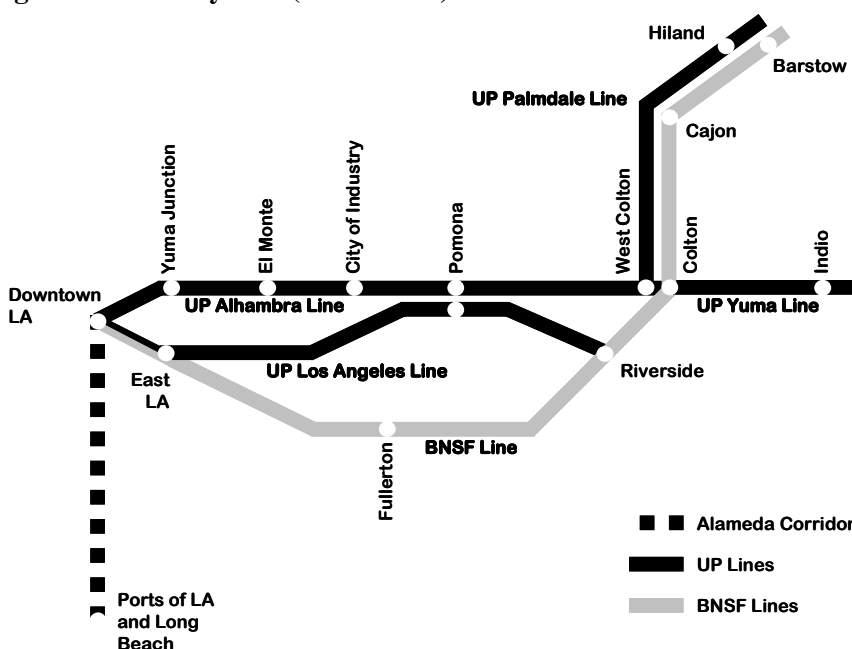
This strategy reduces emissions of all pollutants, including NO_x, PM, and ROG, because it improves train flows.

Emissions Impacts

System Description

The freight rail system under consideration includes the Alameda Corridor from the Ports of LA and Long Beach to downtown Los Angeles, connecting to the UP Alhambra and Los Angeles Lines to Colton, and to the BNSF line to Barstow. The UP Palmdale and Yuma lines are also part of the system (Figure 3-3). Improvements (e.g., additional tracks) are considered on all lines but the Alameda corridor.

¹³⁸ Port of Los Angeles (2006)

Figure 3-3: Rail System (not to scale)

Our analysis relies on one study that modeled operational and emissions improvements due to improved rail flows.¹³⁹ This study calculated the benefits of improved systems in 2010 and 2025 against a baseline scenario. This analysis interpolated the results to 2015 and 2020, and extrapolated them to 2030 and 2035.

Baseline scenarios for future years take into consideration traffic growth and a locomotive fleet that is based on Tier 2 emission standards. Improved scenarios also account for operational improvements (e.g., additional tracks, elimination of grade crossings). Based on baseline and improved results for 2010 and 2025, it is possible to isolate the effects of improved locomotives from the effects of additional train delays, and apply these effects to the remaining years.

Rail emissions are dependent upon rail traffic volume, locomotive age distribution, locomotive emission factors, as well as train delay.

Rail Traffic Volume

The Leachman study relied on a bottom-up approach to estimate rail traffic growth.¹⁴⁰ Based on domestic intermodal, international intermodal, and other carload traffic forecasts, the study determined the number of trains of each type on each rail line. Total rail traffic forecast was accurate when compared to actual train counts provided by BNSF in 2004. Since the study included only traffic volumes for 2000, 2010, and 2025, it was necessary to estimate the volumes associated with the remaining years. Rail traffic relative to 2000 volumes was interpolated for 2015 and 2020 by assuming a constant growth rate from 2000 to 2015. In order to be more conservative, we used a slower growth rate between 2015 and 2035 in order to determine traffic volumes in 2020, 2030, and 2035.

¹³⁹ Leachman R, Hicks G, Fetty G, Rieger M (2005)

¹⁴⁰ Leachman R, Hicks G, Fetty G, Rieger M (2005)

Locomotive Age Distribution and Emission Factors

As discussed in Section 3.1, all locomotives in use along the considered system are assumed to meet EPA's Tier 2 standards by 2010. A separate analysis accounting for the accelerated deployment of Tier 3 and 4 locomotives is also included in this report.

Train Delay

Railroad emissions are generally proportional to traffic volume if the system is not congested (i.e., no delay), assuming that trains have similar speeds and weights, and follow the same route (rail grade has a significant impact on fuel consumption and emissions). Delays are likely if the system is nearing or at capacity, and the emissions caused by additional traffic are also a result of delay. In uncongested systems, transit time remains constant with an increase in traffic volume. However, traffic delay increases exponentially with additional traffic volume when the system is over its capacity. In this case, emissions increase not only with an increase in traffic volume, but also with an increase in delay due to more stops and goes.

The Leachman study relied on simulation to quantify the effects of both train volume and train delay on rail emissions in 2010 and 2025.¹⁴¹ Our analysis simplified the calculation of rail emissions associated with train delay by interpolating rail emissions for 2015 and 2020 based on 2010 and 2025 values. For train emissions in 2030 and 2035, we assume the same delay as in 2025.

Table 3-66 shows the emission reduction associated with improved train speeds.

Table 3-66: Emission Reduction from Inland Rail Improvements (tons/year)

	NO _x	PM _{2.5}	ROG
2010	1,668	56	91
2015	1,908	64	104
2020	2,069	69	113
2025	3,058	102	167
2030	2,390	80	130
2035	2,551	85	139

Costs

SCAG estimates that most sections on the BNSF and UP lines will require at least one additional track by 2025 in order to keep 2000 transit times with 2025 forecasted volumes.¹⁴² The cost for the considered alternatives ranges from \$2.3 to \$2.6 billion. This cost accounts for rail infrastructure projects to raise track capacity to accommodate future rail traffic.

Cost Effectiveness

Table 3-67 summarizes the cost effectiveness of this strategy, based on calculations by the SCAQMD method as explained in the introduction. The ARB method is not applied to this strategy since the method does not work well when large capital investments are spread across multiple years. For all cost effectiveness calculations the discount rate is assumed to be 4%. For the SCAQMD method, total costs (i.e., capital costs) are divided by total emissions reduction in the lifetime of the project. Operational costs are not taken into account due to lack of data. Total emissions reduction for the timeframe considered is estimated by interpolating the results for the calculated years. Daily emissions were annualized by

¹⁴¹ Leachman R, Hicks G, Fetty G, Rieger M (2005)

¹⁴² Leachman R, Hicks G, Fetty G, Rieger M (2005)

assuming 5-day (per week) port operations until 2024, 6-day operations from 2025 to 2029, and 7-day operations from 2030 on.

Table 3-67: Cost Effectiveness (SCAQMD BACT Method)

Lifetime Benefits (tons)			Cost Effectiveness (\$/ton)		
NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
58,084	1,788	3,168	\$42,181	\$1,370,537	\$773,349

3.14. Grade Crossing Separation – Multiple Sites

Description of Strategy

Grade separation allows two crossing axes of traffic (rail-rail or rail-road) to move concurrently without having to stop for one another. This strategy involves building tunnels/underpasses and/or bridges/overpasses to eliminate conflicts. Emission reduction is usually achieved from less vehicle idling emissions at grade crossings. Additionally, the elimination of grade crossings improves rail capacity, thus allowing more cargo to be transported by rail rather than by truck.

This analysis is based on a previous study that quantified emissions reduction of NO_x, PM, and ROG from the elimination of grade crossings along the rail system illustrated in Figure 3-4.¹⁴³

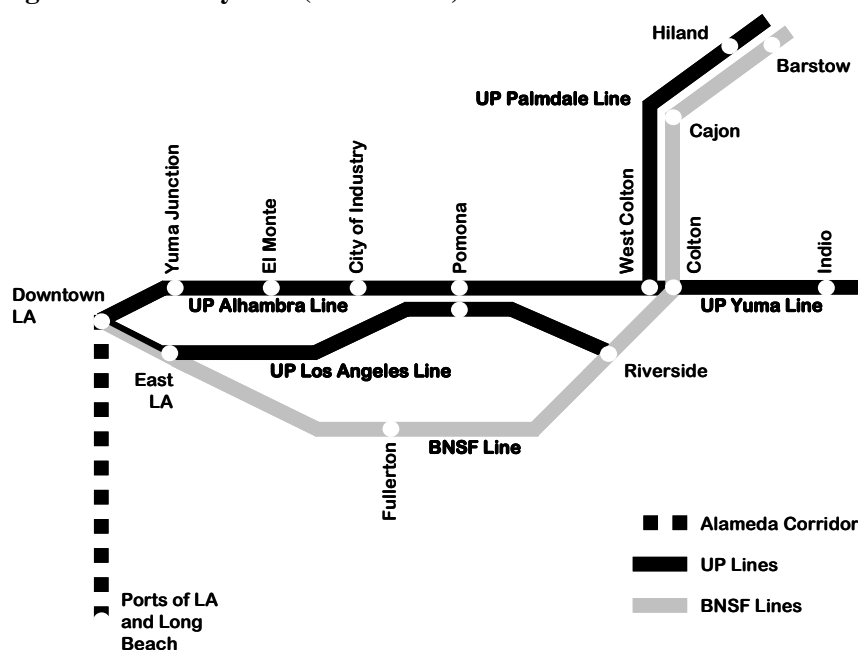
Pollutants Reduced

This strategy reduces emissions of all pollutants, including NO_x, PM, and ROG, because it reduces vehicle idling emissions at grade crossings.

Emissions Impacts

The system under consideration includes the UP Alhambra and Los Angeles Lines from downtown Los Angeles to Colton, and to the BNSF line to Barstow. The UP Palmdale and Yuma lines are also part of the system.

Figure 3-4: Rail System (not to scale)



A previous study identified 49 high priority grade crossings on the east-west main lines that could be eliminated in order to reduce automobile delays and idling emissions, including 11 crossings that are

¹⁴³ Leachman R, Hicks G, Fetty G, Rieger M (2005)

assumed to be eliminated by 2010, and 38 crossing separation projects to be completed by 2025.¹⁴⁴ The Alameda Corridor East Improvement Plan identifies 131 grade separation projects. We consider a range from 49 to 131 grade separation projects.

Our analysis is based on the methodology used on the Inland Empire Railroad Mainline Study developed by Leachman and Associates, which included emissions reduction from less vehicular delay at grade crossings. Traffic delay at grade crossing intersections was estimated for 2010 and 2025, and this analysis interpolated the results to 2015 and 2020, and extrapolated them to 2030 and 2035.

The functional unit used to measure transportation activity was vehicle hours of delay per day. The analysis relied on delay equations that were developed by James Powell and that have been consistently used in every grade crossing delay study in the SCAG region. The equations are used for each train event, whose sum for all trains over a 24-hour period gives an estimated of daily vehicle hours of delay. Important inputs to the equations include:

- Average daily traffic at each crossing by time of day (morning peak, midday, afternoon peak, and night periods)
- Number of lanes at each crossing
- Train speed
- Vehicular departure rate
- Number of trains by length and by time of day

Vehicle delay (D, expressed in vehicle-hours) is a function of the gate-down time (T, expressed in hours), vehicular arrival rate (a, expressed in vehicles per hour), and vehicular departure rate (d, expressed in vehicles per hour).

$$D = \frac{aT^2}{2 \left(1 - \frac{a}{d} \right)}$$

Results

The emissions reduction from the elimination of grade crossings is a result from fewer vehicle hours of delay. Table 3-68 includes the emissions reduction associated with this strategy. The potential for environmental gains decreases over time due to the improvements in emission factors of trucks and automobiles.

Table 3-68: Emission Reduction from Elimination of Grade Crossings (tons/year)

	49 Separation Projects			131 Separation Projects		
	NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
2010	2.4	0.2	1.2	6.4	0.5	3.2
2015	1.9	0.2	0.9	5.0	0.5	2.5
2020	1.4	0.2	0.7	3.6	0.6	1.8
2025	0.8	0.2	0.4	2.2	0.6	1.1
2030	0.3	0.2	0.2	0.8	0.7	0.4
2035	0.3	0.2	0.2	0.8	0.7	0.4

¹⁴⁴ Leachman R, Hicks G, Fetty G, Rieger M (2005)

Costs

Based on the Alameda Corridor East (ACE) Trade Corridor Plan, the costs associated with the 131 grade crossing separation projects amount to over \$4.6 billion (Table 3-69).

Table 3-69: Grade Separation Costs

County	Number of Projects	Cost (\$2007 million)
Los Angeles	39	\$2,087.6
Riverside	40	\$1,048.0
Orange	13	\$631.6
San Bernardino	39	\$840.3
Total	131	\$4,607.5

Cost Effectiveness

Table 3-70 summarizes the cost effectiveness of this strategy, based on calculations by the SCAQMD method as explained in the introduction. The ARB method is not applied to this strategy since there are many grade separation projects that are implemented in different years. For all cost effectiveness calculations the discount rate is assumed to be 4%. For the SCAQMD method, total costs (i.e., capital costs) are divided by total emissions reduction in the lifetime of the project. Operational costs are not taken into account due to lack of data. Total emissions reduction for the timeframe considered is estimated by interpolating the results for the calculated years. Daily emissions were annualized by assuming 5-day (per week) port operations until 2024, 6-day operations from 2025 to 2029, and 7-day operations from 2030 on.

Table 3-70: Cost Effectiveness (SCAQMD BACT Method)

Lifetime Benefits (tons)			Cost Effectiveness (\$/ton)		
NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
29 - 78	5 - 13	15 - 40	\$56,575,168	\$322,150,574	\$112,249,896

It is important to emphasize that the cost effectiveness figures above reflect only emissions reductions from idling vehicles. Grade separation projects are undertaken primarily for other reasons – most notably roadway safety and congestion reduction benefits. Grade separations may also be necessary as part of railway capacity expansion projects, which bring additional benefits from reduced train delay. The cost effectiveness results in Table 3-71 do not reflect any of these additional benefits.

3.15. Individual Grade Crossing Separation

Description of Strategy

This strategy involves building tunnels/underpasses and/or bridges/overpasses to eliminate conflicts between rail and road traffic. Emissions reduction is usually achieved from fewer vehicle idling emissions at grade crossings. Additionally, the elimination of grade crossings might improve rail capacity, thus allowing more cargo to be transported by rail rather than by truck.

The rail-highway crossing under consideration accounts for the intersection between a two-track rail line and a four-lane arterial (i.e., two lanes in each direction). The analysis assumes four scenarios that are differentiated by levels of rail traffic. For each scenario, total number of vehicles delayed, average delay per vehicle (in a 24-hour period), total delay, level of service, and emissions reduction of NO_x, PM, and ROG are quantified for different levels of road traffic.

Pollutants Reduced

This strategy reduces emissions of all pollutants, including NO_x, PM, and ROG, because it reduces vehicle idling emissions at grade crossings.

Emissions Impacts

Methodology

This analysis is based on a standard methodology¹⁴⁵ to calculate vehicle delay at rail-road grade crossings. The functional unit used to measure transportation activity is vehicle hours of delay per day. The analysis relies on delay equations that were developed by James Powell and that have been consistently used in every grade crossing delay study in the SCAG region. The equations are used for each train event, whose sum for all trains over a 24-hour period gives an estimated of daily vehicle hours of delay. Important inputs to the equations include:

Table 3-71: Input Variables

Variable	Value
Average daily traffic (both directions)	0 – 50,000 vehicles/day
Number of traffic lanes (both directions)	4
Number of freight trains	15 – 200 trains/day
Number of passenger trains	10 – 100 trains/day
Length of freight trains	6,500 ft ¹⁴⁶
Length of passenger trains	550 ft
Speed of freight trains	30 mph
Speed of passenger trains	60 mph
Departure rate ¹⁴⁷	1,400 vehicles/hour-lane
Gate warning time	0.5 minutes

¹⁴⁵ Surface Transportation Board (2003)

¹⁴⁶ Based on Leachman (2005)

¹⁴⁷ Based on the Highway Capacity Manual (2000), departure rates (in vehicles/lane-hour) are the following: highways (1,800), arterials (1,400), collectors (900), and local roads (700).

The first step includes the calculation of gate-down time per train event (T).

$$T = T_w + \frac{\bar{L}}{\bar{V}}$$

T_w = Gate warning time

L = Average train length (weighted)

V = Average train speed (weighted)

The number of vehicles delayed per day (N_v) can be calculated as follows:

$$N_v = \frac{T}{24} * N * ADT$$

N = Number of trains per day

ADT = Average daily traffic

24 = Hours per day

The average delay per vehicle in a 24-hour period (D_v) is:

$$D_v = \frac{N_v}{ADT} * \frac{T * \frac{R_D}{R_D - R_A}}{2}$$

R_D = Departure rate (vehicles/hour)

R_A = Arrival rate, average daily traffic converted to vehicles/hour

2 = Denominator to reflect that vehicles do not experience the entire time the train is blocking the grade crossing. They are assumed to arrive on average at the midpoint of the train crossing period.

Total vehicle delay (D) is the product of average delay per vehicle (D_v) and number of vehicles delayed per day (N_v).

$$D = D_v * N_v$$

The level of service (LOS) is a letter grading system developed by the Transportation Research Board¹⁴⁸ to express the amount of road congestion, ranging from A (best) to F (worst). Table 3-72 presents the assumed correlation between LOS and average delay per vehicle¹⁴⁹. The calculation of level of service is done for commute hours. For simplification purposes, it is assumed that 50% of road and passenger rail traffic occurs during commute hours. Freight rail traffic is assumed to be uniform throughout the day.

¹⁴⁸ Transportation Research Board (1994)

¹⁴⁹ Surface Transportation Board (2003)

Table 3-72: Level of Service at Grade Crossings

Level of Service	Average Delay per Vehicle (seconds/vehicle)
A	< 5
B	5 – 10
C	10 – 20
D	20 – 30
E	30 – 45
F	> 45

Road traffic was divided into six vehicle types: light-duty cars (60%), light-duty trucks (20%), light heavy-duty diesel truck (10%), medium heavy-duty diesel truck (5%), and heavy heavy-duty diesel truck (5%), based on the vehicle classification included in EMFAC2007. This is consistent with data obtained from SCAG.

Total idling emissions were calculated by multiplying total delay in each vehicle category by idling emission factors. The latter were taken from EMFAC2007 and accounted for the fleet age distribution of all vehicles in Southern California.

Results

The emissions reduction from the elimination of an individual grade crossing is a result of fewer vehicle hours of delay. The first analysis evaluates the impacts of a combination of rail and road traffic on the total number of vehicles delayed, total delay, level of service, and emissions in grams per day (Tables 3-73 and 3-74). Four scenarios are evaluated: light rail traffic (25 trains/day), medium rail traffic (50 trains/day), heavy rail traffic (100 trains/day), and very heavy rail traffic (200 trains/day). For each of these four scenarios, the average daily traffic ranges from 0 to 50,000 vehicles per day in both directions.

The results do not take into account the possibility that adjacent arterials might get congested if road traffic levels are such that congestion spills upstream to the “previous” intersection. Such an analysis would have to be done on a case-by-case basis, since it would depend on traffic levels on adjacent roads, length of blocks, and number of lanes in each road segment.

Besides emission reduction, there are other benefits from grade separation projects, such as improved safety and reduced delay. The delay experienced by vehicle drivers is substantial in most scenarios.

Table 3-73: Delay and Emissions Reduction

ADT (v/d)	Light Rail Traffic (25 trains/day)						Medium Rail Traffic (50 trains/day)					
	N _v	D (h/d)	LOS	NO _x (g/y)	PM _{2.5} (g/y)	ROG (g/y)	N _v	D (h/d)	LOS	NO _x (g/y)	PM _{2.5} (g/y)	ROG (g/y)
0	0	0.00	N/A	0	0	0	0	0.00	N/A	0	0	0
5,000	140	0.05	C	244	4	22	280	0.22	D	977	15	86
10,000	280	0.11	C	508	8	45	561	0.46	D	2,032	30	180
15,000	420	0.18	C	794	12	70	841	0.71	E	3,176	47	281
20,000	561	0.25	C	1,105	16	98	1,121	0.99	E	4,419	66	391
25,000	701	0.32	C	1,444	22	128	1,402	1.30	E	5,777	86	511
30,000	841	0.41	C	1,816	27	161	1,682	1.63	E	7,264	108	642
35,000	981	0.50	D	2,225	33	197	1,962	2.00	E	8,901	133	787
40,000	1,121	0.60	D	2,678	40	237	2,243	2.41	F	10,712	160	947
45,000	1,261	0.72	D	3,181	48	281	2,523	2.86	F	12,725	190	1,125
50,000	1,402	0.84	E	3,744	56	331	2,803	3.37	F	14,976	224	1,324

Table 3-74: Delay and Emissions Reduction

ADT (v/d)	High Rail Traffic (100 trains/day)						Very Heavy Rail Traffic (200 trains/day)					
	N _v	D (h/d)	LOS	NO _x (g/y)	PM _{2.5} (g/y)	ROG (g/y)	N _v	D (h/d)	LOS	NO _x (g/y)	PM _{2.5} (g/y)	ROG (g/y)
0	0	0.00	N/A	0	0	0	0	0.00	N/A	0	0	0
5,000	520	0.70	F	3,123	47	276	1,041	2.81	F	12,493	187	1,104
10,000	1,041	1.46	F	6,497	97	574	2,081	5.84	F	25,990	388	2,298
15,000	1,561	2.28	F	10,154	152	898	3,122	9.13	F	40,617	607	3,591
20,000	2,081	3.18	F	14,131	211	1,249	4,163	12.71	F	56,523	844	4,997
25,000	2,602	4.15	F	18,471	276	1,633	5,203	16.62	F	73,883	1,103	6,532
30,000	3,122	5.22	F	23,226	347	2,053	6,244	20.89	F	92,906	1,387	8,214
35,000	3,642	6.40	F	28,461	425	2,516	7,285	25.60	F	113,842	1,700	10,065
40,000	4,163	7.70	F	34,249	511	3,028	8,325	30.81	F	136,997	2,046	12,112
45,000	4,683	9.15	F	40,685	608	3,597	9,366	36.60	F	162,741	2,430	14,388
50,000	5,203	10.77	F	47,884	715	4,233	10,407	43.07	F	191,535	2,860	16,933

Costs

Based on the cost of 131 grade separation projects included in the previous strategy, we determined an average cost for a theoretical project (\$35 million).

Cost Effectiveness

Table 3-75 summarizes the cost effectiveness of this strategy, based on calculations by both the ARB and the SCAQMD methods as explained in the introduction. For all cost effectiveness calculations the discount rate is assumed to be 4%. Since the project has a lifetime of 25 years, only the 2010 cost effectiveness is calculated. For the ARB method, annual costs (i.e., annualized capital costs) are divided by the emissions reduction in 2010. For the SCAQMD method, total costs (i.e., capital costs) are divided by total emissions reduction in the lifetime of the project. Operational costs are not taken into account due to lack of data. For simplification purposes, emissions reduction is assumed to be constant throughout the years. Total emissions are based on a scenario that could justify a grade separation project (i.e., heavy rail traffic with 10,000 vehicles per day). The SCAQMD method gives a considerably higher cost effectiveness for NO_x and ROG due to the fact that emissions reduction increase over time.

Table 3-75: Cost Effectiveness in 2010

Method	Benefits			Cost Effectiveness (\$/ton)		
	NO _x	PM _{2.5}	ROG	NO _x	PM _{2.5}	ROG
ARB Annualized	0.0479	0.00072	0.0042	\$47,379,879	\$3,172,900,244	\$535,917,026
SCAQMD BACT	1.1971	0.0179	0.1058	\$29,606,891	\$1,982,692,051	\$334,885,545

As noted in the previous section, this analysis considers only emission reductions from reduction in vehicle idling. Grade separation projects are undertaken primarily for other reasons – most notably roadway safety and congestion reduction benefits. Grade separations may also be necessary as part of railway capacity expansion projects, which bring additional benefits from reduced train delay. The cost effectiveness results in Table 3-76 does not reflect any of these additional benefits.

4. Ocean-Going Vessel Strategies

4.1. Introduction

Overview

Ocean-going vessels are a significant and growing source of NO_x and PM emissions in the SCAG region. Ocean-going vessel (OGV) emissions come from both the ship propulsion and auxiliary engines, and from other minor sources such as on-board boilers or other combustion processes. According to emission inventory data from SCAQMD and CARB (described in Section 1), OGVs currently account for 13% of goods movement NO_x emissions and 24% of goods movement PM_{2.5} emissions in the South Coast Air Basin. Because of the limited regulation on OGV emissions and the rapid growth in imported goods through Southern California ports, emissions from this sector are expected to grow significantly. Absent any new control strategies, by 2030, OGVs will account for 70% and 73% of goods movement NO_x and PM_{2.5}, respectively, in the South Coast Air Basin.

Emission reduction strategies for OGVs include the following general categories:

- Ship fuels and shipboard fuel modifications
- Engine upgrades
- Exhaust after-treatment techniques
- Shoreside power
- Operational measures (such as speed reduction)

We identified promising OGV emission reduction strategies through a review of the port's *Clean Air Action Plan*, CARB's *Emission Reduction Plan for Ports and Goods Movement in California*, the final report by the Port of Los Angeles No Net Increase Task Force, as well as other documents. We have quantified the benefits and costs of six strategies. Our analysis of emission reductions relies heavily on the port's *Clean Air Action Plan*, with modifications to allow comparison with other strategies in this report. Those modifications generally involve (1) extending costs and benefits to 2030, and (2) estimating full costs, rather than just the costs to the ports as presented in the *Clean Air Action Plan*. The *Clean Air Action Plan* does not present ROG emission reductions, so we have not estimated ROG impacts for OGV strategies in this report.

Several other strategies show promise for reducing OGV emissions but were not fully quantified in this report due to lack of information on costs or emissions impacts. One such strategy (crane double-cycling) is presented with only emission reductions (no cost or cost effectiveness) in Section 4.8. Another potential strategy is an over-the-stack exhaust hood for vessel emission control, which is expected to be tested by the Port of Long Beach in the near future. Such a system is analogous to the advanced locomotive emission control system (ALECS) recently tested for locomotives at the UP Roseville yard.

Baseline Emissions

In order to determine the effectiveness of OGV strategies, we first developed an emissions baseline for the combined San Pedro Bay Ports. We relied primarily on the emission inventory developed by ARB for the South Coast Air Basin. This inventory covers the years 2001 through 2030 and includes all vessel emissions in the South Coast Basin extending out to sea for 100 nautical miles (nm). To determine 2035 emissions, we extrapolated the ARB inventory linearly beyond 2030. A linear extrapolation is generally

consistent with the inventory trend over the documented period. Note that ARB has recently been revising the emission inventory and forecast for ocean going vessels, so the data we used (presented below) may not match current ARB estimates.

The ARB emissions inventory we used for OGVs does not reflect the effects of ARB's Auxiliary Engine Rule, which entered into force on January 1, 2007. The rule requires ships to use fuel with lower sulfur levels in their auxiliary engines, which will reduce baseline OGV emissions. In order to account for the effects of this rule, we calculated the percent reduction in emissions due to the rule as presented in the CAAP, and applied this percent reduction to the ARB baseline. Table 4-1 shows baseline OGV emissions.

In addition to the overall OGV emission inventory, we also estimated the at-berth emissions inventory for all years of interest. We relied on ARB's estimate of berthing emissions for all US and foreign-flagged vessels by year from 2001 to 2030, then adjusted this baseline to account for the Auxiliary Engine Rule. We estimated the effects of the rule on at-berth emissions using the emission factor reductions from switching from 1.5% residual oil to low sulfur fuel (0.5% beginning in 2007 and 0.1% after 2010) as presented in the CAAP.¹⁵⁰ Because many vessels already use dual fuel, we applied this reduction to 45% of the at-berth inventory, assuming that 55% of vessels are already using dual fuel.¹⁵¹ Table 4-2 shows the resulting baseline at-berth emissions the at-berth emission inventory for key years.

Table 4-1: Baseline Emissions at the Combined San Pedro Bay Ports (tons/year)

	2010	2015	2025	2035
Base Emissions				
NO _x	22,766	27,796	42,385	62,162
PM	1,916	2,369	3,766	5,613
Assumed ARB Aux Engine Rule Reductions				
NO _x	453	821	2,070	4,236
PM	146	277	750	1,578
Assumed Base Emissions After ARB Aux Engine Rule				
NO _x	22,313	26,975	40,315	57,926
PM	1,771	2,092	3,016	4,035

¹⁵⁰ Port of Los Angeles and Port of Long Beach (2006)

¹⁵¹ Starcrest Consulting Group (2005a)

Table 4-2: Estimated Baseline At-Berth Emissions at the Combined San Pedro Bay Ports (tons/year)

	2010	2015	2025	2035
Baseline At-Berth Emissions				
NO _x	9,800	11,563	15,487	19,411
PM	829	979	1,311	1,643
Assumed ARB Aux Engine Rule Reductions				
NO _x	539	636	852	1,068
PM	246	291	389	488
Assumed Base At-Berth Emissions After ARB Aux Engine Rule				
NO _x	9,261	10,927	14,635	18,343
PM	583	688	922	1,155

4.2. OGV Speed Reduction

Background

OGV activity in the vicinity of a port is often classified into four distinct operating modes: *cruise*, *reduced speed zone (RSZ)*, *maneuvering*, and *hotelling* (time spent at dock or anchorage). Hotelling emissions result solely from operation of auxiliary engines to provide power to the ship for climate control, pump operation, and similar tasks; emissions from the three other modes are due to a combination of the auxiliary and main engines used to propel the ship and provide power.

Cruising is done at service speed, typically about 94% of the maximum continuous engine rating, and typically occurs beyond 25 miles outside of the breakwater – the geographic marker for change from the open ocean to inland waterway.¹⁵² Operation in the RSZ is done at the declared maximum safe speed for the zone, which is between cruise and maneuvering speed and typically 9 – 11 knots, but can be lower. Maneuvering is done at dead slow or reverse, usually around 3 – 5 knots, and within about 2 miles of the berth or anchorage. RSZ and maneuvering are done under the auspices of the local Marine Exchange/Port Authority (MEPA).

Under a vessel speed reduction (VSR) program, the RSZ is extended further into the cruise region, which slows ships earlier in their approach to the port. Because engine load, and thus emissions (NO_x in particular) increase with vessel speed, slower speeds usually result in lower main engine emissions.

Any increase in RSZ distance is accompanied by a decrease in cruise distance, where the speeds are shifted from cruise speed to the RSZ value. Annual vessel emissions by ship type and operating mode are given as the product of annual vessel calls on the port, power of the engines onboard, the load factor of each engine operating in a given mode, the time spent in an operating mode, and the emissions factor of the vessel's engines. The propeller law states that the engine load factor is proportional to the cubed ratio of operating to cruise speed, and speed is distance per unit time. Thus, the change in emissions from an increased RSZ zone is proportional to the increased distance the ships travel at precautionary speeds and the square of the ratio of new to old precautionary speeds.

Because ships are losing time by traveling at slower speeds close to the port, they may try to make up this time in open water further from the port, resulting in increased emissions further from shore. Also, because the emission benefits are related to the amount of speed reduction, VSR is more effective for vessels that cruise at higher speeds, such as container ships, auto carriers, and cruise ships. VSR programs operate largely independently of other mitigation strategies, and thus may be used in conjunction with other mitigation strategies to enhance its effectiveness at reducing OGV emission rates.

Since May 2001, the Ports of Los Angeles and Long Beach have enacted a voluntary VSR program to encourage ships to reduce their speed from cruise to 12 knots within 20 nautical miles (nm) of Point Fermin, both during entrance and exit. Compliance rates have increased steadily over that time: 50% in 2004, 67% in 2005, and 77% for the first eight months of 2006.¹⁵³ The Ports intend to implement a mandatory VSR plan and verify effects of VSR on PM and NO_x through their Technology Advancement Program.

¹⁵² Starcrest Consulting Group (2005a)

¹⁵³ Port of Los Angeles and Port of Long Beach (2006)

Strategy Definition

We define this VSR strategy to be consistent with that described in the CAAP throughout overlapping years. This involves expanding the range of the current VSR program to 40 nm, establishing leasing requirements to replace the voluntary program as leases expire, moving gang assignments to 40 nm to eliminate “line jumping,” and installing improvements to the Marine Exchange radar system that would allow better measurement of vehicle speeds both to ensure compliance and to better estimate emissions.

Pollutants Reduced

This strategy is primarily intended to reduce NO_x emissions, since NO_x emissions are understood to be strongly correlated with vessel speed. Vessel speed reduction *may* have an effect on other pollutants, such as PM and SO_x, but further studies are needed to understand these effects. Both the CAAP and No Net Increase Report assume VSR to have no impact on PM. We make the same assumption for this analysis.

Emission Reduction Potential

The CAAP estimates emissions reductions for years 2006/2007 through 2010/2011 for a combined, enforceable VSR program at both ports. This includes emission reduction estimates from continuation of the current VSR program as well as emission benefit from the envisioned VSR program extended to 40 nm, enforced with radar, and implemented through leasing requirements. Note that, due to uncertainties associated with cargo growth projections, the CAAP currently calculates emission reductions essentially under a “no growth” scenario. Table 4-3 shows the emission reductions anticipated under this “no growth” calculations of the CAAP, including the assumed 100% compliance rate and 40 nm implementation range. Under the “no growth” assumptions of the CAAP, emission reductions for the extended years are constant, due to the universal adoption of the VSR program by this time.

Table 4-3 also shows the total NO_x reduction from implementation of the extended VSR as a percent of baseline OGV NO_x emissions reported in the 2001/2002 inventories for the ports. Note that the CAAP-calculated emission reductions reflect increased auxiliary emissions due to longer transit time.

Table 4-3: VSR Emission NO_x Reductions without Growth Assumptions (tons/year)

	2010	2015	2025	2035
Current VSR (20 nm)	1,721	1,721	1,721	1,721
Expanded VSR (40 nm) Lease-Based	1,721	1,721	1,721	1,721
Total VSR Emission Reductions	3,442	3,442	3,442	3,442
As % of No Growth Baseline	26%	26%	26%	26%

To incorporate the expected growth in activity at the Ports, we applied the percentage emission reductions from Table 4-3 to the baseline OGV emission calculations presented in Section 4.1. This baseline includes the effects of growth and the ARB’s Auxiliary Engine Rule. Table 4-4 shows the emission reduction applied to anticipated baseline NO_x emission levels.

Table 4-4: Expanded VSR NO_x Emission Reductions (tons/year)

	2010	2015	2025	2035
Baseline OGV Emissions	22,313	26,975	40,315	57,926
Reduction from Expanded VSR	5,801	7,014	10,482	15,061

Costs

There are two potential cost components to this strategy:

- Costs to the ports to install enhanced radar tracking, administer the program, and verify compliance
- Operational costs due to delay or attempts to “make up” lost time

The CAAP estimated the costs to the Ports and regulatory agencies associated with an enhanced RSZ program in the San Pedro Bay to be \$4.4 million annually. These costs are associated with installation of upgrades to the Marine Exchange radar to allow better tracking of the vessels and costs to the ports for administrative processes and funding incentives. No data is available on the distribution of these costs between equipment purchase, maintenance, and administrative costs. No cost data for the ports was available for years beyond the CAAP projection, so we estimated the costs to the Ports by continuing the constant trend apparent in the results for later years.

Creating or extending an RSZ from 20 to 40 nm could result in some additional operational cost to ocean carriers due to delay. For example, if no other operational issues are in effect, than the time required to traverse 40 nm linearly at 12 knots is 3.3 hours, while the time for traversing 20 nm at a typical speed of 20 knots and 20 nm at 12 knots is 2.7 hours. Thus, expanding the VSR program would increase delay by up to 80 minutes per call (bi-directional). However, the time lost due to an expanded VSR could be made up in the open ocean at a higher cruise speed. Assuming an OGV cruise speed of 20 knots, vessels could make up lost time by traveling at speeds between 21 and 25 knots for a period of 1.1 to 1.3 hours. Extra fuel would be required during this high-speed time, resulting in additional cost to ocean carriers, some or all of which might be passed on to shippers. It is difficult to estimate these effects without knowing the specific fuel consumption rates, number of calls, vessel schedule, and other parameters of individual ships. Simple calculations suggest that although increases in main engine fuel consumption are expected from the greater power required make up for VSR delay, this could be balanced by the fuel saved by operating at reduced speed in the RSZ.

If we assume that OGVs cannot make up for the VSR delay by cruising at higher speeds, then there is a cost associated with the delay. To estimate this cost, we assume \$3,000 per vessel per hour as the cost of delay.¹⁵⁴ To determine total delay, we first estimated the total number of calls to the Ports for each year of study, using the 2004 value and a 3% annual growth estimate in the ARB’s Goods Movement Plan. We then applied the relevant participation rates from the CAAP at both 20 and 40 nm to these numbers of calls to determine the total delayed calls at the ports for all years. We determined the total number of delayed hours per year based on this estimate of delayed calls, and the average amount of delay per call, based on a 20 or 40 nm RSZ and the overall average Marine Exchange speed of 17 knots for all vessels.¹⁵⁵ Reducing from 17 to 12 knots results in a delay of about one hour per call for each 20 nm

¹⁵⁴ No Net Increase Task Force (2005)

¹⁵⁵ California Air Resources Board and the South Coast Air Quality Management District (2000)

distance over which the VSR is applied. The resulting total hours of delay and estimated costs to shippers are shown in Table 4-5 along with the Ports' costs.

Table 4-5: Annual Costs for the Expanded VSR Program

	2010	2015	2025	2035
Port Costs	\$4,400,000	\$4,400,000	\$4,400,000	\$4,400,000
Vessel Delay Costs	\$39,093,107	\$45,523,913	\$61,749,148	\$83,750,250

Cost Effectiveness

To estimate cost effectiveness, we assumed this strategy to have a one-year life, since the only costs are the operational costs incurred by the ports and (possibly) vessel operators. Thus, the cost-effectiveness is the same under the SCAQMD BACT method and the ARB annualized method. Table 4-15 shows the resulting cost-effectiveness for the analysis years, with and without the vessel delay costs.

Table 4-6: Cost Effectiveness of Expanded VSR Program

	NO _x		PM _{2.5}	
	SCAQMD BACT Method	ARB Annualized Method	SCAQMD BACT Method	ARB Annualized Method
Excluding Vessel Delay Cost				
2010	\$767	\$767	NA*	NA*
2015	\$627	\$627	NA*	NA*
2020	\$480	\$480	NA*	NA*
2025	\$420	\$420	NA*	NA*
2030	\$339	\$339	NA*	NA*
2035	\$292	\$292	NA*	NA*
Including Vessel Delay Cost				
2010	\$7,525	\$7,525	NA*	NA*
2015	\$7,118	\$7,118	NA*	NA*
2020	\$6,681	\$6,681	NA*	NA*
2025	\$6,311	\$6,311	NA*	NA*
2030	\$6,092	\$6,092	NA*	NA*
2035	\$5,853	\$5,853	NA*	NA*

* Strategy does not reduce PM emissions.

4.3. OGV Cold Ironing

Background

A major portion of ocean-going vessel (OGV) emissions occurs while the vessels are at berth. According to CARB's most recent emission inventory, 42% of OGV NO_x emissions and 43% of OGV PM₁₀ emissions in the South Coast Air Basin occur at berth. Several strategies are under consideration to mitigate the emissions from vessels at berth. These strategies can be divided into two classes: 1) using shore power to replace auxiliary engine use ("cold ironing") and 2) applying other retrofit technologies for vessels for which cold ironing is not feasible or cost effective. This strategy covers only cold ironing.

Cold ironing enables ships to shut down their (diesel) auxiliary engines and run off the shore-side electrical power grid to supply power at the dock for refrigeration, electricity, and other needs. The U.S. Navy has been using shore power for many decades to provide electricity to its ships while docked for long periods of time. A growing number of U.S. West Coast and European ports are also adopting shore power to reduce emissions from commercial vessels.

To support shore power, the port or terminal operator must install necessary shore-side infrastructure, including an electrical substation, step-down transformer, underground conduits, electrical wharf boxes (for connection to the ship), and a cable management system. Ship owners also must retrofit their ships to accommodate shore power through a connection interface with the ship's main electrical panel. Onboard electrical equipment upgrades may include a transformer, switchgear and breakers, metering system, and controls.

The Ports of Los Angeles and Long Beach have separate programs aimed at reducing at-berth hotelling emissions, although both share the goal of moving all container and cruise ship berths to shore power (known as Alternative Maritime Power, or AMP, at the Port of Los Angeles) and moving other vessels to alternative at-berth reduction technologies.

Both San Pedro Bay Ports have committed to employ shore power and expand the necessary infrastructure. The Port of Los Angeles already has the necessary main electrical trunk lines in place from which power may be supplied to vessels, while the Port of Long Beach intends to develop this infrastructure over the next five to ten years. The Port of Los Angeles intends to make shore power available at a number of container, liquid bulk, and cruise ship berths, and to provide shore-side power to all dredging operations. The Port of Long Beach plans to have one crude oil and all container terminals equipped with shore power over the next ten years. The Port of Long Beach will also initiate a major electrical infrastructure improvement program to provide additional 6.6 kV sub-transmission lines, complete improvements for other terminals, and provide plug-ins for electric dredges and some yard equipment.

Strategy Definition

This strategy involves major investment in cold ironing infrastructure at the San Pedro Bay Ports over the period of study (2006 to 2035), with most infrastructure in place by 2016, and a dramatic increase in the portion of vessels using cold ironing at the ports. Our strategy is defined to be consistent with the CAAP measure OGV-2 through 2011. For "extended" years beyond 2011, our strategy relies on other sources of information and extrapolations.¹⁵⁶ Under this strategy, 70% of container, cruise, and liquid bulk ship calls will make use of cold ironing by 2015.

¹⁵⁶ California Air Resources Board (2006c)

Pollutants Reduced

Converting to shore power has the potential to drastically reduce all at-berth vessel hotelling emissions of all pollutants, including NO_x, ROG, and PM. For example, the ARB's *Proposed Emission Reduction Plan for Ports and Goods Movement in California* assumes an overall shore power effectiveness of 90% of at berth emissions, while the CAAP assumes 95% effectiveness.

Emission Reduction Potential

The San Pedro Bay Ports have estimated emissions reductions for fiscal years 2006/07 through 2010/11 for the growing shore power program at both ports. Note that, due to uncertainties associated with vessel activity growth projections, the CAAP calculates emission reductions under a “no growth” scenario until better data is available from the upcoming revised emission inventories. In other words, no growth in baseline emissions due to economic expansion and other effects is assumed for purposes of analyzing mitigation performance. To be consistent with the CAAP, we first present emission reduction potential under this “no growth” scenario before considering the effect of growth for extended years out to year 2035.

Table 4-7 shows our estimate of the percent of vessel calls that would be affected by the expanded shore power programs at the combined ports. To estimate these values, we used the CAAP estimates of the number of container, cruise, and liquid bulk vessel calls using shore power for each of its five study years. These calls were assumed to be the only ship types utilizing shore power through 2011. We divided the number of shore powered calls by total vessel calls for each vessel type, obtained from information in the Port of Los Angeles' *Baseline Emission Inventory* and the ARB's *Technical Supplement* to the *Emission Reduction Plan for Ports and Goods Movement in California*.

The ARB's *Goods Movement Plan* estimates that 20% of all ship calls will use shore power by 2010 (within the range of CAAP values), 60% by 2015, and 80% by 2020. We assumed that the total usage for years 2020 and beyond will be fixed at 70% use of shore power. This is consistent with the draft 2007 AQMP, which indicates that *at least 60%* will use shore power, and with the CAAP, which suggests that the ports will maximize shore power usage within the next ten years.

Table 4-7: Estimated Percent of Vessel Calls Using Shore Power

	2010	2015	2025	2035
Container, Cruise, & Tanker Calls	15%	70%	70%	70%
Other Vessel Calls	0%	24%	70%	70%
All Vessel Calls	11%	60%	70%	70%

To estimate the tons of emissions reduced from use of shore power under a “no growth” scenario, we used the values reported in the CAAP for the years 2006-2011, which apply only to tanker, cruise, and container vessels. For 2010 emission reductions and percent reductions, we interpolated between the FY 2009/10 and FY 2010/2011 values in the CAAP. We estimated extended year emission reductions for these vessels by extrapolating the emission reductions as a function of known cold ironing calls by vessel type. The reduction in emissions from other vessel types is lower than for tanker, cruise, and container vessels because (1) they have fewer calls, and (2) they produce fewer emissions while at berth. To estimate the emissions reductions for other vessel types, we first calculated the tons of emissions reduced per tanker, cruise, and container vessel call, and applied this ratio to the number of calls by other vessel types. We then multiplied this value by 34%, which reflects the average per call emissions from other

vessels as a percent of emissions per call of tanker, cruise, and container vessels.¹⁵⁷ Table 4-8 presents estimated NO_x and PM_{2.5} emission reductions from use of cold ironing under a no-growth scenario, as well as the emission reductions as a percent of total OGV no-growth baseline emissions assumed in the CAAP.

Table 4-8: Cold Ironing Emission Reductions without Growth Assumptions (tons/year)

		2010	2015	2025	2035
Cruise, Container, and Liquid Bulk Ships	NO _x	771	4,150	4,150	4,150
	PM _{2.5}	16	101	101	101
Other Vessels	NO _x	0	132	393	393
	PM _{2.5}	0	4	10	10
All Vessels	NO _x	771	4,283	4,543	4,543
	PM _{2.5}	16	105	111	111
As Percent of OGV No-Growth Baseline	NO _x	6%	33%	36%	36%
	PM _{2.5}	2%	11%	12%	12%

The emission reductions in Table 4-8 assume no growth in OGV activity. In reality, baseline OGV at-berth emissions will increase due to the rapid growth in goods movement through the ports. To incorporate this expected growth, we applied the emission reduction percentages in Table 4-8 to the OGV baseline emissions presented in Section 4.1. The total NO_x and PM_{2.5} emission reductions from this strategy for all years out to 2035 are shown in Table 4-9.

Table 4-9: Emissions Impact of Cold Ironing Strategy (tons/year)

	2010	2015	2025	2035
NO _x	1,358	9,031	14,318	20,573
PM _{2.5}	27	209	319	428

Costs

The costs for this strategy include three major components:

- Purchase and installation of shore-side electrical infrastructure
- Costs to retrofit vessels
- Labor associated with shore power operation

For the years through 2011, we assumed costs to the Ports of Los Angeles and Long Beach are as reported in the CAAP. These include infrastructure and incentive costs for the AMP program at the Port of Los Angeles and the Shore Power program at the Port of Long Beach; the PoLB program includes infrastructure costs associated with bringing power to the berths and electrifying additional berths. We assumed all infrastructure costs to the Port of Los Angeles will be covered during the five years of the CAAP study, totaling \$49 million. For the Port of Long Beach, we assumed that infrastructure costs for additional berths will be incurred through 2016, totaling \$322 million over the ten year period.

¹⁵⁷ Starcrest Consulting Group (2005a)

We determined vessel retrofit costs by year by assuming that, on average, a retrofitted vessel calls on the Ports five times per year¹⁵⁸, and used this factor to estimate the number of unique cold ironing callers per year. We then determined the number of retrofits per year by subtracting the number of retrofits previously performed from the number of unique cold-ironing callers for each year. Total retrofit costs were then taken as the number of retrofits multiplied by an average retrofit cost of \$500,000 per vessel.¹⁵⁹

Operating costs for shore power include electricity, labor, and maintenance. Electricity costs vary widely based on the utility provider, time of use, seasonal adjustments, and additional demand charges, among others. At California ports, rates can range from \$0.08 per kilowatt-hour (kWh) for high annual electricity consumers to over a \$1.00 per kWh during peak periods (for example, cruise ships that have brief, intense bursts of energy demand, but low annual electricity usage overall). Savings from not purchasing fuel would be factored into the total energy costs, but currently electricity is more expensive than marine residual fuel. This difference is likely to be reduced with the additional costs of lower sulfur fuel requirements starting in 2007, or with other fuel cost increases. Thus, we have assumed no incremental cost for electricity.

Finally, we also estimated the cost of additional labor associated with moving vessels to shore power. There are also labor costs associated with connecting/disconnecting electrical cables between the ship and the shoreside infrastructure. Connect and disconnect times are expected to require less than one hour each; however, because of International Longshore and Warehouse Union (ILWU) regulations, linemen must clock a minimum of four-hour shifts. Therefore, a shoreside labor crew is assumed to require two people over a four-hour shift for each connect and disconnect task, totaling eight hours per person per port call. At an assumed labor cost of \$50 per hour, shoreside labor cost is roughly estimated to be \$800 per port call. Ship onboard labor is not subject to the same ILWU regulations and is expected to require four people for one hour each to connect and disconnect (two hours in total). At an assumed hourly cost of \$50 per hour, ship onboard labor costs are estimated to be \$400 per port call. Total shore power labor cost is estimated to be \$1,200 per port call.

Ship onboard cost of power generation should reflect the avoided cost of fuel and avoided operations and maintenance (O&M) expense from not having to service diesel engines. Estimated avoided O&M costs are based on deferred cost of engine maintenance, allocated over engine life operating hours and an assumed 60 percent capacity factor on engine nameplate rating. We assume a typical auxiliary engine requires a \$1.25 million major overhaul after 96,000 operating hours. Dividing \$1.25 million by 96,000 hours results in an accrued maintenance expense of \$13.00 per operating hour. Assuming the auxiliary engine operates at 60% of 2,205 kW power rating, O&M costs from the use of fuel equate to roughly \$0.01/kWh. This per kWh O&M cost is used to calculate a per call O&M cost savings of roughly \$650 per call. Thus, the net labor cost is estimated to be \$1,200 less \$650, or \$550 per call.

Table 4-10 shows our resulting estimates of the cost associated with this strategy for key years of analysis. As discussed above, infrastructure costs are assumed to end at the Port of Los Angeles in FY 2010/2011 and at the Port of Long Beach in 2016.

¹⁵⁸ Consistent with the requirements of the NNI and within the range of expected values from the ARB *Cold Ironing Cost Effectiveness Study*.

¹⁵⁹ California Air Resources Board (2006e)

Table 4-10: Costs of Shore Power Strategy for Key Analysis Years

	2010	2015	2025	2035
POLA AMP Infrastructure Costs	\$5,495,890	\$0	\$0	\$0
POLB Shore Power Infrastructure Costs	\$38,363,562	\$43,983,600	\$0	\$0
Vessel Retrofit Costs	\$34,204,110	\$47,226,200	\$5,098,100	\$0
At-Berth Labor	\$319,437	\$1,683,800	\$1,964,400	\$1,964,400
Total Costs	\$78,382,999	\$92,893,500	\$7,062,500	\$1,964,400

Cost Effectiveness

We prepared estimates of cost effectiveness for the shore power strategy using the discounted cash flow method of SCAQMD's BACT analysis. The results are shown in Table 4-11. The ARB annualized cost-effectiveness method cannot be applied to this strategy because of the large capital costs occurring over multiple years.

Table 4-11: Shore Power Strategy Cost Effectiveness

NO _x		PM _{2.5}	
SCAQMD BACT Method	ARB Annualized Method	SCAQMD BACT Method	ARB Annualized Method
\$5,573	NA	\$229,815	NA

For comparison, ARB has performed a detailed estimate of the cost effectiveness of cold ironing at the San Pedro Bay ports, as summarized in Table 4-12.¹⁶⁰ Note that the ARB study uses some different assumptions, including project lifetime and some specific capital costs. Also, ARB assumes a shore-side transformer and 0.1% sulfur fuel in all cases. The cost per ton estimates from ARB are significantly higher than our estimates due to these methodological differences. For example, ARB assumes a 10-year project life, whereas our application of the BACT method uses a 30-year project life.

Table 4-12: ARB Estimates of San Pedro Bay Ports Cold Ironing Cost Effectiveness

Vessel Type	(\$ / ton NO _x)			(\$ / ton PM)		
	All Ships	Ships with 3 or More Visits	Ships with 6 or More Visits	All Ships	Ships with 3 or More Visits	Ships with 6 or More Visits
Container	18,500	14,500	15,500	1,085,000	845,000	885,000
Passenger	44,000	24,000	17,000	2,600,000	1,400,000	1,400,000
Reefer	25,000	29,000	32,000	1,500,000	1,700,000	1,900,000
Bulk	41,000	92,000	55,000	2,400,000	5,300,000	3,200,000
Vehicle Carrier	72,000	75,000	120,000	4,200,000	4,400,000	6,700,000
Crude-Oil Tanker	60,000	37,000	33,000	3,500,000	2,200,000	1,900,000
Product Tanker	110,000	110,000	160,000	6,800,000	6,900,000	10,000,000

Source: California Air Resources Board (2006e)

¹⁶⁰ California Air Resources Board (2006e)

4.4. OGV Expanded Auxiliary Engine Fuel Requirements

Background

Auxiliary engines are responsible for a major portion of OGV emissions in the region. In 2004, auxiliary engine emissions in the South Coast Air Basin were approximately 1.9 tons per day of PM and 21 tons per day of NO_x, or 50% of the total OGV emissions in the basin. Most vessels currently use high sulfur residual oil bunker fuel in their auxiliary engines, which typically has 2.5% sulfur content. ARB's Auxiliary Engine Rule mandates use of fuel with a sulfur content of 0.5% (5,000 ppm) or less starting January 1, 2007 and 0.1% (1,000 ppm) sulfur starting in 2010, within 24 nautical miles of the California Coast.

As a result of ARB's Auxiliary Engine Rule, OGVs will switch from residual fuel to marine diesel oil (MDO) or marine gas oil (MGO) for their auxiliary engines beginning in 2007. This fuel is anticipated to be widely available at ports around the world. ARB estimates about 10% of the OGVs calling on California ports will require modifications to use this fuel in their auxiliary engines, including extra storage capacity and potential modifications to fuel delivery equipment.

Another significant effect of enacting auxiliary engine fuel requirements is that it can operate symbiotically with other mitigation strategies, such as those focusing on operational improvements, auxiliary engine retrofit requirements, main engine fuels, and/or other main engine emissions mitigation schemes.

Strategy Definition

This strategy would require use of 0.2% sulfur fuel in auxiliary engines within the San Pedro Bay reduced speed zone (RSZ) between 2007 and 2010. This is consistent with Strategy OGV-3 in the CAAP. The RSZ is currently 20 nautical miles (nm) of Point Fermin but will be extended to 40 nm under the enhanced VSR strategy. After 2010, this strategy would require 0.1% sulfur fuel in auxiliary engines as specified in the ARB Rule, but would extend that requirement to cover the 40 nm RSZ rather than the 20 nm zone specified in the ARB Rule.

Pollutants Reduced

This strategy primarily targets PM and SO_x emissions from auxiliary engines, but also reduces NO_x emissions.

Emission Reduction Potential

Table 4-13 shows the estimated emission reductions resulting from this strategy out to 2035, above those of ARB's Auxiliary Engine Rule. To estimate emission impacts, we first took the emission reduction tonnage reported for the CAAP OGV-3 strategy, which extends to FY 2010/11 and reflects a no-growth scenario.

Emission reductions beyond FY 2010/11 are assumed to grow only due to economic expansion, not increased implementation of this strategy, since after 2010 the ARB Auxiliary Engine Rule sulfur limit is responsible for the majority of reductions and the expanded RSZ is well established. Thus, under the no-growth scenario, we assumed constant emission reductions between 2011 and 2035. We calculated emission reductions as a percent of the no-growth baseline, then applied these percentages to the OGV baseline discussed in Section 4.1.

Table 4-13: Emission Impacts of OGV Expanded Auxiliary Engine Fuel Requirements (tons/year)

	2010	2015	2025	2035
Emission Reductions from Expanded Aux Engine Fuel Strategy				
NO _x	24	32	47	68
PM _{2.5}	5	5	8	11
Strategy Reductions as Percent of OGV Baseline				
NO _x	0.1%	0.1%	0.1%	0.1%
PM _{2.5}	0.3%	0.3%	0.3%	0.3%

Costs

According to the CAAP, there are no additional costs to the Ports to implement this program. Thus, there are potential two cost components to this strategy:

- Costs to retrofit vessels so they can use lower sulfur fuel in the vicinity of the ports
- Incremental costs of lower sulfur fuel

Depending on the method of implementation, there could be significant additional costs to vessel operators. Shipping lines could be responsible for any retrofits in addition to higher fuel costs. However, as noted above, approximately 10% of vessels calling California ports will require retrofits, and since these retrofits would largely target fuel tanks and delivery systems, which are likely to be required to meet the ARB Auxiliary Engine Rule, they should not be considered here. Due to desired minimization of fuel switching requirements, any retrofits to meet a 0.5% sulfur standard should also be adequate to meet a 0.2% or 0.1% requirement. Hence, the only additional cost allocated to be considered under this strategy is that of lower sulfur fuel.

We estimated the additional unit cost of low sulfur fuel based on the Energy Information Administration's *2006 Annual Energy Outlook*, which includes fuel prices in 2004 dollars for all years out to 2030 for several fuel types, including distillate and residual fuels.¹⁶¹ We took the cost differential between residual and distillate fuel from the EIA report as the cost differential experienced by vessel operators. We determined the amount of fuel needed to implement this strategy from information in the CAAP for years up to 2010. Following 2010, however, only a portion of the fuel is directly attributable to this strategy, as the Auxiliary Engine Rule will require low sulfur fuel within 24 nm of Pt. Fermin. For this period, we extrapolated linearly the fuel requirements reported in the CAAP out to 2035, and assumed that 40% (16 miles out of the 40 mile RSZ) of the fuel demand is attributable this strategy. Table 4-14 shows the resulting cost estimates.

Table 4-14: Cost of OGV Expanded Auxiliary Engine Fuel Requirements

	2010	2015	2025	2035
Low Sulfur Fuel Required for Strategy Implementation (tons)	13,273	10,883	22,097	33,307
Additional Cost Over Current MDO	\$1,807,893	\$3,939,738	\$7,834,676	\$11,061,462

¹⁶¹ Energy Information Administration (2006)

Cost Effectiveness

To estimate cost effectiveness, we assumed this strategy to have a one-year life, since the only costs are the incremental fuel costs. Thus, the cost-effectiveness is the same under the SCAQMD BACT method and the ARB annualized method. Table 4-15 shows the resulting cost-effectiveness for the analysis years.

Table 4-15: Cost Effectiveness of OGV Expanded Auxiliary Engine Fuel Requirements

	NO_x		PM_{2.5}	
	SCAQMD BACT Method	ARB Annualized Method	SCAQMD BACT Method	ARB Annualized Method
2010	\$80,171	\$80,171	\$294,395	\$294,395
2015	\$124,549	\$124,549	\$720,762	\$720,762
2020	\$149,848	\$149,848	\$946,203	\$946,203
2025	\$165,729	\$165,729	\$994,111	\$994,111
2030	\$170,168	\$170,168	\$1,000,927	\$1,000,927
2035	\$162,848	\$162,848	\$1,049,170	\$1,049,170

4.5. OGV Main Engine Fuel Requirements

Background

Main engines on ocean going vessels (OGVs) are responsible for approximately 60% of total OGV NO_x emissions and 80% of total OGV PM emissions at the San Pedro Bay Ports. While ARB's adopted Auxiliary Engine Rule requires use of lower sulfur distillate fuel in OGV auxiliary engines, there is currently no similar regulation for main engines.

As with auxiliary engines, OGVs could replace the high-sulfur fuel used in main engines with lower sulfur fuel to reduce direct emissions of PM and SO_x. This could be low-sulfur distillate fuel, such as marine diesel oil (MDO) or marine gas oil (MGO), or low sulfur residual fuel. Because of the high sulfur fuel typically used in main engines, the emissions savings from main engine fuel switching would be quite large. Enacting a main engine fuel requirement could also operate symbiotically with other mitigation strategies, such as those focusing on operational improvements, auxiliary engine fuels, or potentially even main engine retrofit technologies, should any of these be demonstrated effective. ARB is currently considering a main engine fuel requirement for California ports.

There are number of implementation problems to be resolved when considering fuel switching for main engines. One major barrier is fuel availability. The No Net Increase study indicated that low sulfur, residual IFO 380 fuel with sulfur contents as low as 0.2% (2,000 ppm) may be available. However, principal conclusions of a Port of Los Angeles study on marine fuel availability concluded that marine distillate fuel with sulfur contents as low as 0.5% are available in the U.S., Europe, and possibly Canada at this time but typically not in the rest of the world, and that low sulfur residual fuels are not available.¹⁶² The availability and cost of low sulfur fuel is the primary barrier to use of reduced sulfur fuels in main engines.

The type of fuel selected to meet a given sulfur standard is critical because of technical issues related to fuel consumption in main engines. Using distillate fuel may cause lubricity problems for engines that normally run on residual fuel. There are also concerns over maintaining different fuels at their appropriate temperatures, concerns with filter clogging, engine damage, and safety issues due to flash-point. Increased cylinder wear from use of low sulfur fuel over extended hours of operation may be an additional concern. Finally, some ships may not be able to take on enough low sulfur fuel to power the main and auxiliary engines from 40 nautical miles to the berth, even though many are equipped with smaller tanks for storage of low sulfur auxiliary fuel for berthing.

Another concern with promoting use of low sulfur fuels in main engines is the need for vessels to acquire additional onboard storage for the low sulfur fuel or modify existing tanks to accept the lower sulfur option. Given the high cost of more refined fuels, it is unlikely that vessels will use low sulfur fuels exclusively, therefore some form of fuel switching is necessary. There barriers are not insurmountable, however. For example, Maersk shipping lines has instituted a policy that all its vessels will use distillate fuel in both main and auxiliary engines within 24 miles of California ports.¹⁶³

Strategy Definition

Under this strategy, all vessels calling on the San Pedro Bay Ports will switch to 0.2% sulfur MGO fuel when operating in the VSR zone beginning in 2008. This strategy would be implemented through lease

¹⁶² Starcrest Consulting Group (2005)

¹⁶³ "Maersk Inc. (2006)

requirements, and tariff changes could be considered to offset the costs of installing needed infrastructure. This strategy is consistent with strategy OGV-4 in the CAAP.

Pollutants Reduced

This strategy is primarily intended to reduce PM and SO_x emissions, but also reduces NO_x emissions.

Emission Reductions

Potential emission reductions from use of 0.2% sulfur fuel in main engines will have the largest emissions impact and the least complication when harmonized with the fuel used in auxiliary engines within the VSR zone. We estimated these reductions for all years of our program out to year 2035 as follows. We took emission reductions for years that overlap with the period of study of the CAAP directly as published. Reductions for future years were taken by first linearly extrapolating the vessel participation rate for use of 0.2% sulfur fuel for all years, but capped at 100% participation.¹⁶⁴ In reality, vessel participation would likely grow in a non-linear manner, since implementation would be accomplished through leasing requirements and the expiration of current leases does not follow a linear trend. However, data is unavailable to estimate a non-linear vessel participation trend. Using linear extrapolation, full compliance with low sulfur main engine fuel is achieved by 2025. We then determined the baseline reductions (under a no growth scenario) by extrapolating the emission reductions reported in the CAAP years as a function of the vessel participation rate for all years.

We compared the resulting emission reductions, under the CAAP no growth assumptions, to the baseline year emission levels at the two ports to determine appropriate control strategy effectiveness for all years. We then applied these control effectiveness estimates to the OGV baseline emissions, as reported in Section 4.1.

These reductions are independent of reductions achievable from use of reduced sulfur fuel in auxiliary engines, either through our auxiliary fuel strategies or implementation of the ARB's Auxiliary Engine Rule. The emission benefits calculated from this strategy are shown in Table 4-16.

Table 4-16: Emission Impacts of OGV Main Engine Low Sulfur Fuel Strategy

	2010	2015	2025	2035
Baseline OGV Emissions (tpy)				
NO _x	22,313	26,975	40,315	57,926
PM _{2.5}	1,612	1,904	2,745	3,672
Strategy Participation Rate				
	34%	81%	100%	100%
Emission Reduction (tpy)				
NO _x	491	1,453	2,702	3,882
PM _{2.5}	328	944	1,692	2,262
Emission Reduction as Percent of Baseline				
NO _x	2%	5%	7%	7%
PM _{2.5}	20%	50%	62%	62%

Costs

There are three cost components to this strategy:

¹⁶⁴ Port of Los Angeles and Port of Long Beach (2006)

- Costs to the ports to verify compliance
- Costs to retrofit vessels so they can use lower sulfur fuel in the vicinity of the ports
- Incremental costs of lower sulfur fuel.

The ports would likely incur a small cost associated with verifying and administering the requirements of this strategy. The CAAP strategy OGV-4 mentions this cost but provides no estimate of its magnitude. In this strategy, we assume these costs to be zero, since the magnitude of this cost would be much smaller than the incremental fuel costs and likely result in little additional staffing needs.

Significant costs are likely to be incurred by shipping lines to meet these main engine fuel switching requirements. We have assumed here that the bulk of these costs will be due to increased fuel costs in migrating from high sulfur fuel, such as IFO380, to low sulfur MGO in main engines, rather than retrofit costs. Other costs could be incurred by the shipping lines for retrofits to their vessels to ensure correct fuel switching and operation. However, a large part of the required ship-side infrastructure, such as additional tanks, are likely to have been installed under the requirements of the ARB's Auxiliary Engine Rule, and thus should not be considered here. Because this strategy is intended to harmonize with the auxiliary fuel requirements, the intention is to minimize vessel hardware changes. We recognize that this assumption could result in an underestimate of the total cost to shipping lines if the infrastructure required for the Auxiliary Engine Rule is not adequate to enable main engine fuel switching.

To estimate fuel switching costs, we used the Energy Information Administration's 2006 Annual Energy Outlook to determine the price differential between residual and distillate fuel through 2030, and assumed this differential represents the incremental fuel costs to vessel operators.¹⁶⁵ We took the cost differential between residual and distillate fuel from the EIA report as the cost differential experienced by shippers.

The quantity of main engine fuel needed for our fuel switching strategy is difficult to determine. We estimated the amount of main engine fuel switched using emission reduction control factors published in the CAAP for switching from 2.7% IFO380 to 0.2% MGO fuel and baseline emission factors (in tons pollutant per ton of fuel) as reported in the Port of Los Angeles Fuel Study.¹⁶⁶

Table 4-17 shows the estimated tonnage of low sulfur main engine fuel required to meet the needs of this strategy, the fuel cost differential, and the total incremental fuel cost.

Table 4-17: Total Costs of OGV Main Engine Low Sulfur Fuel Strategy

	2010	2015	2025	2035
Low Sulfur (0.2%) Fuel Required (tons)	68,720	200,177	364,396	502,994
Cost Differential from IFO380 (\$/ton)	\$341	\$362	\$355	\$332
Incremental Cost	\$23,380,620	\$72,466,759	\$129,201,338	\$167,045,215

¹⁶⁵ Energy Information Administration (2006)

¹⁶⁶ Starcrest Consulting Group (2005)

Cost Effectiveness

To estimate cost effectiveness, we assumed this strategy to have a one-year life, since the primary costs are the incremental fuel costs. Thus, the cost-effectiveness is the same under the SCAQMD BACT method and the ARB annualized method. Table 4-18 shows the resulting cost-effectiveness for the analysis years.

Table 4-18: Cost Effectiveness of OGV Main Engine Low Sulfur Fuel Strategy

	NO_x		PM_{2.5}	
	SCAQMD BACT Method	ARB Annualized Method	SCAQMD BACT Method	ARB Annualized Method
2010	\$48,238	\$48,238	\$72,049	\$72,049
2015	\$49,873	\$49,873	\$76,786	\$76,786
2020	\$49,100	\$49,100	\$76,699	\$76,699
2025	\$47,824	\$47,824	\$76,391	\$76,391
2030	\$45,830	\$45,830	\$75,849	\$75,849
2035	\$43,034	\$43,034	\$73,830	\$73,830

4.6. OGV Engine Improvements: Slide Valve Injectors

Background

Emissions from existing OGV engines could be reduced through a variety of retrofit technologies, including slide-valve injection, optimized timing injection, increased compression ratio, selective catalytic reduction (SCR), water injection, diesel particulate filters (DPFs), diesel oxidation catalysts (DOCs), exhaust gas recirculation (EGR), and other control technologies. These technologies could be promoted by requiring that shipping lines either retrofit their main and/or auxiliary marine engines with emission control devices or replace the engines with those that meet more stringent emission standards.

While many technologies and applications have been proven effective at reducing emissions from compression ignition engines, very few have been rigorously proven in the marine environment. Those applications that can be applied will vary between main and auxiliary engines. To accommodate the testing and phase-in of emission reduction technologies for main and auxiliary engines, the Ports of Los Angeles and Long Beach have created a Technology Advancement Program (TAP) to evaluate promising technologies. The TAP is envisioned as a partnership between the Ports, SCAQMD, CARB, and EPA that evaluates technology, potential applications, costs, funding, and potential funding opportunities, as well as reviewing results. The intention is to evaluate promising technologies and then potentially mandate their use in the region.

To date, the only technology approved by the TAP is slide-valve injectors for main engines. The TAP has approved its use and estimated its emissions reduction potential, although the final potential has yet to be quantified.

According to one recent study, slide valve retrofits are simple to undertake on older engines that did not come manufactured with such technology, although most newer engines (approximately model year 2000 and later) are thus manufactured.¹⁶⁷ The retrofit entails removing the old valves, enlarging fuel injector holes in the cylinder covers, and possibly replacing spring housings. The retrofit typically requires several hours of work per cylinder. Slide valve retrofits are expected to be possible for all 2-stroke engines.

Strategy Definition

This strategy involves the replacement of conventional fuel valves with slide valve injectors. It is intended to harmonize with the emission reductions determined in the CAAP strategy OGV-5 for years of overlap, but considers emission reductions out to year 2035.

Pollutants Reduced

Slide valve injectors are principally a NO_x reduction technology, as they tend to reduce combustion temperatures. There is also a PM benefit.

Emission Reductions

The CAAP estimates the emission reduction potential from slide valve injectors at 30% for main engine NO_x emissions and 25% for main engine PM emissions. Table 4-19 shows baseline emissions, estimated vessel participation in a main engine slide-valve injector retrofit program, and estimated emission reduction. To estimate emission impacts, we first took the total emission reductions and vessel

¹⁶⁷ Entec UK Ltd. (2005)

participation through 2010 directly from the CAAP. We estimated vessel participation in extended years by extrapolating the CAAP trend in participation. Participation peaks at 56% in 2015, and we assumed a constant 56% participation rate thereafter, since newer vessels do not require the retrofits. In reality, participation is likely to decline in later analysis years as older vessels are retired, but we do not have the data necessary to estimate this effect.

We determined emission reductions under the CAAP no-growth scenario by extrapolating the CAAP emission reductions as a function of vessel participation for all years of our study. For each analysis year, we divided the emission reduction by the no-growth baseline NO_x and PM_{2.5} emissions to estimate the percent reduction. Finally, we then applied the percent emission reduction to the OGV emissions baseline presented in Section 4.1.

Table 4-19: Emission Impacts of Main Engine Slide Valve Injection Retrofits

	2010	2015	2025	2035
Baseline Emissions				
NO _x	22,313	26,975	40,315	57,926
PM _{2.5}	1,612	1,904	2,745	3,672
Main Engine Slide Valve Injector Participation				
	34%	56%	56%	56%
Main Engine Slide Valve Injector Emission Reductions				
NO _x	1,472	2,935	4,386	6,302
PM	128	249	359	480
Main Engine Emission Reductions as Percent of Baseline				
NO _x	7%	11%	11%	11%
PM	8%	13%	13%	13%

Costs

There are potentially two cost components of this strategy:

- Costs to the ports to verify compliance and fund the TAP
- Costs to retrofit vessels

As envisioned in the CAAP, the Ports would subsidize costs associated with slide valve injectors (and other technology improvements) only through their contributions to the TAP, which would be the ultimate provider of any subsidized funds. However, it is unknown how this funding would be applied to a specific technology. Port administrative costs for this specific program would be relatively small (compared to the retrofit costs), and would likely be covered by the TAP contributions.

The most significant costs associated with this strategy will be the costs to retrofit vessels, incurred largely by vessel owners, although possibly subsidized by the ports or other agencies. A study by Entec estimated the total annualized costs associated with retrofitting European vessels with slide-valve injectors (termed “basic IEM”), including capital costs associated with the equipment, labor, and a 2.5 year lifetime.¹⁶⁸ Their (annualized) cost estimates range from about €500 to €5,200 (\$650 to \$6,760) per vessel, depending on vessel size and age.

We estimated the total costs of this our strategy by first determining the total number of retrofits that would occur in each year of implementation, based on the participation rate by year and the baseline

¹⁶⁸ Entec UK Ltd. (2005)

number of unique vessel calls. We assume that, on average, a vessel calls the San Pedro Bay Ports five times in the baseline year. We then estimated the population distribution of large/medium/small and new/old vessels to which retrofits would apply, and determined the average annualized cost per vessel retrofit at the Ports. The annualized average vessel cost for retrofits is expected to be \$5,000. Multiplying this value by the anticipated total number of retrofit vessels operating in a given year results in the cost estimates shown in Table 4-20.

Table 4-20: Total Costs Associated with Retrofitting Vessels with Slide-Valve Injectors

	2010	2015	2025	2035
Number of Retrofit Vessels Operating	344	567	567	567
Retrofit Cost	\$1,720,070	\$2,835,819	\$2,835,819	\$2,835,819

Cost Effectiveness

To determine cost effectiveness of the current program, we considered the full 30 year lifetime of the strategy. The total cost was determined according to the discounted cash flow method of SCAQMD's BACT analysis. Future year emission reductions for years not shown in Table 4-19 were determined by non-linear, best fit interpolation. The total cost was then compared to the total emission reductions over the project lifetime to compute overall strategy cost effectiveness. Table 4-21 shows the results of these calculations. Because this strategy involves significant retrofit costs spread out over multiple years, the ARB annualized method is not an appropriate method to estimate cost-effectiveness.

Table 4-21: Cost Effectiveness of the Slide Value Injector Retrofit Strategy

NO _x		PM _{2.5}	
SCAQMD BACT Method	ARB Annualized Method	SCAQMD BACT Method	ARB Annualized Method
\$359	NA	\$4,409	NA

4.7. OGV Engine Improvements: Other Technologies

Background

Emissions from existing OGV engines could be reduced through a variety of retrofit technologies. These technologies could be promoted by requiring that shipping lines either retrofit their main and/or auxiliary marine engines with emission control devices or replace the engines with those that meet more stringent emission standards. The Ports of Los Angeles and Long Beach have created a Technology Advancement Program (TAP) to evaluate promising marine engine technologies. The intention is to evaluate promising technologies and then potentially mandate their use in the region.

To date the only technology approved by the TAP is slide-valve injectors for main engines. Other retrofit technologies are currently under study by the TAP. In addition to shore- or barge-based external scrubber technology, these could include:

- Exhaust aftertreatment technologies such as selective catalytic reduction (SCR), diesel particulate filters, oxidation catalysts, and sea water scrubbers
- Other internal engine modifications, including fuel injection timing (retard), improved electronic control, exhaust gas recirculation (EGR), combustion chamber geometry modifications, compression ratio modification, fuel-air mixture enhancement (swirl), and optimized timing
- Optimized or modified fuel injection technology, such as common rail fuel systems, improved injection pressure, improved injector geometry, and enhanced timing and valve control
- Modified fuel/combustion characteristics, such as water injection, emulsified fuels, and humid air (motors)

Many of these technologies could also be applied simultaneously to further enhance emission reductions for several pollutants.

Strategy Definition

Development of most technologies is still in very preliminary stages for marine applications. Consistent technical information on the costs and effectiveness of most potential technologies is not available. To illustrate two possible technologies, we assess the following technologies for ocean going vessels:

- Selective Catalytic Reduction (SCR), and
- Exhaust Gas Recirculation (EGR).

The methodology we applied is consistent with the analysis of slide valve injectors for OGVs.

Pollutants Reduced

All criteria pollutants, especially PM, NO_x, and SO_x, are potentially targeted by certain engine and exhaust stream technology improvements, depending on the technology employed. EGR and SCR target NO_x emissions in particular.

Emission Reductions

To estimate the emissions impacts for the two sample OGV retrofit strategies, we assumed the participation rate to be half that of the slide-valve injector application, presented in Section 4.6. We

assume SCR can reduce OGV NO_x emissions by 95% and PM by 45%, and EGR can reduce OGV NO_x emissions by 35% while slightly increasing PM emissions (+1%).¹⁶⁹ Multiplying the participation by the control effectiveness by the emissions baseline results in emission reductions shown in Table 4-22.

Table 4-22: Emission Impacts of Other OGV Retrofit Strategies

	2010	2015	2025	2035
Baseline Emissions				
NO _x	22,313	26,975	40,315	57,926
PM _{2.5}	1,612	1,904	2,745	3,672
Participation Rate	17%	28%	28%	28%
Emission Reduction -- SCR				
NO _x	3,389	6,747	10,083	14,488
PM _{2.5}	122	238	343	460
Emission Reduction -- EGR				
NO _x	1,318	2,624	3,921	5,634
PM _{2.5}	(3)	(5)	(7)	(10)

Costs

For the technology retrofit strategies we present here, there are two potential cost components:

- Costs to the ports to verify compliance and fund the TAP
- Costs to retrofit vessels

As in the slide valve retrofit strategy, we assume that the bulk of the costs will be due to the retrofits themselves. We estimated the number of retrofits performed in a given year based on the total number of retrofitted vessels operating and the lifetime of existing retrofits. We assumed the cost per retrofit to be \$620,000 for SCR and \$6,600 for EGR, and both technologies are assumed to have a 15-year lifetime. All calculations assume the vessels are already using low sulfur MDO. Table 4-23 shows these calculations for our two sample strategies.

Table 4-23: Estimated Costs of Other OGV Retrofit Strategies

		2010	2015	2025	2035
SCR	Retrofits/year	38	22	42	0
	Total Cost	\$23,313,347	\$13,629,522	\$26,130,011	\$0
EGR	Retrofits/year	38	22	42	0
	Total Cost	\$248,174	\$145,088	\$278,158	\$0

Cost Effectiveness

Table 4-24 shows the estimated cost effectiveness of these two strategies. It is noteworthy that EGR has no previous applications in large ocean going vessels and could pose serious issues with engine performance. It is believed that use of EGR would lead to some increase in PM emissions due to

¹⁶⁹ Entec UK Ltd. (2005)

recirculation of exhaust PM back into the combustion chamber with use of low sulfur fuel and would not be feasible without it. Because this strategy involves significant retrofit costs spread out over multiple years, the ARB annualized method is not an appropriate method to estimate cost-effectiveness.

Table 4-24: Estimated Cost Effectiveness of Other OGV Retrofit Strategies (\$ per ton)

	NO_x		PM_{2.5}	
	SCAQMD BACT Method	ARB Annualized Method	SCAQMD BACT Method	ARB Annualized Method
SCR	\$917	NA	\$27,111	NA
EGR	\$25	NA	(increase)	NA

4.8. Crane Double Cycling

Description of Strategy

This strategy quantifies the reduction in NO_x and PM from the implementation of crane double-cycling at the ports of Los Angeles and Long Beach. Crane double-cycling is a technique that enables the conversion of empty crane moves into productive ones. In a traditional crane movement, unloading and loading of containers happen in different stages, so cranes are empty approximately half the time. In double-cycling, loading and unloading happen concurrently, with cranes always utilized. Double-cycling can reduce operating times by 10%, improving the productivity of vessels, cranes, and berths. It can also reduce the requirements for yard tractors and drivers by 20%.

While this strategy appears to be feasible from a technological standpoint, it introduces major challenges. It requires different operational procedures, training, new container handling equipment, as well as adjustments to how containers are stored and moved within the terminals. Additionally, operational changes at export ports (e.g., Asian ports) are also required since containers need to be positioned inside the vessel in a way that enables double cycling to operate.

Since this strategy reduces hotelling emissions from ocean going vessels, it assumes that cold ironing will not be in place.

Pollutants Reduced

This strategy reduces emissions of all pollutants, including NO_x, and PM, because it reduces hotelling emissions from ocean going vessels.

Emissions Impacts

Methodology

Even though there has been research on the operational aspects of crane double-cycling, there have been no studies on emissions reduction from such strategy. A previous study estimated that operating times can be improved by 10% due to the implementation of crane double-cycling.¹⁷⁰ Therefore, hotelling emissions from ships at berth can also be reduced by up to 10%.

Based on a forecast of vessel activity, it is possible to determine total hotelling time per day (Table 4-25).¹⁷¹ Since the data was limited to 2020, our analysis did not account for the years beyond 2020.

¹⁷⁰ Goodchild A (2006)

¹⁷¹ Mercator Transport Group (2005)

Table 4-25: San Pedro Bay Ports Call Count - Per Week

TEU Class	2010	2015	2020
<1000	1	-	-
1000 - 2000	4	2	1
2000 - 3000	11	11	9
3000 - 4000	7	6	10
4000 - 5000	20	21	23
5000 - 6000	11	13	16
6000 - 7000	10	12	15
7000 - 8000	6	9	12
8000 - 10000	8	9	11
10000 - 12000	-	4	11
Total:	78	87	108

In 2001, hotelling time for container vessels averaged 42.8 hours in the Port of Los Angeles.¹⁷² Assuming that the fraction of hotelling time per TEU remains constant over time, the total number of hotelling hours can be forecasted. Since not all hotelling time is productive (i.e., loading and unloading), we assumed that 85% of hotelling time is productive in 2010. This assumption is based on the author's professional judgment, since no information on this metric was available. This utilization is increased by 5% every 5 years due to the need to increase berth productivity. Daily hotelling hours were calculated by assuming 5-day (per week) port operations. Table 4-26 includes the number of daily hours allocated to loading and unloading container ships at the ports of Los Angeles and Long Beach. As previously mentioned, total loading/unloading times with crane double-cycling are 10% lower than in the baseline scenario.

Table 4-26: Total Loading/Unloading Time (hours per day)

Scenario	2010	2015	2020
Baseline	757	1,000	1,424
Crane Double-Cycling	681	900	1,281

As presented in Table 4-27, ship hotelling emission factors were estimated by multiplying auxiliary engine emission factors (in grams/kWh)¹⁷³, average auxiliary engine power for container ships (in kW)¹⁷⁴, and load factor for container ships while hotelling.¹⁷⁵

Table 4-27: Calculation of Hotelling Emission Factors (grams/hour)

Pollutant	Auxiliary Engine Emission Factor (g/kWh)	Auxiliary Engine Power (kW)	Load Factor	Hotelling Emission Factor (g/h)
NO _x	14.47	6,800	0.17	16,727
PM _{2.5}	0.94	6,800	0.17	1,087

Results

Total emission reductions were obtained by multiplying activity data (i.e., number of idling hours) by emission factors in grams per hour, shown in Table 4-28. PM_{2.5} emission factors were estimated assuming that 91% of total PM emissions are PM_{2.5}. Emission reductions increase over time due to an increase in port traffic.

¹⁷² Starcrest Consulting Group (2004)

¹⁷³ Entec UK Ltd. (2002)

¹⁷⁴ California Air Resources Board (2005b)

¹⁷⁵ Starcrest (2006)

Table 4-28: Emission Reduction (Tons/day)

	NO_x	PM_{2.5}
2010	1.27	0.07
2015	1.67	0.10
2020	2.38	0.14

Costs

Crane double cycling would require relatively little in terms of capital investment, although (as noted above) it entails major operational challenges. There would be some additional costs from the requirements for new container handling equipment. For example, if container handling equipment for storage and retrieval of containers (e.g., top picks) are required for terminal operations, double cycling will double the equipment requirements. One study estimated that these additional costs would amount to approximately \$2 per container.¹⁷⁶ This study estimates crane double-cycling would create financial benefits of approximately \$65 per container due to improved vessel, crane, and berth productivity, as well as less requirements for drivers, yard trucks, and chassis. This strategy requires coordination with export ports, since it affects the positioning of containers inside the vessel.

Additional operational costs will likely occur due to the need of coordination with other ports. Because there is substantial uncertainty in these numbers, cost effectiveness is not calculated for this strategy.

Cost Effectiveness

We are unable to estimate the cost-effectiveness of this strategy because of the difficulty in quantifying strategy costs.

¹⁷⁶ Goodchild A (2006)

5. Harbor Craft Strategies

5.1. Introduction

Overview

The harbor craft category encompasses a wide variety of vessel types: assist tugs, ocean-going towing tugs, ferries, small excursion craft, supply vessels (for off-shore service, cable laying, etc.), dredges, service vessels (such as fire, police, pilot boats, commercial fishing), and other miscellaneous vessels. Harbor craft are largely U.S.-flagged vessels and, therefore, the engines used on the vessels fall under the regulatory authority of EPA and ARB. Harbor craft are typically powered by smaller diesel engines and use a lower sulfur fuel than large OGVs.

We identified promising OGV emission reduction strategies through a review of the port's *Clean Air Action Plan*, CARB's *Emission Reduction Plan for Ports and Goods Movement in California*, the report by the Port of Los Angeles No Net Increase Task Force, as well as other documents. The strategies for harbor craft emission control include many of the same measures used for ocean-going vessels: lower emitting engines, cleaner fuels, after-treatment controls, and shoreside power. To date, some of these strategies have been implemented using Carl Moyer, AQMD, port, and other funds. These strategies have been developed on an ad hoc basis within the available funding limits and include a range of activities. New engines meeting lower emission standards are the primary method for reducing harbor craft emissions, but fuel options and, in some cases, after-treatment controls have been used. We have quantified the benefits and costs of five strategies.

Baseline Emissions

According to emission inventory data from SCAQMD and ARB (presented in Section 1), harbor craft are currently responsible for 7% of NO_x and 8% of PM_{2.5} emissions from goods movement in the South Coast Air Basin. Emissions from this source category are expected to decrease over the study period, both in absolute terms and as a percentage of total goods movement emissions, because of federal and state regulations that will reduce emission from harbor craft. By 2020, harbor craft will account for 6% of NO_x and 5% of PM_{2.5} emissions from goods movement in the South Coast Air Basin. Table 5-1 shows the ARB's estimates of baseline harbor craft emissions in the South Coast Air Basin from 2005 to 2020. As will be discussed below, this analysis makes the 2020 – 2030 emissions proportional to projected harbor craft fuel use during that time interval.

Table 5-1: Projections of Baseline Harbor Craft Emissions (tons/day)

	2005	2010	2015	2020
NO _x	24.94	20.52	15.71	13.67
PM _{2.5}	1.32	1.12	0.83	0.71
ROG	2.45	2.00	1.52	1.32

Source: California Air Resources Board

The emissions from harbor craft engines were initially regulated through EPA Tier 1 standards and phased-in more stringent Tier 2 emission standards from 2004 through 2007. EPA recently announced proposed new emission standards for category 1 and 2 commercial marine engines (which would apply to all harbor craft).¹⁷⁷ If enacted, the new Tier 3 standards would take effect beginning in 2013 and require NO_x and PM emission reductions of 28% and 66%, respectively, compared to the current Tier 2

¹⁷⁷ U.S. Environmental Protection Agency (2007a)

standards. Tier 4 standards would take effect in 2016 – 2018 (depending on engine size) and require NOx and PM emission reductions of 84% and 91%, respectively, compared to the current Tier 2 standards.

CARB has proposed regulations for existing (in-use) commercial harbor craft. These regulations would require the following:

- All harbor craft to use CARB diesel fuel
- Engines acquired for in-use vessels must meet most current EPA engine standards
- Older engines must be replaced with new certified engines meeting EPA Tier 2 or 3 standards, or must use aftertreatment. The compliance schedule is phased-in from 2009 to 2022, targeting the oldest and high use engines first.

5.2. Cleaner Fuels for Harbor Craft – Emulsified Fuel

Strategy Description

This strategy involves substituting emulsified fuels for regular marine diesel in harbor craft propulsion and auxiliary engines. Fuel emulsions typically combine about 77 percent diesel, 20 percent water, and about 3 percent chemical additives to maintain the emulsion properties. The water molecules are completely enclosed by fuel molecules. This prevents corrosion from water from coming into contact with engine and fuel system components, and maintains lubricity. During combustion, evaporation of the water contained in the fuel decreases peak combustion temperatures, lowering NO_x and reducing the size of fuel droplets that are combusted, allowing for more complete combustion.

Note that as of December 2006, Lubrizol Corporation has stopped producing PuriNOx, the most common emulsified fuel. At the present time, it is unclear if other emulsified fuels will be available in sufficient quantities to allow implementation of this strategy.

Pollutants Reduced

The use of emulsified fuel can reduce emissions of both NO_x and PM.

Background

Table 5-2 shows an estimate of the fuel consumption by type of harbor craft in the South Coast Air Quality Management District in 1999-2001. The estimate was calculated from the results of ARB's 2002 commercial harbor craft survey¹⁷⁸ and subsequent emission inventory development.¹⁷⁹

Table 5-2: Estimate of Fuel Use by Vessel Type, South Coast

Vessel Type	Gallons Diesel Fuel Consumed			Average Annual Growth (%)
	1999	2000	2001	
Tug Boats	2,259,529	3,031,524	3,184,025	18.7
Ferry/Excursion Boats	7,419,052	7,602,114	8,887,245	9.4
Commercial Fishing Boats	1,475,295	1,532,788	1,530,695	1.9
Tow Boats	87,593	88,581	91,533	2.2
Commercial Passenger Fishing Boats	2,591,495	2,901,999	3,219,482	11.5
Crew Boats	1,030,711	1,268,018	1,363,523	15
Work boats	377,786	351,495	374,650	-0.4
Pilot Boats	665,753	666,567	667,017	0.1
Totals	15,907,214	17,443,086	19,318,170	10.2

For all harbor craft categories combined, the annual average growth rate in fuel use was 10.2 percent. The largest growth in fuel use (18.7 percent) was for tug boats.

On May 16, 2005 ARB adopted regulations extending California's standards for motor vehicle diesel fuel ("CARB diesel") to diesel fuel used in harbor craft.¹⁸⁰ Harbor craft were defined as marine vessels less than 400 feet in length overall, with weight less than 10,000 gross tons, and that are propelled by marine diesel engines with a per-cylinder displacement of less than 30 liters. For diesel fuel used in the South

¹⁷⁸ California Air Resources Board (2004)

¹⁷⁹ California Air Resources Board (Undated)

¹⁸⁰ California Air Resources Board (2005a)

Coast Air Quality Management District, the regulations became applicable on January 1, 2006. Note that they do not apply to military specification fuel used in military vessels.

The standards that now apply to harbor craft govern the sulfur content and aromatic content of diesel fuels, which are, respectively, 15 parts per million by weight (ppmw) and 10 percent by volume.¹⁸¹ Commercial harbor craft in the South Coast Air Basin currently consume about 24 million gallons of diesel fuel per year (Holmes et al., 2004).¹⁸² Information from an ARB survey of commercial harbor craft¹⁸³ indicates that only about 11 percent of the diesel fuel consumed by harbor craft was, before 2006, CARB diesel.¹⁸⁴ The rest of the harbor craft fuel use is believed to have complied with the USEPA on-road standard of 500 ppmw sulfur (1993-2006). The baseline for sulfur content was therefore 500 ppmw from 2001 through 2005, and 15 ppmw since the beginning of 2006.

Emission Reductions

ARB has verified emission reductions for emulsified fuel used in on-road heavy duty diesel applications – up to a 60% reduction in PM and 15 to 16% reduction in NO_x.¹⁸⁵ Studies of large non-road engines have found 19% reductions in NO_x and 17% reductions in PM using emulsified fuel. However, a recent demonstration project using emulsified diesel in a San Francisco Bay Area ferry showed an increase in NO_x and PM emissions in some operating modes. Thus, more research is needed to estimate likely emission impacts for harbor craft.

Countering the reduction in emissions is a decrease in fuel efficiency. The water in the fuel does not contribute any energy toward combustion, and its evaporation absorbs energy. The result is that the same volume of emulsified diesel will have 10 to 30% lower effective energy content, depending on how much water is in the blend, than the base fuel.¹⁸⁶

We estimated emission reductions as follows.

- We calculated a least-squares regression formula for annual fuel consumption by each harbor craft type, using the 1999-2001 data shown in Table 5.2. The formula was used to extrapolate fuel use to each year from 2005 through 2030. The fuel use by each harbor craft type was then summed to obtain total annual fuel use.
- For every five years from 2005 through 2020, we used the baseline NO_x and PM₁₀ emissions shown in Table 5-1; emissions for intervening years were linearly interpolated.
- To estimate emissions from 2021 through 2030, we used emission factors (in tons per gallon) for each pollutant, based upon the emissions and fuel use in 2020.
- NO_x and PM emission reductions were assumed to be 19 and 17 percent, respectively, of the baseline emissions. It was assumed that PM_{2.5} emissions make up 91% of total PM emissions.

Table 5-3 shows the results of the emission reduction calculations.

¹⁸¹ The regulation also includes a lubricity standard, which is not directly relevant to the subject under discussion.

¹⁸² This value is higher than the totals in Table 1 because fuel use data were not available for the category “Other” in the ARB survey,

¹⁸³ California Air Resources Board (2004)

¹⁸⁴ An exception is for ferry boats, which have been required to use CARB diesel for a longer period.

¹⁸⁵ Simeroth (2002, 2003)

¹⁸⁶ City of New York (2004)

Table 5-3: Harbor Craft Emission Reductions From Use of Emulsified Diesel (tons/yr)

	2010	2015	2020	2025	2030
NO _x	1,423	1,089	948	1,105	1,261
PM _{2.5}	66	49	42	48	55

Costs

Harbor craft would not require engine modifications for use of emulsified fuels as ocean-going vessels do and, hence, initial capital costs would be significantly less. Capital costs will depend somewhat on the arrangement that harbor craft fleet operators use for storing emulsified fuel and dispensing it to individual vessels. If mixed fuel remains undisturbed for a long enough time, the water and fuel molecules separate; it is therefore necessary for the emulsified fuel to be stirred after some time.¹⁸⁷ An alternative to storing emulsified fuel is to store only the non-aqueous portion and mix in the water just before dispensing or use. This combination of segregated storage, addition of water, and mixing could occur onshore, at offshore fueling stations, on fuel service barges, or on board the vessels. Once the emulsified fuel is in the harbor craft fuel tanks, there is again a potential for separation. It is unknown as of this writing whether the turnover of fuel in the harbor craft would be rapid enough to preclude on-board mixing. Because of the uncertainty in the storage and dispensing arrangements, the capital and operating costs of storage tanks and on-shore or on-board mixing has not been included in the analysis.

In Southern California, the cost of emulsified diesel fuel has historically been about 20 cents per gallon higher than that of regular diesel fuel.¹⁸⁸ However, as noted above, the most common emulsified diesel fuel (PuriNOx) is no longer produced as of December 2006. It is unclear if alternative emulsified fuels will be available in sufficient quantities to implement this strategy, and if so, what their price increment would be. For this illustrative analysis, we assume a 20 cent per gallon incremental cost.

Cost Effectiveness

To estimate the cost effectiveness of switching from diesel fuel to emulsified diesel fuel, we performed the following calculations:

- Diesel fuel cost projections for each year from 2005 through 2030 were obtained from the U.S. Department of Energy, Energy Information Administration's *2007 Annual Energy Outlook*.¹⁸⁹
- We assumed that emulsified diesel fuel would have a 20-percent lower energy content than regular diesel. We then multiplied the diesel fuel use estimates by $1/(1 - 0.2) = 1.25$ to obtain emulsified diesel use in each year.
- Emulsified diesel fuel was assumed to cost 20 cents more per gallon than the diesel fuel that would otherwise be used.

We assumed the capital cost of switching to emulsified diesel fuel would be negligible. The annualized cost effectiveness was calculated on the basis of the first year's emission reductions and incremental cost. Table 5-4 shows the resulting cost-effectiveness estimates.

¹⁸⁷ Scott, J., Silverman, I., and Tatham, S. (2005)

¹⁸⁸ General Petroleum (2007)

¹⁸⁹ Energy Information Administration (2006)

Table 5-4: Cost Effectiveness of Substituting Emulsified Diesel Fuel in Harbor Craft

	NO_x	PM_{2.5}
ARB Annualized Method		
Annual Emission Reduction (tons) in 2010	1,423	66
Incremental Annual Cost (\$million)	\$28.6	\$28.50
Cost-Effectiveness (\$/ton)	\$20,066	\$430,917
SCAQMD BACT Method		
Total Emission Reduction (tons)	31,796	1,594
Total Cost (\$million)	\$561.6	\$561.60
Cost-Effectiveness (\$/ton)	\$17,663	\$393,685

5.3. Cleaner Fuels for Harbor Craft – Biodiesel

Strategy Description

This strategy would involve substituting biodiesel fuel for CARB diesel in harbor craft propulsion and auxiliary engines. Biodiesel fuels are methyl or ethyl esters derived from a variety of renewable sources such as vegetable oil, animal fat and cooking oil.¹⁹⁰ Biodiesel is produced in pure form (referred to as “B100”) and often blended with petroleum diesel. The blends are designated BXX, where “XX” is the percentage of Biodiesel. Biodiesel currently sold at retail sites in California ranges from B20 to B100.¹⁹¹

Soy methyl ester diesel (“SME”), which is derived from soybean oil, is the most common biodiesel in the United States. Because they contain up to 10 percent oxygen by weight, stored biodiesel fuels may become rancid.¹⁹² It is therefore necessary to include an antioxidant in the blend.

As of November 14, 2006, there were 87 commercial biodiesel production facilities in the United States, 4 of which were in California.¹⁹³ National annual production capacity was 582 million gallons. The four California plants have a combined capacity of 11.25 million gallons per year, of which 11 million gallons are at plants in Southern California (Port Hueneme and Coachella).

Sixty-five new biodiesel plants are under construction and another thirteen are expanding their operations. National production capacity is projected to be about 2 billion gallons by the spring of 2008.¹⁹⁴ Note that capacity does not equal production or sales. Nevertheless, it is clear that biodiesel is commercially available in the near and long term. In 1998, the B20 blend was designated by the U.S. Department of Energy as an “alternative fuel” under the Energy Policy Act. This designation provides an incentive for government fleet services to purchase B20 for their diesel-powered vehicles, which may stimulate production of biodiesel and result in lower prices.

The ARB has issued a draft advisory on biodiesel use that is relevant to this strategy.¹⁹⁵ First, diesel engines that have been retrofitted with ARB-verified emission control devices may use biodiesel blends up to B20. Presumably use of blends with a higher biodiesel content may negate the certification for the control device. Second, blends of B50 and below must meet the ARB’s sulfur and aromatic hydrocarbon limits for diesel fuel. Biodiesel blends above B50 are not considered as “diesel fuel” and are not subject to the diesel fuel limits.

Pollutants Reduced

The use of biodiesel can reduce emissions of sulfur oxides, PM, and ROG. NO_x emissions may increase as a result of biodiesel fuel use. These effects tend to increase as the percent of biodiesel in the fuel increases.

¹⁹⁰ Esplin, G. (2005)

¹⁹¹ National Biodiesel Board (2006a)

¹⁹² Von Wedel, R. (1999)

¹⁹³ National Biodiesel Board (2006b)

¹⁹⁴ National Biodiesel Board (2006c)

¹⁹⁵ California Air Resources Board (2006b)

Emission Reductions

B100 does not contain any sulfur, aromatic compounds, heavy metals, or crude oil residues. Tests conducted by the Southwest Research Institute and summarized by Von Wedel¹⁹⁶ found that use of B20 in on-road engines reduced particulate matter emissions by about 14 to 20 percent when compared with the diesel fuel with 500 ppmw sulfur.¹⁹⁷ As described in Section 2.9, test by the National Renewable Energy Laboratory found PM reductions from 19.4% to 34.7% in on-road engines.¹⁹⁸ We assume 20% PM reduction for this analysis. Hydrocarbon emissions were reduced by about 12% to 20%.

In contrast, and partly as a result of the higher oxygen content, NO_x emissions from biodiesel are usually slightly higher than those from use of conventional diesel fuels.¹⁹⁹ NO_x emissions can be reduced by retarding the timing of ignition and slowing the fuel burn rate. However, these measures are usually offset by increases in particulate matter, hydrocarbon and carbon monoxide emissions.²⁰⁰

Emissions tests were conducted on a San Francisco Bay Area Water Transit Authority ferry that was operated on normal offroad diesel fuel (500 ppmv sulfur), B20 and B100.²⁰¹ Although results varied with engine speed, use of B20 and B100 consistently resulted in higher NO_x emissions than when 100-percent diesel fuel was used. Use of B100 reduced particulate matter emissions by 46 percent at the lowest engine speed and by 57 percent at the highest engine speed. No particulate matter reduction data for the case of B20 were presented in the report.

Emission reductions are summarized in Table 5-5.

Table 5-5: Harbor Craft Emission Reductions from Use of Biodiesel Fuel (tons/yr)

	2010	2015	2020	2025	2030
PM _{2.5}	78	58	49	57	65
NO _x	Slight increase				

Costs

The price of biodiesel is variable. As described in Section 2.9, the cost of the B20 blend has been about 20 cents per gallon higher than conventional diesel (DOE).²⁰² However, more recent price statistics included in the Clean Cities Alternative Fuel Price Reports, also published by the DOE, indicate that the difference has narrowed in recent years.²⁰³

Cost Effectiveness

Because NO_x emissions tend to increase with use of biodiesel, the cost effectiveness of using the fuel was not calculated for NO_x. To estimate the cost effectiveness of switching from diesel fuel to biodiesel fuel, we performed the following calculations for PM_{2.5}:

¹⁹⁶ Von Wedel, R. (1999)

¹⁹⁷ Emission reductions are higher when oxidation catalysts are used.

¹⁹⁸ National Renewable Energy Laboratory (2006)

¹⁹⁹ Esplin, G. (2005)

²⁰⁰ Von Wedel, R. (1999)

²⁰¹ Walther, C. and A. Barilan (2002)

²⁰² U.S. Department of Energy (2006a).

²⁰³ U.S. Department of Energy (2007).

- We calculated a least-squares regression formula for annual fuel consumption by each harbor craft type, using the 1999-2001 data shown in Table 5-2. The formula was used to extrapolate fuel use to each year from 2005 through 2030. The fuel use by each harbor craft type was then summed to obtain total annual fuel use.
- We assumed that biodiesel fuel would have the same energy content as regular diesel, and its use would reduce PM_{2.5} emissions by 20 percent.
- Diesel fuel cost projections for each year from 2005 through 2030 were obtained from the U.S. Department of Energy, Energy Information Administration's *2007 Annual Energy Outlook*.²⁰⁴
- For every five years from 2005 through 2020, we used the baseline PM₁₀ emissions shown in Table 5-1; emissions for intervening years were linearly interpolated.
- To estimate emissions from 2021 through 2030, we used an emission factor (in tons per gallon) for PM_{2.5}, based upon the emissions and fuel use in 2020.

Table 5-6 shows the resulting cost-effectiveness estimates.

Table 5-6: Cost Effectiveness of Substituting Biodiesel Fuel in Harbor Craft

	<u>PM_{2.5}</u>
ARB Annualized Method	
Annual Emission Reduction (tons) in 2010	78
Incremental Annual Cost (\$million)	\$9.00
Cost-Effectiveness (\$/ton)	\$115,343
SCAQMD BACT Method	
Total Emission Reduction, 2005-2030 (tons)	1,678
Total Cost (\$million)	\$181.60
Cost-Effectiveness (\$/ton)	\$108,209

²⁰⁴ Energy Information Administration (2006)

5.4. Retrofit Harbor Craft with Emission Controls

Strategy Description

This strategy would retrofit the existing Category 1 and 2 engines on harbor craft with emission control devices. Available technologies include diesel oxidation catalysts (DOC), which oxidize and reduce particulate and VOC emissions; diesel particulate filters (DPF), which screen out a significant portion of the PM emissions from the exhaust stream; selective catalytic reduction (SCR) systems, which use a catalytic reducing agent such as urea to reduce NO_x emissions to N₂ and H₂O; or other emission control devices, such as NO_x adsorbers or plasma catalyst systems. Many of these devices could also be combined for increased or multipollutant reductions.

Descriptions of these control technologies are found in other sections of this report. A question to be resolved is whether they can be applied practically to engines in harbor craft service.

This strategy is similar to control measure SPBP-HC1 of the San Pedro Bay Ports *Clean Air Action Plan*. According to that strategy, by 2011, all previously repowered harbor craft based at the Ports of Los Angeles and Long Beach will be retrofitted with the most effective NO_x and/or PM emissions reduction devices verified by the ARB. However, in the present analysis it applies to all harbor craft.

Pollutants Reduced

The use of retrofit devices would reduce emissions of NO_x, ROG, and/or PM, depending upon the device.

Emission Reductions

The DOC promotes the oxidation of ROG and CO with up to 90% efficiency.²⁰⁵ The effectiveness of DOCs at reducing PM emissions varies with the soluble organic fraction of the PM, but is typically about 25% to 33% of the total PM. The U.S.EPA has verified that DOCs result in at least a 25% PM reduction.²⁰⁶ DOCs are ineffective against NO_x, however, and require low sulfur diesel to achieve high efficiencies.

A DOC also promotes oxidation of SO₂ to SO₃, which leads to the generation of particulate sulfate and which may actually increase the total PM emissions despite the decrease in the soluble fraction. These catalysts are therefore designed to be selective in order to obtain a compromise between high ROG and soluble particulate activity and acceptable low SO₂ activity. The performance of the DOC is greatly enhanced by using low-sulfur diesel fuel. The benefits of DOC also include the oxidation of toxic, non-regulated, hydrocarbon-derived emissions, such as aldehydes and polycyclic aromatic hydrocarbons (PAH), and elimination of the diesel odor.²⁰⁷

In the case of the NO_x catalyst / DPF combination, NO_x reduction is estimated to be in the range of 25% to 35%, while PM and ROG reductions of 85% can be achieved. The system requires the use of ultra low sulfur diesel fuel.

The experience with C-DPF indicates that there is virtually complete elimination of odor and in the soluble organic portion of the particulate. However, some catalysts may increase sulfate emissions by

²⁰⁵ Esplin, G. (2005)

²⁰⁶ Chang, A., E. Cheung, T. Kitamura, and F. Robles (2006)

²⁰⁷ Esplin, G. (2005)

oxidizing SO₂ to sulfur trioxide (SO₃). Reformulation of the catalysts can reduce sulfate emissions to acceptable levels. Use of ultra low sulfur diesel fuel will also mitigate this problem.²⁰⁸

SCR can reduce NO_x emissions by up to 95%. Though SCR was developed for such stationary sources as power plants, it has been successfully adapted to large marine vessels. The evidence indicates, however, that the cost of this technology can be prohibitive, and that in some instances, use of existing marine SCR systems have been discontinued due to cost. Furthermore, urea, the chemical relied on by SCR to reduce NO_x emissions, can become a problem pollutant itself. The problem is worsened without the use of low-sulfur diesel and additional controls, such as oxidation catalysts.

Emission reductions for the retrofit technologies are shown in Table 5-7.

Table 5-7: Harbor Craft Emission Reductions from Use of Retrofit Devices (tons/yr)

	2010	2015	2020	2025	2030
DOC					
NO _x	0	0	0	0	0
PM _{2.5}	78	72	61	71	81
DPF with NO_x Catalyst					
NO _x	2,247	1,720	1,497	1,744	1,991
PM _{2.5}	331	246	208	243	277
SCR					
NO _x	5,992	4,587	3,992	4,652	5,309
PM _{2.5}	155	116	98	114	131

Costs

Diesel Oxidation Catalysts

The average installed cost of DOC devices has been reported to be \$12.40 per horsepower, while annual operating and maintenance costs have been estimated to be 2.6 percent of the installed capital cost.²⁰⁹ Using results of the ARB harbor craft survey, we estimate that the cost of retrofitting all the harbor craft in the South Coast Air Basin with DOCs would be about \$8.0 million. Annual operating and maintenance costs would be about \$209,000 per year.

Diesel Particulate Filters With NO_x Catalysts

The average installed cost of C-DPFs range from \$3,300 to \$5,000 for a 40-horsepower engine to \$32,000 to \$44,000 for a 1,400-horsepower engine.²¹⁰ We used the midpoints of the two ranges to develop an interpolation scale. Annual operating and maintenance costs are about 5 to 10 percent of the capital cost.²¹¹ Using results of the ARB harbor craft survey, we estimate that the cost of retrofitting all the harbor craft in the South Coast Air Basin with C-DPFs would be about \$22.0 million. Annual operating and maintenance costs would be about \$1.1 million to \$2.2 million per year.

²⁰⁸ Esplin, G. (2005)

²⁰⁹ Esplin, G. (2005)

²¹⁰ Chang et al. (2006), Appendix A.

²¹¹ Esplin, G. (2005)

Selective Catalytic Reduction

The installation and annual operating costs of a SCR system for ferries have been estimated to be about \$71 and \$20 per kilowatt, respectively.²¹² These values are equivalent to \$95 and \$27 per horsepower, respectively. Using results of the ARB harbor craft survey, we estimate that the cost of retrofitting all the harbor craft in the South Coast Air Basin with C-DPFs would be about \$61.4 million. Annual operating and maintenance costs would be about \$17.5 million per year.

Cost Effectiveness

For all the add-on controls, we assumed that retrofitting would be phased in at a uniform annual rate from the beginning of 2007 to the end of 2011. We also assumed a ten-year life for the DOCs and the SCR systems, and five years for the C-DPFs. In all years from 2012 on, all harbor craft would have add-on controls. Baseline annual emissions were obtained from the emulsified diesel analysis presented above. Table 5-8 shows the resulting cost-effectiveness estimates.

Table 5-8: Cost Effectiveness of Retrofitting Control Devices in Harbor Craft

	DOC		C-DPF		SCR	
	NO _x	PM _{2.5}	NO _x	PM _{2.5}	NO _x	PM _{2.5}
ARB Annualized Method						
Annual Emission Reduction (tons), 2010	0	78	2246.9	331	5992	156
Incremental Annual Cost (\$1000)	NA	\$406.40	\$1,318	\$1,318	\$18,983	\$18,983
Cost-Effectiveness (\$/ton)	NA	\$5,216	\$586	\$3,979	\$3,168	\$121,833
SCAQMD BACT Method						
Total Emission Reduction (tons)	0	1,664	44839	6,367	119571	2,996
Total Cost (\$million)	NA	\$16.10	\$66.6	\$66.60	\$320	\$320
Cost-Effectiveness (\$/ton)	NA	\$9,675	\$1,486	\$10,465	\$2,676	\$106,766

²¹² Esplin, G. (2005)

5.5. Shore Power for Harbor Craft

Strategy Description

Under this strategy, by 2010, all harbor craft at the Ports of Los Angeles and Long Beach would use shore power instead of auxiliary engines when tied up at their home facilities and awaiting their next assignment. For tugboats, implementation of tug shore power would occur at three locations: the Crowley home-port location next to the Port of Los Angeles fireboat facility, Millennium's home location at the end of Timm Way, and Foss Maritime's home location on Pier D in Long Beach. This strategy is consistent with the shore power component of Control Measure SPBP-HC1 of the port's *Clean Air Action Plan*. Foss Maritime has applied for a permit to install infrastructure for cold ironing of its tugboats at the Port of Long Beach.²¹³ At present, there are no plans for cold ironing of harbor craft at the Port of Los Angeles.²¹⁴

Pollutants Reduced

This strategy would reduce emissions of all pollutants because it would eliminate some use of harbor craft auxiliary engines.

Emission Reductions

Emission reductions would equal the emissions that would have occurred from continued use of the replaced auxiliary engines, as limited by regulations and permit conditions. Baseline emissions for each harbor craft vessel type in 2003 were calculated by multiplying vessel-type specific emission factors per engine by the estimated number of engines of each type in the South Coast Air Basin. Average numbers of engines per vessel and emissions per engine were obtained from the ARB's *Draft Emission Estimation Methodology for Commercial Harbor Craft Operating in California*.

To project emissions to the period 2005-2030, we assumed that 2005 emissions would be the same as in 2003. For 2006 – 2030, we assumed that emissions would change in the same proportions as were calculated in Section 5.2. All the baseline emissions were assumed to be eliminated through the use of shore power. Partially offsetting the emissions reduction would be an increase in emissions from the electric power plants supplying the electricity.

To estimate the emission reduction potential of this strategy, we performed the following calculations:

- Data on harbor craft population, engine characteristics, and fuel consumption, as well as vessel type-specific emission factors were obtained from the California Air Resources Board's *Statewide Commercial Harbor Craft Survey Final Report* and from ARB's *Draft Emission Estimation Methodology for Commercial Harbor Craft Operating in California*.
- We estimated the volume of diesel fuel use that would be eliminated by switching to shore power. Total fuel use for 2003 (the year of the ARB harbor craft inventory) for each harbor craft type was estimated by the methods described in Section 5.2. Information on the distribution of fuel use between auxiliary and propulsion engines was not reported. However, average operating hours per year by the two engine types were reported for each type of vessel. We assumed that auxiliary engine fuel use was proportional to the auxiliary engines' fraction of total operating hours. We then estimated the total diesel fuel use by harbor craft auxiliary engines in the South Coast Air

²¹³ Jelinic, T. (2006)

²¹⁴ Huang, E. (2006)

Basin in 2003 (11,858,719 gallons). For the analysis of emulsified diesel fuel, we had projected annual diesel fuel by harbor craft from 1999 to 2030. For the shore power analysis, we used the following relationship to estimate auxiliary fuel use for each year of interest:

$$AUX_i = AUX_{2003} (TOT_i / TOT_{2003})$$

where the subscripts indicate years and TOT is the total volume of diesel fuel consumed.

- The next step was to calculate the useful energy equivalent of the diesel fuel consumption. We used a heating value of 137,000 Btu per pound for diesel oil,²¹⁵ a stationary internal combustion engine efficiency of 35 percent, and a conversion factor of 0.000293 kilowatt-hours per Btu. For NO_x, PM_{2.5}, and ROG, we assumed emission factors of 0.11, 0.080, and 0.063 pounds per megawatt-hour, respectively.²¹⁶ We subtracted the power-generation emissions from the emissions reductions due to switching to shore power.

Table 5-9 shows the estimated net reduction in emissions from the use of shore power for harbor craft, assuming full implementation by 2010.

Table 5-9: Harbor Craft Net Emission Reductions from Use of Shore Power (tons/yr)

	2010	2015	2020	2025	2030
NO _x	5,762	3,633	3,078	3,584	4,090
PM _{2.5}	431	315	262	299	349
ROG	1,117	700	591	688	785

Note: Net reduction = auxiliary engine emissions eliminated – electric utility power plant emissions.

Costs

The use of shore power would incur significant one-time capital costs to install the necessary shore-side electrical infrastructure and modify harbor craft to accommodate the cable connection. Shore-side infrastructure costs vary depending on the existing infrastructure at the terminal and the expected electrical load demands of the harbor craft. Installation costs are expected to be smaller for harbor craft than they would be for larger ocean-going vessels. Dockside installation costs could range from cabling only with dockside modifications to extensive electrical system upgrades and construction of shore-side substations. However, this strategy would most likely be employed in unison with shore power for OGVs, which would spread the dockside infrastructure costs over a larger number of vessels.

Operating costs for shore power include electricity, labor, and maintenance. Electricity costs vary widely based on the utility provider, time of use, seasonal adjustments, and additional demand charges, among others. At California ports, rates can range from \$0.08 per kilowatt-hour (kWh) for high annual electricity consumers to over a \$1.00 per kWh during peak periods (for example, cruise ships that have brief, intense bursts of energy demand, but low annual electricity usage overall). According to a representative of Southern California Edison, which serves the Port of Long Beach, the cost of electricity for cold-ironing of harbor craft would be roughly 12.5 cents per kilowatt-hour.²¹⁷ Savings from not purchasing fuel would be factored into the total energy costs, and would be greater than for OGVs since harbor craft will run on more expensive ULSD beginning in 2007.

²¹⁵ U.S. Environmental Protection Agency (1985)

²¹⁶ ENVIRON (2004)

²¹⁷ Raskin, R. (2006)

Cost Effectiveness

There is limited information available on the cost-effectiveness of shore power for harbor craft. One estimate (for tugboats) can be obtained from an application for an emission reduction incentives grant through the Texas Emissions Reduction Plan (TERP), which is similar to the Carl Moyer Program in California.²¹⁸ A tugboat fleet operator applied for a grant of \$60,500, all of which was for purchase of equipment and installation of shore power on a barge. Relatively old, high-emitting auxiliary engines onboard the tugboats were replaced with the shore power. The operator estimated a reduction of 1.24 tons per year of NO_x.²¹⁹ Considering only capital recovery, and using this project's discount rate of 4 percent over five years, the cost-effectiveness of the change to shore power was about \$11,536 per ton of NO_x eliminated. However, this TERP example is much smaller in scale and scope than the strategy we analyzed for the San Pedro Bay Ports, with emission reductions more than 1000 times lower. As such, the TERP example costs and cost effectiveness cannot be applied to this strategy.

An analysis of cold ironing for the specific case of ocean-going vessels docked at the Port of Long Beach concluded that cold ironing would generally reduce net operating costs if the vessel's annual power consumption exceeds 1,500,000 kilowatt-hours per year.²²⁰ Calculations for the present study indicate that cold ironing would reduce net operating costs even if a harbor craft vessel's annual power consumption were as low as about 237,500 kilowatt-hours per year.

Given the lack of information on the costs of this strategy, we have not quantified cost effectiveness.

²¹⁸ Texas Commission on Environmental Quality (2006)

²¹⁹ Dayton, S.A. (2006)

²²⁰ ENVIRON (2004)

5.6. Harbor Craft Repowering

Strategy Definition

This strategy could take two forms. First, it could consist of replacement or rebuilding of existing harbor craft propulsion engines to meet Federal and State emission standards before the deadlines set by Federal and State requirements. In the short run, the total emission reductions with and without this measure would be the same; the measure would only change the implementation schedule. However, since our analysis will cover a longer time period than that of the Clean Air Action Plan, emissions beyond 2010 will decrease. Second, the measure could consist of repowering with engines whose emissions are significantly lower than Federal and State requirements. In that case, there would be a decrease in emissions below regulatory requirements.

Of the approximately 400 harbor craft at the Port of Los Angeles, about 38% have been repowered with cleaner engines through funding mechanisms such as the Carl Moyer program, demonstrating the feasibility of emissions reduction at the ports through repowering vessels.

Pollutants Reduced

The pollutants reduced by this measure would include ROG, NO_x and PM.

Background

Federal Regulations

On December 29, 1999, the U.S. EPA promulgated emission standards for new diesel marine engines rated at or above 37 kilowatts (about 50 horsepower).^{221,222} The 50-horsepower threshold includes about 96 percent of propulsion engines and about 62 percent of the auxiliary engines use on harbor craft in California.²²³ For the purpose of applying emission limits, the USEPA regulation divides marine engines into three “categories,” according to their displacement per cylinder:

- Category 1: < 5 liters
- Category 2: ≥ 5 liters and < 30 liters
- Category 3: ≥ 30 liters

Category 1 engines are typically used for propulsion on small harbor craft such as tugboats, fishing vessels and crew boats, and as auxiliary engines on a variety of vessels. Category 2 engines are used for propulsion on larger harbor craft and for auxiliary engines on ocean-going vessels.

The USEPA standards in 40 CFR 94 apply to marine engines and marine vessels that are manufactured (or are otherwise considered to be “new”) after January 1, 2004. Table 5-10 shows the mandatory standards and their implementation dates. The USEPA regulations also include voluntary “Blue Sky” emission limits, which apply to engines through the 2010 model year. Table 5-11 shows the Blue Sky limits.

²²¹ U.S. Environmental Protection Agency (1999b)

²²² The standards were added as Part 94 to 40 Code of Federal Regulations.

²²³ Calculated from survey results in ARB, 2004.

Table 5-10: Primary Tier 2 Exhaust Emission Standards (grams per kilowatt-hour)

Engine size – liters/cylinder, rated power	Category	Model Year	THC+NO _x g/kW-hr	CO g/kW-hr	PM g/kW-hr
Displacement < 0.9 and power ≥ 37 kW	1	2005	7.5	5.0	0.40
0.9 ≤ displacement < 1.2 all power levels	1	2004	7.2	5.0	0.30
1.2 ≤ displacement < 2.5 all power levels	1	2004	7.2	5.0	0.20
2.5 ≤ displacement < 5.0 all power levels	1	2007	7.2	5.0	0.20
5.0 ≤ displacement < 15.0 all power levels	2	2007	7.8	5.0	0.27
15.0 ≤ displacement < 20.0 all power levels	2	2007	8.7	5.0	0.50
< 3300 kW					
15.0 ≤ displacement < 20.0 all power levels	2	2007	9.8	5.0	0.50
≥ 3300 kW					
20.0 ≤ displacement < 25.0 all power levels	2	2007	9.8	5.0	0.50
25.0 ≤ displacement < 30.0 all power levels	2	2007	11.0	5.0	0.50

Table 5-11: Voluntary Emission Standards (grams per kilowatt-hour)

Rated Brake Power	THC+NO _x	PM
Power ≥ 7 kW, and displ. < 0.9	4.0	0.24
0.9 ≤ displacement < 1.2	4.0	0.18
1.2 ≤ displacement < 2.5	4.0	0.12
2.5 ≤ displacement < 5	5.0	0.12
15 ≤ displacement < 15	5.0	0.16
15 ≤ displacement < 20, and power < 3300kW	5.2	0.30
15 ≤ displacement < 20, and power < 3300kW	5.9	0.30
20 ≤ displacement < 25	5.9	0.30
25 ≤ displacement < 30	6.6	0.30

As discussed in Section 5.1, EPA recently announced proposed new emission standards for category 1 and 2 commercial marine engines.²²⁴ If enacted, the new Tier 3 standards would take effect beginning in 2013 and require NO_x and PM emission reductions of 28% and 66%, respectively, compared to the current Tier 2 standards. Tier 4 standards would take effect in 2016 – 2018 (depending on engine size) and require NO_x and PM emission reductions of 84% and 91%, respectively, compared to the current Tier 2 standards. In addition, CARB has proposed regulations for existing (in-use) commercial harbor craft.

Emissions Reduction Potential

The No Net Increase Task Force estimates that repowering harbor craft engines can reduce NO_x and PM emissions by an average 60 percent and 25 percent, respectively.²²⁵ We were not able to obtain detailed data on the characteristics of the harbor craft fleet in the region. As an alternative, we obtained and analyzed applications for harbor craft engine replacement through the Carl Moyer Program, as administered by the South Coast Air Quality Management District. Tables 5-12 and 5-13 show the mean per-engine NO_x and PM_{2.5} emissions reductions actually achieved through engine replacement, to date. It was assumed that PM_{2.5} make up 91% of total PM emissions. Sample variances are fairly high, reflecting the small sample sizes and the variability among the emission reduction values.

²²⁴ U.S. Environmental Protection Agency (2007a)

²²⁵ No Net Increase Task Force (2005)

Table 5-12: Actual Per-Engine NO_x Reductions through the Carl Moyer Program

Vessel Type	Number of Engines In Sample	Mean NO_x Reduction Per Engine (tons/year)	95% Confidence Interval for NO_x Reduction (tons/year)
Passenger	5	3.57	2.11 – 5.03
Crew Boat	5	7.35	4.65 – 10.04
Commercial Fishing	18	3.47	2.21 – 4.73
Charter Fishing	5	4.18	2.70 – 5.66
Tugboats and Towboats	7	6.57	1.68 – 11.46
Work Boats	9	5.33	0.49 – 10.17

Table 5-13: Actual Per-Engine PM_{2.5} Reductions through the Carl Moyer Program

Vessel Type	Number of Engines In Sample	Mean PM_{2.5} Reduction Per Engine (tons/year)	95-% Confidence Interval for PM_{2.5} Reduction (tons/year)
Passenger	4	0.16	0.072 – 0.265
Crew Boat	4	0.35	0.186 – 0.505
Commercial Fishing	4	0.25	0 – 0.752
Charter Fishing	5	0.12	0.105 – 0.140
Tugboats and Towboats	3	0.10	0 – 0.274
Work Boats	9	0.21	0.069 – 0.349

Using the results in Tables 5-12 and 5-13 with the ARB's estimates of numbers of vessels of each type in the SCAB and the average number of engines per vessel per vessel type, we estimated that the total emission reduction potential for NO_x and PM_{2.5} would be 8,043 and 342 tons per year, respectively. However, as noted above, about 38 percent of the harbor craft engines in the Port of Los Angeles have already been repowered. Assuming that this percentage applies to all harbor craft in the basin, the maximum available emission reductions for 2010 and beyond would be 4,987 tons per year of NO_x and 212 tons per year of PM_{2.5}. Tables 5-14 and 5-15 show the emission reductions of NO_x and PM_{2.5}, respectively, per year under different percentages of engines replaced per year. In the tables, it is assumed that the percentage shown applies to the number of *non-repowered engines* remaining at the beginning of each year.

Table 5-14: Cumulative Reduction in Annual NO_x Emissions through Repowering

% of Remaining Engines Replaced Per Year	Cumulative Tons per Year of Emissions Reduced				
	2010	2015	2020	2025	2030
5	249	1,321	2,150	2,792	3,289
10	499	2,337	3,422	4,063	4,441
15	748	3,106	4,152	4,617	4,823
20	997	3,680	4,559	4,847	4,941
25	1,247	4,099	4,776	4,937	4,975
30	1,496	4,400	4,888	4,970	4,984

Table 5-15: Cumulative Reduction in Annual PM_{2.5} Emissions through Repowering

% of Remaining Engines Replaced Per Year	Cumulative Tons per Year of Emissions Reduced				
	2010	2015	2020	2025	2030
5	11	57	92	120	141
10	21	100	147	175	191
15	32	133	178	198	207
20	43	158	196	208	212
25	54	176	205	212	214
30	64	189	210	214	214

Costs

Costs to clean up engines range from minimal component costs to system costs comparable to newer engines. This analysis included replacement costs only, as no data on changes in operating and maintenance costs were available. Funding under the Carl Moyer Program is for the difference between the cost of a replacement engine and the cost of refurbishing a new engine. For this analysis, we considered only the replacement cost.

Cost Effectiveness

Using the Carl Moyer data provided by the SCAQMD, we calculated the cost-effectiveness of each engine replacement, and then determined average per-engine cost-effectiveness for each type of harbor craft. By doing the analysis engine-by-engine, we took into account variations in the useful life of different engines. Tables 5-16 and 5-17 show the results for NO_x and PM, respectively, using the annualized approach. Tables 5-18 and 5-19 show the results of using the SCAQMD BACT approach.

Table 5-16: Cost Effectiveness of NO_x Reduction – ARB Annualized Method

Vessel Type	Number of Engines In Sample	Mean NO _x Cost Effectiveness (\$/ton)	95-% Confidence Interval for NO _x Cost Effectiveness (\$/ton)
Passenger	5	\$2,763	\$862 – \$4,664
Crew Boat	5	\$2,227	\$737 – \$3,717
Commercial Fishing	18	\$2,126	\$1,466 – \$2,787
Charter Fishing	5	\$2,454	\$1,820 – \$3,089
Tugboats and Towboats	7	\$1,893	\$859 – \$2,928
Work Boats	9	\$4,812	\$2,469 – \$7,156

Table 5-17: Cost Effectiveness of PM_{2.5} Reduction – ARB Annualized Method

Vessel Type	Number of Engines In Sample	Mean PM _{2.5} Cost Effectiveness (\$/ton)	95-% Confidence Interval for PM _{2.5} Cost Effectiveness (\$/ton)
Passenger	4	\$54,729	\$21,026 - \$88,433
Crew Boat	4	\$52,213	\$14,005 - \$90,420
Commercial Fishing	4	\$90,233	\$16,863 - \$163,601
Charter Fishing	5	\$81,154	\$54,667 - \$107,640
Tugboats and Towboats	3	\$67,751	\$24,257 - \$111,246
Work Boats	9	\$80,490	\$54,495 - \$106,485

Table 5-18: Cost Effectiveness of NO_x Reduction – SCAQMD BACT Method

Vessel Type	Number of Engines In Sample	Mean NO _x Cost Effectiveness (\$/ton)	95-% Confidence Interval for NO _x Cost Effectiveness (\$/ton)
Passenger	5	\$2,123	\$748 – \$3,149
Crew Boat	5	\$1,613	\$583 – \$2,643
Commercial Fishing	18	\$1,789	\$1,232 – \$2,345
Charter Fishing	5	\$1,946	\$1,443 – \$2,449
Tugboats and Towboats	7	\$1,470	\$786 – \$2,153
Work Boats	9	\$3,476	\$1,823 – \$5,129

Table 5-19: Cost Effectiveness of PM_{2.5} Reduction – SCAQMD BACT Method

Vessel Type	Number of Engines In Sample	Mean PM _{2.5} Cost Effectiveness (\$/ton)	95-% Confidence Interval for PM _{2.5} Cost Effectiveness (\$/ton)
Passenger	4	\$42,192	\$21,163 - \$63,220
Crew Boat	4	\$37,497	\$10,222 - \$64,771
Commercial Fishing	4	\$55,579	\$0 - \$128,015
Charter Fishing	5	\$64,353	\$43,351 - \$85,357
Tugboats and Towboats	3	\$50,764	\$10,039 - \$91,488
Work Boats	9	\$58,603	\$40,526 - \$76,682

6. Cargo Handling Equipment Strategies

6.1. Introduction

Cargo handling equipment (CHE) at ports and rail yards include yard tractors, cranes, forklifts, container handlers (e.g., top picks and side picks), and bulk handling equipment, such as tractors, loaders, dozers, excavators, and backhoes. Among these CHE types, yard tractors are the most common equipment at ports and rail yards, followed by forklifts and container handlers. More than 90% of the existing CHE is powered by diesel engines. The remaining CHE includes some smaller forklifts (those with maximum loading capacity of less than 15,000 lbs) that are powered by LPG engines or electricity, and a few LPG or LNG yard tractor demonstration fleets.

CHE is responsible for about 4% and 3% of the total NO_x and PM_{2.5} emissions, respectively, from goods movement in the South Coast Air Basin in 2005. While CHE contributes a relatively small fraction of total goods movement emissions in the region, control of emissions from this sector is often easier to implement than controls on ocean-going vessels or harbor craft. More than 90% of CHE emissions are from yard tractors, container handlers, and cranes. Table 6-1 shows emissions for CHE for 2010, 2015, and 2020 in the South Coast Air Basin, as reported in ARB's Emission Reduction Plan for Port and Goods Movement. These can be used as approximate emission estimates for CHE within the SCAG region.

Table 6-1: South Coast Air Basin CHE emissions (tons/day)

Pollutant	2010	2015	2020
Diesel PM	0.4	0.3	0.1
NO _x	11.6	8.2	4.5

Source: California Air Resources Board (2006c)

In 2004, EPA set new emission standards (Tier 4) for non-road engines that include most CHE, to be primarily phased in from 2011 through 2015.²²⁶ In December 2005, CARB adopted a regulation that requires the replacement or retrofit of existing CHE engines with ones that use the cleanest available verified diesel emission control (VDEC).²²⁷ It also requires that, beginning January 1, 2007, that newly purchased, leased, or rented CHE to equip with engines that have been certified to meet MY 2007 or later on-road diesel engine emission standards, Tier 4 non-road diesel engine emission standards, or the highest non-road diesel engine emission standards with a highest-level VDEC available.

The recently adopted San Pedro Bay Ports Clean Air Action Plan (CAAP) would require that by 2010, all yard tractors operating at the ports will have the cleanest engines meeting 2007 on-road emission standards or Tier 4 non-road engine standards.²²⁸ The CAAP also requires that all remaining CHE with diesel engines less than 750 hp to meet at a minimum the 2007 on-road standards or Tier 4 standards by 2012, and all remaining CHE with engines greater than 750 hp to meet Tier 4 standards by 2014 and prior to that, be equipped with the cleanest available VDEC.

As a result of these regulations and the CAAP, opportunities for further reductions of CHE emissions are somewhat limited to a certain number of years for certain applicable equipment to fill in gaps between these regulations and CAAP.

²²⁶ U.S. Environmental Protection Agency (2004a)

²²⁷ California Air Resources Board (2005c)

²²⁸ Port of Los Angeles and Port of Long Beach (2006)

In order to assess the potential emission reductions for CHE control strategies, it was necessary to estimate the CHE equipment population by equipment type and model year. We used population information available from the ARB CHE regulations to estimate South Coast CHE populations by equipment type.²²⁹ The 2004 populations by model year available in the document were used to estimate 2010 and 2020 age distributions so that control measures could be evaluated for these future calendar years. The 2010 and 2020 South Coast population estimates by equipment type used in the CHE control strategy assessments are shown in Table 6-2.

Table 6-2: South Coast CHE Population Estimates

Equipment Type	2010	2020
Yard Trucks	1,988	2,681
Container Handling Equipment	519	781
Cranes	335	429
Forklifts	372	426

²²⁹ California Air Resources Board (2005d)

6.2. Accelerated CHE Engine or Equipment Replacement

Description of Strategy

By far the most widely employed method for reducing emissions from CHE engines is the replacement of the engines with new lower-emitting engines or replacement of the entire piece of equipment with cleaner equipment. This strategy evaluates the effect of accelerating the replacement of older CHE engines with model year 2010 on-road engines for yard tractors, and Tier 4-equivalent engines for container handling equipment, forklifts, and cranes. The Tier 4 emission standards will be phased-in from 2008-2015, depending on the engine horsepower. The expected percentage emission reduction from this strategy will depend upon the engine model year to be replaced and the emission standard that the new engine meets.

This strategy would apply to all non-yard tractor CHE within the SCAG boundaries as well as yard tractors within SCAG boundaries and outside of POLA/POLB.

For the yard tractors, two scenarios were investigated:

- 1) Accelerating the replacement of yard-tractor equipment outside of POLA/POLB, which is scheduled to meet the ARB CHE regulations by 2017 (i.e. assuming the CHE measure in the CAAP is in-effect); and
- 2) Accelerating the replacement of yard-tractor equipment within the SCAG boundaries (i.e. assuming the CHE measure in the CAAP is not in-effect).

This strategy would also accelerate the replacement of non-yard tractor equipment, scheduled to fully meet the ARB CHE regulations by 2015 or CAAP targets by 2014.

The analysis year applicable for this accelerated engine/equipment replacement strategy is 2010, as 2015 would assume to be too late to provide significant emission impacts, and 2020 and later analysis years would provide no emission impacts for the strategy because the CHE regulations and CAAP CHE measure would be fully implemented around 2015 to 2020.

Pollutants Reduced

This strategy primarily reduces NO_x and PM emissions. Impacts on ROG emissions are minimal.

Emission Reductions

Emission reductions depend on the equipment that replaces the CHE equipment. When determining the emissions benefits of this strategy, it is important to consider and clearly define the eligible equipment or engines and the project/emission credit life. Otherwise, there may be double counting of emission reductions that occur due to normal turnover rates or due to compliance with emission regulations.

We estimated the characteristics of CHE engines under a baseline scenario for each equipment type based on the CHE age distribution reported by ARB.²³⁰ Baseline CHE engines were assumed to have emissions characteristics equivalent to emissions characteristics for the fleet average model year, and emissions factors were estimated for these engines according to ARB.²³¹

²³⁰ California Air Resources Board (2005d)

²³¹ California Air Resources Board (2005d)

We calculated emission reductions from CHE replacement and repowers by assuming a 10% penetration. Table 6-3 tabulates the per engine baseline emissions, the effects of the strategy on an engine, and the total regional emission reduction in 2010. These values are based on horsepower range calculations applied by equipment category across all horsepower types for brevity. For small changes in the penetration rate, the emission reductions would generally be scalable (i.e., emission reductions at 15% penetration would be 1.5 times the values shown in Table 6-3).

Table 6-3: Emission Reductions from Accelerated CHE Replacement, 2010

Parameter	Yard Trucks (w/o CAAP)	Yard Trucks (w/ CAAP)	Container Handling Equipment	Forklifts	Cranes
Population Available For Retrofit	422	194	194	125	103
Average Model Year	2005	2005	2003	2000	2001
NO_x Emissions					
Baseline Engine Emission (tons/year)	1.05	1.05	1.90	0.30	1.75
Emission Reduction (tons/engine)	1.00	1.00	0.92	0.19	1.57
Percent Reductions (per engine)	95.6%	95.6%	49.8%	58.9%	92.9%
Annual Emission Reductions at 10% Penetration (tpy)	42.3	19.5	17.9	2.4	16.2
ROG Emission					
Baseline Engine Emission (tons/year)	0.04	0.04	0.10	0.04	0.12
Emission Reduction (tons/engine)	0.00	0.00	0.04	0.03	0.10
Percent Reductions (per engine)	2.4%	2.4%	43.1%	82.8%	81.5%
Annual Emission Reductions at 10% Penetration (tpy)	0.04	0.02	0.81	0.37	1.01
PM_{2.5} Emission					
Baseline Engine Emission (tons/year)	0.03	0.03	0.05	0.01	0.04
Emission Reduction (tons/engine)	0.03	0.03	0.04	0.01	0.04
Percent Reductions (per engine)	92.4%	92.4%	87.3%	93.3%	98.9%
Annual Emission Reductions at 10% Penetration (tpy)	0.98	0.46	0.75	0.15	0.35

Costs

The incremental costs associated with the engine replacement would include incremental equipment costs. For the yard tractors, we assumed that the equipment cost for a new 176 to 250 horsepower yard tractor would be \$60,000, based on the ARB's cost analysis for its CHE regulations.²³² The incremental equipment cost for accelerating the replacement of a yard tractor would be the remaining salvage value of the equipment based on a straight-line depreciation as used in the ARB's cost analysis for its CHE regulations. To estimate engine costs for other horsepower ranges, we applied to the 176 to 250 horsepower equipment cost and the ratio of average horsepower of the various horsepower ranges to the average horsepower of the 175 to 250 horsepower range. In addition to the incremental engine cost associated with the on-road engine, we added an additional \$1,500 incremental cost to account for the cost differential between an on-road and off-road engine for each engine in each horsepower category, which is also consistent with ARB's cost analysis for the CHE regulations.²³³ As there are no such prices

²³² California Air Resources Board (2005d)

²³³ California Air Resources Board (2005d)

for low emission off-road engines needed in non-yard tractor CHE equipment, the assumptions described above were applied to all equipment types for this measure. The incremental equipment costs by equipment type estimated for this strategy are summarized in Table 6-4.

Table 6-4: Incremental Equipment Costs for Accelerated CHE Replacement

Horsepower Range	Yard Trucks	Container Handling Equipment	Forklifts	Cranes
26 to 50	NA	NA	\$2,600	NA
51 to 120	NA	\$11,200	\$5,820	NA
121 to 175	\$20,300	\$19,500	\$10,100	NA
176 to 250	\$28,500	\$28,000	\$14,500	\$19,000
251 to 500	NA	\$49,400	\$25,600	\$33,500
501 to 750	NA	\$82,200	NA	\$55,800
751 to 1000	NA	NA	NA	\$78,100

Cost-Effectiveness

The NO_x cost effectiveness calculations are based on the SCAQMD BACT methodology reported in MSBACT Guidelines, as described in Section 1.²³⁴ In addition to the BACT methodology, we have also calculated a cost-effectiveness per pollutant using the annualized capital cost, similar to the Carl Moyer method, and incorporating annual operational costs. For both the BACT and annualized CE methodologies, a 10-year equipment life and 4% interest rate were assumed.

Table 6-5 shows the annual per ton cost-effectiveness values by equipment type and pollutant.

Table 6-5: CHE Replacement and Repower Cost Effectiveness (\$/ton), 2010

	Yard Trucks (w/ & w/o CAAP)	Container Handling Equipment	Forklifts	Cranes
NO_x Emissions				
Annualized CE (\$/ton)	\$2,983	\$4,564	\$8,570	\$3,053
BACT CE (\$/ton)	\$2,373	\$3,609	\$7,229	\$2,790
ROG Emissions				
Annualized CE (\$/ton)	\$368,044	\$151,954	\$46,770	\$49,582
BACT CE (\$/ton)	\$558,940	\$116,633	\$38,221	\$49,889
PM_{2.5} Emissions				
Annualized CE (\$/ton)	\$129,003	\$115,025	\$129,019	\$142,682
BACT CE (\$/ton)	\$98,853	\$87,259	\$102,529	\$131,799

²³⁴ South Coast Air Quality Management District (2006a)

6.3. Use of Alternative Fuels in CHE

Description of Strategy

This strategy is similar to the accelerated equipment replacement strategy, except that it would replace diesel engines or equipment with lower emissions alternative fuel engines or alternative fuel engine retrofits. This strategy considers the use of liquid propane gas (LPG) forklifts, LPG and liquid natural gas (LNG) yard tractors, and electrification of forklifts and RTG cranes. Other potential long term alternative fuel technologies include diesel-electric hybrids, fuel cells, and plug-in hybrid-electric engines; we have not analyzed these newer technologies because of the limited information on their emissions impacts and costs.

The analysis year applicable for this accelerated alternative fuels equipment replacement strategy is 2010; 2015 and later analysis year would provide insignificant emission impacts because emissions from Tier 4 diesel engines would be as low as those from alternative fuel engines. The analysis also considers two scenarios of with and without the CAAP for the yard tractors.

Pollutants Reduced

This strategy would reduce emissions of all pollutants, including NO_x, ROG, and PM.

Emission Reduction Potential

Potential emission reductions would depend on the model year of the baseline engine and the alternative fuel technology implemented. We estimated the characteristics of CHE engines under a baseline scenario for each equipment type based on the CHE age distribution reported by ARB.²³⁵ Baseline CHE engines were assumed to have emissions characteristics equivalent to emissions characteristics for the fleet average model year, and emissions factors were estimated for these engines according to ARB.²³⁶

In order to assess the effects of alternative fuel strategies, we assumed a 10% penetration rate each for LNG, LPG, and electrification. Table 6-6 shows the emissions impacts of LPG and LNG yard trucks and forklifts on a per-engine and region-wide basis in 2010. For small changes in the penetration rate, the emission reductions would generally be scalable (i.e., emission reductions at 15% penetration would be 1.5 times the values shown in Table 6-6).

Table 6-7 shows the emissions impacts of electrification of RTG cranes and forklifts.

²³⁵ California Air Resources Board (2005d)

²³⁶ California Air Resources Board (2005d)

Table 6-6: Emission Impacts of LPG and LNG Yard Trucks and Forklifts, 2010

Yard Trucks (w/ CAAP)		LNG	LPG
NO _x	Assumed Percent Penetration	10%	10%
	Number of Equipment	42	42
	Emission Reduction (tons/engine)	0.8390	0.7348
	Percent Reductions (per engine)	80%	70%
	Annual Emission Reduction (tons/year)	16.32	14.29
ROG	Emission Reduction (tons/engine)	0.0409	0.0390
	Percent Reductions (per engine)	92%	88%
	Annual Emission Reduction (tons/year)	0.79	0.76
PM _{2.5}	Emission Reduction (tons/engine)	0.0248	0.0243
	Percent Reductions (per engine)	99%	97%
	Annual Emission Reduction (tons/year)	0.48	0.47
Yard Trucks (w/o CAAP)		LNG	LPG
NO _x	Assumed Percent Penetration	10%	10%
	Number of Equipment	19	19
	Emission Reduction (tons/engine)	0.8390	0.7348
	Percent Reductions (per engine)	80%	70%
	Annual Emission Reduction (tons/year)	35.44	31.04
ROG	Emission Reduction (tons/engine)	0.0409	0.0390
	Percent Reductions (per engine)	92%	88%
	Annual Emission Reduction (tons/year)	1.73	1.65
PM _{2.5}	Emission Reduction (tons/engine)	0.0248	0.0243
	Percent Reductions (per engine)	99%	97%
	Annual Emission Reduction (tons/year)	1.05	1.03
Forklifts		LNG	LPG
NO _x	Assumed Percent Penetration	10%	10%
	Number of Equipment	13	13
	Emission Reduction (tons/engine)	0.1805	0.1564
	Percent Reductions (per engine)	83%	70%
	Annual Emission Reduction (tons/year)	2.07	1.79
ROG	Emission Reduction (tons/engine)	0.0094	0.0090
	Percent Reductions (per engine)	89%	86%
	Annual Emission Reduction (tons/year)	0.11	0.11
PM _{2.5}	Emission Reduction (tons/engine)	0.0059	0.0058
	Percent Reductions (per engine)	95%	94%
	Annual Emission Reduction (tons/year)	0.07	0.06

Table 6-7: Emission Impacts of Electric RTG Cranes and Forklifts, 2010

		Electrification	
		Cranes	Forklifts
Percent Penetration		10%	10%
Number of Equipment		10	13
NO _x	Emission Reduction (tons/engine)	0.0627	0.0207
	Percent Reductions (per engine)	83%	88%
	Annual Emission Reduction (tons/year)	7.11	0.83
ROG	Emission Reduction (tons/engine)	0.0162	0.0034
	Percent Reductions (per engine)	84%	88%
	Annual Emission Reduction (tons/year)	0.83	0.13
PM _{2.5}	Emission Reduction (tons/engine)	0.0021	0.0005
	Percent Reductions (per engine)	84%	89%
	Annual Emission Reduction (tons/year)	0.13	0.02

Costs

The costs associated with the use of alternative fuels would include incremental equipment and refueling station capital cost as well as operating costs, such as potential increases in fuel consumption and maintenance costs. For this study, we assumed that the incremental equipment costs for the LNG and LPG yard tractors of 175 to 250 horsepower range were \$33,000 and \$29,000, respectively, with a baseline diesel equipment cost of about \$60,000.²³⁷ Costs associated with other horsepower ranges were estimated by applying to the equipment cost the ratio of average horsepower of the various horsepower ranges to the average horsepower of the 175 to 250 horsepower range. LPG and LNG forklifts were assumed to be equivalent to yard truck incremental costs by horsepower.

Incremental electrification costs were based the electrification costs of aircraft tug equipment reported in a study on electrification of airport ground support equipment.²³⁸ We assumed an added cost of \$13,000 and an \$8,500 incremental battery cost per electrified equipment. Incremental engine and battery costs were adjusted to account for horsepower by applying to the equipment cost the ratio of average horsepower of the various horsepower ranges to the average horsepower of the 175 to 250 horsepower range.

In addition, we assumed a maintenance facility upgrade capital cost of approximately \$3,000, \$2,000, and \$2,000 per equipment to train and equip the facility to service LNG, LPG, and electric equipment, respectively. As for the refueling station cost, we estimated that a refueling station would cost about \$500,000 to \$1.0 million for LNG and \$100,000 to \$200,000 for LPG, depending on the capacity and configuration of the station. Battery charger costs were estimated at \$4,000 per piece of equipment.²³⁹

In addition to incremental capital costs, fuel cost differences were also included in the cost-effectiveness analysis. Table 6-8 shows our assumptions for the price of diesel, LNG and LPG (in diesel equivalent gallons or DEG), and electricity. Diesel and LPG costs are based on DOE's *Annual Energy Outlook*, while LNG costs are based on the assumption that the price of LNG would be \$0.45 less than the price of

²³⁷ These estimates were based on approximate prices from yard tractor dealers, as well as information provided by the Port of Long Beach and Port of Los Angeles.

²³⁸ TIAX (2000)

²³⁹ TIAX (2000)

diesel.²⁴⁰ Electricity costs were estimated as the average of 2003 electricity cost²⁴¹ and 2020 projected cost.²⁴² Fuel costs were assumed to be unchanged from the inception of the project. Depending on the engine model year and type, the estimated incremental fuel costs range from (\$8,000) to \$13,000 for LNG fuel, (\$17,000) to \$4,000 for LPG fuel, and (\$11,000) to \$9,000 for electrification, as compared to baseline diesel fuel.

Table 6-8: Assumed Fuel Prices, 2020

Diesel (\$/gal)	\$2.94
LNG (\$/diesel-equivalent gallon)	\$2.49
LPG (\$/diesel-equivalent gallon)	\$2.32
Electricity (\$/kWh)	\$0.17

Cost-Effectiveness

The NO_x cost effectiveness calculations are based on the SCAQMD BACT methodology reported in MSBACT Guidelines, as described in Section 1.²⁴³ In addition to the BACT methodology, we have also calculated a cost-effectiveness per pollutant using the annualized capital cost, similar to the Carl Moyer method, and incorporating annual operational costs. For both the BACT and annualized CE methodologies, a 10-year equipment life and 4% interest rate were assumed.

Table 6-9 shows annual and BACT cost effectiveness for each control measure. Negative BACT cost effectiveness values indicate that fuel cost savings exceed the capital, maintenance, and operation costs over the project lifetime. As shown in Table 6-9, LPG and LNG yard tractors have much better cost-effectiveness values than those for the electrification of forklifts or RTG cranes.

²⁴⁰ Energy Information Administration (2006)

²⁴¹ 2003 South Coast Edison Electricity Price

²⁴² ENVIRON (2004)

²⁴³ South Coast Air Quality Management District (2006a)

Table 6-9: CHE Alternative Fuel Strategy Cost Effectiveness

		LNG	LPG	Electrification
Yard Tractors				
NO _x	Annualized NO _x CE (\$/ton)	\$5,371	\$240	NA
	BACT NO _x CE (\$/ton)	\$4,424	< 0 *	
ROG	Annualized ROG CE (\$/ton)	\$107,612	\$2,925	
	BACT ROG CE (\$/ton)	\$86,781	< 0 *	
PM _{2.5}	Annualized PM CE (\$/ton)	\$177,486	\$3,942	
	BACT ROG CE (\$/ton)	\$140,264	< 0 *	
RTG Cranes				
NO _x	Annualized NO _x CE (\$/ton)	NA	NA	\$73,764
	BACT NO _x CE (\$/ton)			\$58,705
ROG	Annualized ROG CE (\$/ton)			\$287,274
	BACT ROG CE (\$/ton)			\$225,846
PM _{2.5}	Annualized PM CE (\$/ton)			\$2,257,464
	BACT ROG CE (\$/ton)			\$1,750,690
Forklifts				
NO _x	Annualized NO _x CE (\$/ton)	\$96,011	\$93,237	\$266,492
	BACT NO _x CE (\$/ton)	\$80,628	\$76,377	\$234,120
ROG	Annualized ROG CE (\$/ton)	\$1,475,831	\$1,302,451	\$1,385,575
	BACT ROG CE (\$/ton)	\$1,210,383	\$1,040,400	\$1,200,472
PM _{2.5}	Annualized PM CE (\$/ton)	\$2,372,546	\$2,042,568	\$10,964,881
	BACT ROG CE (\$/ton)	\$1,920,311	\$1,610,564	\$11,173,662

* An entry of "< 0" indicates a negative cost-effectiveness value – under the BACT methodology, the fuel cost savings exceeds any incremental capital costs and operations and maintenance costs over the lifetime of the project.

6.4. NO_x Control Retrofits for CHE

Description of Strategy

Potential retrofit technologies that reduce NO_x emissions include lean NO_x catalysts, selective catalytic reduction, and exhaust gas recirculation. The ARB CHE regulations already require that CHE to be equipped with the best available control technology, including certified 2007 on-road engines or Tier 4 engines, or highest level of certified off-road engines (Tier 2 or 3) retrofitted with the highest level of Verified Diesel Emission Control Strategy (VDECS) designed primarily for the reduction of diesel PM emissions. Thus, certified retrofit devices for reducing PM emissions, such as diesel particulate filters (DPFs), are assumed to be implemented in the baseline emissions. Retrofit devices for reducing NO_x emissions are not reflected in the baseline and therefore represent a potential strategy. This strategy would encourage fleet owners and operators to accelerate retrofitting their in-use CHE to couple the required PM retrofits with one of three NO_x retrofit devices: lean NO_x catalysts, exhaust gas recirculation (EGR), and selective catalytic reduction (SCR). Two analysis years of 2010 and 2020 were investigated for this strategy.

Pollutants Reduced

This strategy targets only NO_x emissions. NO_x control retrofit devices can be coupled with PM control retrofits to achieve significant reductions in both pollutants.

Emission Reductions

Baseline engines for each equipment type were determined based on age distribution estimations documented by ARB.²⁴⁴ We assumed baseline CHE engines have emissions characteristics equivalent to emissions characteristics for the Tier 4 engines. We estimated emission factors for these engines based on the technical support document for the ARB CHE regulations. Table 6-10 shows the baseline diesel engine emissions for different CHE equipment types.

Table 6-10: Baseline Diesel Engine Emissions (tons/engine/year)

Equipment Type	NO _x	ROG	PM
Yard Trucks	0.0664	0.0123	0.0025
Container Handling Equipment	0.1173	0.0211	0.0042
Cranes	0.0525	0.0098	0.0020
Forklifts	0.0239	0.0024	0.0004

In order to calculate the potential emission reductions from use of CHE retrofit devices, we assumed a 10% penetration rate for each device. We assumed per-engine NO_x reductions of 25%, 80%, and 40% for lean NO_x catalysts (LNC), SCR and EGR, respectively. Table 6-11 shows impacts of applying the implementing the three retrofit devices on yard trucks, container handling equipment, cranes, and forklifts. These values are based on by horsepower range calculations by equipment category across all horsepower types for brevity. There are no ROG and PM reductions as a result of this strategy. For small changes in the penetration rate, the emission reductions would generally be scalable (i.e., emission reductions at 15% penetration would be 1.5 times the values shown in Table 6-11).

²⁴⁴ California Air Resources Board (2005d)

Table 6-11. Emission Impacts of NO_x Control Retrofits for CHE, 2010 and 2020

	2010			2020		
	LNC	SCR	EGR	LNC	SCR	EGR
Percent Penetration:	10%	10%	10%	10%	10%	10%
Yard Tractors						
Emission Reduction (tons/engine)	0.1456	0.4659	0.2330	0.0166	0.0531	0.0266
Percent Reductions (per engine)	25%	80%	40%	25%	80%	40%
Annual Emission Reduction (tons/year)	39.04	124.91	62.46	4.45	14.24	7.12
Container Handling Equipment						
Emission Reduction (tons/engine)	0.2502	0.8006	0.4003	0.0293	0.0938	0.0469
Percent Reductions (per engine)	25%	80%	40%	25%	80%	40%
Annual Emission Reduction (tons/year)	19.54	62.54	31.27	2.29	7.33	3.66
RTG Cranes						
Emission Reduction (tons/engine)	0.2064	0.6606	0.3303	0.0191	0.0610	0.0305
Percent Reductions (per engine)	25%	80%	40%	25%	80%	40%
Annual Emission Reduction (tons/year)	8.86	28.36	14.18	0.75	2.41	1.21
Forklifts						
Emission Reduction (tons/engine)	0.0299	0.0958	0.0479	0.0060	0.0191	0.0095
Percent Reductions (per engine)	25%	80%	40%	25%	80%	40%
Annual Emission Reduction (tons/year)	1.28	4.08	2.04	0.24	0.78	0.39

Costs

The incremental costs associated with the retrofits strategy would include the cost of the retrofit technology. For this study, we assumed that the incremental equipment cost would be the added cost associated with the NO_x control of a NO_x+ PM retrofit package. We estimated these incremental costs to be \$8,000, \$27,500, and \$5,000 for the lean NO_x catalyst, SCR, and EGR, respectively, for 176 to 250 horsepower engines. To estimate engine costs for other horsepower ranges, we applied to the 176 to 250 horsepower equipment cost the ratio of average horsepower of the various horsepower ranges to the average horsepower of the 176 to 250 horsepower range.

Cost-Effectiveness

The NO_x cost effectiveness calculations are based on the SCAQMD BACT methodology reported in MSBACT Guidelines, as described in Section 1. In addition to the BACT methodology, we have also calculated a cost-effectiveness per pollutant using the annualized capital cost, similar to the Carl Moyer method, and incorporating annual operational costs.

Table 6-12 shows the cost-effectiveness for the four CHE types and three retrofit devices in 2010 and 2020. EGR systems are generally the most cost effective, and lean NO_x catalyst retrofits are generally the least cost effective.

Table 6-12: Cost Effectiveness of NO_x Control Retrofits for CHE (\$ per ton), 2010 and 2020

	2010			2020		
	LNC	SCR	EGR	LNC	SCR	EGR
Yard Tractors						
Annualized CE	\$11,637	\$7,974	\$7,796	\$102,080	\$69,947	\$31,084
BACT CE	\$9,885	\$6,378	\$6,406	\$81,368	\$55,754	\$24,777
Container Handling Equipment						
Annualized CE	\$10,880	\$7,195	\$7,475	\$94,096	\$62,238	\$29,383
BACT CE	\$8,624	\$5,703	\$5,925	\$74,729	\$49,428	\$23,335
RTG Cranes						
Annualized CE	\$15,912	\$12,916	\$9,214	\$119,041	\$96,000	\$31,539
BACT CE	\$14,714	\$10,918	\$9,257	\$94,872	\$76,510	\$30,858
Forklifts						
Annualized CE	\$26,712	\$24,727	\$13,284	\$181,507	\$168,193	\$40,969
BACT CE	\$21,309	\$19,724	\$10,597	\$145,026	\$134,388	\$32,734

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