Locomotive Emission Study

California Air Resources Board

Prepared By
Booz·Allen & Hamilton, Inc.

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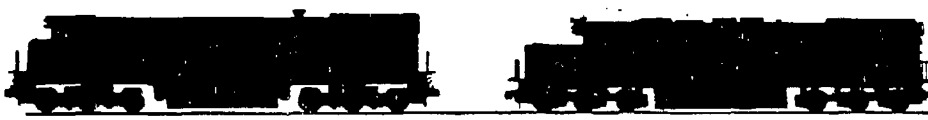

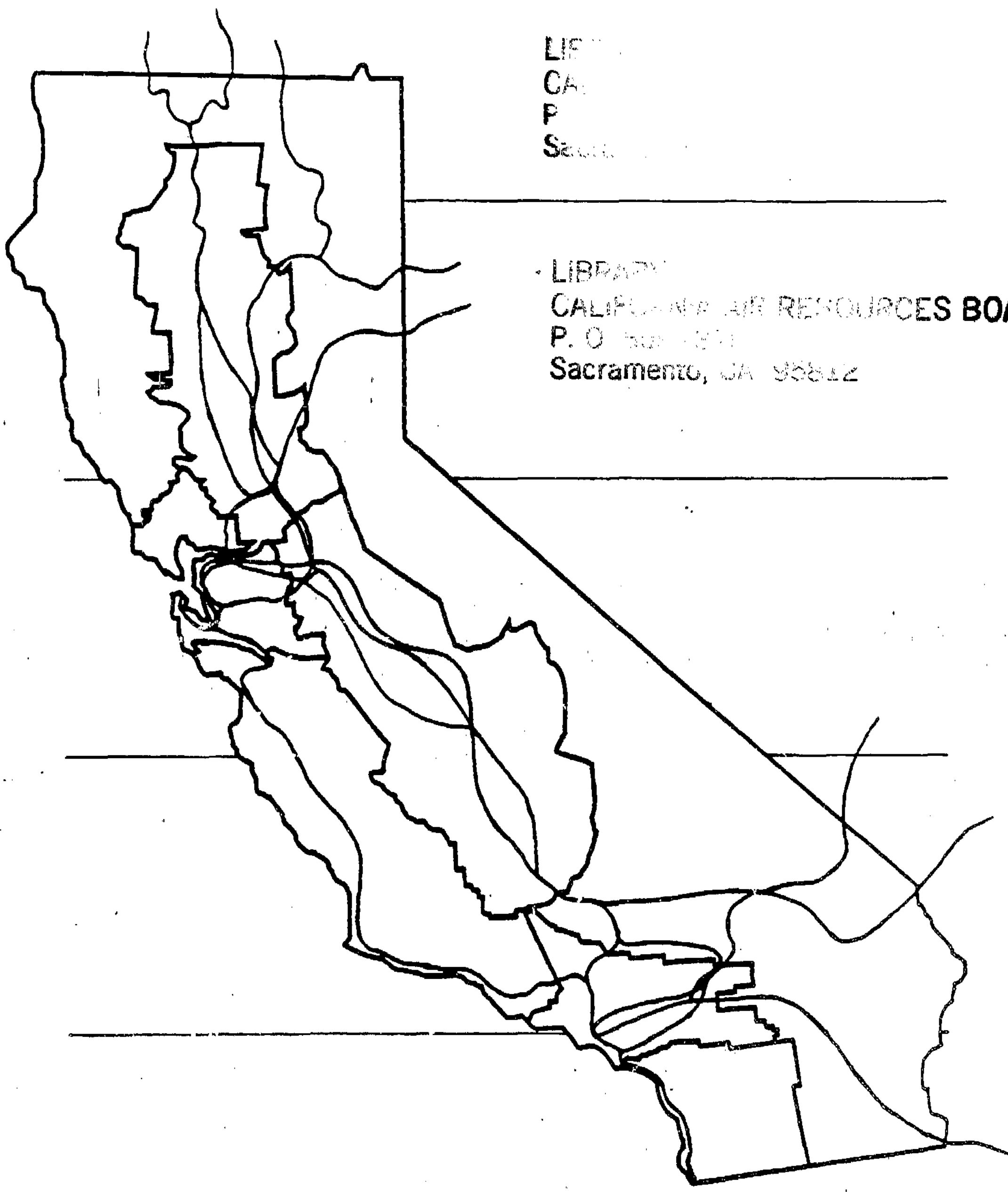

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF EXHIBITS

ACKNOWLEDGEMENTS

We want to acknowledge the assistance of many groups and individuals in the preparation of this report. In particular, the California rail carriers exerted extraordinary efforts to assure current and reliable throttle notch data, the manufacturers were helpful and forthcoming with specific model emission data and the AAR went to great lengths to supply reports and data from past and on-going research. The Air Resources Board staff involved in this project offered guidance and editorial assistance at every step in the process. We wish to thank the Locomotive Emission Advisory Committee for its assistance and forbearance with late and sometimes poorly edited reports. Specific contributions were made by the following:

- The Locomotive Emission Advisory Committee
- The Research Branch of the Association of American Railroads
- The AAR Library
- The ElectroMotive Division of General Motors
- The Transportation Division of General Electric
- The Caterpillar Corporation
- The Atcheson, Topeka and Santa Fe Railway Company
- The Southern Pacific Transportation Company
- The Union Pacific Rail Road
- The California Air Resources Board, specifically:
    - Mr. Jerry Wendt
    - Mr. Richard Remillard
- Southwest Research Institute, Inc

Many others, too numerous to name, have made significant contributions to our understanding of locomotive emissions in California and should be acknowledged. We appreciate the responsiveness of all those in the industry and in California who freely contributed to this work.

John Winner
BOOZ • ALLEN & HAMILTON Inc.

EXECUTIVE SUMMARY

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The California Air Resources Board (CARB) is charged by the State, and ultimately by the citizens of California, with the development of methodologies and the design of programs, standards, regulations, and other actions that will improve air quality within the State. In Assembly Bill 234, enacted in late 1987, the government of California authorized the Air Resources Board to conduct, jointly with the California railroad industry, a study of railroad locomotive emissions. The study was to be directed by a Locomotive Emission Advisory Committee (LEAC), composed of the following members:

- The Secretary of Environmental Affairs.
- The Chairman of the State Energy Resources Conservation and Development Commission.
- The Secretary of the Business, Transportation and Housing Agency
- One representative each from one northern California and one southern California air pollution control district or air quality management district in non-attainment areas.
- One representative from each of the four major operating railroads in the state.

This report is a part of that effort. Under the direction of the Locomotive Emission Advisory Committee (LEAC), the work for this report involved the estimation of the air pollution emissions arising from the operation of railroad locomotives in six non-attainment air management basins within California. The six air basins are the Bay Area, the Central Coast (which includes the North Central Coast and the South Central Coast basins), the South Coast, San Diego, San Joaquin, and Sacramento Valley basins. In addition, the effort involved the development of information about the efficacy and cost of feasible control strategies for locomotive-generated air pollution emissions, for both long and short term implementation.

The information presented and analyzed in this report was gathered from many sources including the Air Resources Board, the South Coast Air Quality Management District, the California Energy Commission, the Association of American Railroads, all Class I and II railroads operating in California, locomotive and large engine manufacturers, and the Southwest Research Institute. The work was overseen by the Locomotive Emission Advisory Committee. As such, this report represents the most up-to-date and comprehensive characterization of rail generated emissions and the means to control these emissions that we are aware of.

This is the final report of the Locomotive Emission Study project. It documents the estimates that have been developed for locomotive-generated air pollution sources as well as the methodologies used to create these estimates. Likely strategies and technologies for the reduction of locomotive generated air pollution are reviewed. A part of the Locomotive Emission Study involved determining whether any of these technologies were sufficiently viable to warrant a demonstration project -- several are. A recommended set of demonstration projects is documented in this report.

Principal findings and conclusions described in the report are:

- Railways have made significant reductions in air pollution emissions in the past. These reductions have been related to improvements in locomotive technology, changes in railway operations and significant improvements in fuel efficiency arising from a combination of many different actions taken by both railroads and locomotive manufacturers.

- Locomotive generated emissions are a significant fraction of the total mobile source emissions in California. Locomotive emissions as a percent of total and total mobile source emissions are shown on the following page.

Source (1)	HC (2)	CO	NOx	SOx	PM 10 (3)
Stationary Sources	1,862	2,087	804	183	3,711
On-Road Sources	1,375	9,943	1,678	111	152
Other Mobile Sources (4)	250	1,552	452	176	58
Total for All Sources	3,487	13,582	2,934	470	3,921
Trains (Booz, Allen 1987 Estimate)	4.23	13.2	99.1	7.3	2.22
Trains: Percent of Total	.12%	.10%	3.38%	1.55%	.06%
Trains: Percent of Total Mobile Sources	.26%	.11%	4.65%	2.54%	1.06%

1) Taken from ARB's 1987 Emission Inventory Estimates by Category
2) Reactive HC only
3) All locomotive particulates are assumed to be PM10
4) Includes ARB's estimate of 1987 train emissions

Railway contributions to air quality problems are most significant for NO_X emissions.

- The largest source of locomotive-generated emissions is from the operation of through freight trains. Emissions from through freight operations represent about two-thirds of all locomotive-generated emissions with switching and local service operations accounting for the rest. Total annual emissions for each train type are shown below.

1987 Base Year: Tons

Train Type	HC (Tons)	CO (Tons)	NO_X (Tons)	SO_X (Tons)	PM (Tons)
Mixed Freight	551	1,770	13,627	1,008	297
Intermodal Freight	412	1,344	10,163	745	221
Local Trains	351	1,117	7,774	580	167
Yard Operations	201	504	3,440	187	78
Passenger Trains*	35	81	1,183	110	26
All Operations	1,550	4,816	36,188	2,630	789

* The passenger train data supplied by Amtrak is for its 1989 operations, they were not substantially different than those in the 1987 base year.

- The contribution from locomotives varies between basins, based upon the level of rail operations and on the level of other source activity in the basin. For example, locomotive-generated NO_X emissions represent about 9 percent of all NO_X emissions in the Sacramento Valley basin, 4 percent in the San Joaquin basin, 4 percent in the Central Coast basin, but as little as 0.25 percent of such emissions in the San Diego basin. Locomotive contributions to total emissions by basin are shown on below.

Basin	HC	CO	NO_X	SO_X	PM
Bay Area					
% of Total	0.10	0.07	2.17	0.83	0.05
% of Total Mobile	0.18	0.08	3.03	1.88	0.83
Central Coast					
% of Total	0.10	0.09	3.62	2.33	0.06
% of Total Mobile	0.26	0.12	5.58	6.36	1.43
South Coast					
% of Total	0.12	0.09	2.90	1.76	0.06
% of Total Mobile	0.22	0.10	3.91	2.97	0.96
San Diego					
% of Total	0.01	0.01	0.25	0.09	0.01
% of Total Mobile	0.02	0.01	0.29	0.10	0.08
San Joaquin					
% of Total	0.14	0.16	4.44	2.34	0.05
% of Total Mobile	0.51	0.23	7.27	5.29	1.22
Sacramento Valley					
% of Total	0.26	0.14	8.58	6.96	0.10
% of Total Mobile	0.51	0.23	9.91	8.42	2.50

Several rail industry characteristics influence the development of effective locomotive emission reduction strategies. The most important is the long life of locomotives. Locomotives last 25 to 30 years, or more. Regulation which depends upon the development and introduction of new locomotive prime mover systems is likely to take a long time to have any material affect on air quality in California. Moreover, California has been pre-empted by the Federal government from imposing regulations on new locomotives.

Nevertheless, several emission reduction strategies have been identified. These include both operations related changes which depend upon no new technology; relatively near term technology-based actions applicable to existing locomotives; and intermediate and longer term technology development strategies for new model locomotives.

OPERATIONAL CHANGES

- Changes in railway operating practices and improved maintenance of locomotive starting systems can reduce emissions associated with idling locomotives. These changes could reduce locomotive-generated NOx emissions by about 10 percent

NEAR-TERM RETROFIT TECHNOLOGIES

- Short term efforts which may reduce NO_X emissions include retarded timing and the use of lighter fuels. Such strategies, most effective when applied to local and yard locomotives, could reduce NO_X emissions by 20 percent from these units--achieving a 6 percent reduction in overall NO_X emissions. These techniques require no new technology.

- The modification of selected existing locomotives with higher pressure injectors to permit retarding timing without a significant fuel consumption or particulate penalty appears possible. It is estimated that this modification could reduce overall NO_X emissions by about 7 percent.

The emission reductions resulting from these near-term operational and retrofit strategies are shown below.

Emission Reductions (Tons/Year)

Strategy	HC	CO	NO_x	SO_x	PM
Injector Retrofit	--	162	2,479	--	--
Reduced Idling	95	261	794	56	24
Retarded Injection	Increase	Increase	2,243	--	Increase
High Quality Fuel	Nullifies above increase	Nullifies above increase	--	--	Nullifies above increase
TOTAL	95	423	5,516	56	24
% Reduction from Baseline Emissions	6.13%	8.78%	15.22%	2.13%	3.04%

The cost effectiveness of these near-term control strategies is detailed in the exhibit below.

Control Strategy	Cost Effectiveness
Reduced Idling	[$.19/lb] (1)
EMD High Rate Injector Retrofit	$1.25/lb of NOx + CO
Retarded Injection Timing	$.10/lb of NOx
High Quality Fuel	$.93/lb of NOx (2)

(1) Refers to the collective mass of all species of pollutants reduced. There is a net cost savings and emission reduction from reduced idling.

(2) High quality fuel is assumed to be used in conjunction with retarded timing. NOx reductions are attributable to the retarded timing.

INTERMEDIATE-TERM TECHNOLOGIES

- Recommended demonstration projects include the use of charge air cooling and adaptation of selective catalytic reduction devices. While research on engines of this size is limited, indications are that such devices could reduce locomotive NOx emissions by between 50 and 80 percent. These devices would be applicable to new model locomotives, therefore, the timeframe for a significant reduction in locomotive emission levels is likely to be extended by the life of existing railway locomotives. It is possible however that retrofitable charge air cooling and selective catalytic reduction systems could be developed, at least for some locomotives in some circumstances. SCR devices are already successfully being used in service on marine vessels.

- It is not likely that a *practical*, retrofitable alternative fuels package could be developed for line haul locomotives. Therefore, alternative fuels such as methanol, LNG, or CNG are not likely to be near-term solutions for reducing locomotive-generated emissions from line-haul operations. Development of working locomotive engines, even in demonstration programs, is likely to take between 2 and 4 years. Development of a new generation locomotive engine powered by an alternative fuel is more feasible but will take longer and cost between $500 million and $1 billion.

- The use of alternative fuels for local and switching operations is more feasible. However, the costs and emission benefits of developing a commercially acceptable alternative fueled engine is unclear since only limited research in this area has been performed. Our preliminary assessment suggests that LNG offers economic and operational benefits over other alternatives. Because of the large costs involved in an alternative fueled locomotive demonstration, we recommend that such a demonstration be contingent upon financial participation by the railroads and locomotive manufacturers.

- Electrification of railways can significantly reduce rail-generated emission levels in California. Basin locomotive emissions could be reduced by as much as 70 percent if all line-haul routes were electrified (yard and local trains would remain diesel-powered). This locomotive-based emission reduction must be balanced against any increases associated with the generation of electric power.

Electric locomotive technology is available and well developed, nothing must be invented. However, this alternative is too expensive for railways to fund by themselves. Estimated cost to electrify tracks in the South Coast Air Basin is over $1 billion. Electrification of the main trackage in other basins would cost several times this amount. Large scale electrification could be completed within a seven to ten year time period.

More precise determination of the costs and benefits for various alternatives must be preceded by a better and more common understanding of locomotive emission testing standards. Standards for the basic physical measurement process, laboratory methods and equipment, and a duty cycle definition are needed. Such a determination should not be time consuming, there is already much common agreement. This Locomotive Emission Inventory is a further step in reaching a common understanding. Significant locomotive emission testing has taken place in recent years. The techniques and methodologies used in this testing have much in common and a defacto emission testing methodology has already evolved. This methodology should be recognized, codified and become the standard by which changes in locomotive emission levels are measured.

1.0 INTRODUCTION

1.0 *INTRODUCTION*

Air pollution in much of the State of California exceeds state and federal standards. If air quality degradation continues, the health and welfare of the citizens of California will be adversely affected. The California Air Resources Board (ARB) is charged by the state, and ultimately by the citizens of California, with the development of methodologies and the design of programs, standards, regulations, and other actions that will improve air quality within the State. In Assembly Bill 234, enacted in late 1987, the government of California authorized the Air Resources Board to conduct, jointly with the California railroad industry, a study of railroad locomotive emissions. The study was to be directed by a Locomotive Emission Advisory Committee (LEAC), composed of the following members:

- The Secretary of Environmental Affairs.
- The Chairman of the State Energy Resources Conservation and Development Commission.
- The Secretary of the Business, Transportation and Housing Agency
- One representative each from one northern California and one southern California air pollution control district or air quality management district in non-attainment areas.
- One representative from each of the four major operating railroads in the state.

This report is a result of this bill. In this case ARB, in association with the LEAC and other California air management groups, sought assistance in the definition of the air quality impacts arising from the operation of railroad locomotives in six non-attainment air management basins within California. In addition, this group sought information about the efficacy and cost of feasible control strategies for locomotive-generated air pollution emissions for both long and short term implementation.

This is the final report of the Locomotive Emission Study project. The estimates that have been developed for locomotive-generated air pollution sources are documented in the report. The report also describes the methodologies used to create these estimates. Likely technologies for the reduction of locomotive-generated air pollution are also reviewed. A part of the Locomotive

Emission Study involved determining whether any of these technologies were sufficiently viable to warrant a demonstration project. We believe that several methods for reducing emissions warrant further study. We also conclude that there is sufficient information on which to base testing standards and that basic work involving the adoption and codification of standard testing methodologies and practices is needed.

The report is divided into seven sections:

1.0 Introduction to the report

2.0 Background on the rail industry and the railway supply industry in the United States.

3.0 A description of the basic technologies used in diesel-electric locomotives, the state of development of these technologies, and the emission characteristics of both current generation and prior generation locomotive engines.

4.0 The results of the locomotive emission inventory for each basin, along with a description of the inventory estimation process and likely sources and estimated size of associated estimation errors.

5.0 A discussion of technologies and methods for the reduction of locomotive-generated air pollution emissions.

6.0 Evaluation of emission reduction strategies

7.0 Recommended demonstration projects for the reduction of locomotive emissions, along with a discussion of the health and safety impacts and the methods and practices associated with each recommended demonstration technology.

* * * * *

The results of the emission inventory calculations are summarized in the body of the report and shown in detail in Appendix A, which is published as a separate document. A bibliography of articles and research work associated with the reduction of the emission of air pollutants in medium and low speed diesel engines is contained in Appendix B, published as a separate document.

2.0 INDUSTRY BACKGROUND

2.0 *INDUSTRY BACKGROUND*

2.1 RECENT HISTORY OF THE INDUSTRY

The transportation industry has undergone significant change over the last two decades. This change has been driven by several basic forces operating in the transport marketplace: increasing costs to provide transport services; the changing nature of the competitive environment; the availability of basic resources required for transport; and the financial returns associated with being in the transport business. These forces have affected all sectors of the transport market -- passenger and freight, long haul, and short haul services. While railroads and other agencies operate some passenger services, most rail operations are concentrated in long haul, intercity freight transport -- the focus of this section on industry background.

The rail industry, historically providing about 35 to 40 percent of all intercity freight transport (on a ton-mile basis), has been greatly affected by the changes taking place in the transport marketplace. Several key factors affecting the transport industry have led to major changes in the rail sector, its efficiency, and its use of the locomotive fleet. These changes have influenced the character of rail traffic, railway operations, locomotive purchases and, ultimately, the level of gaseous emissions generated as a by-product of providing transport services by rail.

The significant changes affecting the rail industry began with the bankruptcy of the Penn Central, almost 20 years ago. First, Penn Central, then six other northeastern rail carriers failed. Soon, the failures spread to the Midwest and West, with the failure of the Rock Island and Milwaukee systems. These events shocked the industry, Wall Street, and government policy makers. It started a series of events which, coupled with other shocks and events, caused a massive transformation in surface transport within the United States. Rail carriers and motor common carriers had been burdened with excessive regulation for decades prior to the failure of the Penn Central. It was this failure which necessitated changing the way in which surface transport was regulated and controlled.

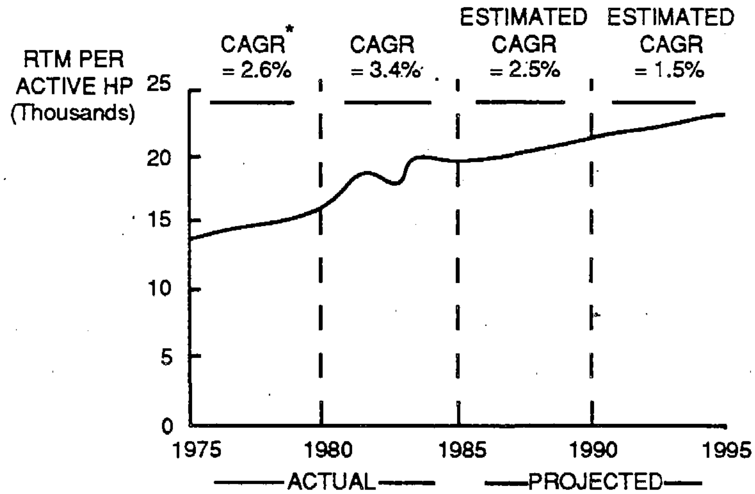
The oil price shocks of the 1970s added to the turmoil in the transport marketplace and changed the competitive posture of the major players in the industry. At the same time as the bankruptcies of the eastern carriers, a new national rail passenger carrier was being formed -- The National Railway Passenger Corporation, also known as Amtrak. This government corporation assumed the responsibility for the operation of money losing passenger services which the rail carriers had not been able to abandon under earlier regulations. Formation of Amtrak was an attempt to help a sick and failing industry.

However, seeds of the real recovery came later, contained in a series of federal legislative acts starting in the late 1970s. The 3R and 4R Acts set the basis for a major restructuring within the industry, starting the deregulation process by requiring the industry and its regulators to perform capital needs and revenue adequacy analyses, and forming Conrail from the bankrupt carriers in the east. The Staggers Rail Act of 1980 and the companion Motor Carrier Deregulation Act capped the legislative change process. This series of legislation eased strictures on service changes, gave rail carriers the ability to price competitively and enter into long term service contracts, and reduced the restrictions on the ability of carriers to merge and abandon uneconomic services and lines. The Motor Carrier Act eased restrictions on regulated truck services, making it easier to enter and exit markets, and eased size and weight restrictions on trucking operations. Suddenly, surface transportation, already a very competitive business, became very different -- more innovative and potentially more profitable.

To survive and compete in the rapidly changing transport environment, rail carriers had to become more efficient, less capital intensive, and provide better service. Motor carriers faced similar competitive pressures with owner-operators and non-union motor carriers providing low cost competition. Coupled with the decline of industry in the "rust-belt," the increase in just-in-time manufacturing practices, and the fruition of several important mergers, the new competitive environment had a tremendous impact on rail carrier operations. Cost control, more specialized transportation service offerings, more focused marketing, and more efficient operating practices all became an important part of running a rail system. Rail systems sought competitive advantage in consolidations and mergers. Joint use agreements, trackage rights agreements, and run-through train arrangements between rail carriers grew to provide competitive advantage in a market in disarray.

As traffic recovered over the past few years, rail carriers have learned to use capital assets more productively. Exhibit 2-1 shows the improvement in locomotive productivity, as measured by revenue ton-miles per active horsepower.

EXHIBIT 2-1
Locomotive Utilization for Class I Railroads

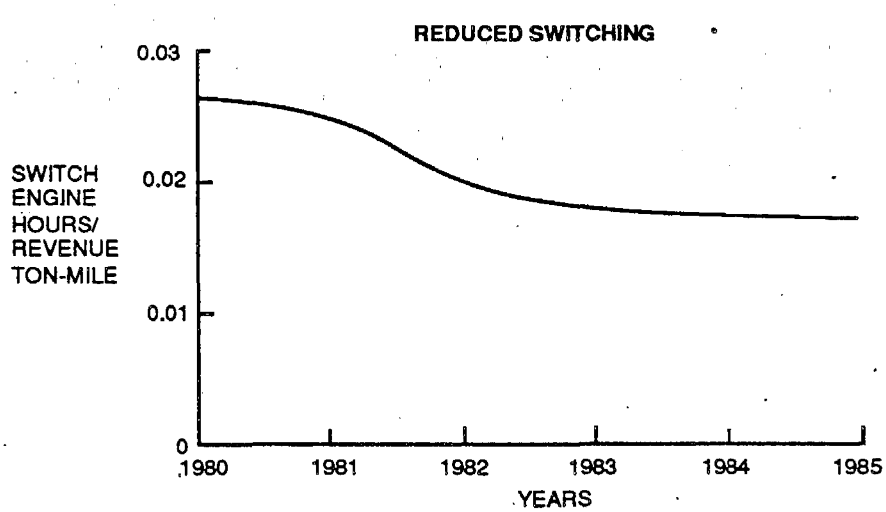


* CAGR = Compounded Average Growth Rate

Source: AAR, Rail Interviews, Booz, Allen analysis.

Operating practices have changed significantly, becoming much less switching intensive and more customer responsive. In the 1970s, rail carriers constructed many new major classification yards and reconstructed and modernized older yards to increase switching capacity. In the environment of the 1980s, rail carriers began to offer more discrete, customized services, both to compete with trucking services as well as to reduce the delays and costs associated with switching rail cars. These changes led to the closure of many now unneeded yards. As a result yard and switching activities have been reduced significantly, as shown in Exhibit 2-2.

EXHIBIT 2-2
Class I Rail Carrier Switching Activity



Source: AAR

These changes have led to a greater diversity in rail operations, more fast intermodal trains, the introduction of double stack services (where containers are stacked two high on special rail cars), and increased use of heavy-duty unit train services. These new service requirements have changed the types of equipment which railways require. New locomotive designs with higher horsepower, better traction control and more fuel efficient engines were needed to provide cost effective high speed services and for more efficient heavy-duty unit-train operations. Locomotive consists (the number and type of locomotives operating to pull or push a single train) have changed considerably. With the first and second generation diesel electric locomotives, trains typically operated with four, five or more locomotives. New, more customized trains with new design locomotives operate with two or three units. Some are operating with only one high speed, high horsepower unit.

These same shifts have also affected the types of locomotives rail carriers use in gathering and yard services. Low horsepower switching locomotives (ranging from 900 to 1,500 HP) are being replaced with rebuilt second generation road locomotives with more horsepower and better traction control. Increasingly, the shift to intermodal operations is eliminating the need for gathering and switching services -- trucks bring trailers and containers to the railhead.

These changes have had a significant impact on the operating characteristics of railroads and the locomotives used in typical service. Switching intensive work is being reduced. Locomotives are used more intensively (more hours per day) and more specifically, i.e. closer to their design limits. The design of locomotives is such that they operate most efficiently and with lower emissions per unit of work performed at high throttle settings. With fewer locomotives producing greater output, overall emissions, as a function of work done, should be considerably lower today than in the past. The changing emission characteristics of diesel engines used in locomotives are addressed in a later section.

2.2. RAIL INDUSTRY STRUCTURE AND RECENT OPERATING AND FINANCIAL TRENDS

United States railways are, for the most part, operated as for-profit private enterprises. Exceptions are passenger operations like those of the National Railway Passenger Corporation, (Amtrak) and local services in some communities which are operated by government units to provide commuter services in urban areas. An example of such services is the San Jose-San Francisco commuter service operated by CalTrans over Southern Pacific trackage. There are 16 large railways operating in the United States. These are classified as "Class I" railways by the

Interstate Commerce Commission (ICC) for financial and regulatory reporting purposes.[1] In addition to the Class I carriers, there are some 484 other, smaller railroad operations in the United States. These range in size from regional railroads, with several thousand miles of track, to short line operations serving only local communities.

The Association of American Railroads (AAR), the rail industry trade group, reported that, in 1987, the Class I carriers employed about 90 percent of the total industry labor force (about 235,000 employees out of 262,000), and operated about 80 percent of total industry track miles (148,000 track-miles out of a total U.S. track-miles of about 181,000).[2]

Over the past decade, the rail industry has had to adapt to a rapidly changing competitive and regulatory environment. It has done so by becoming more efficient, investing in the higher service components of its operations and becoming much more aggressive in its pricing actions. As a result of the industry's aggressive actions, real freight rates have declined, service levels have improved, traffic levels have been increasing and the industry is much more productive.

The most current data indicate that rail freight rates, as measured by constant dollar revenues per ton-mile, have declined by about about one-third since 1980. Even on a current dollar basis, freight rates have declined by over 5 percent (to 2.72 cents per revenue ton-mile in 1988 from 2.867 cents in 1980). Investment in new service related equipment (e.g. high-speed high-efficiency locomotives and intermodal and double stack rolling stock) has increased and rail carriers have reduced employment levels and operating costs significantly. Over the past decade, Class I carrier employment has declined nearly 50 percent (from about 471,000 in 1978 to about 235,000 in 1987)[3] while output, as measured by revenue ton-miles of freight moved, has increased by some 10 percent (from 857 billion revenue-ton-miles in 1978 to 943 billion in 1987)[4] . The resulting increases in productivity are remarkable--up by about 100 percent (from 1.9 million freight revenue ton-miles per employee in 1978 to more than 3.8 million in 1987). Recent figures from the industry indicate that these trends are continuing--1989 revenue ton-miles are a record 1,003 billion while employment has continued to drop.

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1 The Class I designation is given to railroads which have annual net revenues of more than $90 million in 1988, a figure that is adjusted for inflation each year.

2 Association of American Railroads, **Railroad Facts**, 1988 Edition

3 Ibid.

4 Ibid.

The rail industry has also made significant progress in reducing its capital intensity. In 1980, there were about 1,710,000 rail cars with a total capacity of about 135 million tons in the U.S. fleet. By 1988, this car fleet declined to 1,240,000 rail cars with a combined capacity of about 107 million tons. The reduction in the fleet was accomplished partly by purchasing larger cars (capacity per car is up about 10 percent) and partly by improving car utilization by some 36 percent. Locomotive fleet utilization has increased similarly. In 1980, Class I railroads had a locomotive fleet totaling more than 28,000 units with an aggregate horsepower of about 65 million. By 1988, the total locomotive fleet had been reduced to about 19,700 units with an aggregate horsepower of about 51 million.[5] As indicated above, while aggregate fleet horsepower declined by some 20 percent, revenue ton-miles have increased by about 10 percent.

Both changes in rail carrier operations and new more fuel efficient locomotive designs have contributed to increasing the fuel economy of the national locomotive fleet. In 1987, the Class I rail carriers consumed a little over 3 billion gallons of diesel fuel while generating over 940 billion revenue ton-miles of freight movement. The level of fuel economy achieved, about 307 revenue ton-miles per gallon of fuel, was nearly double the levels achieved 20 years ago. Rail carrier fuel efficiency is, on a ton-mile basis, about four times that of its trucking industry competitors.

Unfortunately, rail system profitability has not kept pace with productivity. Class I carriers earned, on average, about 5.6 percent on their railway investment in 1987[6]. This is considerably below the industry's cost of capital (determined to be about 12 percent by the ICC). While profitable, the railway business does not earn extraordinary returns -- over the past decade return on investment has ranged between 1.6 and 5.7 percent. Return on investment is a critical measure of financial viability for the rail industry because it is a capital intensive business. The Class I carriers had a net investment in railway operating properties valued at about $45 billion in 1987[7]. Return on shareholder equity for the industry has improved markedly, reaching 9.1 percent in 1988 from an average level of about 6 percent in 1980.

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5 "Watching Washington", *Railway Age*, January, 1990, page 10.

6 The cited rate of return figure excludes extraordinary items and special charges arising from the recent deregulation and tax considerations.

7 Association of American Railroads, **Railroad Facts**, 1983 through 1987 editions

2.3 RAILWAY SUPPLY INDUSTRY TRENDS

Industry restructuring and U.S. economic conditions had a devastating impact on the railway supply industry. The deep recession of 1982-1983 reduced transport demand significantly. The combination of the changes in the transport industry, the recession, and a major restructuring of much of the U.S. industrial base nearly destroyed the railway supply industry. Starting in about 1981, rail carrier orders for new equipment, particularly cars and locomotives, plummeted. At one point in the mid-1980s, United States rail carriers had idled nearly 250,000 rail cars (out of about 1.4 million at the time) and nearly 25 percent of its locomotive fleet. Industry orders for rail cars dropped from a high of about 98,000 per year in 1979/80 to only 3,000 by 1983/84. Car orders have slowly recovered to about 20,000 in 1989. Locomotive sales also declined sharply, from about 1,800 in 1979 to about 200 in 1983. Recently, locomotive sales to Class I railroads have increased to the 500 to 600 units per year level (roughly, a billion dollar per year business in new locomotive and parts sales).

In an environment which had become suddenly more competitive and price sensitive, investments in locomotives and other equipment were made to help reduce costs and improve service. The industry wanted far more efficient and reliable locomotives with greater performance. These pressures lead to the introduction of two new series of locomotives by the major U.S. locomotive manufacturers -- GE introduced its Dash 8 Series locomotives; EMD its 60 Series. These units were designed to produce more tractive effort, used microprocessors to increase reliability and improve fuel efficiency, and had higher horsepower. The primary driver behind these new locomotives was to improve the cost effectiveness of railroad operations while permitting reductions in the total fleet needed -- allowing a three for four unit exchange, for example.

There are currently two major manufactures of locomotives in North America, the Electro-Motive Division of General Motors Corporation (EMD) and General Electric Transportation Systems, a division of the General Electric Company (GE). EMD has been the locomotive sales leader since its diesel-electric locomotives began to displace steam driven locomotives in the late 1930s. About 70 percent of the locomotives in the U.S. fleet were manufactured by EMD. EMD's diesel-electric locomotives are powered by a 2-cycle diesel engine developed in the 1930s. Since that time, the engine has been extensively improved, modified and produced in many different versions.

GE, the other major locomotive manufacturer, uses a 4-cycle diesel engine originally developed by Cooper-Bessemer. This engine has also been continually improved and modified over the years. In recent years, the two major locomotive manufacturers have essentially split the U.S. market. GE's largest locomotive, the 16-cylinder, turbocharged Dash 8, generates a rated 4,000 horsepower. EMD's latest unit, the 710G used in its 60 series locomotives, is rated at 3,800 horsepower.

A third engine manufacturer, Caterpillar Inc. (CAT) has recently developed two diesel engines that are being offered as replacement engines during locomotive rebuilds. The CAT engines are relatively recent additions to the locomotive engine market and there are few of them installed in locomotives in the U.S. The chart in Exhibit 2-3 summarizes the current basic engines offered by each engine manufacturer.

EXHIBIT 2-3
Current Locomotive Engine Characteristics

	MANUFACTURER				
	EMD		GE	CATERPILLAR	
MODEL DESIGNATION	645	710	FDL	3500	3600
Operating Cycle	2	2	4	4	4
Bore (inches)	9.0625	9.0625	9.0	6.69	11.02
Stroke (inches)	10.0	11.0	10.5	7.48	11.81
Displacement/Cylinder (in^3)	645	710	668	263	1123
Maximum Rated Speed (RPM)	900	900	1050	1800	900
Maximum Power/Cylinder (BHP)	238	267	256	130	262
Cylinders Available	V8, V12, V16, V20	V8, V12, V16	V12, V16	V8, V12, V16	V6, V8, V12

While modern locomotives are relatively expensive, roughly $1.5 million each (including about $400,000 for the engine itself), the limited volumes currently produced make the development of new engine technologies a relatively risky investment. Because of the size and complexity of the prime movers used in modern diesel electric locomotives, the development of new engine technologies requires a significant financial undertaking. Once a new engine system is developed (including the diesel engine and its associated turbocharger), the investment needed for tooling to produce the new engine is approximately $300 million. Testing and final design add to total costs. Booz, Allen estimates that the investment needed to produce a new locomotive, even one based upon current models, will approach $400 million over a 5 to 7 year period.

While demand for cars and locomotives has increased in recent years, the industry is not likely to see the high levels of investment which occurred in the 1970s. For example, Booz, Allen projects that long term demand for new locomotives will be about 700 to 900 units annually. The rail industry has become much more efficient and cost sensitive. In an industry dominated by two major manufacturers with demand at about 700 units per year, it will be difficult to assemble the financial resources needed to make these investments.

2.4 AN HISTORICAL REVIEW OF RAILROAD AND LOCOMOTIVE EXHAUST EMISSIONS

Advances in locomotive technology have been a major influence in the development of the railroad industry since its inception. Performance, efficiency, reliability and operating costs have been the traditional drivers of locomotive technology. Until recently, air quality concerns have had a relatively small influence on the development of locomotive technologies. However, locomotive exhaust emission levels have generally been reduced with the development of new technologies.

The earliest concerns about locomotive exhaust emission go back to wood-fired boilers in the 1840s -- hot cinders in the smoke created a fire hazard. These concerns led to stack modifications, traps, and changes in firebox design to reduce soot emissions. The move to coal-fired steam engines was driven by the higher energy content of the fuel as well as fuel availability and pricing. A by-product was less smoke, soot and hot cinders. The use of oil for firing locomotive boilers had the same basic drivers -- more widespread availability of the fuel and at a lower overall cost. Higher energy content of the fuel also permitted greater power and greater range. Smoke and soot emissions were also generally lower. The development of diesel-electric power was driven by the same concerns and diesel-electrics promised greater reliability and lower operating costs. Generally exhaust emissions were reduced and their chemical composition changed.

In the early 1970s, concerns about smoke emissions led to the development and widespread use of low-sac fuel injectors on the current generation of locomotive engines. Low-sac injectors reduced smoke and particulate emissions by limiting the dribbling of fuel into the combustion chamber after the fuel injection event, which was characteristic of standard fuel injectors of that time. This improvement not only reduced smoke and particulates, it also improved fuel economy.

Industry concerns about fuel efficiency and operating costs forced real improvements in brake specific fuel economy and increases in the capabilities of new generation locomotives. Fuel economy improvements were achieved by making significant improvements in combustion efficiency. Such improvements have generally led to reductions in exhaust emissions -- the subject of the next section.

3.0 CURRENT ENGINE TECHNOLOGY

3.0 *CURRENT ENGINE TECHNOLOGY*

3.1 CHARACTERISTICS OF DIESEL-ELECTRIC LOCOMOTIVES

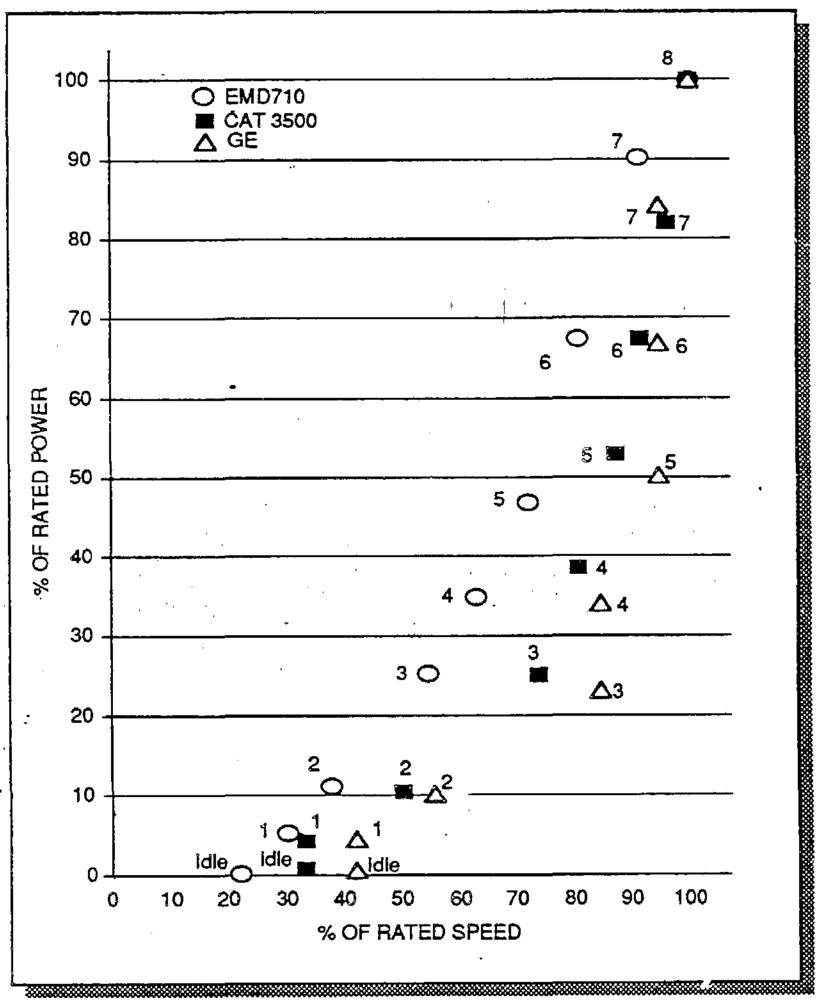
A basic understanding of several characteristics of the use of diesel engines in locomotives is important to the understanding of the operation of locomotives and the emission control strategies which might be useful in reducing emission levels.

Locomotives are powered by large bore medium speed diesel engines. In well designed Diesel-cycle engines, exhaust emissions are greatest during transient events in the combustion cycle. In over-the-road truck and bus operations, acceleration is initiated by changing engine speed through changes in the air-fuel ratio -- over-fueling to accelerate. Because the engine is directly coupled to the vehicle's wheels through the gear box, transients occur while the whole vehicle and its load is accelerated or decelerated. Typical operation of these engines is characterized by continuous fluctuations in engine speed, resulting in continuous transient conditions.

Control of locomotive engines is fundamentally different than that of most other diesel engines. Locomotive engines work at eight distinct constant loads and constant speeds, called throttle notches. Three other settings: low idle, normal idle, and dynamic brake are also normally available. In diesel-electric locomotives used in the United States, the engine is not directly coupled to the driving wheels but rather to an alternator or generator which produces electric power. It is this electric power which drives traction motors directly coupled to the drive wheels. Typical operation of locomotive engines is characterized by continuous operation at one of the eight throttle notches, the transients which occur as throttle notches are changed are fundamentally different from truck engine transients since the air-fuel ratio is not optimum only for as long as it takes to accomplish the change in engine speed, not the change in vehicle (or train) speed. The locomotive's micro-processor or traction control system sets the engine governor and controls the traction alternator load to assure engine operation at only these notch points. The traction control system also controls the rate at which the alternator load is increased or removed during transition from one notch position to another.

While nearly all locomotives have the basic 8 throttle notch control scheme, there are no standards which define these notches, as illustrated by Exhibit 3-1. At a given throttle notch setting, engine speed and power (as a percent of rated speed and power) can vary by as much as 25 percent and 5 percent, respectively, among the three engine manufacturers (as shown in Exhibit 3-1). The largest variations occur at the mid-power notch settings. These differences in control strategies could theoretically compromise the comparability of emission test data obtained from a notch-based test cycle since brake specific emission measurements would be taken at different engine operating conditions. However, because the variations in percent power at each notch are relatively small among the currently available locomotive engines, and because emission test data (highlighted later in this report) reveals that brake specific emissions are fairly constant at the various throttle settings (except for idle), we believe that published emission test data and that made available by the engine manufacturers and published in this report for the first time can be used for comparing the relative emission characteristics among engines.

EXHIBIT 3-1
Throttle Notch Versus Power and Speed



The low speed and heavy duty construction of diesel engines used in locomotives give them a long life. Locomotive diesel engines typically last 25 to 30 years. Because of their expense, it is common practice to overhaul and rebuild them several times over their lifetime.

Locomotive engines have been designed with modular components to permit piece by piece changes between major overhauls. Because of this, as improvements in injector and cylinder assembly design are developed, the improvements are generally retrofitable into older engines of the same family. Rail carriers tend to avail themselves of this feature as components are changed and during engine rebuild to obtain better fuel efficiency, engine performance and reliability. Thus, older units benefit from the evolutionary changes in engine component design. Of course, some design changes are not retrofitable.

Over time, manufacturers responded to the continuing demand for higher horsepower units and improved combustion efficiency by making improvements in engine design, increasing combustion pressures and fuel injection pressures, as well as changes in traction control systems and systems that manage parasitic loads. The chart in Exhibit 3-2 shows this trend in increasing power output for various EMD locomotives over time.

EXHIBIT 3-2
Engine Power for Road Class Locomotives

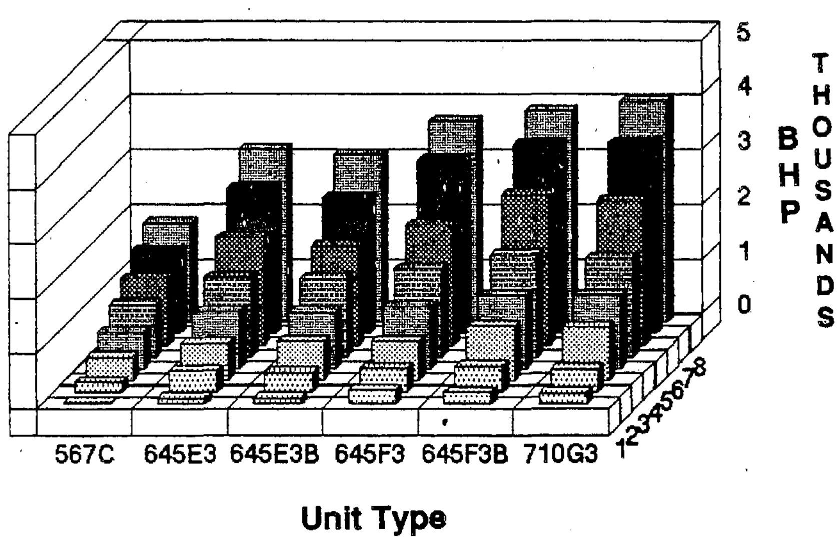
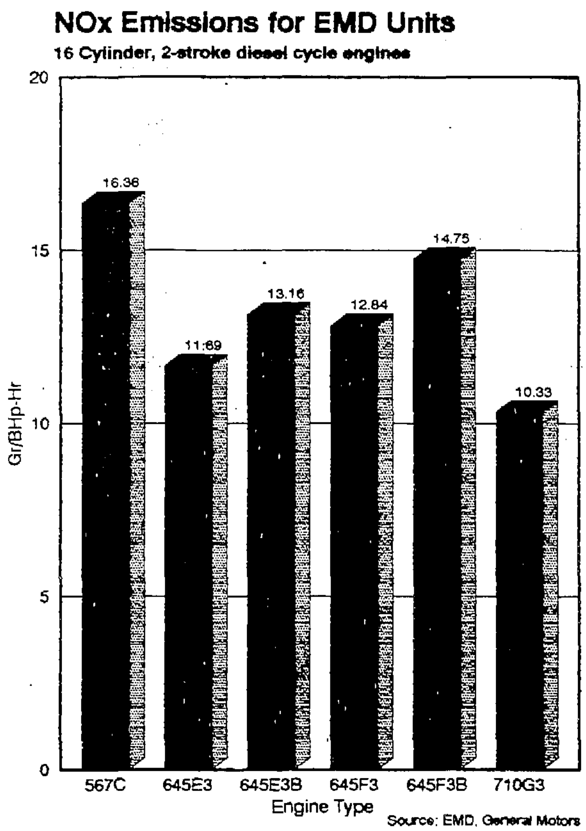
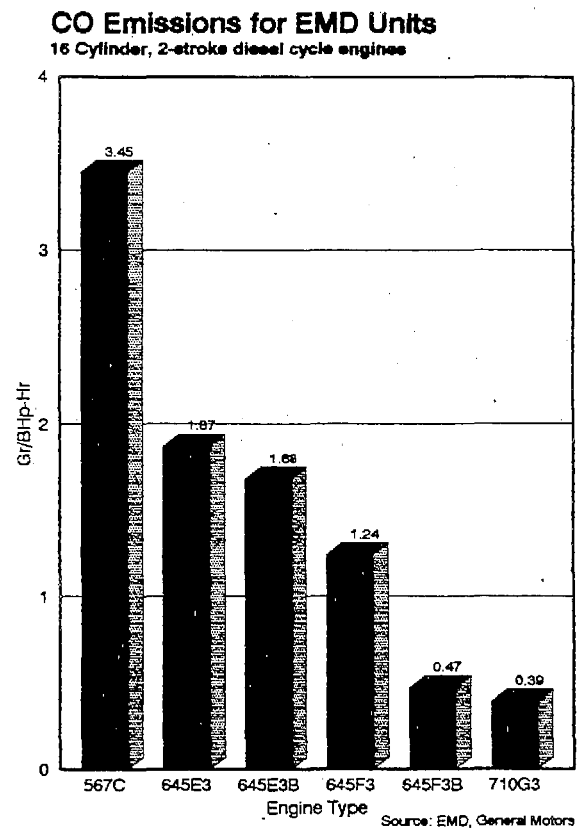
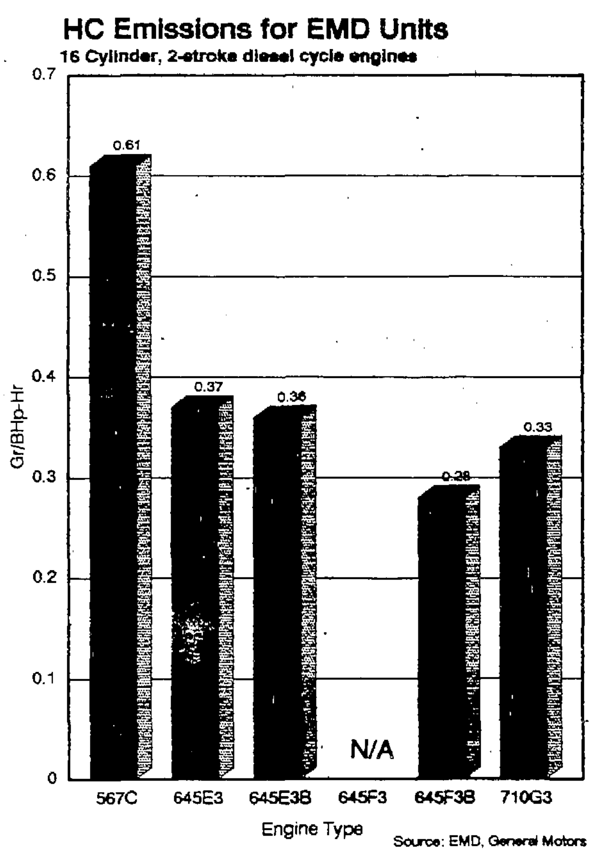


EXHIBIT 3-3
Evolution of Exhaust Emissions for EMD Engines at Throttle Notch 8







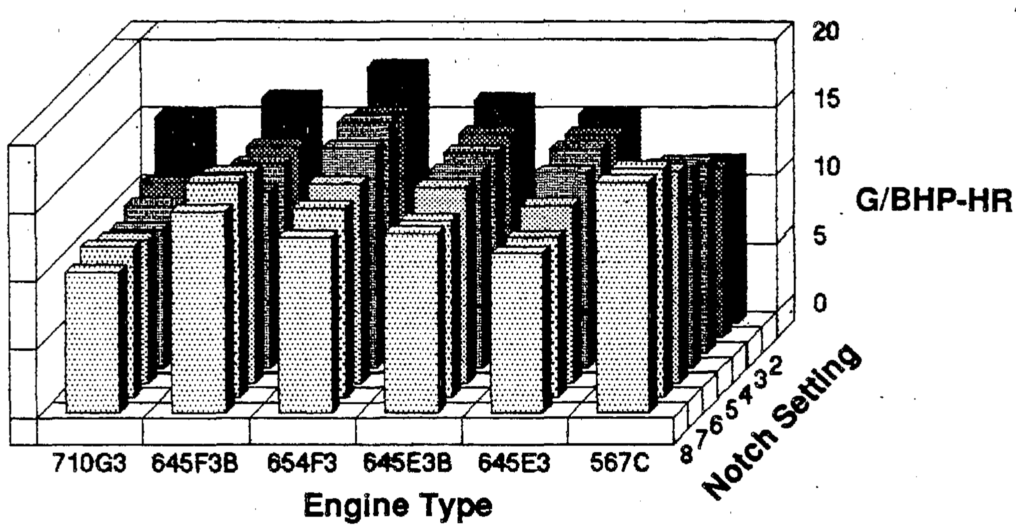
Emission data for EMD engines shown at throttle notch 8, peak power setting.

Exhibit 3-2 shows the trend in power output from successive engine designs. The 567 engine, a 16-cylinder Roots blown unit with 567 cubic inch displacement from each cylinder, was used in EMD's GP-9 locomotives in the late 1960s and early 1970s. The next generation engine was the 645 series (645 cubic inch displacement per cylinder), used in a series of locomotives in various configurations. The turbocharged 645E3 was used in GP and SD 40 series locomotives. Improvements in the turbocharger and other components evolved into the 645E3B engine. The 16-cylinder, turbocharged version of this engine was used in GP and SD 40-2 units, perhaps the most popular engine built by any locomotive manufacturer. Continuing evolution of the 645 series engine produced units with increasing horsepower and improved fuel economy per unit of work. In the late 1980s, EMD produced the next generation engine (the 710 series) with improved fuel injection, higher injection pressures, higher specific power output and better overall fuel economy.

3.2 EMISSION CHARACTERISTICS OF CURRENT LOCOMOTIVE ENGINES

Conventional wisdom indicates that increases in power output would be accompanied by increases in some exhaust emission levels. EMD emission measurements show that modern engine designs have reduced exhaust emission levels significantly. While the more recent development of high efficiency, high horsepower locomotive units has improved fuel economy, recent measurements indicate that all exhaust constituents have been reduced as well. Exhibit 3-3, on the facing page, shows the evolution of exhaust emissions from each of these engines at throttle notch 8, the peak power output notch setting. Exhibit 3-4 below, shows a map of the NO_X emissions by notch setting for these same EMD engines.

EXHIBIT 3-4
EMD NOx Emissions



These measurements indicate that engine-specific exhaust emission levels for EMD locomotives have declined considerably over the past decade. On a grams per horsepower-hour basis, NO_X emissions have been reduced by about 38 percent; CO emissions have been cut to one-tenth and HC emissions reduced by half. Particulate emission measurements have been undertaken only recently so there is no comparable data showing changes in particulate emissions over time. While some particulate measurement values do exist in the literature (AAR), comparison of particulate data is not useful due to the lack of a standardized measurement procedure. The marked decrease in visible exhaust smoke over the past decade indicates that particulate emissions have been reduced in newer locomotives.

While the other engine manufacturers do not have emissions data on older engine models, there is no reason to expect that GE engine development has not produced similar significant reductions in locomotive engine exhaust emissions. Air quality and the level of exhaust emissions is becoming a more important factor in the development of locomotive engine and control technologies. Concerns about exhaust emissions have already refocused some of the research and development activities related to locomotive technology. Currently, considerable research effort is directed towards defining emission levels and understanding what technologies are applicable for reducing locomotive exhaust emission levels. Such research will help improve the understanding of the combustion process in large-scale medium-speed diesels and should lead to productive refinements in engine design which reduce emission levels further.

3.3 ON-GOING RESEARCH ACTIVITY

Basic research activity on locomotive diesel engines is probably at an all time high with three major groups sponsoring most current work in the United States:

- EMD, GE and CAT
- Association of American Railroads
- U.S. Department of Energy

Both locomotive manufacturers and Caterpillar are continuing large scale and costly engine development programs. The impetus for this effort is to remain competitive or to gain a competitive edge in a very tough market. Manufacturer-funded development is focused in two broad areas:

- Meeting customer needs
    - More cost effective locomotives
    - More fuel efficient locomotives

- Improved locomotive durability and reliability
- Improved locomotive performance

- Making a profit on the product
  - Reduced product and production cost
  - Reduced warranty cost
  - Maintaining a share of the aftermarket parts business

Attaining an understanding of the emissions characteristics of locomotives has recently moved to a higher priority because of potentially costly regulation, and the resulting increased level of interest by locomotive purchasers. Studies and tests are underway to determine how responsive large-bore, medium-speed engines are to the emission reduction technologies developed for heavy duty truck diesel engines. Some of these projects have overtaxed the manufacturers' internal capability -- resulting in test programs being contracted to engine research institutions. There are only a limited number of research facilities in the United States which can accommodate engines of this size.

In addition to manufacturer-sponsored research, a great deal of work has been done by the rail industry through the Association of American Railroads (AAR), the rail industry trade association. Through the AAR, railroads are able to establish standards and conduct test programs that benefit all members. Through the AAR, the rail industry has funded many projects focused on examining a number of issues related to locomotive engines:

- Heavy petroleum fuels
- Alternative non-petroleum fuels
- Engine wear characteristics
- In-service engine emissions
- New engine emissions characteristics.

For example, a major long range program focused on identifying fuels that might have a more secure supply system and which might reduce fuel costs by identifying suitable fuels less costly than industry-specified diesel fuel. A major current program is focused on emission characterization of both EMD and GE locomotive engines. Twelve-cylinder versions of both engines have been installed at Southwest Research Institute and emission data are currently being generated. Railroad use of the AAR to direct and perform this type research has proven valuable and will probably continue.

The U.S. Department of Energy (DOE) has a broad engine improvement program underway which is directed toward more long range research efforts. One current development project is the coal-slurry fueled locomotive diesel. This program is about four years old and is at the point of transitioning from a single-cylinder research engine to a multi-cylinder development engine. The program is being performed by, and cost shared with, GE. In a similar DOE program, EMD and Allison Gas Turbine Division are developing a coal-dust fired gas turbine that ultimately could be suitable for locomotives. Other DOE diesel programs are focused on adiabatic technology for heavy duty truck engines and research of fuel cell technologies. Some of the products of this research may be applicable to locomotive diesels.

3.4 LIMITATIONS ON DATA

With a new sensitivity to air quality issues, truly serious measurement of locomotive emissions has only recently been undertaken. Much of the previous data was obtained using a mixture of different duty cycles and measurement techniques. AAR data was taken from locomotives that were available in the field and no control vehicles were used for comparison to established baselines. In fact, baseline data is only now being developed. There is no established standard "duty cycle" for locomotive engines, nor is there an accepted standard procedure, like the EPA's transient test procedure for the characterization of truck and bus operating duty cycles. The size and combustion characteristics of the engines used in locomotives are very different from most engines for which standard sampling procedures have been established. As a result, there are no commonly agreed upon testing procedures for some components of locomotive exhaust emissions--particulate matter measurement techniques are the major problem area; testing procedures for many components of locomotive exhaust emissions are already well accepted.

SwRI recently published a draft preliminary assessment of locomotive emissions reduction strategies[1] for the AAR. The Conclusions section reads as follows:

> *The following conclusions can be drawn from the information available at the time of writing:*
>
> - *The existing published data on locomotive engine emissions is inadequate for assessing the contribution of locomotive engine exhaust to air pollution.*
> - *There exist no standardized procedures for measuring locomotive engine emissions.*
> - *Experimental data on the effectiveness of many proposed emission reduction techniques is not available.*
> - *Insufficient baseline data exists on locomotive engine emissions to predict reductions with various control strategies. SwRI has intentionally refrained from presenting a list of the various control strategies in some sort of preferred order.*
> - *The costs of implementing various emissions control strategies are to be addressed in the California Locomotive Emissions Advisory Committee (LEAC) study by Booz, Allen. However, the cost benefit ratios will be suspect in the absence of actual engine emissions reductions data.*

We concur with most of these conclusions, however we have some significant reservations. In conducting this study we believe we have received the best available locomotive engine exhaust emission data ever compiled to date. Much of the data received from engine manufacturers was previously unpublished. The test data from EMD includes testing on 50 different engines over a 15-year period. These engines were tested on fuels with varying sulfur content and in varying states of engine wear. We have also used all of the recent emission testing data available from SwRI. While extensive data on locomotive emission degradation factors does not exist, we believe that sufficient data does exist to establish the relative contribution of locomotive emissions to total air

1 Southwest Research Institute, "Locomotive Engine Emissions Reduction Strategies: A Preliminary Assessment," Prepared for the AAR; October 1989; pg. iii.

pollution in the State of California -- with a degree of accuracy at least as reliable as estimation procedures used for other mobile source emissions. An examination of the inventory methodology we have followed, as well as the extensive data on train operations that have been provided by the railroads clearly supports the integrity of the inventory estimates.

While there is limited data available on the exact level of emission reduction that can be expected from some of the control strategies we have outlined in this report, cost/benefit analyses can still be performed with a reasonable degree of accuracy using the data that does exist for locomotive engines, and/or data from development work on other large diesel engines. These cost/benefit analyses can be used to rank order the relative cost effectiveness of various control strategies. Such analyses are useful to help prioritize engine development efforts as well as legislative initiatives for reducing emissions from this source.

We have included with our emissions reduction technology assessment a recommendation for the development of test procedures and standards which can be agreed to by the industry (through the AAR), the engine manufacturers, academia, and researchers in emission measurement techniques. It is hoped that the on-going work being sponsored by the AAR at SwRI, as well as that being conducted currently by the manufacturers, will become the foundation upon which a valuable data base on locomotive emissions is built. We believe that agreement can quickly be reached on testing standards, including those for particulates. We recommend that the test procedure involve determining steady-state emission levels at each throttle notch. Different duty cycles can be used for different types of service. It should be noted that some standardization in procedures and methodologies is already being achieved between manufacturers, the AAR, and other researchers in the field.

4.0 EMISSION INVENTORY ESTIMATES

4.0 *EMISSION INVENTORY ESTIMATES*

4.1 OVERVIEW

Booz, Allen & Hamilton has completed a detailed estimate of emission inventories from locomotives operating in the following six air basins in California:

- Bay Area
- Central Coast*
- South Coast
- San Diego
- San Joaquin
- Sacramento Valley

Inventory estimates were made for the following pollutants:

- Hydrocarbons
- Particulates
- Oxides of Nitrogen
- Sulfur Dioxide
- Carbon Monoxide

Emission inventories have been categorized as follows:

- By type of service:
  - Intermodal freight
  - Mixed freight
  - Local service
  - Yard operations
- By throttle notch: Notch 1 through 8; idle, and dynamic brake.
- By basin

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* The "Central Coast" consists of the South Central Coast plus the North Central Coast Air Basins combined.

Data required for calculating inventories were supplied by the locomotive manufacturers, the railroads, the AAR, and Southwest Research Institute. Detailed data are contained in Appendix A and include the following:

- Emission factors supplied by the locomotive manufacturers and SwRI
- Nominal emission factors for line haul, local, and yard engines for the SP, UP, and Santa Fe railroads
- Train operations data including origin/destination, average HP and trailing tons, train type, and frequency of operation
- Throttle position profiles for the trains operated in each basin.

This chapter summarizes the emission inventory calculations and is organized as follows:

- Overview
- Summary of results
    - Inventories by basin
    - Inventories by train type
- Characterization of California rail operations
    - Emissions, fuel consumption and work performed
    - Throttle notch profile analysis
- Rail activity levels by basin
    - Overview of basin activity
    - Inventory and train operations data
- Methodology and assumptions used in estimating emissions
- Variability analysis of emission estimates
- Implications of emission inventory.

EXHIBIT 4-1
Annual Locomotive Emissions in California

1987 Base Year: Tons

	Pollutant				
	HC	CO	NO_X	SO_X	PM
Bay Area	204	612	4,500	324	99
Central Coast	116	369	3,183	242	67
South Coast	563	1,718	11,492	813	259
San Diego	9	25	236	20	5
San Joaquin	378	1,179	9,045	662	196
Sacramento Valley	281	913	7,733	569	163
TOTAL	1,550	4,816	36,188	2,629	789

1987 Base Year: Percent

		Pollutant				
		HC	CO	NO_X	SO_X	PM
	TOTAL TONS	1,550	4,816	36,188	2,629	789
Percent By Basin	Bay Area	13.2	12.7	12.4	12.3	12.6
	Central Coast	7.5	7.6	8.8	9.2	8.4
	South Coast	36.3	35.7	31.8	30.8	33.8
	San Diego	.6	.5	.65	.77	.6
	San Joaquin	24.4	24.5	25.0	25.2	24.9
	Sacramento Valley	18.0	18.9	21.4	21.6	20.6
	TOTAL %	100.0	100.0	100.0	100.0	100.0

4.2 SUMMARY OF RESULTS

The locomotive emission inventory results indicate that railroad locomotive operations annually contribute a total of about 46,000 tons of five measured air pollutants to the air in the six non-attainment air basins studied for this report. The single largest effluent is NO_X; with 36,200 annual tons -- nearly 80 percent of total measured effluents. Total annual emissions from the operation of locomotives in California's non-attainment air basins are shown for each basin and effluent in Exhibit 4-1 on the facing page.

Locomotive generated emissions are also compared with similar emissions from both stationary and mobile sources in Exhibit 4-2, shown below. In total, rail operations contribute 3.4 percent of total NO_X emissions and about 1.5 percent of total SO_X emissions. Rail operations appear to be much less significant contributors to CO, HC, and particulate inventories.

EXHIBIT 4-2
Locomotive Emissions Versus All Other Sources
(Total for Six Basins: Tons/Day)

Source (1)	HC (2)	CO	NOx	SO_X	PM 10 (3)
Stationary Sources	1,862	2,087	804	183	3,711
On-Road Sources	1,375	9,943	1,678	111	152
Other Mobile Sources (4)	250	1,552	452	176	58
Total for All Sources	3,487	13,582	2,934	470	3,921
Trains (Booz, Allen 1987 Estimate)	4.23	13.2	99.1	7.3	2.22
Trains: Percent of Total	.12%	.10%	3.38%	1.55%	.06%
Trains: Percent of Total Mobile Sources	.26%	.11%	4.65%	2.54%	1.06%

1) Taken from ARB's 1987 Emission Inventory Estimates by Category
2) Reactive HC only
3) All locomotive particulates are assumed to be PM10
4) Includes ARB's estimate of 1987 train emissions

EXHIBIT 4-3
Emissions from All Sources by Basin (Tons/Day)

	HC (1)	CO	NO_X	SO_X	PM 10 (2)
BAY AREA					
Stationary Sources	284	248	160	61	523
On-Road Sources	277	1,965	343	27	29
Other Mobile Sources (3)	51	301	63	21	7
Trains (Booz, Allen Estimate)	0.6	1.7	12.3	0.9	0.3
Trains (% of Total)	0.10%	0.07%	2.17%	0.83%	0.05%
Trains (% of Total Mobile)	0.18%	0.08%	3.03%	1.88%	0.83%
CENTRAL COAST					
Stationary Sources	174	201	84	19	315
On-Road Sources	99	749	128	8	11
Other Mobile Sources (3)	18	116	28	3	3
Trains (Booz, Allen Estimate)	0.3	1	8.7	0.7	0.2
Trains (% of Total)	0.10%	0.09%	3.62%	2.33%	0.06%
Trains (% of Total Mobile)	0.26%	0.12%	5.58%	6.36%	1.43%
SOUTH COAST					
Stationary Sources	614	219	282	51	1,102
On-Road Sources	602	4,278	664	32	59
Other Mobile Sources (3)	75	512	141	42	14
Trains (Booz, Allen Estimate)	1.5	4.7	31.5	2.2	0.7
Trains (% of Total)	0.12%	0.09%	2.90%	1.76%	0.06%
Trains (% of Total Mobile)	0.22%	0.10%	3.91%	2.97%	0.96%
SAN DIEGO					
Stationary Sources	105	162	28	5	268
On-Road Sources	135	977	138	6	11
Other Mobile Sources (3)	17	102	70	95	15
Trains (Booz, Allen Estimate)	0.03	0.1	0.6	0.1	0.02
Trains (% of Total)	0.01%	0.01%	0.25%	0.09%	0.01%
Trains (% of Total Mobile)	0.02%	0.01%	0.29%	0.10%	0.08%
SAN JOAQUIN					
Stationary Sources	535	597	217	43	1,040
On-Road Sources	142	1,072	242	24	27
Other Mobile Sources (3)	53	317	99	10	14
Trains (Booz, Allen Estimate)	1	3.2	24.8	1.8	0.5
Trains (% of Total)	0.14%	0.16%	4.44%	2.34%	0.05%
Trains (% of Total Mobile)	0.51%	0.23%	7.27%	5.29%	1.22%
SACRAMENTO VALLEY					
Stationary Sources	150	660	33	4	463
On-Road Sources	120	902	163	14	15
Other Mobile Sources (3)	36	204	51	5	5
Trains (Booz, Allen Estimate)	0.8	2.5	21.2	1.6	0.5
Trains (% of Total)	0.26%	0.14%	8.58%	6.96%	0.10%
Trains (% of Total Mobile)	0.51%	0.23%	9.91%	8.42%	2.50%

1) Reactive HC only
2) All locomotive particulates assumed to be PM10
3) Includes ARB's estimate of 1987 train emissions

4.2.1 Emission Inventories by Basin

Locomotive emissions are compared with emission inventories from stationary, on-road and other mobile sources for each basin in Exhibit 4-3 on the facing page. On-road vehicles include cars, light duty trucks, heavy duty trucks, and motorcycles. Other mobile sources include off-road vehicles, aircraft, industrial mobile equipment, ships, utility engines and locomotives. The mobile source inventory data is drawn from the Air Resources Board's 1987 base year inventory data and includes ARB's estimates for locomotive emissions. (ARB's total locomotive emission estimates are about 6 percent higher than the emission levels computed here. The differences are discussed in section 4.5 of this chapter.

Several observations from this data can be made:

- The relative contribution of locomotives to total emissions varies substantially by basin. For example, NO_X emissions from rail operations in the San Diego Basin represent 0.3 percent of total basin NO_X emissions; while in the Sacramento Valley, locomotives contribute about 8.6 percent of NO_X emissions from all sources.

- The South Coast, San Joaquin, and Sacramento Valley basins contain the highest regions of locomotive activity. On an absolute basis, railroad generated NOx emissions are 31, 25 and 21 tons per day respectively.

- Compared with total mobile source NO_X emissions, the contribution from locomotives is relatively high in the Central Coast (5.6 percent), Sacramento Valley (9.9 percent) and San Joaquin (7.3 percent) basins versus the contribution in other basins.

- Rail operations are very light in the San Diego basin with total rail generated emissions of about 1 ton per day.

Some basins with relatively high rail activity also have high emissions from other mobile sources -- this tends to reduce the relative contribution to total emission levels in that basin from locomotive operations. Conversely, other basins have relatively little other mobile sources and the rail contribution appears relatively high.

4.2.2 Emission Inventories by Train Type

As noted earlier, train operations can be broadly characterized by the type of service performed. For emission inventory purposes, rail operations were classified into five different service types:

- Intermodal Freight Service: This service includes trains dedicated to carrying trailers and containers on flat cars (TOFC and COFC services). Double stack trains, which carry containers stacked two-high, are included in the intermodal freight service classification. Intermodal trains are generally high service trains, i.e. they operate at higher speeds and with higher power density (more horsepower per ton of train) than other types. Intermodal trains usually have modern high-speed, high horsepower locomotives.

- Mixed Freight Service: Mixed trains are point-to-point trains which carry all types of equipment, tank cars, box cars, gondolas, etc. Mixed service trains are the most common and operate with a wide range of power densities. Mixed freight services use a wide range of road power but usually high horsepower units. Because there were less than 10 percent bulk or unit trains operating in the air basins studied, bulk trains were included in the mixed freight service category for this analysis.

- Local Train Service: Local trains perform services that are a mixture of those performed by mixed freight service trains and yard service operations. Typically, local train services include moving a mixed train some distance and then performing switching work, picking up and setting out cars along the way. They generally operate with lower power densities than mixed freight service trains--fewer horsepower per ton of train--and therefore generally accelerate and move over the road more slowly than the either of the point-to-point services described above. Older medium horsepower locomotives are generally assigned to local train services.

EXHIBIT 4-4
Annual Emissions by Train Type: All Six Basins

1987 Base Year: Tons

Train Type	HC (Tons)	CO (Tons)	NO_X (Tons)	SO_X (Tons)	PM (Tons)
Mixed Freight	551	1,770	13,627	1,008	297
Intermodal Freight	412	1,344	10,163	745	221
Local Trains	351	1,117	7,774	580	167
Yard Operations	201	504	3,440	187	78
Passenger Trains*	35	81	1,183	110	26
All Operations	1,550	4,816	36,188	2,630	789

1987 Base Year: Percent

Train Type	HC (Tons)	CO (Tons)	NO_X (Tons)	SO_X (Tons)	PM (Tons)
Mixed Freight	35.5	36.7	37.7	38.3	37.6
Intermodal Freight	26.5	27.9	28.0	28.3	28.0
Local Trains	22.7	23.2	21.5	22.0	21.1
Yard Operations	13.0	10.5	9.5	7.1	9.9
Passenger Trains*	2.3	1.7	3.3	4.2	3.3
All Operations	100	100	100	100	100

* The passenger train data supplied by Amtrak is for its 1989 operations, they were not substantially different than those in the 1987 base year.

- Yard Services: Yard operations are characterized by intense stop and start type movements. Smaller locomotives predominate in yard operations and there is little line haul movement.

- Passenger Services: Passenger trains are generally high speed line haul type operations. In California, Amtrak and CalTrans passenger trains use specially developed locomotives (GE P30CH and EMD F40P), which are designed to operate at a constant engine speed.

Emission inventory results are shown by type of train in Exhibit 4-4 on the facing page. In total, mixed freight trains are the predominant train service operated in the six basins examined and the largest train type source. Line haul trains, including both mixed and intermodal freight services, account for about two-thirds of each effluent (ranging from 63 percent of HC emissions to 68 percent of sulfur emissions). Local and yard services account for most of the remaining emissions. Passenger operations comprise only two to four percent of overall emissions in any pollutant.

EXHIBIT 4-5
Calculated Gross Ton-Mile and Fuel Consumption Data by Basin and Train Type

Annual California Train Operations Data by Train Type
(1987)

Train Type	Gross Ton Miles		Fuel Consumption		Gross Ton Miles Per Gallon of Fuel
	Millions	%	1000s Gallons	%	
Total	51,279	100	141,529	100	400
Mixed Freight	28,226	55.1	54,395	38.4	522
Intermodal Freight	15,190	29.6	40,640	28.7	375
Local Trains	6,831	13.3	29,086	20.6	235
Yard Operations	--	--	12,498	8.8	--
Passenger Trains	1,033	2.0	4,910	3.5	210

Annual California Train Operations by Basin

Train Type	Gross Ton Miles		Fuel Consumption		Gross Ton Miles Per Gallon of Fuel
	Millions	%	1000s Gallons	%	
Total	51,279	100	141,529	100	400
Bay Area	4,468	8.7	17,352	12.3	258
Central Coast	6,208	12.1	12,396	8.7	517
South Coast	11,823	23.0	44,980	31.8	262
San Diego	241	.5	973	.7	247
San Joaquin	16,652	32.4	35,461	25.0	475
Sacramento Valley	11,886	23.2	30,367	21.5	396

1987 Rail Operations Data (ICC)

	Fuel Consumption (Millions Gallons)	Gross Ton Miles (Billions)	Revenue Ton Miles (Millions)	Gross Ton Miles Per Gallon	Revenue Ton Miles Per Gallon
Total SP	265	131	66	493	251
Total SF	313	147	72	469	230
Total UP	493	309	157	625	319
Total U.S.	3,069	1,847	940	602	306
Total West	1,903	1,137	597	599	313
Total East	1,165	710	342	610	293
California (Booz, Allen Estimates)	128	51.1	--	400	--
California as aPercent of Western Operations	6.7%	4.5%	--	67%	--

4.3 CHARACTERIZATION OF CALIFORNIA RAIL OPERATIONS

To more fully describe rail operations in California and to provide a basis on which to check the reasonableness of the emission inventory, fuel consumption and gross ton-mile estimates were computed for each basin and train type. Total gross ton-miles (GTM) and fuel consumption estimates were then compared with similar publicly available data to assess the reasonableness of the California emission inventory estimates.

Calculated gross ton-mile and fuel consumption data are shown by basin and train type in Exhibit 4-5 on the facing page. Exhibit 4-5 also shows comparable publicly available data from the Interstate Commerce Commission (ICC) for 1987. The computed average gross ton-miles per gallon of fuel for the six California air basins is relatively low compared to any of the system-wide measures shown in Exhibit 4-5. Several characteristics of California rail operations and of the system-wide measures account for the variances.

- The California operations for which emissions have been computed are characterized by a higher level of switching and local operations than any of the other system wide measures. California operations are characterized by traffic origination and termination activities rather than through line haul services. Major switching operations occur in Los Angeles, Long Beach, West Colton, San Bernardino, Bakersfield, Fresno, Stockton, Roseville, Oakland, Richmond, Fremont, San Jose and Marysville. Switching activities consume fuel but do not contribute to gross ton-miles in our calculation methodology -- this will tend to reduce calculated fuel efficiency as measured by gross ton-miles per gallon of fuel consumed.

- The terrain in California is comparatively hilly, reducing fuel efficiency somewhat.

- California rail operations have a much higher percentage of intermodal freight operations than any of the system averages. Intermodal operations are less fuel efficient on a gross ton-mile basis due to high train speeds and high dispatch power compared to other train types.

- Most of the non-California figures for gross ton-miles per gallon of fuel have a significant bulk train component. Bulk trains are inherently very fuel efficient operations because of the relatively low power densities characteristic of those movements. This will tend to inflate the relative fuel efficiencies shown in those averages.

EXHIBIT 4-6
ARB 1987 Rail Operations Emission Estimates (Tons/Day)

Basin	HC	CO	NOx	SO_x	PM	
Bay Area	1.3	2.0	5.3	.8	.34	
Central Coast	2.0	2.5	7.0	.75	.45	
South Coast	4.6	7.0	18.0	2.1	1.1	
San Diego	.27	.35	.98	.11	.06	
San Joaquin	6.3	8.2	22.3	2.4	1.4	
Sacramento Valley	5.6	7.5	19.7	2.1	1.3	
Total Tons	20.07	27.55	73.3	8.26	4.65	133.8 tons/day
% of Total	15%	21%	54%	6%	4%	100 %

EXHIBIT 4-7
Booz, Allen 1987 Rail Operations Emission Estimates (Tons/Day)

Basin	HC	CO	NOx	SO_x	PM	
Bay Area	0.6	1.7	12.3	0.9	0.3	
Central Coast	0.3	1.0	8.7	0.7	0.2	
South Coast	1.5	4.7	31.5	2.2	0.7	
San Diego	0.03	0.1	0.6	0.1	0.02	
San Joaquin	1.0	3.2	24.8	1.8	0.5	
Sacramento Valley	0.8	2.5	21.2	1.6	0.5	
Total Tons	4.2	13.2	99.1	7.2	2.2	125.9 tons/day
% of Total	3%	11%	79%	6%	2%	100 %

	HC	CO	NOx	SO_2	PM	
Emissions of EMD 16-645E3 weighted by GE line haul cycle (percent)	3%	12%	79%	5%	1%	100%

The computed gross ton-mile per gallon of fuel consumed in mixed trains, 522 GTM/gal, compares well with both SP and ATSF systemwide data. The UP's value of 625 GTM/gal is influenced by its Powder River Basin coal operations. Also, the computed 517 GTM/gal for operations in the Central Coast, where operations are more typical of the line haul services in the rest of the country, compares well with total average value per gallon for western U.S. operations (599 GTM/gal). In general, the comparisons shown in Exhibit 4-5 provide some assurance that the calculation methodology used in the emission inventory is reasonable and produces meaningful results.

Another means to check the reasonableness of this emission inventory is to compare it with other such estimates. The ARB's Emission Inventory Branch is charged with estimating the inventories of all emission sources. Their inventory includes an estimate for rail operations. The latest available data is from the 1987 Emission Inventory, published in 1989. Exhibit 4-6, on the facing page, is taken from that data. Exhibit 4-7, on the facing page, is from Booz, Allen calculations performed for this study Significant differences appear between the estimates for different effluents. Compared to the latest ARB inventory estimates, the Booz, Allen inventory shows significantly lower HC and CO emission levels, NO_x is significantly higher, SO_x is about the same, and particulates are marginally lower.

However, as shown on the facing page, the relationships between the Booz, Allen computed inventories of each effluent appear reasonable based on a comparison with engine emissions factors weighted by an industry standard duty cycle. The 1987 ARB inventory data does not reflect the proportion of effluents which would be found in normal rail operations.

There is sufficient basis to believe that the inventory estimates calculated as part of this project are not only reasonable but are considerably more accurate than earlier estimates. The methodology used in this inventory recognizes the many factors which drive emission levels, including differences in rail operations, locomotive fleet types, geography, direction of operation, and traffic base. The engine emission factors supplied by the locomotive manufacturers, AAR, and SwRI, and used in the inventory calculations are the most accurate and most current available. They are locomotive and throttle notch specific, the calculation methodology is designed to take into account the diverse operating characteristics of the different rail operations and uses train specific time-in-notch data from actual and simulated operations as a basis.

We do not believe that the data available will support a more accurate method of computing locomotive based emission levels. (Estimates of the reliability of the emission inventory calculations are discussed in section 4-6.) However, we will show in the next section that, based upon the data developed in this analysis, simpler methods can now be used to yield relatively accurate estimates of locomotive emission levels.

EXHIBIT 4-8
Annual Emissions by Train Type: All Six Basins
(1987 Base Year: Tons)

Train Type	HC (Tons)	CO (Tons)	NO_x (Tons)	SO_x (Tons)	PM (Tons)	Fuel Consumption (1000s Gallons)	GTM (Millions)
Mixed Freight	551	1,770	13,627	1,008	297	54,395	28,226
Intermodal Freight	412	1,344	10,163	745	221	40,640	15,190
Local Trains	351	1,117	7,774	580	167	29,086	6,831
Yard Operations	201	504	3,440	187	78	12,498	--
Passenger Trains	35	81	1,183	110	26	4,910	1,032
All Operations	1,550	4,816	36,188	2,630	789	141,529	51,159

EXHIBIT 4-9
Annual Emissions by Train Type: All Six Basins
(1987 Base Year: Percent)

Train Type	HC	CO	NO_x	SO_x	PM	Fuel Consumption	GTM
Mixed Freight	35.5	36.7	37.7	38.3	37.6	38.4	55.0
Intermodal Freight	26.5	27.9	28.0	28.3	28	28.7	29.6
Local Trains	22.7	23.2	21.5	22.0	21.1	20.6	13.3
Yard Operations	13.0	10.5	9.5	7.1	9.9	8.8	--
Passenger Trains	2.3	1.7	3.3	4.2	3.3	3.5	2.0
All Operations	100	100	100	100	100	100	100

4.3.1 Emissions, Fuel Consumption and Work Performed

Locomotive emissions, fuel consumption and work performed, as measured by gross ton-miles were compared to help understand what activities were related to higher emission levels and to provide some basis of comparison with other known data for other modes. Exhibit 4-8 on the facing page summarizes emission levels for each pollutant, as well as fuel consumption and gross ton-miles by type of train operation. Exhibit 4-9 on the facing page shows the relative percentage of each measure for each train type.

It is clear from these tables that fuel consumption is closely correlated with emissions, while work performed, as measured by gross ton-miles, is not. The relationship between gross ton-miles and fuel consumption varies dramatically by both type of operation and by basin. Basin data is shown in Exhibit 4-10 below. This is because differences in operating characteristics between train types cause differences in fuel efficiency. Similarly, fuel consumption per gross ton-mile varies between basins because of the different mix of train services performed in the basin and because of each basin's unique geography. In the South Coast Air Basin, for example, moving gross tons eastbound,up Cajon Pass requires more work to be performed than moving the same gross tons westbound, down the Pass. In general, since any work performed requires energy inputs, the generation of gross ton-miles in hilly terrain will require more work to be performed than in flat territory. For example, the South Coast basin accounts for 32 percent of total NO_X emissions but only 23 percent of total gross ton-mile generation. This is partly due to the fairly hilly terrain in the basin (and partly to the relatively high concentration of switching and local train service in the basin).

EXHIBIT 4-10
Annual Train Operations by Basin

Train Type	Gross Ton Miles		Fuel Consumption		NOx Emissions		Gross Ton Miles Per Gallon of Fuel
	Millions	%	1000s Gallons	%	Tons/ Day	%	
Total	51,279	100	141,529	100	99	100	401
Bay Area	4,468	8.7	17,352	12.3	12.3	12.4	258
Central Coast	6,208	12.1	12,396	8.7	8.7	8.8	517
South Coast	11,823	23.0	44,980	31.8	31.6	31.9	262
San Diego	241	.5	973	.7	.7	.7	247
San Joaquin	16,652	32.4	35,461	25.0	24.8	25.0	475
Sacramento Valley	11,886	23.2	30,367	21.5	21.2	21.4	396

The close correlation between emission levels and fuel consumption can be expressed in fuel based emission factors for rail operations. These factors can provide both a further check on the reasonableness of the emission inventory data computed in this report as well as a simple method to estimate emission levels if fuel consumption is known. The data in Exhibit 4-11, below, shows the emission factors computed for operations in the six California non-attainment basins on the basis of train type. The average of this data represents the emission factors we would recommend for computing emission levels if total fuel consumption is known. If, however, fuel consumption data for the different types of train operations (i.e., yard vs. local vs. mixed, etc.) is available, then the emission factors for these types of service should be used. These factors are compared with emission factors from AP-42 and from SwRI's report to the EPA in 1985 on off-road gaseous emission factors. The Booz, Allen factors show considerably less CO and HC emissions per 1,000 gallons of fuel than other published emission factors. As noted however, the relationship among effluents suggested by emission data from the locomotive manufacturers supports our estimates.

EXHIBIT 4-11
Emission Factors for California Rail Operations
(Pounds per 1000 Gallons of Fuel)

Train Type	HC	CO	NOx	SO_x	PM
Mixed Freight	22	66	500	38	11
Intermodal Freight	20.3	66.1	500	36.7	10.8
Local Trains	24.1	76.8	535	40	11.5
Yard Operations	32	80.6	550	30	12.5
Passenger Trains	15	35	483	35	10.8
All Operations	22	68.4	512	37.1	11.1
AP-42 Factors	94	130	370	--	--
Revised Factors Line Haul (1)	39	226	558	--	--
All Engines (1)	41	187	533	--	--

RECOMMENDED EMISSION FACTORS FOR CALIFORNIA TRAIN OPERATIONS (← All Operations)

(1) From SwRI Report to the EPA entitled, "Recommended Revisions to Gaseous Emission Factors From Off Highway Mobile Sources," 1985.

EXHIBIT 4-12
Nominal Throttle Position Profiles for Mixed and Intermodal Freight Service in California versus Industry Standard Profiles

Calculated California Locomotive Duty Cycle Profiles

California Rail Operations (1)		Notch										Total
		8	7	6	5	4	3	2	1	Idle	Brake	
Mixed Freight	Actual Total Hours	35,125	10,012	12,266	14,295	14,455	14,047	13,573	13,122	155,797	37,123	320,166
	Percent	11.10	3.13	3.83	4.46	4.51	4.39	4.26	4.10	48.65	11.59	100
Intermodal Freight	Actual Total Hours	27,574	7,238	9,606	10,887	10,177	9,948	9,356	9,153	150,652	27,045	271,637
	Percent	10.15	2.66	3.54	4.01	3.75	3.66	3.44	3.37	55.46	10.01	100

Industry Standard Profiles

Industry Standard Profiles (Percent)	Notch										Total
	8	7	6	5	4	3	2	1	Idle	Brake	
G.E. Line Haul	14	3	3	4	4	3	5	5	50	4	100
EMD Medium Road Duty	17	4	4	4	4	4	4	4	46	9	100

(1) Local, yard, and passenger trains excluded

4.3.2 Throttle Notch Profile Analysis

The throttle notch profiles submitted by the railroads for their operations in California were analyzed by basin and train type to develop average or "standard" duty cycles for train operations in the state. These duty cycle profiles can be compared with published industry standard duty cycles for all U.S. locomotive operations that have been prepared by the locomotive manufacturers, and others.

Because of the very large sample of actual and calculated throttle position profiles submitted by Amtrak, the Santa Fe, the Southern Pacific, and the Union Pacific Railroads, the duty cycle profiles presented here represent the best available data for describing various types of train service in California. (Throttle profiles for switch service are shown in Section 4.2) These throttle position profiles can be used by others who may wish to describe similar types of train service in regions similar to those examined in California. Nominal throttle position profiles for mixed and intermodal freight service in California, along with "standard" throttle profiles for the industry are shown in Exhibit 4-12 on the facing page. The following observations can be made:

- California's rail operations are characterized by somewhat less time spent in Notch 8 and more time in intermediate and dynamic brake throttle positions than industry standard duty cycles. The average California train spends about 10.5 percent of the time in Notch 8, while EMD and GE duty cycles project 17 percent and 14 percent, respectively, in Notch 8.

- Mixed and intermodal trains in California have very similar throttle profiles with the mixed trains spending 1 percent more time in Notch 8 and 2 percent more time in dynamic brake than intermodal trains.

The throttle positions presented here for California trains reflect the geography, mix of service, and freight type that characterize California's rail operations.

EXHIBIT 4-13
Annual Locomotive Emissions by Notch (Tons)

NO_x

Train Type	Notch										Total
	8	7	6	5	4	3	2	1	Idle	Brake	
TOTAL	14,387	3,594	3,310	3,073	2,842	1,884	1,056	523	4,387	1,133	36,188
Line Haul	11,261	2,664	2,406	2,201	1,620	1,024	546	261	1,952	1,038	24,974
Local	2,038	818	642	673	834	627	362	188	1,498	95	7,774
Yard	1,089	112	262	198	388	233	148	74	938	0	3,440

HC

Train Type	Notch										Total
	8	7	6	5	4	3	2	1	Idle	Brake	
TOTAL	402	91	78	68	65	52	41	32	587	134	1,550
Line Haul	312	67	57	48	36	28	20	15	290	125	998
Local	56	21	14	14	18	16	13	10	180	10	352
Yard	33	3	7	5	11	8	8	7	117	0	199

CO

Train Type	Notch										Total
	8	7	6	5	4	3	2	1	Idle	Brake	
TOTAL	1,634	379	332	204	148	96	79	58	1,587	298	4,816
Line Haul	1,142	265	259	154	87	51	38	28	893	277	3,195
Local	276	106	62	43	45	30	23	19	492	21	1,117
Yard	215	9	11	7	15	15	18	12	202	0	504

SO_x

Train Type	Notch										Total
	8	7	6	5	4	3	2	1	Idle	Brake	
TOTAL	1,069	263	240	219	197	139	81	33	290	99	2,630
Line Haul	853	192	180	160	115	76	42	17	137	91	1,863
Local	161	64	47	49	61	48	28	12	101	8	579
Yard	55	6	13	10	21	14	10	5	52	0	186

Particulate

Train Type	Notch										Total
	8	7	6	5	4	3	2	1	Idle	Brake	
TOTAL	292	66	69	52	50	44	25	8	140	43	789
Line Haul	232	49	52	38	28	24	13	4	65	40	544
Local	41	15	13	11	14	14	8	3	45	3	167
Yard	19	2	5	3	7	6	4	1	30	0	77

Note: Line-haul includes passenger train operations.

Emission inventories by throttle notch were developed to help assess the impact of control strategies focused on specific locomotive operating modes (such as idle versus full load). Exhibit 4-13 on the facing page lists total tons produced in each notch by each type of train. Exhibit 4-14 below shows the percent of total annual emissions produced in each throttle notch for each effluent.

EXHIBIT 4-14
Annual Locomotive Emissions Inventories by Notch
(Percent)

Effluent	Notch										Total	Total Tons
	8	7	6	5	4	3	2	1	Idle	Brake		
NO_x	40	10	9	9	8	5	3	1	12	3	100	36,188
HC	26	6	5	4	4	3	3	2	38	9	100	1,550
PARTICULATE	37	8	9	7	6	5	3	1	18	5	100	739
SO_x	41	10	9	8	8	5	3	1	11	4	100	2,629
CO	34	8	7	4	3	2	2	1	33	6	100	4,816

As would be expected, the majority of locomotive emissions are produced in Notch 8. Approximately 40 percent of total NO_x inventories are produced in Notch 8 but only 26 percent of HC inventories. In contrast inventories produced from idle operations account for 38 percent of HC emissions and only 12 percent of the total NO_x emissions. Control strategies focused on reducing idle time would be particularly effective for controlling HC and CO emissions. For example, a 25 percent reduction in idle time for all locomotive operations would reduce NO_x emissions by 3 percent (or 3 tons per day) while HC emissions would be reduced by about 10 percent (or .4 tons per day).

EXHIBIT 4-15
Annual Locomotive Emissions by Train Type and Notch
(Tons and Percent)

ANNUAL NO_X EMISSIONS: ALL BASINS

NOTCH	8	7	6	5	4	3	2	1	IDLE	BRAKE	TOTAL
% BY NOTCH	40%	10%	9%	9%	8%	5%	3%	1%	12%	3%	100%
% LINE HAUL	78%	74%	72%	72%	57%	54%	51%	50%	44%	92%	69%
% LOCAL	14%	23%	20%	22%	29%	33%	35%	36%	34%	8%	22%
% YARD	8%	3%	8%	6%	14%	12%	14%	14%	21%	0%	10%

ANNUAL HC EMISSIONS: ALL BASINS

NOTCH	8	7	6	5	4	3	2	1	IDLE	BRAKE	TOTAL
% BY NOTCH	26%	6%	5%	4%	4%	3%	3%	2%	38%	9%	100%
% LINE HAUL	78%	74%	73%	72%	55%	53%	49%	47%	49%	93%	64%
% LOCAL	14%	23%	18%	21%	28%	31%	32%	31%	31%	7%	23%
% YARD	8%	3%	9%	7%	17%	16%	20%	22%	20%	0%	13%

ANNUAL PARTICULATE EMISSIONS: ALL BASINS

NOTCH	8	7	6	5	4	3	2	1	IDLE	BRAKE	TOTAL
% BY NOTCH	37%	8%	9%	7%	6%	5%	3%	1%	18%	5%	100%
% LINE HAUL	79%	74%	74%	73%	57%	53%	52%	50%	46%	93%	69%
% LOCAL	14%	23%	19%	21%	29%	33%	32%	38%	32%	7%	21%
% YARD	7%	3%	7%	6%	14%	14%	16%	13%	22%	0%	10%

ANNUAL CO EMISSIONS: ALL BASINS

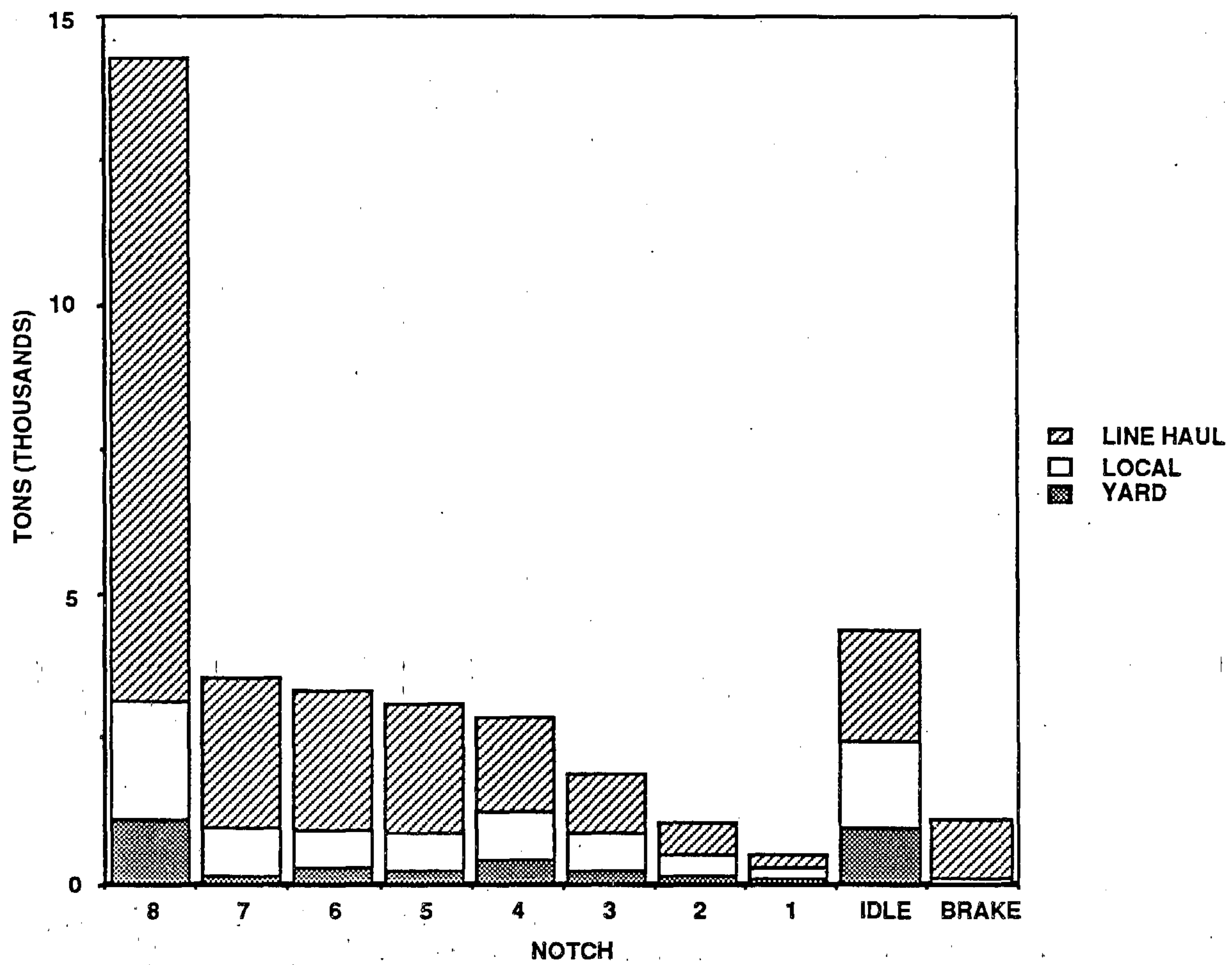
NOTCH	8	7	6	5	4	3	2	1	IDLE	BRAKE	TOTAL
% BY NOTCH	34%	8%	7%	4%	3%	2%	2%	1%	33%	6%	100%
% LINE HAUL	70%	70%	78%	75%	59%	53%	48%	47%	56%	93%	66%
% LOCAL	17%	28%	19%	21%	31%	31%	29%	33%	31%	7%	23%
% YARD	13%	2%	3%	3%	10%	16%	23%	21%	13%	0%	10%

ANNUAL SO_X EMISSIONS: ALL BASINS

NOTCH	8	7	6	5	4	3	2	1	IDLE	BRAKE	TOTAL
% BY NOTCH	41%	10%	9%	8%	8%	5%	3%	1%	11%	4%	100%
% LINE HAUL	80%	73%	75%	73%	58%	55%	53%	48%	47%	92%	71%
% LOCAL	15%	25%	20%	22%	31%	35%	35%	36%	35%	8%	22%
% YARD	5%	2%	5%	5%	11%	10%	13%	15%	18%	0%	7%

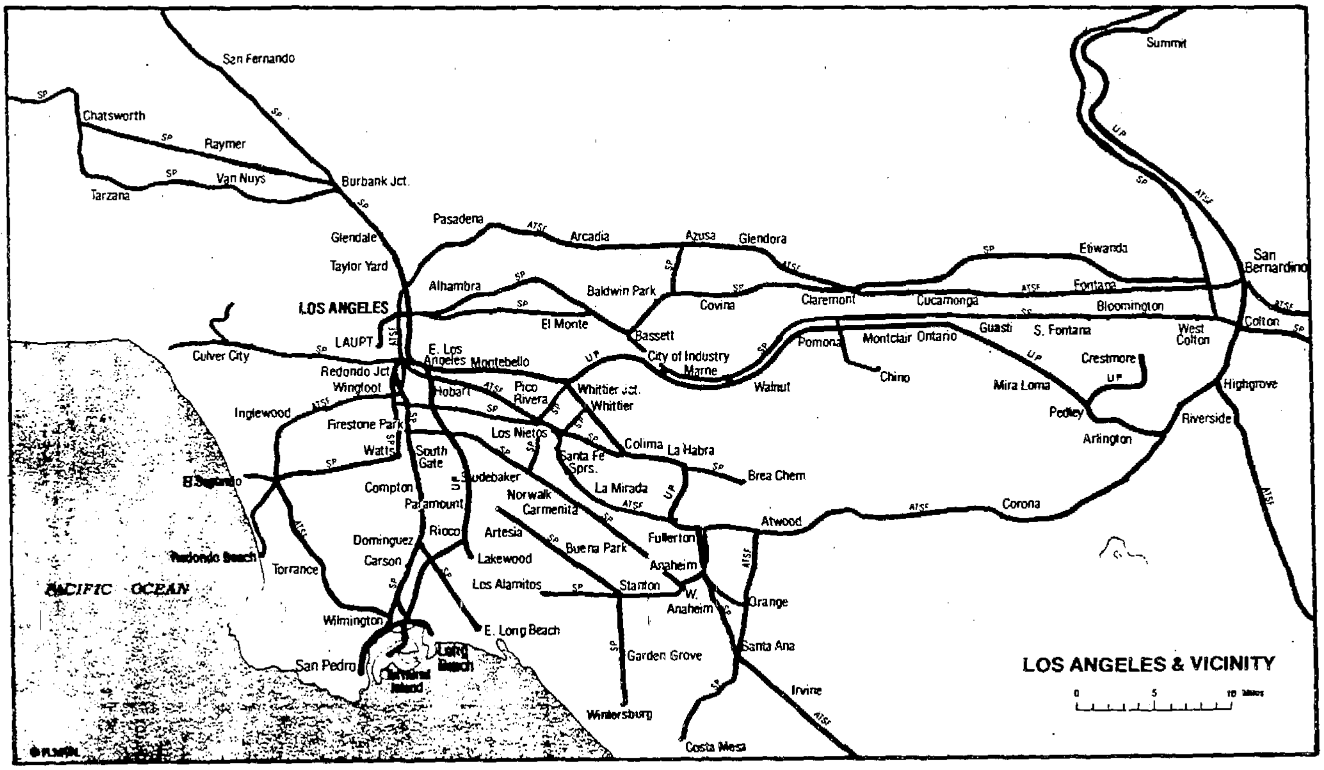
A further examination of emission inventories in each notch setting by type of train service in shown in Exhibit 4-15 on the facing page. NO_X emission inventories by notch and train type are shown in Exhibit 4-16 below.

EXHIBIT 4-16
NO_X Emission Inventories by Notch
(Total for Six Basins: 1987 Base Year)



The data indicates that line haul operations account for about two-thirds (between 66 and 71 percent) of all rail produced emissions. Local trains account for 21 percent to 23 percent and yard service for 10 to 13 percent of all locomotive emissions. Local and yard operations combined account for about 55 percent of total idle generated NO_X emissions (and idle NO_X emissions are 12 percent of total NO_X emissions). Thus if idle time could be reduced by 50 percent from local and yard locomotives NO_X inventories would be reduced by about 3 tons per day (about 3 percent of total).

EXHIBIT 4-17
Map of Major Rail Lines in the South Coast Air Basin



4.4 RAIL ACTIVITY LEVELS BY BASIN

Railroad activity levels vary considerably among the six air basins examined with regard to total number of trains operated, intensity of local and yard operations, and the average HP and trailing tons of each train. Also the geography and terrain of each basin is unique and affects the work (and emissions) required to move freight and passengers through the basins. An overview of train operations in each basin is presented followed by a summary of the emission inventories and train activity data for each basin.

4.4.1 Overview of Basin Activities

South Coast Basin -- Rail operations in this basin are the most intense of all the basins examined for all train types, including line haul, local trains, and yard operations. Rail activity level is high due to the size of the population, location of several important ports, and major industrial shipping centers. There are three major carriers -- the Atcheson, Topeka and Santa Fe (ATSF); the Southern Pacific (SP); and the Union Pacific (UP) -- and one major shortline or connecting carrier (the LA Junction Railway) operating in the basin. In addition, Amtrak operates over parts of the ATSF and SP and a segment of the joint trackage operated by the ATSF and UP. Exhibit 4-17, on the facing page, shows the major lines in the area.

The Atcheson, Topeka and Santa Fe (ATSF) typically operates about 12 to 14 road trains in each direction between Summit in Cajon Pass and Los Angeles. These road trains are of different types including Santa Fe's special articulated TOFC trains, double stack, and regular freight trains. The grade is quite steep to Summit and the Santa Fe occasionally operates helper locomotives on the grade from San Bernardino. The emissions generated per gross-ton-mile (GTM) on the upward trip are quite high. Between San Bernardino and Hobart Yard in Los Angeles, the Santa Fe normally operates over both its second and third subdivisions. Only westbound trains operate on the "northern route" while both east and westbound trains operate on the "southern route." This creates a continuous circular movement which returns both crews and locomotives to San Bernardino. Santa Fe road trains normally have between 3 and 5 units per train and most operate into Hobart.

In addition to its road freight operations, the Santa Fe operates about 5 road switching/local gathering service trains on a 5 or 6 days per week basis in the Los Angeles area. It further operates between 15 and 20 yard, transfer and industrial assignments daily in and between Hobart and San Bernardino. Finally, Amtrak operates 2 trains each way between Summit and Los Angeles and 8 trains each day from Fullerton over Santa Fe trackage.

The Southern Pacific (SP) is the largest carrier in the Los Angeles area, operating an extensive network of road trains through the South Coast basin. The SP typically operates about 3 or 4 trains each way daily on the Coast Route to and from the Bay Area and 2 or 3 trains each way daily on the Valley Route via Saugus to Los Angeles. It also runs between 8 and 10 trains daily to and from the north via Palmdale to West Colton Yard. Some of these trains operate to and from Los Angeles. Road trains operate out of West Colton, a major hump yard, primarily to the east. Several trains from the east bypass West Colton and operate to/from the SP's Los Angeles Transportation Center (LATC), City of Industry, Los Angeles Yard and Los Angeles Harbor at Long Beach. The SP normally operates trains north of West Colton via Cajon Pass with helper locomotives. It also sometimes operates helpers on eastbound trains to Beaumont. SP's road trains include TOFC, stack packs, unit trains and mixed freights. The SP operates approximately 40 to 50 local assignments and about 60 yard switch engines in the South Coast basin. Amtrak operates 3 to 4 trains per day over the SP on the Coast Route to the north. It also operates over the Sunset route every other day.

The Union Pacific (UP) operates 10 to 15 road trains each way daily from the east via Summit (the UP operates over ATSF's mainline trackage from Riverside to Dagget via Summit under a joint tenant agreement with the ATSF). These trains are composed of TOFC/COFC, stack pack, unit trains, and mixed freights.

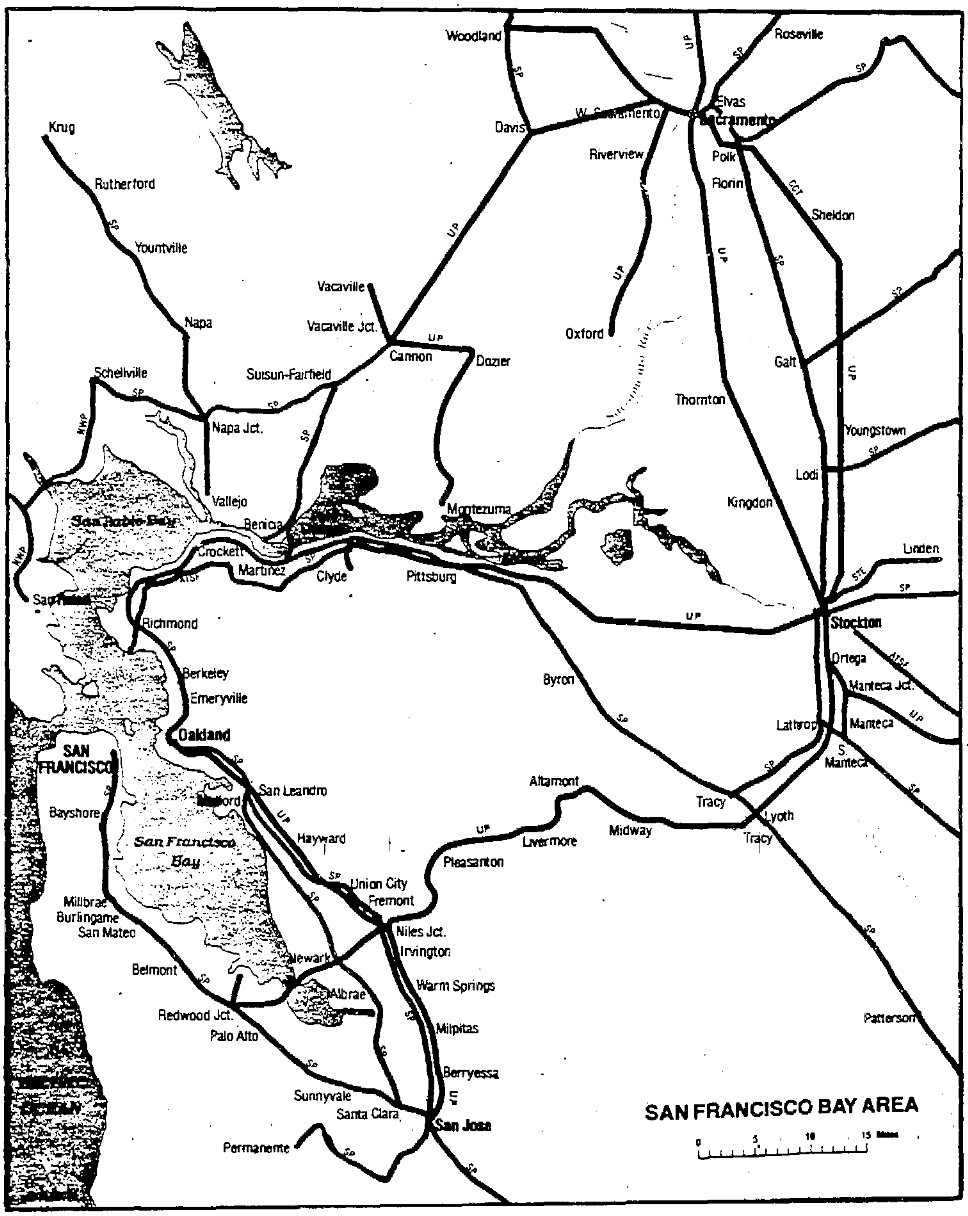
The UP operates major yards at Riverside, Fullerton, and Long Beach. The UP operates between 10 and 15 road switchers and 10 to 15 industrial and yard assignments daily in this area.

The Los Angeles Junction (LAJ) railway is an industrial switching road operating in the East Los Angeles/Los Angeles area. The LAJ handles cars on a switch delivery basis for all three major railroads but primarily for the ATSF and UP. LAJ operates about 15 yard and industrial crews daily.

Amtrak operates about 20 to 25 trains daily into the Los Angeles Union Passenger Terminal. They also operate 2 or 3 yard assignments between the terminal and coach yard and for train make-up.

The South Coast basin is the most complex of the six air basins involved in this study. It is characterized by relatively intense switching and industrial operations at several major hump and industrial switching yards as well as port and container terminal operations. It also supports intense road freight and passenger operations. Road freight operations include high speed TOFC and container trains of several different designs including new lightweight, articulated unit trains for trailers and double stack container operations. Several carriers operate drag freight trains, including unit trains, industrial and mixed freights. There are helper districts on the major grades on several lines and from two directions. Long distance and commuter passenger operations are also represented.

EXHIBIT 4-18
Map of Major Rail Lines in the Bay Area Basin



Bay Area Basin -- As in the Los Angeles area, there are three major rail carriers operating in the San Francisco Bay Area -- ATSF, SP and UP. Rail operations in this basin are also quite complex although they are dominated by the SP. Amtrak operates through and commuter passenger services through San Jose. The map in Exhibit 4-18 on the facing page shows the major lines in the area.

The ATSF operates 6 to 8 road trains daily in each direction towards Bakersfield via Stockton. It has yard and industrial service at two major locations -- Richmond and Oakland. Between 5 and 7 yard assignments work in these areas too. Amtrak operates 2 trains daily in each direction to and from Bakersfield.

The SP operates 6 to 10 trains daily to and from Sacramento, 1 or 2 each way over the Valley route, and 3 to 5 each way towards San Jose and Los Angeles along the Coast Route. In addition, the SP has extensive yard and industrial operations at Oakland, Richmond, San Francisco, San Jose and Warm Springs. A total of 30 to 40 yard and industrial assignments work in the basin. The SP also operates 15 to 20 road switching/local freight assignments in the area.

Amtrak conducts extensive operations over the SP in the Bay Area. It operates 2 trains each way daily to and from Pittsburg, 2 daily each way to Elvas and Sacramento and 1 each way daily along the SP's Coast Route to Los Angeles. Finally, about 20 commuter trains are operated for CalTrans over SP trackage between San Francisco and San Jose and return each weekday. CalTrans' weekend operations are at about half this level.

UP operates between 6 and 8 road freights to and from Sacramento daily. It has about 10 to 12 yard assignments working between Oakland and Warm Springs. A further 2 or 3 local freight/road switching assignments work in the area.

As in the Los Angeles area, the major carriers operate a complex set of road trains in the Bay Area. This basin is characterized by very heavy switching and local service. Line haul operations are split evenly between mixed and intermodal freight.

Central Coast Air Basin -- The SP Coast Route is the only major rail operation in this basin. They typically operate between 2 and 4 road freights (TOFC/COFC and mixed freight trains) and 2 or 3 local freight assignments in the area. There is a helper grade near San Luis Obispo where 2 helper assignments operate. There is no yard activity in this basin.

Amtrak operates one train each way daily over the SP route. A short line, the Valley Railway, operates between Santa Maria and Guadalupe. They use 1 or 2 assignments on a 5-day per week basis as traffic demands.

Sacramento Valley Air Basin -- Major rail operators in the Sacramento Valley air basin include the SP and the UP. There are several short lines operating in the area as well -- the Sacramento Northern (SN) and the Central California Traction (CCT).

> The SP operates 6 to 8 road trains each day to and from the north via the Cascade Route. It also operates a similar number to the east via the overland route and from 6 to 10 daily to and from Oakland. A further 6 to 8 operate daily over the Valley route to Fresno. In addition, the SP operates about 7 local trains daily in the Sacramento Valley area. Between 20 and 30 yard assignments are involved in work at the SP's two major yards at Roseville and Sacramento. Amtrak operates daily in each direction over the Overland Route to the east and to the north over the Cascade Route.
>
> The UP operates 6 to 8 trains daily to and from Oakland and Warm Springs and between 7 and 9 trains daily towards Keddie to the northeast. UP also operates 2 to 3 local assignments and between 4 and 6 yard assignments in the Sacramento area.

Operations in this basin are characterized by intensive line haul operations with very little switching or local train activity. Overall traffic is dominated by the SP.

San Diego Air Basin -- The major rail carrier in the San Diego area is the ATSF. The Santa Fe normally operates 1 turnaround assignment from San Bernardino to San Diego which uses 2 or 3 locomotives as the tonnage dictates. This assignment also does some enroute work as required. This makes it look somewhat like a local service. The ATSF occasionally operates unit trains in the basin.

Amtrak operates 8 daily round trips between Los Angeles and San Diego, over the Santa Fe. Finally, a short line switching railway operates in San Diego.

San Joaquin Valley Air Basin -- Major rail carriers operating in this area include the ATSF and the SP, including an area of joint operations between Bakersfield and Mojave through the Tehachapis. The UP operates in the northern end of the basin. Overall traffic is again dominated by the SP. Several short lines also operate in the area. These include the Modesto and Empire Traction (MET) which is jointly operated by the ATSF and the SP, the Stockton Terminal and Eastern (ST&E) and the CCT.

The SP operates 8 to 12 trains each way daily. These are TOFC/COFCs, mixed freights and occasionally a unit train. In addition, the SP operates 8 to 10 local assignments and 10 to 14 yard assignments between Bakersfield and Fresno. There is a helper grade between Bakersfield to Mojave and West Colton.

The ATSF operates between 8 and 10 trains each way daily. It has yards at Bakersfield and Calwa (near Fresno) which require about 10 assignments daily. ATSF also operates about 6 locals in the area on a daily basis.

Amtrak operates 2 trains each way daily between Bakersfield and Pittsburg.

The UP typically operates 3 to 4 through freights at the north end of the basin. It also operates about 3 yard assignments at Stockton and Modesto.

EXHIBIT 4-19
Annual Locomotive Emission Inventories for CO, HC, SO_X, and Particulates

Annual CO Emissions by Train Type
(1987 Base Year: Tons)

Train Type	Basin						Total
	Bay Area	Central Coast	South Coast	San Diego	San Joaquin	Sacramento Valley	
Total	612	369	1,718	25	1,179	913	4,816
Mixed	125	160	569	12	463	441	1,770
Intermodal	126	45	559	-	360	25515	1,344
Local	220	157	296	-	285	9	1,117
Yard	118	-	272	-	64	50	504
Passenger	24	7	22	13	7	8	81

Annual SO_X Emissions by Train Type
(1987 Base Year: Tons)

Train Type	Basin						Total
	Bay Area	Central Coast	South Coast	San Diego	San Joaquin	Sacramento Valley	
Total	324	242	813	20	662	569	2,630
Mixed	70	114	256	5	276	287	1,008
Intermodal	64	33	281	-	197	171	745
Local	115	83	150	-	149	83	580
Yard	42	-	101	-	26	17	187
Passenger	34	12	25	15	13	11	110

Annual Particulate Emissions by Train Type
(1987 Base Year: Tons)

Train Type	Basin						Total
	Bay Area	Central Coast	South Coast	San Diego	San Joaquin	Sacramento Valley	
Total	99	67	259	5	196	163	789
Mixed	21	31	81	2	81	81	297
Intermodal	20	9	86	-	59	48	221
Local	33	24	44	-	43	24	167
Yard	18	-	42	-	10	8	78
Passenger	8	3	6	4	3	3	26

Annual HC Emissions by Train Type
(1987 Base Year: Tons)

Train Type	Basin						Total
	Bay Area	Central Coast	South Coast	San Diego	San Joaquin	Sacramento Valley	
Total	204	116	563	9	378	281	1,550
Mixed	39	49	180	4	147	133	551
Intermodal	39	14	173	-	110	75	412
Local	69	50	93	-	90	50	351
Yard	46	-	108	-	28	19	201
Passenger	11	3	9	5	4	4	37

4.4.2 Inventory and Train Operations Data

Annual locomotive emission inventories for CO, HC, SO_X, and particulates are shown in Exhibit 4-19 on the facing page. NO_X inventories are shown in Exhibit 4-20 below Exhibit 4-21 below shows the average miles travelled per train, the average horsepower per train, the average trailing tons, and the total number of trains operated within or across each basin for 1987. (Yard operations are excluded from the analysis.)

EXHIBIT 4-20
NO_X Emissions by Train Type (1987 Base Year: Tons/Day)

Train Type	Basin						Total
	Bay Area	Central Coast	South Coast	San Diego	San Joaquin	Sacramento Valley	
Total	12.3	8.7	31.6	.6	24.8	21.2	99.1
Mixed Freight	2.6	4.2	9.6	.2	10.3	10.6	37.4
Intermodal Freight	2.4	1.2	10.5		7.5	6.3	27.9
Local Trains	4.2	3.0	5.6		5.5	3.0	21.3
Yard Operations	2.2	.4	5.1		1.2	.9	9.4
Passenger Train	1.0		.7	.4	.4	.3	3.2

EXHIBIT 4-21
Summary of Locomotive Activity Levels by Basin

	Train Type	Basin						
		Bay Area	Central Coast	South Coast	San Diego	San Joaquin	Sacramento Valley	Average All Six Basins
Average Miles Travelled Per Train	Mixed Freight	62	332	57	62	117	148	95
	Intermodal Freight	54	365	66	--	107	154	86
	Local Trains	75	75	75	--	75	75	75
	Passenger Trains	92	76	71	63	251	82	85
Average Trailing Tons	Mixed Freight	4,366	5,500	4,558	2,536	4,449	5,118	4,616
	Intermodal Freight	3,260	4,100	3,624	--	3,150	3,777	3,466
	Local Trains	3,839	4,726	3,155	--	4,362	4,003	3,862
	Passenger Trains	602	545	478	400	400	800	495
Average HP Per Train	Mixed Freight	10,586	13,400	12,891	13,289	11,034	12,719	12,149
	Intermodal Freight	11,513	12,400	12,901	--	11,675	11,719	12,225
	Local Trains	9,289	11,815	7,877	--	10,893	9,823	9,561
	Passenger Trains	4,515	4,091	3,585	3,000	3,000	6,000	3,711
Total Trains Operated in the Basin	Mixed Freight	5,807	2,401	25,177	627	16,919	9,741	60,672 (2)
	Intermodal Freight	6,427	545	21,350	--	13,713	5,747	47,782 (2)
	Local Trains	4,781	2,701	7,535	--	5,287	3,278	23,582 (2)
	Passenger Trains	14,884 (1)	1,144	8,000	5,715	1,428	1,456	32,624 (2)
	Total Number of Trains	19,899	6,791	62,062	6,339	37,347	20,222	152,660

(1) Includes 12,000 CalTrans trains operating in the Bay Area annually.
(2) Total all six basins.

EXHIBIT 4-22
Average California Locomotive Profiles by Basin(1)

Basin		Notch										Total
		8	7	6	5	4	3	2	1	Idle	Brake	
Bay Area	Total Hours	5,551	1,109	1,751	2,013	3,473	3,018	3,114	2,428	38,269	7,046	67,772
	%	8.19	1.64	2.58	2.97	5.12	4.45	4.59	3.58	56.47	10.40	100.0
Central Coast	Total Hours	6,272	1.910	1,955	2,266	2,543	1,745	2,867	2,829	12,596	2,136	37,119
	%	16.90	5.15	5.27	6.10	6.85	4.70	7.73	7.62	33.93	5.75	100.0
South Coast	Total Hours	26,032	4,192	4,081	4,655	5,850	6,393	4,686	6,084	143,081	29,848	234,900
	%	11.08	1.78	1.74	1.98	2.49	2.72	1.99	2.59	60.91	12.71	100.0
San Diego	Total Hours	3,325	130	348	206	856	311	52	52	12,015	278	17,573
	%	18.92	0.74	1.98	1.17	4.87	1.77	0.30	0.30	68.37	1.58	100.0
San Joaquin	Total Hours	16,083	5,309	8,686	10,693	8,966	8,752	7,358	7,030	89,794	19,530	182,202
	%	8.83	2.91	4.77	5.8	4.92	4.80	4.04	3.86	49.28	10.72	100.0
Sacramento Valley	Total Hours	16,010	6,063	7,231	7,639	7,012	6,546	7,232	6,101	47,513	7,251	118,598
	%	13.5	5.11	6.10	6.44	5.91	5.52	6.10	5.14	40.06	6.11	100.0

(1) Does not include local and yard operations.

Average line haul locomotive throttle notch profiles for each basin in California are shown in Exhibit 4-22 on the facing page along with the total hours spent in each throttle notch. The following observations can be made from this analysis:

- South Coast basin trains spend a fairly high percentage of time in idle and dynamic brake (probably due to the density of traffic and the Cajon Pass descent).

- Central Coast and Sacramento Valley trains are in Notch 8 a higher percentage of the time than trains in other basins and employ dynamic braking less than trains in other basins. They also spend a relatively higher percent of time in intermediate throttle notches and less time in idle.

- Bay Area trains are characterized by a relatively even distribution of time in each throttle notch with very little time spent in Notch 8.

- San Joaquin trains are also characterized by a relatively flat duty cycle profile.

Overall, the duty cycles in California reflect increased idle time, increased use of dynamic brake, and reduced time in Notch 8 compared with the industry average train profile.

EXHIBIT 4-23
Fuel Consumption Data by Basin and Train Type

Annual Fuel Consumption
(Thousands of Gallons)

Train Type	Basin						Total
	Bay Area	Central Coast	South Coast	San Diego	San Joaquin	Sacramento Valley	
Total	17,352	12,395	44,979	973	35460	30,366	141,529
Mixed Freight	3,749	6,015	14,039	287	14,935	15,368	54,395
Intermodal Freight	3,479	1,731	15,384	--	10,914	9,129	40,640
Local Trains	5,730	4,111	7,663	--	7,428	4,153	29,086
Yard Operations	2,890	--	6,769	--	1,611	1,225	12,497
Passenger Trains	1,502	537	1,122	686	571	489	4,910

Fuel Consumption: Percent by Basin and Train Type

Train Type	Basin						Total
	Bay Area	Central Coast	South Coast	San Diego	San Joaquin	Sacramento Valley	
Basin as a Percent of Total	12.3	8.8	31.8	.7	25.0	21.4	100
Train Type as a Percent of Basin							
Mixed Freight	21.6	48.5	31.2	29.5	42.1	50.6	38.4
Intermodal Freight	20.0	14.0	34.2		30.8	30.1	28.7
Local Trains	33.0	33.2	17.0		21.0	13.7	20.6
Yard Operations	16.7	--	15.1		4.5	4.0	8.8
Passenger Trains	8.7	4.3	2.5	70.5	1.6	1.6	3.5
Total	100	100	100	100	100	100	100

Fuel consumption data by basin and by train type are shown in Exhibit 4-23 on the facing page. The following observations can be made from the previous sets of analyses.

- The South Coast air basin has the most rail activity in all categories; i.e., line haul, local, and yard operations, and accounts for 32 percent of total locomotive emissions in the state. The San Joaquin and Sacramento Valley air basins are the next largest centers of rail activity and account for 25 percent and 21 percent, respectively, of total locomotive emissions in the state.

- The percent contribution to total locomotive emissions from each train type varies by basin. Local and yard service, for example, account for 53 percent of the NO_X emissions in the Bay Area, 33 percent in the South Coast basin, and only 18 percent in the Sacramento Valley. Emission reduction strategies focused on controlling emissions from yard and local operations would therefore be particularly effective in the South Coast and Bay Area basins.

- The San Joaquin and Sacramento Valley basins have a high percentage of mixed freight and intermodal activity. Strategies focused on line haul operations would be particularly effective in these basins as well as in the Central Coast basin.

As is evident from these analyses, considerable variability in train densities by type of service, average horsepower, and trailing tons exist among the basins examined. To the extent practical, emission control strategies should address these peculiarities to increase the effectiveness of emission reduction efforts while mitigating effects on railroad operations and competitiveness.

EXHIBIT 4-24
Santa Fe 1987 Locomotive Roster

Engine Model	BHP	Units	Available for Service		
			Line Haul	Local	Yard
EMD					
16-567BC	1500	211			√
16-567C	1750	53			√
16-567D2	2000	71		√	√
16-645E	2000	69		√	√
12-645E3	2300	62		√	
12-645E3B	2300	60		√	
16-645E3	2500	231	√	√	
16-645E3	3000	18	√	√	
16-645E3B	3000	203	√	√	
16-645F3	3500	52	√		
16-645F3B	3600	15	√		
20-645E3	3600	243	√		
16-710G3	3800	20	√		
GE					
GE-12	2350	60		√	
GE-12	3000	10	√	√	
GE-16	3000	226	√	√	
GE-16	3600	43	√		
GE-16	3900	3	√		
GE-16	4000	20	√		

EXHIBIT 4-25
Union Pacific 1987 Locomotive Roster

Engine Model	BHP	Units	Available for Service		
			Line Haul	Local	Yard
EMD					
12-645BC	1200	56			√
12-567A	1200	12			√
12-645E	1500	281			√
16-567CE	1500	35			√
16-645E	2000	365		√	√
12-645E3C	2300	24		√	
16-567D3A	2500	16		√	
16-645E3	3000	828	√	√	
16-645E3B	3000	446	√	√	
16-645F3	3500	36	√		
16-645F3B	3600	60	√		
16-71063	3800	227	√		
GE					
GE-12	2300	106		√	
GE-12	3000	57	√	√	
GE-16	3000	156	√	√	
GE-16	3750	60	√		
GE-16 (DASH 8)	3800	256	√		

4.5 METHODOLOGY AND ASSUMPTIONS USED FOR ESTIMATING EMISSIONS

Data used in the emissions model is presented in Appendix A and includes the following:

- Emission factors for EMD and GE engines
- Average emission factors for locomotives operated by each railroad
- Train operations data for the various type of trains operating in each basin
- Throttle position profiles for these same trains.

A brief review of this methodology is provided below.

Step 1: Determine Average Engine Emission Factors for Each Type of Service (Yard, Local, Line Haul) at Each Railroad

In this first step, engine emission factors (supplied by EMD, GE, and SwRI) for each locomotive model are weighted based on locomotive roster data (supplied by each railroad) to determine average emission factors for each class of service. The locomotive rosters used in determining average emissions are listed in Exhibits 4-24, 4-25 and 4-26 for the SF, UP, and SP, respectively.

EXHIBIT 4-26
Southern Pacific 1987 Locomotive Roster

Engine Model	BHP	Units	Available for Service		
			Line Haul	Local	Yard
EMD					
12-567C	1200	11			√
12-645E	1500	286			√
16-567BC	1500	37			√
16-567C	1750	326		√	
16-567D2	2000	145		√	
16-645E	2000	84		√	
12-645E3	2300	12		√	
16-645E3	2500	137	√	√	
16-645E3	3000	92	√		
16-645E3B	3000	353	√		
16-645F3	3500	4	√		
20-645E3	3600	425	√		
16-710G3	3800	65	√		
GE				√	
GE-12	2300	15	√		
GE-12	3000	107	√		
GE-16	3600	20	√		
GE-16	3900	92	√		

EXHIBIT 4-27

EMD and GE Locomotives for Which Emission Factors Are Available

EMD

Engine Model	Locomotive Model	BHP
12-567BC	SW10	1200
12-645E	SW1500, MP15, GP15-1	1500
16-567C	GP9	1820
16-645E	GP38, GP38-2, GP28	2000
12-645E3B	GP39-2	2300
12-645E3	GP39-2, SD39	2300
16-645E3	GP40, SD40, F40PH	3000
16-645E3B	GP40-2, SD40-2, SDF40-2, F40PH	3000
16-645F3	GP40X, GP50, SD45	3500
16-645F3B	SD50	3600
20-645E3	SD45, SD45-2, F45, FP45	3600
16-710G3	GP60, SD60, SD60M	3800

GE

Engine Model	Locomotive Model	BHP
127FDL 2500	B23-7	2500
127FDL 3000	SF30B	3000
167FDL 3000	C30-7, SF30C	3000
167FDL 4000	B40-8	4000

Emission factors from EMD and GE were made available for the models shown in Exhibit 4-27 on the facing page.

Emission factors for models not listed here were established based on horsepower rating, and number of cylinders from data on like engine models.

In developing locomotive emission factors, particulate data was unavailable from either GE or EMD for any models. However, particulate measurements were made by Southwest Research Institute for both EMD and GE 12-cylinder, 2300 HP engines. Particulate data was estimated for other GE and EMD engines based on fuel consumption data when available, or on HP ratios between the engines if fuel consumption data were not available. Calculated particulate emission factors for each engine are presented in Appendix A.

It should be noted that the engines tested at SwRI were recently overhauled and are recent versions of each manufacturer's respective engine models (i.e., they are turbocharged and have high specific HP output). The brake specific particulate emissions from these engines are likely lower than the average in-service unit and therefore the particulate emission estimates in this report are likely on the low side.

Step 2: Establish Throttle Position Profiles for Each Type of Service

For line haul operations, throttle position profiles were established using both Train Performance Calculation (TPC) data and actual "tape" or event recorder data supplied by the railroads. In many cases, profiles had to be constructed by piecing together smaller subsegments within a particular Origin/Destination Combination. Also, TPC and/or tape data were not available for all train operations. In these cases, profiles were established by scaling the profiles of trains that were operating on the same track and in the same direction based on total "link" miles. Generally, profiles established with the TPC matched actual event recorder data fairly well for a given train mission. TPC data agreed with event recorder data most closely for uphill train operations while the greatest discrepancies occurred in downhill train simulations.

The throttle profiles developed from either event recorders or TPC data must be modified to account for additional idle time experienced by line haul trains in the train yards between dispatch. Data supplied by Santa Fe indicates that the turnaround time for line haul locomotives in yards is approximately 8 hours. For each train pair coming into and going out of the yard, an additional 8 hours of idle time is applied. (Alternatively, for each locomotive entering or leaving the yard, 4 hours of idle time is applied.)

For local operations, throttle position profiles were again based on both event recorder and TPC data. Assumptions used to develop throttle profiles for local operations include the following:

- Average hours per assignment: 10 hours
- Additional average idle time per day per locomotive: 10 hours

The throttle position profiles used for local and switch engines are shown below in Exhibit 4-28. The switch engine duty cycle applies to a 24-hour day. The service duty cycle for local engines applies to a single assignment.

EXHIBIT 4-28
Throttle Position Profiles for Local and Switch Engines

	Yard Engine Throttle Profiles				Local Service Throttle Profiles	
	Santa Fe & UP		SP		All Railroads	
Notch	%	Time (Minutes)	%	Time (Minutes)	%	Time (Minutes)
1	4.5	63.4	4	57.6	9.0	54
2	4.5	63.4	4	57.6	8.3	50
3	3	42	2.9	41.8	8.0	48
4	3	42	2.9	41.8	7.0	42
5	1	14	1	14.4	4.3	26
6	0	0	1	14.4	3.3	20
7	0	0	0	0	3.0	18
8	2	28	3.3	4.7	6.7	40
Idle	82	1154	63.8	918.7	46.7	280
Brake	--	--	--	--	3.7	22
Total	100	23' 28"	82.9	19'54"	100	600 min. (10 hours)
Dead Time			17.1	4:06		

It should be noted that while the average local assignment (for inventory purposes) is 10 hours per day, a locomotive assigned to local duty may work more than one assignment per day. We estimate that a local unit works about 14 hours per day on average and is idle 10 hours per day.

EXHIBIT 4-29
Santa Fe Hobart Yard Switch Engine Duty Cycle

	Loco 2266 Watson SW		Loco 2292 Yard SW		Loco 2272 CA461-30		Loco 2009 CA491-29		Loco 2200 Yard SW		Loco 2244 CA511-31		Loco 2268 CA511-30		Average Switch Duty Cycle	
Throttle Position	Time HH.MM	%	Time HH.MM	%	Time HH.MM	%	Time HH.MM	%	Time HH.MM	%	Time HH.MM	%	Time HH.MM	%	Time HH.MM	%
1/2	2.37	5	1.33	3	4.53	10	7.21	15	1.43	4	5.47	11	6.23	13	4.33	9
3	0.44	1	0.22	1	0.25	1	1.40	3	0.29	1	0.39	1	1.07	2	0.78	3
4	0.32	1	0.14	0	1.32	3	0.45	2	0.16	1	1.06	2	1.07	2	0.79	3
5	0.19	1	0.10	0	0.01	0	0.15	1	0.10	0	0.21	1	0.25	1	0.24	1
6	0.07	0	0.07	0	0.08	0	0.09	0	0.04	0	0.16	1	0.10	0	0.15	0
7	0.05	0	0.04	0	0.02	0	0.04	0	0.03	0	0.11	0	0.19	1	0.11	0
8	0.47	2	0.10	0	0.52	2	0.29	1	0.11	0	0.56	2	0.39	1	0.58	2
Idle	44.21	90	46.44	95	41.34	84	37.56	78	42.27	94	41.39	82	39.58	80	42.09	82
Total	49.32	100	49.24	100	49.27	100	48.39	100	45.23	100	50.55	100	50.08	100	49.07	100

Note: The above data was taken from even numbered Santa Fe switch engines operating in the Hobart Yard on September 1, 1989

The duty cycle used for switch engines was developed based on actual tape data supplied by the Santa Fe Railroad on 8 switch engines operated over a 2-day period. These profiles are shown in Exhibit 4-29 on the facing page. Yard engines were assumed to operate 350 days per year allowing 2 weeks for inspections and maintenance.

Step 3: Calculate Train Emissions Using Train Operations Data, Emissions Factors, and Throttle Position Profiles

In this final step, emission inventories are calculated on a train-by-train basis. Data supplied by the railroads included:

Line Haul	Local	Yard
• Train type (bulk intermodal mixed)	• # of runs per year	• # of units assigned
• # of runs per year	• Avg. consist HP	• Avg. HP per unit
• Average consist HP	• Avg. units per consist	• # of assignments
• Avg. units per consist	• Avg. trailing tons	• Fuel consumption (optional)
• Origin/destination (O/D)	• Origin/destination (O/D) (if applicable)	
• Link miles		

For line haul engines, the information is used to determine the appropriate throttle profile to apply (based on origin, destination and train type) as well as the emission factors to be used.

Emission inventories are then calculated for each train by multiplying:

Emission factors per locomotive x locomotives per consist x time in notch per train x total trains per year.

Finally, emissions from local and yard engines are calculated using standard duty cycles and information on number of assignments (supplied by the railroads). These inventories are then added to those for line haul locomotives.

EXHIBIT 4-30
EmissionsTesting Variability
(Measurements in Grams per Hour)

ONE ENGINE: 3 TESTS OF EMD12-645E3B

NOTCH		NOX	CO	HC
8	AVERAGE	26735	1211	558
	STD DEV	1237	259	21
	COEFF OF VARIANCE (%)	4.63	21.37	3.84
7	AVERAGE	22562	1131	399
	STD DEV	2049	270	24
	COEFF OF VARIANCE (%)	9.08	23.84	5.92
6	AVERAGE	16318	842	338
	STD DEV	1688	134	23
	COEFF OF VARIANCE (%)	10.34	15.87	6.72
5	AVERAGE	12556	388	317
	STD DEV	711	25	9
	COEFF OF VARIANCE (%)	5.66	6.49	2.98
4	AVERAGE	10309	314	248
	STD DEV	414	21	2
	COEFF OF VARIANCE (%)	4.01	6.58	0.63
3	AVERAGE	7052	291	187
	STD DEV	610	20	15
	COEFF OF VARIANCE (%)	8.65	6.73	8.12
2	AVERAGE	4963	321	135
	STD DEV	235	20	9
	COEFF OF VARIANCE (%)	4.74	6.26	6.68
1	AVERAGE	1812	194	86
	STD DEV	93	8	4
	COEFF OF VARIANCE (%)	5.13	4.15	5.22
IDLE	AVERAGE	1255	566	172
	STD DEV	164	61	7
	COEFF OF VARIANCE (%)	13.04	10.85	4.33
BRAKE	AVERAGE	2584	767	291
	STD DEV	284	93	28
	COEFF OF VARIANCE (%)	10.98	12.20	9.76
WEIGHTED AVERAGE USING GE LINE HAUL CYCLE	AVERAGE	7105	605	237
	STD DEV	458	87	11
	COEFF OF VARIANCE (%)	6.45	14.31	4.56

15 ENGINES AND TESTS OF EMD16-645-E3

NOTCH		NOX	CO	HC
8	AVERAGE	36933	5908	1169
	STD DEV	4026	2329	345
	COEFF OF VARIANCE (%)	10.90	39.42	29.51
7	AVERAGE	31188	5029	878
	STD DEV	4242	1716	216
	COEFF OF VARIANCE (%)	13.60	34.12	24.60
6	AVERAGE	25568	1912	611
	STD DEV	2885	703	123
	COEFF OF VARIANCE (%)	11.28	36.77	20.13
5	AVERAGE	20899	760	424
	STD DEV	2313	186	79
	COEFF OF VARIANCE (%)	11.07	24.47	18.63
4	AVERAGE	15416	435	321
	STD DEV	1717	65	50
	COEFF OF VARIANCE (%)	11.14	14.94	15.58
3	AVERAGE	10179	329	247
	STD DEV	1227	55	37
	COEFF OF VARIANCE (%)	12.05	16.72	14.98
2	AVERAGE	6040	292	201
	STD DEV	722	39	31
	COEFF OF VARIANCE (%)	11.95	13.36	15.42
1	AVERAGE	2810	267	156
	STD DEV	385	79	26
	COEFF OF VARIANCE (%)	13.70	29.59	16.67
IDLE	AVERAGE	1635	564	185
	STD DEV	314	401	64
	COEFF OF VARIANCE (%)	19.20	71.10	34.59
DYN BR	AVERAGE	4104	655	293
	STD DEV	587	167	42
	COEFF OF VARIANCE (%)	14.30	25.50	14.33
WEIGHTED AVERAGE USING GE LINE HAUL CYCLE	AVERAGE	10055	1429	368
	STD DEV	1211	623	101
	COEFF OF VARIANCE (%)	12.05	43.62	27.55

4.6 VARIABILITY ANALYSIS OF EMISSION ESTIMATES

The emission inventory estimates presented here are subject to variances from several sources, the most important are:

- Variability in Emission Measurements: Emission measurements reported by EMD and SwRI, as well as those presented in AAR Report No. 688, indicate considerable variability exists in testing results -- both among different engines of the same model -- and between different tests of the same engine. Data from EMD, for example, shown in Exhibit 4-30 on the facing page, indicates that for a series of tests on 15 different engines of the same model, the coefficient of variance is 12 percent for NO_X, 44 percent for CO, and 27 percent for HC. Testing variability is demonstrated by data from SwRI for three separate tests on a single engine. The coefficient of variance for these tests is only 6 percent for NO_X, 14 percent for CO, and 5 percent for HC.

- Variability in Throttle Position Data: Throttle position profiles for like trains over the same track also vary considerably. Time in notch data supplied by the railroads varies depending on track conditions, opposing traffic conflicts, windage, engineer skill level, etc. For example, throttle notch 8 time shares can vary by more than 20 percent for similar trains over the same track. The throttle position profiles for several trains operating between San Bernardino and Cajon are shown in Exhibit 4-31 on the following page.

Fortunately the variability in data between selected engines and/or trains will tend to converge as the data sample grows large. While a complete statistical analysis has not been performed, Booz, Allen estimates that the combined effects of both variability in emissions factors and throttle data yields a confidence interval of ± 20 percent. Even so, we believe that this effort has resulted in the most accurate inventory possible with the given data.

EXHIBIT 4-31
Throttle Position Profiles for Several Trains Operating Between San Bernardino and Cajon

	ORIGIN: CAJON		DESTINATION:		SAN BERNADINO							
	TONS	HP	HP/TON	1/2	3	4	5	6	7	8	BRAKE	TOTAL
	5021.00	11100.00	2.21	5.00	0.00	0.00	0.00	0.00	0.00	0.00	47.00	52.00
	2954.00	14500.00	4.91	2.00	1.00	0.00	0.00	0.00	0.00	0.00	50.00	53.00
	5902.00	13100.00	2.22	3.00	0.00	0.00	0.00	0.00	0.00	0.00	51.00	54.00
	6234.00	13700.00	2.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	61.00	61.00
	9697.00	17600.00	1.81	2.00	4.00	1.00	0.00	0.00	0.00	0.00	64.00	71.00
	3176.00	14600.00	4.60	4.00	0.00	0.00	0.00	0.00	0.00	0.00	66.00	70.00
	3770.00	9600.00	2.55	2.00	3.00	0.00	0.00	0.00	0.00	0.00	48.00	53.00
	2223.00	9600.00	4.32	0.00	0.00	1.00	0.00	0.00	0.00	0.00	48.00	49.00
	2619.00	10200.00	3.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	45.00	45.00
	4893.00	1200.00	0.25	2.00	0.00	0.00	0.00	0.00	0.00	0.00	50.00	52.00
	4909.00	12600.00	2.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	42.00	42.00
	5418.00	14400.00	2.66	0.00	0.00	1.00	1.00	1.00	0.00	0.00	50.00	53.00
	2359.00	10800.00	4.58	1.00	2.00	2.00	1.00	0.00	0.00	0.00	54.00	60.00
	2749.00	13200.00	4.80	1.00	1.00	0.00	0.00	0.00	0.00	0.00	41.00	43.00
AVERAGE	4423.14	11871.43	3.11	1.57	0.79	0.36	0.14	0.07	0.00	0.00	51.21	54.14
STD DEV	1970.92	3678.59	1.35	1.55	1.26	0.61	0.35	0.26	0.00	0.00	7.35	8.50
COEFF OF VARIANCE (%)											14.35	15.70

	ORIGIN:	SAN BERNADINO		DESTINATION:		CAJON						
	TONS	HP	HP/TON	1/2	3	4	5	6	7	8	BRAKE	TOTAL
	3617.00	9600.00	2.65	0.00	0.00	0.00	0.00	0.00	0.00	66.00	0.00	66.00
	4873.00	14700.00	3.02	0.00	6.00	4.00	7.00	5.00	1.00	64.00	3.00	90.00
	3908.00	13600.00	3.48	6.00	2.00	1.00	0.00	0.00	0.00	67.00	0.00	76.00
	2953.00	9800.00	3.32	9.00	4.00	3.00	1.00	1.00	1.00	65.00	5.00	89.00
	2570.00	16800.00	6.54	4.00	1.00	1.00	0.00	0.00	0.00	46.00	0.00	52.00
	2624.00	15100.00	5.75	9.00	6.00	4.00	4.00	23.00	1.00	63.00	0.00	110.00
	2851.00	12600.00	4.42	7.00	1.00	14.00	0.00	0.00	0.00	82.00	4.00	108.00
	3919.00	11000.00	2.81	0.00	0.00	0.00	1.00	8.00	17.00	70.00	0.00	96.00
	3431.00	17600.00	5.13	0.00	0.00	0.00	0.00	0.00	0.00	66.00	0.00	66.00
	2757.00	9600.00	3.48	9.00	2.00	0.00	0.00	0.00	0.00	53.00	0.00	64.00
	4084.00	10800.00	2.64	0.00	3.00	0.00	1.00	3.00	0.00	57.00	0.00	64.00
	3583.00	10800.00	3.01	9.00	0.00	0.00	1.00	0.00	0.00	81.00	0.00	91.00
	4843.00	14700.00	3.04	5.00	1.00	0.00	0.00	0.00	0.00	54.00	0.00	60.00
AVERAGE	3539.46	12823.08	3.79	4.46	2.00	2.08	1.15	3.08	1.54	64.15	0.92	79.38
STD DEV	748.42	2673.85	1.22	3.84	2.08	3.75	1.99	6.23	4.48	9.85	1.73	18.27
COEFF OF VARIANCE (%)										15.36		23.02

5.0 EMISSION CONTROL TECHNOLOGIES

5.0 *EMISSION CONTROL TECHNOLOGIES*

5.1 IMPLICATIONS FROM THE INVENTORY AND INDUSTRY STRUCTURE

The background information on the rail and locomotive industries presented in Chapters 2 and 3 together with emission inventory results in Chapter 4 provide guidance for reviewing technologies to control locomotive emissions in California. The following characteristics of the industry are particularly important in considering the effectiveness of reduction technologies and regulatory frameworks.

- Railroad locomotives are designed to last a long time, typical lifetimes are between 25 and 30 years. Over this life, they are overhauled several times and, perhaps, re-engined once.

- Locomotives and the diesel engines used in them are relatively expensive. New road locomotives cost about $1.5 million, the engines about $400,000.

- Relatively few locomotives are sold each year--approximately 700 in the U.S. market.

- Two major manufacturers currently split the market. A third engine manufacturer is entering the locomotive engine market -- an optimistic market assessment for locomotive engines would have each entrenched manufacturer producing about 300-350 engines annually and the third, perhaps as much as 100 annually. Gross revenues from new engine sales are likely to be about $150 million for the majors and $40 million for the new entrant -- total engine based gross revenues are likely to be about $350 million annually, not including the replacement parts market.

- New engine development costs are about $300 to $500 million, including tooling to produce the new engine. Variants from an existing design are less costly to develop, up to $200 million for development of a significant engine modification.

From this it can be concluded that new engine development will be limited in the current marketplace. The last major engine developments, which were variants on current designs, were underway when locomotive sales were fairly high, in the 1,200 units per year range. In order for locomotive manufacturers to achieve a reasonable return on investment in a reasonable business timeframe, the price for locomotives with a new design engine must be significantly more than $1.5 million. However, the railroad industry return on capital is about 6 percent per year and its cost of capital is 12 percent. Rail carriers must obtain substantial operational improvements to justify significant investment in new locomotive technologies and the early replacement of existing locomotives.

Industry operating practices and a review of the transport marketplace reveals other implications:

- Line haul train movements, i.e. intermodal, mixed and bulk intercity trains, generally come from or go to locations outside the air basins, and outside the state in many cases. Locomotives are assigned to trains on the basis of need, availability, and type of locomotive -- not geography. Thus a locomotive on an intermodal train, for example, may be in California today, Chicago three days from now, and Texas two days later. Such assignment practices give the rail carriers considerable operating flexibility and reduce fleet size requirements.

- Locomotives used in yard and local service are assigned to much more routine work, with movement to and from distant locations limited to major shopping events. That is, yard and local locomotives are generally captive to a region for extended periods of time.

The implication of this situation is that it would be expensive to introduce emission reduction technologies that have significant operating cost penalties in *line-haul* train operations because the cost penalties would be propagated throughout a carrier's operation, or would require that a road locomotive fleet be significantly larger since the economies of national fleet interchangeability would be lost. Conversely, since yard and local locomotives are more captive to a geographic area, any operating cost increases associated with emission reduction can be contained to the areas where the benefits accrue.

Both in total tons and by contribution as a percentage of the total effluent, the emission inventory indicates that the largest contributor to air pollution from railway operations is NO_X. Therefore, emission reduction technologies which affect NO_X levels would likely be more cost effective at reducing rail-generated air pollution than other emission reduction strategies targeted at other effluents. The inventory indicates that about 66 percent of NO_X emissions are associated with line haul operations, the remaining 34 percent is associated with yard and local operations. Locomotives contribute the least to particulate matter inventory, probably due in large measure to the emphasis placed on reduction of locomotive smoke emissions during the past several decades. Generally, NO_X and particulate emissions tend to work against each other in diesel engines, i.e., one moves upward as the other is reduced and vice-versa.

Thus, the best emission reduction strategies would reduce NO_X emissions in road locomotives but not increase other emissions, while imposing no operating penalty and having only limited effect on capital costs. The technologies should be retrofitable on existing locomotives if the impact on air quality is to be felt quickly. Next best strategies would reduce NO_X emissions in yard and local operations, again with limited impact on operating costs. With these implications in mind, the applicable emission reduction technologies are examined in the next section.

5.2 CANDIDATE TECHNOLOGIES

Numerous proposals and candidate technologies can be found in the literature that could reduce emissions from locomotives. Many involve considerable operational and packaging constraints and are applicable to new locomotives only, while others may be applied to the existing locomotive fleet. The task in this section is to assess the many proposals and to develop a list of likely candidate emission reduction technologies for further analysis. In order to bring an element of organization to this assessment, emission reduction technology candidates are classified by the way they could be implemented in the California air basins. The classifications have been defined as follows:

- Changes in railroad operating practices
- Retrofit technologies for existing engines
- Technologies requiring new locomotives

- Alternative fuels (all of which would require significant engine changes or new engine designs)

- System electrification (using existing technology).

A description of candidate technologies is presented by category in the following sections. A discussion of evaluation factors and an assessment of the most cost-effective candidate technologies is presented in the following chapters.

5.2.1 Changes in Railroad Operating Practices

Selected changes in rail operating practices and policies offer the potential for reducing emissions from locomotive operations.

Reduced Idle Time -- Our review of throttle position profile data submitted by the rail carriers indicates that locomotives generally idle when not in use. For yard and local units, such idle time can be a significant part of the total duty cycle. Engine shut down policies were enforced on most railroads during the oil shortage periods of the mid- and late-1970s but the practice has been largely abandoned, as indicated by the throttle profile data. While this may seem foolish to those outside the industry, the conditions under which a locomotive can be shut down are stringent, given local operating practices, and the penalties for not being able to start a unit can be severe. Locomotive engines are difficult to start because of their large size and long history of water leakage into cylinders during shutdown. Water leakage into cylinders can cause a hydraulic lock, damaging the crankshaft, connecting rods, pistons, and wrist pins when starting. Starter and battery systems must be well maintained and temperatures cannot be too low. It is thermodynamically difficult to start a cold-soaked, large-bore diesel engine and locomotive engines do not use antifreeze. However, shutting down locomotives whenever they are planned to be idle for a period of time and the local ambient temperatures will permit ready restart (typically, temperatures above 50°F), will eliminate all forms of emissions during the shut-down period, in addition to saving fuel. Discussions with the manufacturers indicate that their engines can be stopped and restarted while temperatures are above 50°F if the following conditions are met:

- The battery, charging and starter systems must be functional and properly maintained.

- GE locomotives should be fitted with the unitized cylinder and head introduced in 1985 with the Dash 8 series locomotives. GE indicates that all cylinder assemblies sold since the introduction of the Dash 8 meet this requirement.

- EMD locomotives should be fitted with the post-1987 copper clad, full width head gaskets. EMD has indicated that all head gaskets they have sold since 1987 have been of this type. Most of the older gaskets that were prone to failure have already failed and have been replaced. EMD also recommends that locomotives that are frequently shut down and restarted should be fitted with the Engine Purge Control Kit or "creepy crank". The engine purge control system is a system which slowly cranks the engine through a few revolutions, purging any water which may have leaked into the cylinders and/or stopping the cranking process if the high pressures of a hydraulic lock is encountered.

The first condition can be met with a battery and starter system campaign performed at the next regular shopping event of a locomotive and continued attention to starter, charging and battery systems during the periodic maintenance program. Older locomotives which do not meet the head sealing criteria can be placarded for no shut-down pending a major shopping event. "Creepy crank" can be viewed as an $1,800 to $2,400 insurance policy against head, piston and connecting rod damage resulting from hydraulic lock during cranking for restart.

We believe that many locomotives operated in the six California basins will meet the above conditions and could be shut down with little difficulty. However, cold start emission characteristics of locomotives are not well known and some period of poor emission performance is likely after cold starting. Therefore, cold start emission tests should be performed with both GE and EMD engines to characterize the length of the poor emission period to determine what length of idle/off time will provide the best overall emission reduction benefits.

EXHIBIT 5-1
Summary of SwRI Locomotive Testing
(Regular vs. Low Sulfur Fuel -- Testing Performed Late 1989)
(Grams per Hour)

ENGINE: EMD 645-12-E3B TEST FUEL: .33%

	TEST RESULTS (1)				
TEST #	PM	HC	CO	NO_x	SO_x
1	159	197	435	7,158	333
2	177	198	450	6,942	333
3	158	185	502	6,212	332
Average	165	193	462	6,771	333

ENGINE: EMD 645-12-E3B TEST FUEL: .01%

	TEST RESULTS (1)				
TEST #	PM	HC	CO	NO_x	SO_x
1	130	227	567	6,226	10
2	133	209	559	6,570	10
3	115	191	571	6,327	10
Average	126	209	566	6,374	10

ENGINE: GE 12-7FDL TEST FUEL: .33%

	TEST RESULTS (1)				
TEST #	PM	HC	CO	NO_x	SO_x
1	175	371	1,391	6,079	325
2	128	302	1,274	6,213	326
3	145	373	1,261	6,586	328
Average	149	349	1,309	6,293	326

ENGINE: GE 12-7FDL TEST FUEL: .01%

	TEST RESULTS (1)				
TEST #	PM	HC	CO	NO_x	SO_x
1	154	336	1,248	6,857	9.8
2	180	352	1,278	6,406	9.8
3	129	387	1,293	6,158	10
Average	154	358	1,273	6,474	10

(1) Average grams per hour based on GE line haul duty cycle.

Change to Low Sulfur Fuel -- Changing switcher and local locomotive fuel to the low sulfur diesel fuel already required for trucks and buses in California offers the potential for reduced particulate and NO_X emissions however, test results to date are somewhat inconclusive. SO_X emissions should be reduced by an amount proportional to the sulfur content of the fuel. Exhibit 5-1 on the facing page lists the results of recent emission testing at SwRI of EMD and GE engines on both "regular" (.33 percent) and "low" (.01 percent) sulfur fuel. Each engine was tested three times on each fuel. The EMD engine showed a 23 percent reduction in particulates and a 6 percent reduction in NO_X emissions. HC emissions increased by 8 percent and CO emissions increased by 22 percent. The GE engine showed essentially no change in emissions when operating on the low sulfur fuel. It should be noted that the fuel used in these tests was considerably below the .05 percent sulfur content currently allowed for on-highway vehicles in the South Coast Air Basin. Also, the aromatic content of the low sulfur fuel was about 10 percent lower than the diesel baseline. The cetane number of both fuels were almost identical, at about 43.

Given the level of variances found in the SwRI test data, there is a great deal of uncertainty about any emissions benefit, except on sulfur emission, and additional testing of low sulfur fuel should continue to verify the effects on other effluents. EMD expressed some concern regarding fuel injector durability with low sulfur fuel, since the sulfur may provide some degree of injector lubrication. The risk of locomotive injector problems resulting from low sulfur fuel is judged to be low for the following reasons:

- Historically, Detroit Diesel fuel injectors, which are similar to EMD fuel injectors, have been tolerant of low lubricity fuels such as #1 Diesel, methanol, and even gasoline. The much larger size of EMD unit injectors, assembled to the same fit tolerances as the smaller injectors, may void some of the comparisons with Detroit Diesel equipment. Several pump and line fuel systems used on GE engines have not been tolerant of low lubricity fuels.

- Few GE locomotives are operating in switcher and local service.

- Fuel injector scuffing and seizure occurs at high speeds and loads where switcher and local service locomotives do not operate for sustained periods.

- The technologies and injector modifications developed by Detroit Diesel to extend injector durability with methanol can be applied to EMD injectors.

Since the U.S. Congress is expected to mandate 0.05 percent maximum sulfur content in all on-highway diesel fuels by 1994, this fuel should become widely available even in the absence of any action undertaken in California. Should a Federal mandate for low sulfur diesel fuel include off-road engines (i.e., locomotives), and all locomotives were operated on this fuel, the SO_X reduction in the six California air basins will be 2,346 tons or 90 percent of current levels. California is considering legislation that would further reduce allowable sulfur in diesel fuel to 0.02 percent. Operation of local trains and switchers on this fuel would further reduce air basin SO_X emissions an additional 156 tons per year.

As shown in the above calculations, only Federal action to reduce sulfur levels will have a substantial impact on SO_X inventory since such legislation would affect the fueling of the line haul locomotive fleet outside California.

Change to High Cetane, Low Sulfur #1 Fuel -- The following recommendation is based on proprietary data from truck engine manufacturers, the anecdotal experience of truck and bus fleet operators, and the opinion of several recognized diesel engine experts. There is no test data in the public domain to support the recommendation, however the potential benefits justify undertaking a test program.

The use of high cetane, low sulfur #1 diesel or kerosene specification fuel could offset at least some of the negative effects on particulate and smoke emissions from the retarded injection timing suggested in the next section. In the absence of retarded injection, use of this fuel could reduce other measured pollutants as well as improve cold starting and reduce white smoke during warm-up and sustained idle. The potential benefits of this fuel are:

- Reduced ignition delay and reduced smoke, during start-up, cold idle, and running because of the higher cetane rating.

- Solvent action of the light fuel maintains injector tip and, possibly, combustion chamber cleanliness. This should reduce emission degradation with time.

- Reduced black smoke at high power, as has been demonstrated on transit bus engines for years.

Some railroads often operate their locomotives on #1 fuels, or blends of #1 and #2, in cold conditions to circumvent fuel clouding and filter waxing. Since there is only limited anecdotal experience with hot, low viscosity fuel, there is concern about fuel injector durability which may be exacerbated by lower lubricity fuel. Thus, fuel cooling may be necessary in hot weather conditions. Durability testing of EMD, GE, and CAT fuel systems is necessary to qualify #1 low sulfur fuel for year-round use in California.

Diesel #1 fuel has a lower heating value than #2 fuel, which implies a power reduction by as much as 7 percent per volume. Locomotive fuel systems have the capacity to offset at least some of this power loss by readjusting the governor, thereby converting the power loss into a fuel consumption penalty of about the same magnitude. The ability to recover power through governor adjustment varies by locomotive engine model and not all engines have a 7 percent adjustment reserve. In particular, units which must operate at high altitudes have little reserve and may suffer significant power derating.

This change in fuel quality is potentially very costly to the railroads, especially if applied to all classes of locomotives. As stated, the fuel consumption penalty for recovering power lost to lower heating value can be as high as 7 percent. An additional cost penalty of up to 10 percent is possible due to the higher demand for a kerosene #1, or Jet A type fuel, along with a 1/2-cent per gallon or 1 percent penalty for a cetane improver additive. Finally, the 2 to 3 cent per gallon (5 percent) cost penalty for desulfuring would be added, for a total fuel cost penalty of about 12 cents, compared to a current 50-cent per gallon fuel price. This does not include mark-up on refinery cost for desulfuring or cetane enhancement, but the desulfuring cost may be applied by regulation to railroads even in the absence of this candidate change in operating practice.

The Air Resources Board, Stationary Source Division, is advocating a 10 percent aromatic limit on diesel fuels with low sulfur and high cetane for reducing particulate emissions. This proposal has generated considerable debate over the cost and benefits of such a fuel: cost penalties estimates range from 5 to 25 percent; benefits estimates range from "significant" to none.

Retard Injection Timing -- Manufacturer research indicates that retarding the fuel injection timing by approximately 4° from specification in locomotive-type diesel engines will reduce NO_X by about 20 percent in all throttle notches. The retardation of timing results in several significant penalties including a decrease in fuel economy of about 2 percent, increases in smoke and particulate emission levels, and a reduction in rated power under some operating conditions.

Minimal preconditions for either EMD, GE, or CAT locomotive engines are required to implement the timing change. Several offshore oil rig workboats harbored in Ventura and fitted with EMD engines are currently operating with 4° injection retard. No problems associated with durability and/or performance have been noted by the oil companies operating these vessels. It is also relevant to note that these engines generally operate at somewhat higher load factors than an "average" locomotive duty cycle, according to EMD.

It should also be noted however that the above experience was of course at sea level. There is some concern that retarding injection timing could pose durability problems for locomotives operating at high altitudes. At high altitudes there is less scavenging air available to cool the combustion chamber, exhaust valves, and turbocharger. Because the combustion process may not be complete when the exhaust valves open, and because of the reduced air flow, exhaust temperatures could rise sufficiently to threaten durability of both the exhaust valves and turbocharger. (Essentially the engine is being throttled at a peak power condition.) It is unclear at this time if retarding of injection timing would indeed have any measurable effect on engine durability, or at what altitudes such degradation might begin to occur.

One clear solution to the potential problem is to reduce the fuel delivery rate (and therefore the power) at the Notch 8 setting. This would effectively lower the peak combustion chamber temperature. It seems reasonable that any such requirement for derating in Notch 8 would be route and train specific (i.e., dependent on length of duration at altitude, train speed, and other factors).

A railroad might consider installing instrumentation (thermocouples for exhaust gas) locomotives operating on those routes they suspect could result in excessively high temperature. The train engineer would need to initiate a reduced fuel condition in Notch 8 at specific points on specific routes. A more practical solution might be the development of an altitude sensing device to automatically reduce fuel in the Notch 8 setting only at high altitudes.

The fuel consumption penalty and turbocharger durability questions necessitate that the change be first implemented on switcher and local service locomotives. The potential NO_X reduction from just switcher and local service locomotives in all six air basins could be 2,243 tons per year or 6.2 percent of the current locomotive total. Additional NO_X reductions can be attained by introducing the timing retard to road locomotives. In the absence of a "California only" locomotive fleet, the associated fuel efficiency penalty would extend to the railroads' operations nationwide.

The manufacturers indicate that timing retardation could be implemented during a light shopping event.

Most of the above mentioned emission reduction approaches depend upon changes in operating practices which will result in operating cost penalties to the railroads. The penalties are maintenance cost increases for batteries and starting systems for the idle time reduction strategy; fuel cost increases and some performance degradation for the other approaches. Estimates cannot be made of freight modal shifts due to the increased cost of operating locomotives in California with these changes. However, trucks, the primary competitor of railroads, may themselves suffer considerable cost penalties due to the 1991 and 1994 Federal emission regulations. Additional cost penalties may be imposed on trucks by pending and proposed California regulations.

5.2.2 Retrofit Emission Reduction Technologies

We have identified several candidate technologies that could be applied to the existing locomotive fleet with varying degrees of difficulty -- and benefit. Some require simply further testing and development, some may have major packaging problems, while others could be implemented very quickly.

In general, all retrofit technologies presented here must be carefully considered since they are targeted at reducing NO_X and offer the potential for a much more immediate implementation than technologies that could only be applied to new equipment. The candidate technologies are presented in the following sections.

EMD Injector Retrofit -- In responding to the preliminary draft of this report, EMD suggested a technology that is applicable to 16-645E3 engines in pre-1979 series 40 and 40-2 locomotives. The change centers on installing fuel injectors with larger diameter plungers, similar to those used on 16-645E3B engines. Use of these higher pressure injectors will put the proper (same) quantity of fuel into the combustion chamber in less time than the original injector. This allows retarding the beginning of injection timing event while maintaining the same end of injection time. This timing change will reduce NO_X approximately 20 percent and CO by 10 percent without a fuel consumption penalty. No new technologies are required to be developed since only proven and existing hardware is needed. There are three known downside risks:

- The turbocharger speed is increased by as much as 10 percent at high power and high altitude and may require derating in Notch 8.
- Injector actuator loads are increased because of higher injection rates and therefore later design cams and crown rollers are recommended.
- Higher injection rates cause higher peak cylinder pressures with resulting increased structural loading on pistons, wrist pins, connecting rods, etc.

While at the outset of this injector development program the above risks were of concern, in-service testing has shown good results thus far. Santa Fe Railroad has been testing a locomotive equipped with this retrofit package for over two years. They have reported no reliability or durability related problems to date.

The change could be implemented for approximately $20,000 in parts, including a new governor, cams, and rollers. Reusing the old parts could cut the cost in half, at some risk in camshaft and follower durability.

A similar package could probably be developed for newer engines in the 645 series that would require installation of 710 series injectors. EMD is studying the feasibility of machining 645 heads to accept the physically larger 710 injector or fitting 710 heads to 645 engines. Similar NO_X reductions with no fuel efficiency penalty would be expected from this change.

Low NOx Engine --Many manufacturers of large bore, medium-speed diesels have developed low NO_X engines for stationary power applications. The NO_X reduction techniques are similar, relying on substantial retardation of injection and exhaust events, with associated fuel consumption penalties. EMD's low NOx engine is a 16-645E3C with experimental constant beginning of injection event fuel injectors set at 5° BTDC. The camshafts are retarded one tooth and a different turbocharger drive ratio is used. The modified EMD engine reduces NO_X emissions by 50 percent but carries a 5 to 8 percent increase in fuel consumption. Highly retarded engines are generally unstable at most operating conditions except at rated speed and load. There is no experience with severely retarded B.O.I. timing in locomotives and because of the extremely retarded condition there are serious issues to resolve before locomotive applications could be considered. These include:

- Steady state and transient smoke
- Throttle response/transient load capabilities
- Part load/idle performance
- Altitude performance
- Particulate emissions
- Long term durability/reliability.

Should these issues be satisfactorily resolved by testing, the technology could be applied to many existing locomotives at various cost levels, depending upon engine type. The EMD conversion discussed above applies only to 645E3C engines, of which almost none are in locomotives. Conversion of earlier 645 engines would cost over $100,000 in parts and labor. Similar changes in timing and turbocharger design could likely be applied to 4-cycle engines with similar results.

External Devices/Systems -- There are several devices that could be added to either the intake or exhaust side of the engine to reduce emissions. None of these devices has been evaluated in the locomotive environment and all will have serious packaging and installation problems due to the size of the devices and/or support systems. None of the external devices is currently developed to the point where immediate application to locomotive diesel engines is possible. They could be retrofitable to locomotives but only after extensive modifications and interface with the original manufacturer.

- Water addition is a system where water is introduced by one of a number of methods into the inlet airstream to quench combustion during the NO_X formation process. Quality and quantity of the water supply are major implementation problems in addition to the basic packaging and water metering issues.

- Particulate traps are the subject of extensive development for reducing only particulate emissions from highway diesel trucks to meet the 1994 emissions standards. Particulate traps are the most highly developed of the exhaust after-treatment devices for truck-sized diesel engines but no hardware is yet in volume production. Current development problems are primarily durability and reliable trap regeneration. These problems are likely to be exacerbated as the trap hardware is scaled up for locomotive-sized engines (since temperature gradients in the trap monolith will be much larger than for truck sized units). All ceramic based after-treatment devices would likely have major durability problems in locomotive applications, along with very substantial acquisition and monolith replacement costs. Fuel consumption penalties associated with the use of particulate traps are expected to be about 1/2-percent, and are due to increased back pressure and fuel used for trap regeneration.

- An ammonia catalytic reactor is being developed to reduce NO_X outside the engine and has become the state-of-the-art device for stationary power systems. It requires ammonia injection in the exhaust up-stream of a catalytic bed at a flow rate of 1 to 3 percent of fuel flow. NO_X reductions in the 50 to 80 percent range have been demonstrated. The technique is in the infancy of development for mobile diesel engines and many questions remain unanswered, particularly:

- Effect of soot accumulation on reactor effectiveness and engine durability
- Basic durability of the reactor
- Back pressure resulting from the reactor which may require changes in turbocharger design
- Ammonia emissions
- Ammonia storage and logistics
- Control system
- Cost
- Poisoning of the catalyst
- Thermal deactivation
- Safe handling, transport and onboard storage of ammonia

None of the above appear to be insurmountable problems or fatal flaws in the technology. Ammonia catalytic reduction is particularly attractive since retrofitability of the system appears possible if the packaging and control system problems, along with some safety issues can be resolved.

This emission control technique (generically known as selective catalytic reduction or SCR) is being aggressively pursued by several engine manufacturers, and has been tested on a limited basis in a truck. Research in Japan is particularly aggressive. Research is also underway in Germany, where at least one system is under test in a locomotive. Most manufacturers feel that SCR systems are less difficult to implement than particulate traps since the regeneration process is not necessary. The basic principles and technologies have been developed, however, a considerable degree of application engineering is required to bring such a system to commercialization for mobile applications.

- RAPRENOx systems, or the addition of isocyanic acid to the exhaust stream, resulted from ammonia injection research. Chemical radicals formed from photolysis of isocyanic acid react rapidly with nitric oxide. Reductions of NO_X of 80 to 90 percent appear feasible with a developed system. Several approaches to introducing the acid are under development. None have been tested in locomotive-sized engines so little is known about their commercial feasibility or potential health and safety impacts.

5.2.3 New Product Emission Reduction Technologies

New product technologies are under the control of the engine manufacturers and their retrofitability into existing locomotives is highly speculative. In the absence of legislation that forces a trade-off in locomotive performance and efficiency for reduced NO_X or particulate emissions, future locomotives are likely to feature improvements demanded by the railroads -- fuel efficiency, power, and durability.

Every few years new locomotive models are introduced that feature a compilation of incremental improvements that together warrant a new designation. These incremental improvement models are described as "new model" locomotive technologies. Improvements offered on new model locomotives are likely to include further power increases and fuel efficiency gains attained by engine and locomotive systems refinements.

A number of emission reduction candidate technologies are possible for "new model" locomotives, assuming that there are minimal penalties to all U.S. railroads or that emission reductions are Federally mandated. These include:

- Increased aftercooling
- Combustion improvements
- Electronically controlled fuel injection systems
- Exhaust gas recirculation
- Variable geometry turbochargers.

In contrast to new models, "next generation" locomotives are introduced about once every decade and feature one or more relatively major improvements. Candidate technologies for next generation locomotives include:

- New engine designs
- Adiabatic diesel engines
- New powerplants
- Major locomotive systems
- AC traction control and motors.

The distinction is made between next generation locomotives and new models primarily because of the development time frame. New model technologies may be relatively close at hand while next generation technologies are rather distant in the future.

New Model Locomotives -- New model locomotives may incorporate some combination of the following features. Although the effects of these features are highly interrelated and must be developed as an integrated package, they are discussed individually below.

Increased aftercooling of the inlet air between the turbocharger and the inlet manifold can act to reduce all exhaust emissions and improve fuel efficiency. Charge air cooling can be based on an air/engine coolant, an air/separate intercooler liquid, or an air/air cooling system.

Air/engine coolant systems are currently in production but the other approaches involve substantial packaging problems in locomotives -- for increased radiator load, increased cooling fan requirements, separate radiators as well as for the intercooler device itself. This packaging problem, which could be manifested in a requirement for longer locomotives, dictates that charge air cooling be developed as an integrated system by each locomotive engine manufacturer. The system is not likely to be retrofitable into the existing locomotives fleet since substantial internal and external packaging changes are necessary. The weight penalty, due primarily to the additional locomotive length as well as additional cooling system componentry, will be a major problem on 4-axle locomotives since locomotive axle loads are presently at the limits of rail strength. Introducing offsetting weight reductions for current generation locomotives is an expensive and time consuming engineering design problem and would require use of more costly, lightweight components.

The benefits of lower inlet air temperature are substantial. EMD data suggests that an additional 50°F reduction from the current 180°F charge air temperature could yield a:

- 15 percent reduction of NO_X
- 30 percent reduction of HC
- 50 percent reduction of CO
- 2-1/2 percent reduction of BSFC.

All of these benefits make increased charge air cooling attractive to all locomotive buyers, not just the California railroads. We believe this feature is likely to appear on new model locomotives in the relatively near future.

Combustion improvements have been under continuous development since the diesel engine was introduced. Combustion improvements involve increasing the quantity of air introduced into the engine, better utilization of the incoming air and optimization of the combustion process. The design of combustion improvements is an iterative process involving virtually all systems of the engine.

Increasing the peak firing pressure leads to improved efficiency and power output. Peak firing pressures drive the structural design of the engine while turbocharger boost, compression ratio, and injection pressure drive firing pressure. Improved air flow through the inlet ports and valves improves efficiency and enhances turbocharger performance. Combustion chamber shape affects efficiency, emissions, ignition delay, and overall performance. It is now realized that seemingly unrelated aspects of the engine design, such as top ring location and overall oil consumption, can affect both emissions and engine performance.

All locomotive engine manufacturers have continuous large scale and costly engine development programs aimed at developing engine performance improvements. The competitive nature of the locomotive business keeps this process going, ensuring continuous improvement.

In the medium term (next 10 years) it is likely that the locomotive manufacturers will introduce at least one new model featuring incremental improvement in the existing diesel engines and improvements in other locomotive systems. However, in light of the improvements already implemented on existing designs, capturing additional performance is likely to be achieved at a higher level of risk and cost.

Electronically controlled fuel injection timing could be grouped with combustion improvements above, but since this feature by itself offers some performance and emission improvements it is discussed separately.

On today's engines, timing of the beginning of injection event is selected as a compromise based on limitations of the mechanical fuel injection equipment and the performance characteristics of the engine. Notch 8 fuel efficiency and power output weigh heavily in the compromised timing. Altering the beginning of injection event as operating conditions change could reduce NO_X, particulate, CO and HC emissions. Variable timing would also improve cold starting and reduce smoke during engine warm-up.

Such a system is under development at EMD in the form of an upsized Detroit Diesel electronic injector system. The benefits of such a system would not be nearly as great in locomotives as in highway trucks because locomotive engines do not change speed and load as frequently and do not have the fuel-to-air matching problem associated with high-torque-rise engines. The system integration requirements of an effective electronic fuel timing system control necessitates development by the locomotive engine manufacturers. Once developed, the system could be retrofitable into older locomotives, but at considerable expense if highway truck experience holds true for locomotives.

Like increased aftercooling and combustion improvements, electronically controlled fuel injection timing has national appeal because it offers overall fuel economy benefits. Implementation of electronic fuel injection is paced by the system cost weighed against the real performance benefits.

Exhaust Gas Recirculation (EGR) allows a controlled amount of exhaust gases to be recirculated back into the air inlet stream. EGR reduces NO_X emissions but extracts a penalty in higher particulate emissions and lower fuel efficiency. Two-cycle engines can achieve EGR by lowering the scavenge ratio, thereby avoiding exhaust gas piping. While EGR has been part of the emissions reduction system on gasoline-fueled automobiles for many years, it has seen only limited use with diesels (light duty). Although NO_X is reduced, EGR introduces some serious concerns about engine durability, fuel efficiency, and the emission of other effluents. In smaller diesel engines, a 50 percent reduction of NO_X by EGR appears to increase particulates by two to three times, more than doubles HC and CO, and reduces fuel efficiency by as much as 7 percent, in addition to introducing contaminants into the lube oil system.

Such devices do not exist for either EMD or GE locomotive engines and little or no development work has been performed. Development and qualification of such a device along with quantification of its emission benefits and total cost impact would pace the implementation of this reduction technology. The problems listed above are likely to preclude the development of EGR systems for many years.

Variable Geometry Turbochargers can deliver more compressed air to the engine over a wider range of operating conditions. This is increasingly proving beneficial on heavy duty truck diesel engines allowing high torque rise along with smoke and emission reductions. Because locomotive engine speed is completely decoupled from wheel speed by the electric traction system, the benefits of torque rise in locomotives are at this time perceived to be nearly negligible. Increasing power at lower engine speeds by high torque rise could allow slowing the engine speed at a given notch setting thereby providing a marginal reduction in friction losses, a marginal fuel savings, and marginally higher NO_X emissions.

A comprehensive analysis of this candidate should be concluded before hardware development is proposed. Complex turbochargers, even for truck engines, represent major cost penalties and these penalties are likely to increase at a greater rate with very large turbochargers used on locomotive engines. Unless complex turbocharger designs are shown by analysis to be highly beneficial, development should not be considered.

Next Generation Locomotives -- Next generation locomotives will incorporate at least one major new technology as well as a substantial combination of those improvements identified with new model locomotives.

Since both the EMD 60-Series and the GE Dash-8 locomotives are relatively new to the market, a new generation of products is probably 5 to 10 years away. Given the long life of locomotives and the low replacement rate, any substantive emission benefits from next generation locomotives will require a long time to have an effect on overall air quality.

Candidate technologies possible for new generation locomotives are reviewed below with a brief description of the most relevant features and characteristics. The lack of hard data on most candidates, particularly in the railroad environment, precludes an in-depth evaluation. Those most promising at this time are identified below.

> *New diesel engine designs* do not appear to be under aggressive development by the U.S. locomotive manufacturers. The CAT 3600 is the newest design engine suitable for use in heavy locomotives, and although it is the most modern of the engines suitable for locomotives, it appears to have no specific feature or configuration that will make either the current EMD engine or the current GE engine obsolete.
>
> The cost to develop and tool a new engine is in the several hundred million dollar range and requires 7 to 10 years to complete There appears to be no major improvement available with a new technology that justifies design and development of an entirely new engine at this time.
>
> The *adiabatic diesel* is a principal whereby the combustion process occurs without heat loss. This implies that the combustion chamber is insulated to preclude heat rejection and there is no cooling system. Additional heat energy released to the exhaust is recovered downstream. The primary benefits of an adiabatic engine would be improved fuel efficiency and reduced size, weight and power losses to the cooling system. NO_X emissions are likely to increase because

of the high temperatures within the combustion chambers. Therefore, for most applications adiabatic engines will require exhaust after-treatment devices to reduce NOx emissions.

Adiabatic engine designs require the development of substantial new technologies. The U.S. Department of Energy is currently involved with cost-sharing projects with a number of firms working on basic high temperature materials technologies such as ceramics; lubrication; and ring, piston, and cylinder interface. Candidate ceramic parts include piston crowns, exhaust valves, exhaust ports, complete heads, liners, and turbocharger rotors. Work is focused on highway truck-sized engines and progress is slow, but ultimately some of the products and technologies developed in this process may be applicable to locomotive-sized engines.

Because of the low rate of progress on the total adiabatic engine, the technology will be incrementally applied to "low heat rejection (LHR) engines." LHR engines could evolve from current engine designs as the maximum permitable temperatures of various components are raised. Ceramic turbocharger turbines, exhaust valves and other components could then be introduced as incremental improvements on new model locomotives.

With *turbo compounding*, another power turbine downstream of the turbocharger, captures otherwise wasted energy, and by gears and shafts adds this power directly to the crankshaft. It is likely that turbo compounding technologies will be developed first for LHR engines and later for adiabatic engines as their high operating temperatures will increase energy levels in the exhaust stream.

Bottoming cycle is a steam boiler in the exhaust system, downstream of the turbocharger and turbo compound system designed to capture the last elements of energy in the exhaust stream. The steam thus generated drives a turbine that is geared to the crankshaft. A condensing system is necessary to preclude carrying and exhausting clean water. The bulk of the vapor generator (boiler) and the condenser system implies a major packaging effort for locomotives. Any practical application of the bottoming cycle for locomotive diesel engines is far in the future.

New powerplants most likely to be introduced into locomotives are fuel cells and gas turbine engines. Both offer a potential for substantial emissions reduction.

- The *fuel cell* is very far in the future because of the status of development. Currently, fuel cells are extremely costly because of numerous plates and other components, the use of precious metals, and the complex nature of control and fuel generation systems. Designs for phosphoric acid fuel cell buses are being developed, but these require massive battery packs to overcome shortcomings of the fuel cell system. In these preliminary designs, the fuel cell stack is hydrogen (reformed from methanol) fueled with air supplying the oxygen. Current technology phosphoric acid fuel cells are approximately 5 to 10 times the cost of locomotive diesel engines on a per horsepower basis. Even more preliminary design work is just beginning with proton exchange membrane (PEM) fuel cells fueled with liquified hydrogen and oxygen. PEM fuel cells are an order of magnitude more costly than phosphoric acid fuel cells.

- *Gas turbine* engines were tested years ago in locomotives and performed well at high power settings, although there were noise and high temperature exhaust related problems. The fundamental problem was and continues to be very high fuel consumption at part load and idle. The fuel consumption problem can only be solved by improving the basic thermodynamic cycle of the engine, which requires a higher turbine inlet temperature. The U.S. Department of Energy (DOE) is jointly funding programs, similar to the adiabatic diesel projects, to develop ceramic materials and designs that will allow substantive temperature increases. Availability of engines with the high temperature capability to compete with diesel efficiency in locomotive service, like fuel cells, is too many years away to be included in the detailed evaluation of low emission technologies in this project.

Some *locomotive systems improvements* are likely to be made in the future. While these improvements are likely to increase locomotive efficiency and performance they should not be counted on for substantive emission reductions. The use of *AC drive* systems may be the most substantial change likely to be introduced to locomotive traction control systems in the foreseeable future. AC drive systems will offer locomotive productivity and performance improvements along with long term maintenance cost reductions but overall fuel efficiency is likely to be equal to or slightly poorer than current DC drive systems. Given essentially the same fuel use there will be no reduction in emissions from AC drive. However, AC drive technology may spur the development of new more powerful locomotive engines since they will enable the design of more capable traction motors. Traction motor capabilities currently limit the useful maximum diesel engine power.

5.2.4 Alternative Fuels

In the U.S. there has been greater interest in alternative fuels in the past 10 years than since the conversion from coal as the major domestic and commercial heating source. Spurred by the fuel "crises" of the 1970s, research was directed at non-petroleum fuels for most forms of transportation. The railroads are continuing development of a locomotive fuel that is less costly and in abundant supply, focusing on coal-based and off-spec or heavy fuel oils.

During the past 5 years the focus for alternative fuels work for automotive, bus and truck applications has shifted from energy independence to lower emissions. The greatest efforts towards clean, alternative fuels are clearly centered in California but federal level activities are increasing.

Except for the AAR and SwRI work directed at broad specification lower cost fuels, other alternative fuels activities have focused on methanol and natural gas fuel development. At times both alternative fuels have been at least theoretically price competitive with diesel fuel. Liquified natural gas (LNG) is rapidly becoming a viable alternative fuel candidate. It is currently made and used by utilities for peak demand shaving. An estimate for a current possible open market price, with several major assumptions, is in the range of $.50 per diesel equivalent gallon.

Methanol -- Methanol became the early fuel of choice because it is easily adapted to automotive Otto-cycle engines, is readily available, and is transportable and storable with generally the same type of equipment used for petroleum-based fuels. Methanol suffered dramatic price fluctuations in the 1980s. These wide fluctuations appear to be the result of a severely restricted supply/demand marketplace.

To alleviate the problems associated with price fluctuations the California Energy Commission has established the California Fuel Methanol Reserve. This reserve represents a long term contract with five methanol suppliers for methanol at $0.40 per gallon at terminals in Wilmington and Richmond, California. This reserve has sufficient quantities committed to maintain the methanol demonstration projects in the state.

Currently, the California Fuel Methanol Reserve has only chemical grade methanol. Establishment of a fuel grade methanol specification by California is an important step in reducing the cost of methanol by lessening the burden of storage and transportation. Exhibit 5-2 is the California Fuel Grade Methanol Specification.

EXHIBIT 5-2
California Fuel Grade Methanol Specification

Methanol, By Volume	98.0% minimum
Hydrocarbon, By Volume	2.0% minimum
Acidity, Wt ASTM D1613	0.003% maximum
Distillation Residue and Range, Wt ASTM D86	0.5%
Chloride, Wt ASTM D3120 and D2988	0.0002%
Lead, ASTM D3237 Modified	0.001 gms/L maximum
Phosphorous, ASTM D3231	0.0002 gms/L maximum
Sulfur, Wt ASTM D3120	0.005% maximum
Particulate	Clear and bright
Water, Wt ASTM E203	1.0% maximum

In addition to Otto-cycle applications, methanol has been applied to Diesel-cycle engines using the following approaches:

- Direct injected as a neat fuel (M-100) with auto-ignition
- Direct injected M-100 with a cetane improver additive
- Fumigated with diesel pilot ignition
- Dual injected with diesel pilot ignition
- In emulsion with diesel fuel.

Experiments have been conducted with methanol in a locomotive-sized engine primarily as a partial diesel fuel replacement, retaining the diesel fuel injection system as an ignition source for fumigated methanol. In spite of methanol's low cetane index it has been successfully applied to diesel engines. Probably the most successful diesel/methanol conversion is Detroit Diesel Corporation's (DDC) 6V-92 engine. Work on this engine, fueled with neat methanol, has been under way for nearly 10 years with each successive generation of engine being progressively more reliable. The 6V-92 is a 2-cycle design that is thermodynamically similar to, but much smaller than EMD engines. During this 10-year development period DDC worked extensively on fuel injector and engine durability problems. Similar problems could be expected with locomotive-sized engines. The most persistent problem has been fuel injector scoring and siezing due to methanol's lack of lubricity. While DDC's electronic fuel injector was believed to be somewhat more tolerant of poor fuel lubricity, injector failures remain a problem. Recently DDC has indicated they will specify the use of a fuel additive to improve methanol's lubricity. The mechanical unit injectors used on locomotive engines will require much of the same development work that is being conducted on smaller engines.

Fuel tank capacity, materials compatibility, fuel handling and safety procedures are issues which have been resolved for transit buses, the service in which nearly all the methanol 6V-92 engines are operating. Similar operating issues must be resolved for rail service if methanol is to be used for locomotive fuel. However, methanol use in diesel locomotive engines will present some additional packaging and logistics problems for some types of service. The low energy content of methanol will reduce the range of locomotives. There is little room for extra fuel tankage on locomotives nor much weight reserve should added capacity be available on some locomotive models. Fuel tender cars would be required to provide the between-fueling range achieved in current locomotive models. Refueling outside California would also be a significant issue--most rail carriers provide their own fuel storage and would be required to install additional fuel storage tanks to service the methanol fleet. Any new facility installation could be made compatible with both methanol and any petroleum product. Finally, other than the California fuel reserve there is no infrastructure to supply fuel grade methanol anywhere else in the U.S. However, chemical grade methanol is shipped throughout the country by tank car, tanker trucks, and by barges.

For yard and local service, fuel storage and locomotive range constraints are much less severe. These locomotives are centrally fueled, operate only within the state, and do not experience as severe range constraint problems as line-haul locomotives. Local engines can generally complete several work assignments before refueling (refueling once or twice a week is typical for some local services). Methanol may be a more practical alternative fuel for these types of service.

<u>Natural Gas</u> -- Natural gas has become a more viable alternative fuel in the past few years. One reason for its success is the aggressive posture of several gas utilities and gas industry associations -- and its price compared to that of methanol.

There are two methods of storing natural gas on board the vehicle -- as a highly compressed gas (CNG) and as a liquid (LNG). Onboard storage of CNG has several major disadvantages:

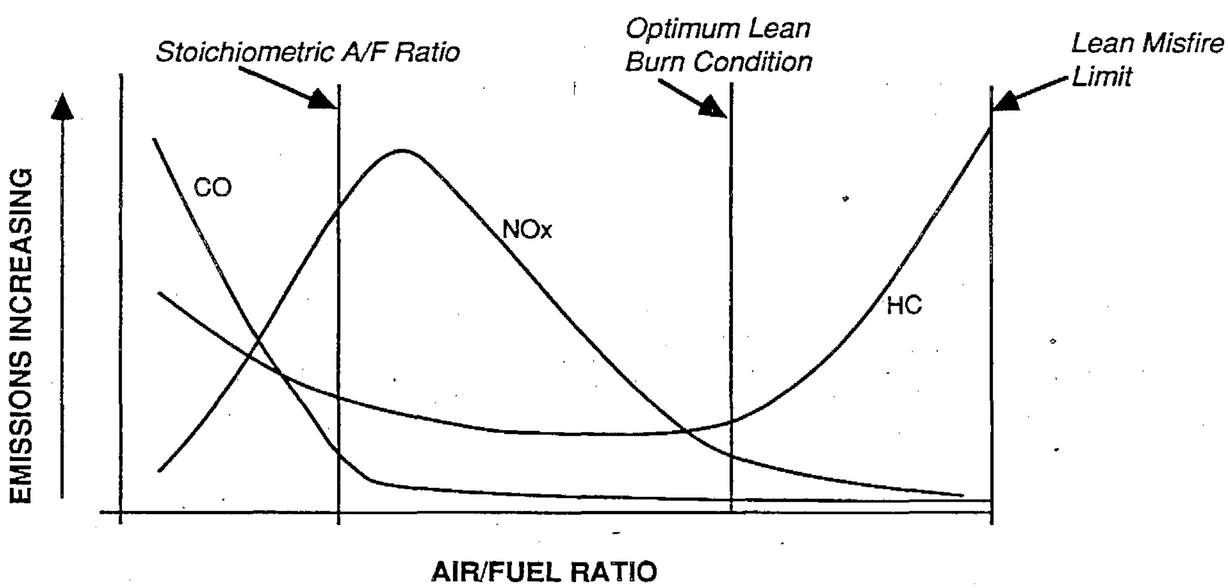
- Size and weight of fuel tanks (six times diesel volume for same range)
- Size and cost of the gas compression refueling system
- Inability to refuel off pipeline (constrained to purchase fuel through local utility)
- Safety issues associated with the fuel tender.

Natural gas can, however, be stored on board the vehicle as a liquid (LNG), thus reducing infrastructure costs and gaining the user's independence from the local gas utility. Cryogenic technology has advanced greatly as a result of the space program, reducing the problem of natural gas boil-off from the storage tank. Tank volume requirements for LNG are higher than diesel fuel but less than methanol (1.7 times diesel). Safety issues associated with storage and daily handling must be defined and reduced to operating practices.

Regardless of storage method, the fuel is introduced to the engine in gaseous form. The engine is most often of the spark ignited Otto-cycle type although work has been done on diesel pilot ignition. Serious work is just beginning on direct injected gas and almost no work is focused on direct injected liquid. Several experiments have been conducted on gas fumigated diesel engines with diesel pilot ignition. The Burlington Northern Railroad ran a dual-fueled diesel/CNG EMD locomotive for several years.

Most large medium-speed diesel engine manufacturers (EMD and GE are exceptions) offer Otto-cycle gas fueled versions for stationary power applications. These gas engines operate in the lean-burn range to minimize emissions, as shown in Exhibit 5-3. Power output of natural gas engines is less than their diesel counterparts due to a lower compression ratio, inlet throttling and detonation limit. However, natural gas designs providing as much as 90 percent of the equivalent diesel power rating appear feasible.

EXHIBIT 5-3
Lean Burn Range for Otto-Cycle Gas Fueled Engines



Since stationary gas engines operate at constant speed and near constant load there has been no control system development for operations over wide speeds and loads, as required for locomotive or any mobile application. The requirements for the control system are:

- Maintain lean burn conditions without misfire or excessive emissions
- Prevent detonation
- Accommodate variations in fuel chemistry
- Provide smooth transitions in engine speed and load from idle to full rated power.

Development of such control systems will determine the rate of development of natural gas fueled locomotives. Adaption of an existing, proven, large-bore gas engine technology to locomotives is the best near-term possibility for alternative fueled railroad operations. Locomotives with on-board LNG fuel tanks assigned to local service would have no range problems and would not require a tender. On an equivalent energy basis LNG also appears to be economically advantaged compared to other alternative fuels. The locomotive would suffer the efficiency losses of throttled inlet and lower compression ratio.

Coal-Derived Fuels -- EMD, GE and Caterpillar have been working for several years on coal-based locomotive fuels. EMD and GE have focused on a coal-slurry fueled, Diesel-cycle engine, while Caterpillar is working on an on-board coal gasification processor and fuel cleaning system. All projects are jointly funded by the U.S. Department of Energy and the engine manufacturers. All work to date has been on single-cylinder engines. The coal slurry is direct injected into the engine at notch settings of 4 and above. Below that setting, normal diesel fuel injection is used. Emissions from the engine trend toward lower NO_X but are highly dependent on the efforts expended in cleaning the coal before introduction to the engine. At this point in the project a multi-cylinder development and locomotive demonstration engine is being built. A locomotive is planned to be operable in 1991.

The primary problem with coal based fuels has been injector and engine durability. To date, all coal slurry mixtures have dramatically increased fuel injector wear rates. Considerable efforts are being expended to both increase the lubricity inherent in the fuel, as well as to improve the tolerance of fuel injection components to the abrasive nature of these fuels. In a parallel effort EMD and Allison Gas Turbine are developing a coal-dust-fired gas turbine engine. The corrosive/erosive nature of the coal continues to be a problem in this development.

While it is likely that solutions to these durability problems will eventually be found, they may also be expensive. We believe that the various control techniques reviewed in this report and focused on diesel fuel (with an improved emissions-control fuel specification), will offer more cost effective solutions to reducing emissions.

Synthetic, Other Alcohols and Other Renewable Resource Based Oils -- These have been considered to various degrees during the past 15 years. Synthetic fuels efforts focused on making gasoline and diesel fuel from coal and oil shale. The major problem with these fuels is that they are costly to produce and do not match the specification of the fuel they are designed to replicate. Methanol is much less costly to make from these same feedstocks but it is still not cost competitive with methanol from natural gas. Synthetic gasoline and diesel fuel have no inherent emission advantage over products produced from crude oil.

The other alcohol given consideration as an alternative fuel is ethanol. Distilled from surplus or off-quality grain crops, ethanol has considerable political support in the farm states. The price of ethanol is traditionally much higher than methanol with no substantial performance advantages. As a mainstream replacement fuel, ethanol fails simply because not enough can be made to supply any major transportation segment. Farm land can be used to grow food or grow ethanol feedstock but not both.

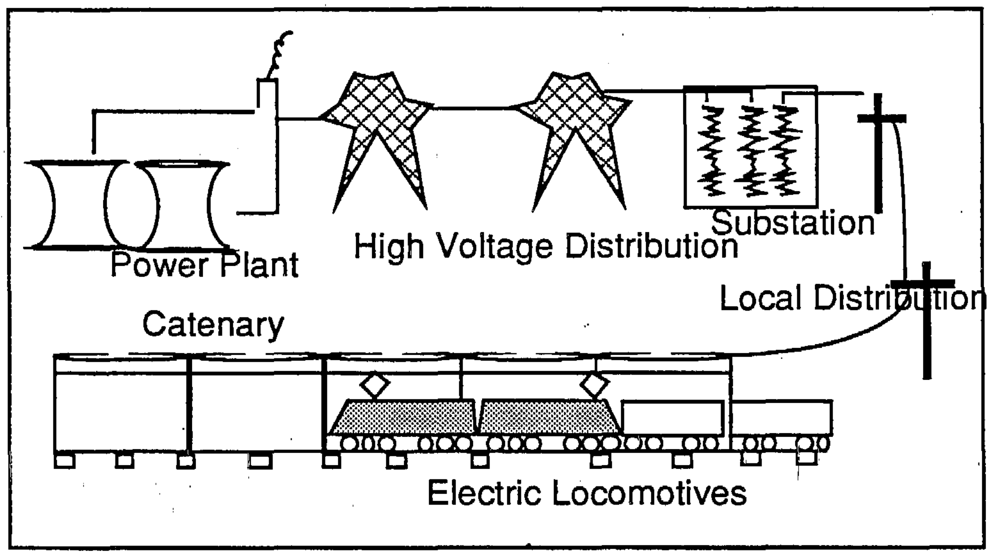
Sunflower seed oil, peanut oil and other oils have been demonstrated as fuels in engines of various types with varying results. Like ethanol these oils require crop lands to raise the feedstock and require a costly process to extract the fuel product.

5.2.5 Electrification as an Emission Reduction Strategy

A large part of the world's railways are electrified. That is, they operate with electric locomotives rather than diesel-electric. To the extent that stationary power plants produce and deliver energy to operate trains with lower overall levels of air pollution emissions than diesel electric locomotives, electrification becomes a viable option as an alternative fuel or mode of operation in a locomotive emission reduction strategy.

In simple terms, electrification of a railway line substitutes a stationary power plant, electrical distribution system, track side electricity delivery system and locomotive based power transformer system for the diesel portion of existing locomotives and the diesel fuel delivery system. Exhibit 5-4 below shows the major components of an electrified rail system:

EXHIBIT 5-4
Menu of Major Electrification Components



The powerplant may be hydro-electric, nuclear, or fuel fired steam turbine (usually coal or oil fired). It may also be constructed in a non-critical attainment area where concentrated emissions from a fuel fired plant may pose less overall risk. Power requirements for rail operations will represent a significant part of a major powerplant's total output (say, 300 megawatts for the LA basin at peak periods[1]). Powerplant output is normally distributed over a combination of new and existing high voltage distribution systems to a track side substation where it is stepped-down to the operating voltage of the railway, usually 25 kilovolts (although 50 kv systems have been built). The final electrical delivery system is either an overhead catenary or a track-side third rail. For freight systems, access to the track-side is important and so, for safety and cost

1 Assumes the ability to run one hundred 3,000 horsepower locomotives at any one time (about 200,000 kilowatts), times 1.5 for line and conversion losses, or about 300,000 kilowatts.

considerations, an overhead catenary is normally used. Locomotives in such systems are electric with equivalent horsepower ratings of between 2,000 and 7,000 horsepower. For freight rail operations, usable rail horsepower is limited by the deliverable tractive effort at the rail which is a function of locomotive weight and wheel slip control technologies. In practical terms, this limits usable locomotive horsepower to about 4,000 to 5,000 although higher horsepower units could be useful for high speed applications.

While electric railways are relatively common on a worldwide basis, electric operations are relatively rare in the United States. Electricity is used as a primary power source only in passenger services (e.g. the Northeast Corridor passenger services operated by Amtrak and many subway and commuter rail operations) and several special purpose shortlines carrying coal or ores from mine to production plant. U.S. freight railroads have studied rail electrification extensively over the last 20 years. Driven by the rapidly escalating price of diesel fuel in the 1970s several proposals for electric operations were discussed and a bill was introduced in the United States Congress to provide for a nationwide 20,000-mile electrification program. What has halted all such projects to date has been the enormous initial cost of electrification. Initial costs are generally too great for a privately financed rail company to afford. Most other world rail systems are publicly financed and electric operation is a part of both a national energy policy and a national transportation policy. Such conditions do not prevail in the privately operated and privately financed rail operations in the United States. State financed electrification, where the benefits from the electrification effort are found in lower locomotive generated emission levels, would be required for any major electrification effort.

The costs for major components of an electrified railway are shown in Exhibit 5-5. It is assumed that the cost of the powerplant and high voltage distribution system will be borne by the power company and paid for from electricity sales over the 50 year life of the electrification investment. It is generally too costly to electrify anything but main and major secondary lines. Yard trackage cannot normally be electrified because its use is relatively light and intermittent. Diesel-electric locomotives would still be used for yard and most local services (customer sidings are not normally electrified either).

EXHIBIT 5-5
Major Component Cost of Electrification

COMPONENT	UNIT	UNIT COST
CATENARY	TRACK MILE	$ 200,000
SUBSTATION	15 MILE	$4,000,000
CIVIL WORKS	TRACK MILE	$ 500,000
IMMUNIZATION	TRACK MILE	$ 200,000
LOCOMOTIVES	EACH	$4,000,000

A significant cost of electrification is in the civil works required to elevate bridges and other overhead structures sufficiently to allow for clearance of the catenary. Exhibit 5-6 shows the estimated cost of electrification in the Los Angeles basin, and reflects the relatively dense nature of rail and highway overpasses in the Los Angeles area. Further, railway train control, communication and signalling systems must be immunized against interference from the high voltages associated with electrical operations. Similarly, in populated areas, the catenary and transmission lines must be insulated and surrounding residences and businesses must often be immunized.

While this estimate must be considered very rough, it is at least indicative of the cost to electrify significant portions of the mainline trackage in the Los Angeles basin. A more accurate estimate of total costs will require significant engineering and survey work to estimate the civil work required. This element of the estimate probably has the greatest range of error. The number of locomotives needed is also only a considered estimate based upon diesel equivalent units.

EXHIBIT 5-6
Estimated Cost of Electrification in the L.A. Basin

ITEM	NUMBER OF UNITS	COST (MILLIONS)
CATENARY	400 MILES	$ 80
SUBSTATIONS	25 EACH	$ 100
CIVIL WORKS	400 MILES	$ 200
IMMUNIZATION	400 MILES	$ 80
LOCOMOTIVES	150	$ 600
ROUGH TOTAL, LA BASIN MAINLINES		*$1,060*

Since these locomotives would be captive to the Los Angeles basin, significant reductions in locomotive utilization would occur as trains must stop at the end of the electrified territory to change locomotives.

Electrification would bring benefits to the railroads in the form of reduced fuel costs, reduced motive power maintenance costs, and some investment credit would have to be recognized for the diesel-electric locomotives released to other parts of the respective rail systems. However, electric train operations do not bring the kinds of motive power benefits that would have been expected a few years ago. At that time, electric locomotives could produce more total horsepower and greater tractive effort than the largest diesel locomotives available. Today's diesel locomotives produce about as much tractive effort as can be practically used given locomotive weight and the strength of rail and track structure limitations. Total operating savings usually associated with electrification could make a government financed pay-as-you go system economically attractive. It is the significant first cost, not the lack of operating savings, which has stopped major investment in electrification in the United States.

6.0 EVALUATION OF EMISSION REDUCTION STRATEGIES

6.0 *EVALUATION OF EMISSION REDUCTION STRATEGIES*

6.1 EVALUATION CRITERIA

The emission reduction technologies described in the previous chapter were analyzed and evaluated using an evaluation matrix shown in Exhibit 6-1 below.

EXHIBIT 6-1
Technology Evaluation Criteria

Emission Reduction Potential: Evaluation criteria include all regulated pollutants. The evaluation is based on locomotive test data when available. In its absence, evaluation is based on data from other heavy duty diesel engine research or on expert opinion from manufacturers, refiners, and recognized engine development experts. Such data was used only to determine the direction of emission changes.

Railroad Impacts: This evaluation included an assessment of the factors rail carriers will encounter in implementing the technology. Capital and operating costs, in the form of changes in fuel efficiency, durability and support logistics issues were considered.

Research and Development Issues: This criterion summarizes the state of the development of the technology and an estimate of the work required to develop and commercialize the technology. Risks relate to the likelihood that the development effort will produce a useful product or result. A performer most likely to prosecute the research is identified.

Retrofitability: This evaluation criterion includes an assessment of whether the technology might be installable on existing locomotives. This is an important consideration since technology available only in new locomotives will require many years to have an effect on air quality levels.

Health and Safety: This evaluation criterion includes an assessment of any change from existing industry conditions which may affect the health and safety of train crews or railway workers. No attempt was made to estimate the health effects on the general population by a change in overall air quality.

Applicability Outside California: This evaluation criterion includes an assessment of whether the technology would be applied generally in the rail industry, rather than just in California. Generally, those technologies which impose a cost or operating penalty would be only reluctantly applied outside California, reducing the size of the market for which the technology would apply. Technologies associated with substantial penalties would force the formation of California only locomotive sub-fleets.

These factors were most useful for the evaluation of retrofit, new model and alternative fuel technologies. The lack of qualitative or quantitative data on new generation technologies precludes an in-depth or detailed evaluation. Electrification as a system concept is not comparable to the development of new heat engine technologies and has been evaluated separately. Exhibits 6-2, 6-3, and 6-4 are summaries of the retrofit, next generation and alternative fuel technology evaluation worksheets. Pluses (+) on the charts represent a favorable change from current equipment, i.e., lower emission levels or better fuel efficiency. Similarly, negatives (-) represent unfavorable changes. Multiple pluses or minuses designate a major change. The value of the change is included in parenthesis where data is available.

The evaluation of the various alternative technologies was the basis for the recommendations of the most productive technology development projects. We have also included recommendations for emission control techniques which do not depend upon new technology but require changes in operating practices or modifications based upon existing technologies. It should be noted that such changes, while nearer term, all bear some cost. An attempt has been made to evaluate these costs or to determine the reasons that a currently available technology has not been implemented.

The recommended development and methodology projects are described in the next chapter.

EXHIBIT 6-1
RETROFIT TECHNOLOGY EVALUATION

EVALUATION FACTORS	EMD INJECTOR	LOW NOX ENGINE	REDUCE IDLE TIME	LOW SULFUR FUEL	RETARD INJECTION TIMING 4°	HIGH CETANE --LOW SULFUR- #1 FUEL
Emissions Reduction Potential						
• Smoke/Particulates		– –	+ (Reduced by amount of off time)	+	–	++
• NOx	++ (20%)	+++ (50%)	+ (Reduced by amount of off time)	Nil (+ %)	++ (20%)	+
• HC	Nil	Nil	+ (Reduced by amount of off time)	Nil (–%)	+ (8%)	+
• CO	+ (10%)	Nil	+ (Reduced by amount of off time)	Nil (–%)	Nil	+
Impact on Railroads						
• Initial Cost	$10K - $20K/loco	$100K - $150K/loco	Nil	Nil	Reset governor to recover power loss	– Reset governor Separate fuel tanks
• Fuel Cost	Nil	– (5-8%)	+ (Reduced by amount of off time)	– (3% - 5%)	– (1-2%)	– – (up to 25%)
• Maintenance Cost	Nil	Nil to –	+ (Reduced by amount of off time)	+	Nil	+
• Operations	Nil	Nil	Risk of no-start	Nil	Nil	Reset governor
• Applicable Class of Service	All	All 645 engines	Switcher/local	Switcher/Local	All	Switcher/local
Research and Development						
• Needs	Verify turbo speed	Medium scale development	Start/warmup emissions	Verify injector durability	NOx vs particulate trade-off	Quantify benefits and verify injector durability
• Risk	Nil	Medium	Nil	Nil	Nil	Nil
• Timeframe	Immediate	2-3 years	Immediate	Immediate	Immediate	Immediate
• Cost	– (<$100K)	– (<$500K)	– (<$500K)	Nil	– (<$500K)	– (<$500K)
• Performer	EMD	EMD	Contract laboratory	Nil	Contract laboratory	Contract laboratory
Retrofitability	Early 40-2 locos with E-3 engines	All 645 engines	Yes GE requires -8 integral head/liner EMD requires latest head/liner	Yes	Yes (during PM)	Yes
Health and Safety	Nil	– (Increased smoke)	+	+	– (Increased smoke)	+
Applicability Outside California	Yes (no penalties)	Yes	Yes	Yes	Yes -- but increased smoke would be judged as a negative	Yes

C1rev

EXHIBIT 6-2

NEXT GENERATION LOCOMOTIVE TECHNOLOGY EVALUATION

EVALUATION FACTORS	MORE EFFECTIVE CHARGE AIR COOLING	COMBUSTION IMPROVEMENT	ELECTRONICALLY CONTROLLED TIMING	EXHAUST GAS RECIRCULATION	WASTE GATE/VARIABLE GEOMETRY TURBO
Emissions Reduction Potential					
• Smoke/Particulates	+	+	+	– – –	+
• NOx	++ (15%)	Nil to –	+	++ (30%-60%)	+
• HC	++ (30%)	++	+	–	+
• CO	+++ (50%)	+	+	Nil	+
Impact on Railroads					
• Initial Cost	– ($100K)	– ($15-25K)	– ($10-20K)	– ($25-30K)	– ($80K)
• Fuel Cost	+ (2-3%)	+	+	– – (7%)	+
• Maintenance Cost	–	–	Nil to +	– –	–
• Operations	Risk of engine overheating	Nil	Better cold start	Risk of control failure in high EGR	Nil
• Applicable Class of Service	Line haul	All	All	All	Line haul
Research and Development					
• Needs	Cooling system packaging	Major engine development	F.I. system/locomotive integration	Control/EGR rate	Turbo/engine match
• Risk	Nil	–	Nil	Nil	–
• Timeframe	1-2 years	5-10 years	3-5 years	1-3 years	5-10 years
• Cost	– ($1-2M)	– ($10-100M)	– ($1-2M)	– ($.5-1.0M)	– ($2M +)
• Performer	Engine manufacturer	Engine manufacturer	Engine manufacturer	Engine manufacturer	Engine manufacturer
Retrofitability	– Packaging	Possibly but OEM must develop	Yes but OEM must develop	Yes but OEM must develop	Yes but OEM must develop
Applicability Outside California	Yes	Yes	Yes	Yes but would be disconnected	Yes

C2rev

EXHIBIT 6-3

ALTERNATIVE FUELS EVALUATION

EVALUATION FACTORS	METHANOL	CNG	LNG	FUMIGATED OR MIXED ALTERNATIVES
Emissions Reduction Potential				
• Smoke/Particulates	++++ (None)	++++ (None)	++++ (None)	+ Smoke from diesel pilot
• NOx	+++ (50%)	+ (Reduction possible but requires tight control)	+ (Reduction possible but requires tight control)	Tends to be worse of both fuels
• HC	− − (200% but less reactive)	+	+	Tends to be worse of both fuels
• CO	Nil aldahydes higher	+	+	Tends to be worse of both fuels
Impact on Railroads				
• Initial Cost	− (new facilities)	− − − Gas compressor High pressure tender	− − Crynogenic tanks	− − Double facilities
• Fuel Cost	− (2-3 times now) (long-term outlook good)	+ Less than diesel	++ Much less than diesel	?
• Maintenance Cost	− (injection sytem)	− (ignition system)	− (ignition system)	− Mainstream two fuel systems
• Operations	− (half range)	− − (complicated refueling)	− (Less power - more locos)	Double fueling
• Applicable Class of Service	All	− Lower power may preclude line haul	Lower power may preclude line haul	All
Research and Development				
• Needs	Total development for locomotives	Total development for locomotives	Total development for locomotives	Near total development for locomotives
• Risk	High-low cetane fuel	Low-Otto cycle technology	Low - Otto cycle technology	Medium (Fall back to diesel)
• Timeframe	5-10 years	5-76 years	5-76 years	1 - 4 years
• Cost	$5 - $10M	$5 - $8M	$5 - $8M	$1M - $4M
• Performer	Locomotive manufacturers	Locomotive manufacturers	Locomotive manufacturers	Locomotive manufacturers
Retrofitability	possible, not likely	possible, not likely	possible, not likely	possible, not likely
Health and Safety	−	−	Not yet defined	Depends on fuel
Applicability Outside California	Yes whenmethanol price goes down	Yes	Yes	Yes

C3 rev

7.0 RECOMMENDED DEMONSTRATION PROJECTS

7.0 *RECOMMENDED DEMONSTRATION PROJECTS*

From the list of candidate technologies and strategies reviewed in Chapter 5 and evaluated on a gross basis in Chapter 6, we have selected projects in four broad categories which, in our judgement, will best advance ARB's efforts to reduce emissions from locomotives. Some can be implemented almost immediately to reduce today's locomotive emissions levels, while others are targeted at more dramatic reductions from future products. In recommending these projects, we have also considered the level of effort and focus of ongoing research in these areas by others so that ARB sponsored activities would complement and/or fill gaps in existing medium-speed diesel engine research. Finally, we have considered the special characteristics of California's rail operations in selecting these projects. The four project areas are listed below (not in any order of preference) and described in the sections that follow:

- Develop emission testing standards
- Railroad electrification study
- Implementation of near term retrofit technologies and changes in operating procedures
- Retrofit technology research program
- Review of alternative fuels options.

A cost/benefit analysis has been included for specific hardware recommendations. These analyses encompass the cost to reduce various emissions from locomotives in all California air basins studied. The analysis is expressed in dollars per pound of all controlled effluents reduced per year. The costs included are estimated operating and maintenance costs and capital costs amortized over the life of the locomotive, or a 10-year average. Costs incurred on a fleet-wide or national basis are included, while emission reduction benefits are considered for California air basins only. Technology development costs are not included.

7.1 DEVELOP EMISSION TESTING STANDARDS

The establishment of industry-wide/nationwide emission testing standards for locomotives is essential. A considerable amount of data already exists regarding typical train operating profiles -- both for the nation as a whole and for California. Additionally, because of the relatively small number of industry players, standard locomotive testing procedures should be easily established. The testing procedures used by SwRI, for example, could become the basis for establishing the mechanics of the testing methodology. The ARB, SwRI, both locomotive manufacturers, Caterpillar, the AAR and the U.S. EPA should form a task force to use the existing body of knowledge regarding locomotive emission testing procedures to establish industry-wide standards. Some recommendations for developing these standards are presented below.

7.1.1 Test Cycle

Several alternative locomotive duty cycles have been recommended by various industry participants and used for testing purposes. The GE line haul and EMD road unit duty cycles are shown in Exhibit 7-1 below, together with the average line haul duty cycle for California train operations (developed for this report).

EXHIBIT 7-1
Industry Standard Profiles
(Percent Time in Notch)

PROFILE NAME	NOTCH									
	8	7	6	5	4	3	2	1	IDLE	BRAKE
GE LINE HAUL	14%	6%	3%	4%	4%	3%	5%	5%	50%	4%
EMD ROAD DUTY	17%	4%	4%	4%	4%	4%	4%	4%	46%	9%
AVG. CA. PROFILE	11%	3%	4%	4%	5%	4%	4%	4%	49%	12%

There is relatively little variation between these locomotive duty cycles. Additionally, it is clear that because the brake specific emissions of locomotive engines do not vary a great deal by throttle notch (except for idle), the percentage of time spent in each notch is not critical to the weighted brake specific test results. Whatever duty cycle is selected would have to be followed by all engine manufacturers. An alternative is simply to measure emissions at each available throttle notch. Different standard duty cycles can be used for each specific application.

7.1.2 Test Methodology

Test procedures should be adaptable to both engine alone and installed (load box) configurations. Test procedures should allow accurate measurement at more than one or two laboratories. Test equipment and instrumentation should be readily available, reasonably priced, practical, and easy to use. The railroads should be able to accurately test locomotives in load box configuration. Special attention should be directed to simplifying particulate measurement. All testing should be at throttle notch conditions -- transient testing should be avoided.

7.2 RAILROAD ELECTRIFICATION STUDY

The cost and complexity of electrification in one or more air basins or most of California is of such a magnitude that it cannot be evaluated within the scope of this project. This report has roughly quantified the costs of electrification in the South Coast Air Basin and the benefits are obvious--no road locomotive emissions--representing about a 70 percent reduction in all emissions from locomotives. Should the ARB believe that there is a role for the public sector in implementing either basin or state-wide electrification, then a detailed study should be commissioned.

The study should examine the South Coast Air Basin possibly other air basins and major portions of the state. Sufficient detailed work should be performed to identify lines which could be consolidated and electrified along with the political and other issues to be addressed in line consolidation and abandonment. The largest unknown cost element is for civil works associated with providing catenary clearances. Other issues that should be included in the study are right-of-way sharing among railroads, public financing, and construction schedules.

Equally important, power requirements should be estimated and sources identified. The emissions resulting from increased electric power generation should be estimated and compared to current emission levels. Finally, the cost/benefit analysis should take into account the likely stream of payments from using railroads for the purchase of power as well as a rental or lease payment for the electrification infrastructure. Electrification can bring rail carriers significant financial benefits.

7.3 IMPLEMENTATION OF NEAR TERM RETROFIT TECHNOLOGIES AND CHANGES IN OPERATING PROCEDURES

The following are recommendations for retrofit technologies and changes in railway operating practices that will reduce emissions in the near term.

- Adopt EMD Injector Retrofit
- Reduce Locomotive Idle Time
- Retard Injection Timing
- Use High Cetane, Low Sulfur #1 Fuel.

7.3.1 EMD Injector Retrofit

In some instances, NO_X reductions can be made without significant increases in fuel consumption. This can occur when injection rates are increased and beginning of injection timing retarded. EMD indicates that the larger injectors from its 645E3B engines can be retrofitted into 645E3 engines. This would permit timing retardation without increasing fuel consumption. In the EMD case, no new technology must be developed. We recommend that this retrofit be demonstrated and urge EMD to examine the hardware development requirements for similar retrofits to later model 645 engines. We also recommend that GE examine the possibility of developing a similar retrofit.

Emission Reduction Potential. Good emissions reduction data was provided for the EMD injector retrofit. It indicates that at full load, reductions of approximately 20 percent NO_X and 10 percent CO are possible. With the large number of candidate engines in service, the total NO_X reductions will be substantial. In California, approximately 2,600 tons of effluents per year can be eliminated. If similar modifications can be applied to other 645 engines, further reductions of NO_X can be achieved in the air basins. (Exhibit 7-2 on Page 7-6 details these calculations.)

Impact on Railroads. The impact on the railroads will be relatively limited. Initial cost, if implemented during overhaul will be about $20,000 per locomotive, less if rebuilt components are used and if existing cams and rollers are retained. If implemented between overhauls, the cost will be higher. If retrofitted locomotives are retained in California, the cost/benefit ratio becomes more attractive but at the loss of locomotive scheduling flexibility.

Fuel Consumption. Fuel consumption is not expected to change.

Maintenance Cost. Maintenance cost should not change.

Operations. Operations will not be affected. If modified units are retained in California some increases in locomotive fleet size may be necessary.

Class of Service. Both local and line haul locomotives use 645E3 engines.

Research and Development. Only limited testing is needed to verify turbocharger durability, determine the need for updated cams and crown rollers and verify overall engine durability with the marginally higher peak firing pressures. This testing could be performed on in-service locomotives. The Santa Fe has operated a locomotive for two and one-half years.

Retrofitability. The objective of this project is to retrofit to a large population of the current locomotive fleet. The roster shows 2048 candidate locomotives owned by the SF, SP and UP railroads. This represents 35 percent of their combined fleets.

Health and Safety. Health and safety of railroad employees is not likely to be significantly impacted by this modification. The recommended testing will indicate any increase in particulate emission levels, which could have a detrimental impact. The degree of change is not likely to be significant.

Applicability Outside California. The retrofits could be applicable to all locomotives with 645E3 engines. Since there is no fuel consumption penalty there is no barrier to nationwide acceptance of this modification, other than initial retrofit cost.

EXHIBIT 7-2
Cost/Benefit of EMD Injector Retrofit

	LINE HAUL	LOCAL	TOTAL
EMD + GE Locomotives In Service Nationwide	3,363	2,451	5,814
EMD Locomotives with 645E3 Engines	1,368	680	2,048
Percent of Total	41%	28%	35%
Annual California NOx Emissions (Tons)	24,973	7,774	32,747
California NOx Emissions from 645E3 Engines (Tons/Year)	10,239	2,157	12,396
20% NOx Reduction from E3 Engines (Tons/Year)	2,048	431	2,479
Annual California CO Emissions (Tons)	3,195	1,117	4,312
California CO Emissions from 645E3 Engines (Tons/Year)	1,310	310	1,620
10% CO Reduction from 645E3 Engines	131	31	162
Total Emission Reduction (Tons/Year) in California	2,179	462	2,641

Total Retrofit Cost ($20,000 x 2,048 units)	= $40,960,000
Ammortized Annual Cost for the Fleet Assuming 10-year Life and 10 Percent C.O.C.	= $ 6,666,051
Cost Per Pound of Emissions Reduced in California	= $1.25/Lb

Cost/Benefit Analysis. The cost/benefit analysis is shown in Exhibit 7-2 on the facing page. If all 2048 candidate locomotives are retrofitted with new parts, new cams and crown rollers and the new governor during overhaul, at $20,000 each, the three railroads will have a combined $41 million investment over the 8-10 year engine overhaul cycle. If testing and the demonstration show that new cams and crown rollers are not needed along with any other premium components to maintain adequate durability the cost will be much lower.

The cost calculations shown in Exhibit 7-2 assume that <u>all</u> 645E3 SP, ATSF, and UP units will be retrofitted but that emission "benefits" will only be enjoyed in California, (i.e., the emissions reduced from the unit when it is operated outside California are not counted in the benefit calculation). Even so, the cost per ton of emissions reduced is $2,520 or $1.26 per pound. (This assumes a 10-year life for the retrofit package,. $20,000 per retrofit, and a 10 percent cost of capital.)

7.3.2 Reduce Locomotive Idle Time

Switch and local service locomotives can be shut down rather than idled whenever the local ambient temperature is predicted to remain above 50°F. This operating practice has been proposed in locomotive emission reduction studies since the mid-1970s. Most rail carriers have engine shutdown policies which generally require engines to be shut down if the temperature is above 50°F and the locomotive will not be in use for at least 2 hours. Data gathered for this study indicates that locomotives are rarely, in fact, shut down. Apparently, railroads feel that the fuel savings benefits are not enough to offset the increased operational difficulties that might be encountered if engines fail to re-start, are damaged during restarting, or require excessive warm-up times before the unit can be put back into service.

Since cold-starting is likely to generate high emission levels until warm-up, emission testing is required to determine the emissions output during the starting and warm-up period. Should the testing disclose high emission levels at start-up then this practice should be limited to those locomotive units that are expected to be unused for long enough period to assure that the policy will have a positive impact on overall emissions.

EXHIBIT 7-3
Reduced Idle Time Emission Impact
(Yard Engines: Annual Tons)

	NO_x	HC	CO	SO_x	PM	TOTAL
Total Annual Yard Emissions in California (Tons)	3,440	199	504	186	77	4,406
Total Annual Idle Emissions (Tons)	938	117	202	52	30	1,339
Reduced Emissions Due to 28 Percent Reduction in Idle Time (Tons)	263	33	57	15	8	361
Percent Reduction in Total Yard Emissions from Reduced Idling	7.6%	16.6%	11.3%	8.1%	10.4%	8% (avg.)

EXHIBIT 7-4
Reduced Idle Time Emission Impact
(Local Engines: Annual Tons)

	NO_x	HC	CO	SO_x	PM	TOTAL
Total Annual Local Emissions in California (Tons)	7,774	352	1,117	579	167	9,989
Total Annual Idle Emissions (Tons)	1,498	180	492	101	45	2,316
Reduced Emissions Due to 53 Percent Reduction in Idle Time (Tons)	794	95	261	56	24	1,230
Percent Reduction in Total Local Emissions from Reduced Idling	10.2%	27.1%	23.3%	9.2%	14.3%	12% (avg.)

Emission Reduction Potential. To calculate the emission reduction from reduced locomotive idling, the typical daily assignments for switch and local service locomotives were examined. Switch engines are assigned 18 hours per day and left to idle the balance of the day. Switch engines also are at idle about 75 percent of the time while they are assigned. However, because of the unpredictable/random usage patterns while they are assigned, it is impractical to shut engines down during this period. If the engine was shut off while not on assignment, the idle savings for switch locomotives would be 6 hours per day or about a 31 percent decrease in total idle emissions from switch engines.

If we assume that about 10 percent of the days in the California basins have temperatures below 50°F then the practical reduction in idle time for switch engines is about 28 percent. As shown in Exhibit 7-3 on the facing page, this represents a reduction in emissions ranging from 17 percent for HC to 7.6 percent for NO_X. The weighted average emission reduction is 8 percent.

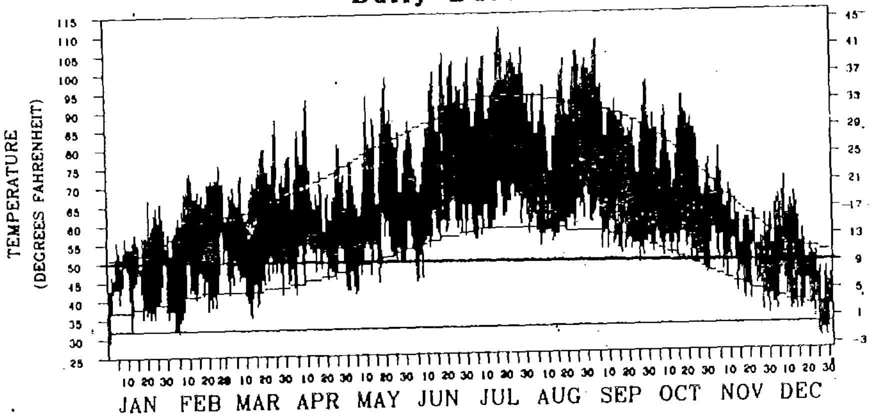
Local service locomotives are nominally assigned 14 hours per day with a 50 percent idle rate while on assignment. During the remaining 10 hours each day the locomotive is not assigned and at idle. Shutting down local engines 10 hours per unit per day during non-assigned time reduces total idling by 59 percent. Again, if we assume that the number of days below 50°F statewide equals 10 percent, then the practical reduction in total idle time amounts to 53 percent. As shown in Exhibit 7-4 on the facing page, this represents a reduction in emissions ranging from 27 percent for HC to 10 percent for NO_X. The weighted average emission reduction is 12 percent.

Impact on Railroads. To minimize the initial impact on the railroads, the recommendation calls for a minimum temperature cutoff of 50°F. Exhibit 7-5 shows the 1988 daily temperature data for several major California cities. Although railroad facilities are not at the airport where the data is recorded, it is clear that a 50°F minimum cutoff temperature will permit idle time reductions on most days within California. We estimate that on perhaps 10 percent of the days each year the temperature drops below 50°F. There will be an impact on locomotive operating cost and availability associated with the implementation of this procedural change. Amtrak provided an estimate of $500 per year for

EXHIBIT 7-5
Local Climatological Data

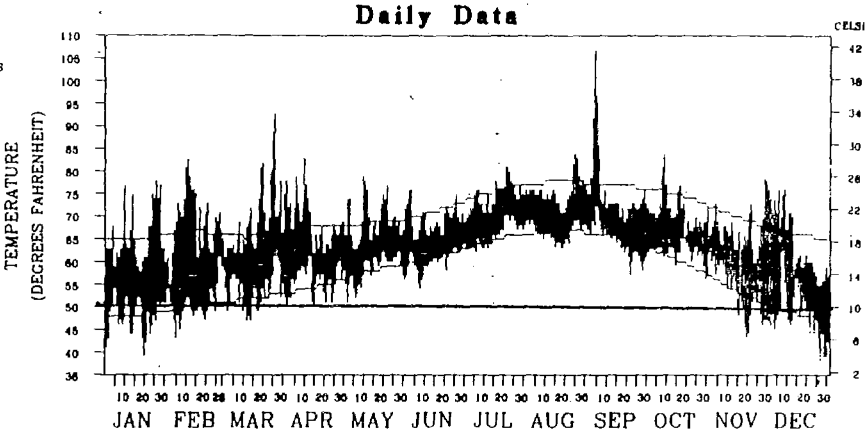
SACRAMENTO, CALIFORNIA

Daily Data



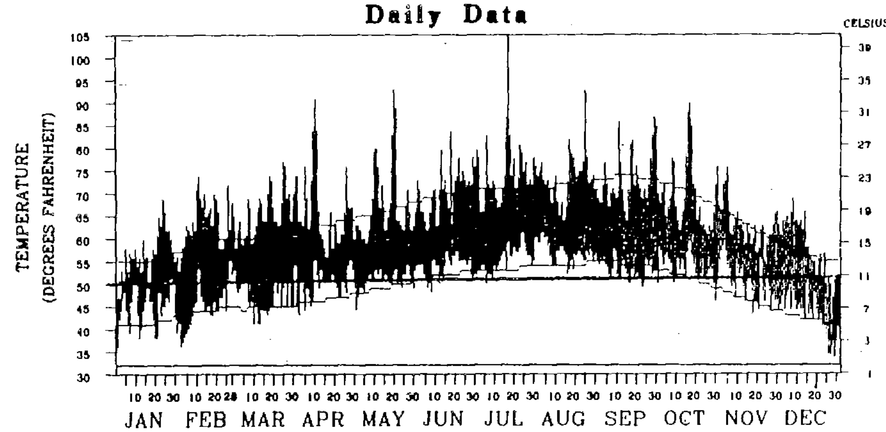
SAN DIEGO, CALIFORNIA

Daily Data



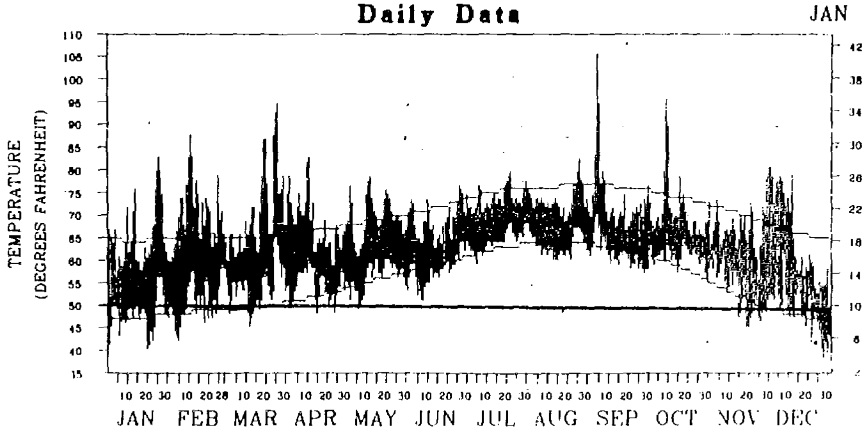
SAN FRANCISCO, CALIFORNIA
INTERNATIONAL AIRPORT

Daily Data



LOS ANGELES, CALIFORNIA
INTERNATIONAL AIRPORT

Daily Data



additional preventive maintenance costs for battery and start systems. No estimate was made for costs from availability impacts due to no-starts or for the cost of jumpstarts.

Fuel cost will be reduced by the amount of idle time reduced. The amount of fuel saved depends on whether the locomotives are equipped with the low idle option, which reduces idle fuel consumption by approximately one-third. In the absence of a low idle option, a typical local service locomotive will save approximately 13,300 gallons of fuel per year, while a typical yard locomotive will save about 6,600 gallons per year. Our analysis shows this is sufficient to offset increased costs due to improved starting systems and maintenance.

Initial Costs. Initial cost will include inspection and replacement of batteries, and other charging and starting system components to make the system operationally reliable. This is estimated to require 8 hours labor during the first 90 day inspection ($400) and $1,000 in parts and supplies per locomotive. The recommendation does not contemplate a premature overhaul.

EMD strongly recommends that the "creepy crank" option be installed on locomotives that will be frequently shut down. Depending on locomotive model this kit costs between $1,800 and $2400 plus one day for installation. It is not known how many switch and local service locomotives assigned to California air basins are presently equipped with "creepy crank." Each railroad must decide if "creepy crank" must be installed on their locomotives before implementing reduced idle time policy.

Maintenance costs will primarily consist of battery and starter maintenance during scheduled periodic maintenance activities. Additional maintenance costs will be incurred when locomotives won't start, for whatever reason (see "Operations" below).

Operations. Operations will be negatively impacted when a locomotive won't start. Some additional time will be required to start locomotives prior to crew assignment. We have estimated this cost at about 1/4-hour per day on average or about $2,500/year for a typical locomotive. This figure is presented with the lowest confidence of accuracy and tends to drive the cost/benefit analysis.

Class of Service. Class of service is switching and local service locomotives. Imposition of the requirement on road locomotives is more tenuous since these engines must be fueled and readied for their next dispatch assignment. This involves moving the units from place to place during layover periods. However, inclusion of road engines could reduce emissions by an additional 2 to 3 percent on average and reduce fuel consumption by an additional 1 to 2 million gallons.

Research and Development. Research is needed to quantify, by test, the emissions generated during starting and warm-up. Test results will be used to determine the recommended unassigned time before shutdown is attempted. (Note: a cold starting test should be performed with the high cetane #1 fuel since white smoke and other emissions should be much less than with #2 diesel fuel. There is no risk associated with the research program needs. Cost of testing 6 to 10 locomotives should be about $500,000. This testing should be performed under the direction of the AAR.

Retrofitability. The EMD head gasket and GE integral head/liner hardware are retrofitable into older locomotives. Locomotives equipped with the Caterpillar 3600 engine can be safely shut down without modification. If individual railroads determine that installation of "creepy crank" is a prerequisite to shutdown then this device would be retrofitted at the next major shopping event. Therefore, once all the older locomotives have gone through an overhaul cycle, the entire California based fleet of switch and local service locomotives can be shut down when not in service.

Health and Safety. The health benefits to railroads workers in yards would be realized by the reduction of the smoke generated by idling locomotives.

Applicability Outside California. The no-idle policy could be implemented nationwide. Once the fuel savings are verified, and if they offset increased battery maintenance costs, railroads could again adopt the policy throughout their fleets, particularly in warm climates. No regulatory action is likely to be required. However, since cold starting diesel locomotives generally will produce increased levels of smoke, local smoke regulations should be modified.

EXHIBIT 7-6
Cost Benefit of Reduced Idle

	LOCAL	YARD	TOTAL
Locomotives In Calfornia	185 (1)	140 (2)	325
Total Emissions (All Species) (Tons/Yr)	9,989	4,406	14,395
Total Idle Emissions (Tons/Yr)	2,316	1,339	3,655
Total Idle Time (Hrs/Day)	17	20.4	---
Idle Time Reduction	53%	28%	---
Emission Reduction (Tons/Yr)	1,230	361	1591
Idle Fule Per Unit Per Year (Gal)	25,130	23,455	48,585
Total Idle Fuel Use In California (Gal)	4.7M	3.2M	8M
Idle Fuel Saved (Gal/Locomotive/Yr)	13,319	6,557	19,886
Idle Fuel Saved In California (Gal/Yr)	2.46M	.92M	3.88M
Idle Fuel Saved ($/Yr) @ 50¢/Gal	$1.23M	$.46M	$1.7M
Ammortized Annual Battery/Starter Upgrade Cost for the Fleet *(3)*	$72,259	$54,682	$126,941
Maint. Cost @ $500/Locomotive/Year	$92,500	$70,000	$162,500
Daily Starting ($2,500/Yr/Loco)	$462,500	$350,000	$812,500
Total Annual Costs	$627,259	$474,682	$1,101,941
Net Cost After Fuel Savings	($602,741)	$14,682	($598,059)
Cost Per Pound	($.24/lb)	$.02/lb	($.19/lb)

(1) Based on number of local assignments as reported by the railroads, the number of units per assignment, and an average locomotive utilization rate of about 1.4 assignments per day.

(2) Number of yard engines as reported by the railroads.

(3) Assumes $1,400 starter/battery upgrade cost per unit, and Creepy Crank installed on 50 percent of the fleet at $2,000 per installation; 10-year life; and 10 percent cost of capital.

Note: Numbers in ( ) are negative. Overall the fuel savings from shutting off engines during idling will more than offset the costs of maintenance and improved starting systems.

Cost/Benefit Analysis. Our estimated cost/benefit analysis is shown in Exhibit 7-6 on the facing page. This analysis assumes that:

- All local and yard engines are shut off during all unassigned time (above 50°F)
- None of the locomotives have/use a low idle option
- "Creepy crank" is installed on one-half of the fleet at $2,000 per installation
- Baseline emissions inventory from Exhibit 4-13
- Idle fuel consumption
    - Local 4.5 gallons/hour
    - Switch 3.5 gallons/hour
- Locomotive availability -- 90 percent.

7.3.3 Retard Ignition Timing

The third specific emission reduction recommendation is to retard fuel injection timing to reduce NO_X emissions. Although locomotive-specific data is limited, retarded timing should produce a substantial near term NOx reduction -- estimated to be about 20 percent for 4 degrees of retard. The practice increases both fuel consumption and the generation of other effluents, especially particulate emissions and visible smoke. As a result, we believe that timing retardation may only be practical for yard and local locomotives which remain in California and will thus experience a favorable trade-off between reduced NO_X emissions and increased fuel consumption. (If the timing was retarded on line haul locomotives, a fuel economy penalty would be paid whether the unit was operated within or outside State borders.)

Emissions Reduction Potential. All diesel engine manufacturers have demonstrated the sensitivity of NO_X formation to injection timing. Retarded injection timing reduces the peak combustion chamber temperature and resident time of hot gases in the combustion chamber. Retarded timing also increases smoke, particulate formation and fuel consumption. Current industry estimates indicate that a 15 to 30 percent reduction in NO_X may be achieved with 4 degrees of retardation. Fuel consumption is increased 1 to 2 percent. Retarded timing will increase smoke and particulate emissions but the use of premium fuel <u>may</u> offset some of these increases.

Impact on Railroads. Initial costs will be limited to the time expended in retiming the injectors during an inspection. At this time the governor and rack adjustments should be made to get full engine power under the retarded condition. We estimate that these adjustments will require about 8 man-hours of labor. The cost should be less than $400 per locomotive including overhead and supplies. Fuel costs will increase by 1 to 2 percent with a 4 degree retardation. Manufacturers indicate that locomotive maintenance costs are not expected to change significantly, although exhaust temperatures are increased with injection retardation which, especially at high altitude, could be too high for the turbocharger. Operations could be affected if notch 8 power is reduced to protect the turbocharger. Locomotives in all classes of service could be modified for retarded timing. However, because of the fuel efficiency penalty involved, we believe that only yard and local units which are commonly assigned and relatively captive to a geographic area, should be included.

Research and Development. Because of the fuel cost penalty associated with this option, a major testing program should be devoted to this strategy. The testing should be coincident with the premium fuel work described in the following section. Results of the testing will determine the viability of the approach based on fuel consumption and particulate increases. Cost of the testing would be included with that for premium fuel tests. The ARB should assume responsibility for the testing because of the likelihood that controversial and significant fuel cost penalties will be identified.

Retrofitability. The concept of NO_X and particulate reduction via timing changes is targeted at the existing California fleet of switch and local service locomotives

Health and Safety. Retarded timing could have a slight negative effect on rail worker health if smoke and particulate emissions are higher. Some of this effect could be mitigated by premium fuel.

Applicability Outside of California. Since road locomotives are the major NO_X contributors in the air basin, they would logically be the first to be set at the retarded condition. However, the fuel cost penalty will necessitate that these locomotives be dedicated to California; this implies additional costs associated with locomotive logistics. Such costs have not been quantified in this analysis.

Cost/Benefit Analysis. Because of the number of variables involved, the cost/benefit analysis is shown in chart form. Exhibit 7-7 below shows the 20 percent NO_X reduction in pounds per year for yard and local locomotive services. This analysis assumes:

- A 1-1/2 percent fuel consumption penalty
- A fuel cost of $0.50 per gallon which is the 1987 western railroad average
- Fuel consumption from Exhibit 4-23.

The impact of any increase in particulate or other emission has not been quantified.

EXHIBIT 7-7
Cost/Benefit Analysis of 4-Degree Injection Retard

	LOCAL	YARD	TOTAL
Locomotives in California	185	140	225
Annual California NOx Emissions (Tons)	7,774	3,440	11,214 ~~1,121~~
20 Percent NOx Reduction (Tons/Year)	1,555	668	2,243
Increase in Particulate Emissions	Unknown	Unknown	–
Fuel Consumption (Gal/Year)	29,086,00	12,497,000	41,583,000
1-1/2 Percent Fuel Penalty (Gal/Year)	436,290	187,455	623,745
1-1/2 Percent Fuel Penalty ($/Year) @ 50¢/Gal	$218,145	$93,728	$311,872
Cost to Retime Injectors @ $400/Locomotive	$74,000	$56,000	$130,000
Total Cost Increase ($/Year)	$292,145	$149,728	$441,872
Cost Per Pound (NO_X)	$0.09	$0.11	$0.10

7.3.4 High Cetane, Low Sulfur, #1 Fuel

The fourth demonstration/test recommendation is to refuel California-based locomotives with a #1 grade diesel or kerosene fuel that has a high cetane index and a sulfur content of less than 0.05 percent. The proprietary data from large high-speed diesel engine manufacturers and the anecdotal experience of truck and bus operators suggests that #1 diesel fuel will have a favorable impact on particulate emissions and smoke. The smoke and particulate reduction from this fuel could offset the increase from retarded ignition timing (previous recommendation). It is recommended that both retarded timing and #1 fuel be implemented simultaneously. Testing is required to verify satisfactory fuel injector life with this lower viscosity fuel as well as to determine the emission benefits, if any, associated with the use of a premium fuel. This fuel is currently in use in several transit bus fleets, but qualitative data on the benefits are lacking.

Emissions Reduction Potential. Quantitative data on the use of fuel of this type in locomotive engines is lacking. All diesel engine experts conferred with on this subject agree that this specification fuel is likely to have a positive effect on emissions, particularly smoke. Experts consulted on this issues include: EMD, GE, Detroit Diesel Corp., SwRI, Chevron Research, and EPA.

Impact on Railroads. Implementation of a policy of using a different fuel for basin captive locomotives than that used for interstate rail operations may be costly in that rail carriers would be required to make capital investment for separate fuel storage and handling facilities for the new fuel. Initial cost of implementing this recommendation as a demonstration project is limited to the cost of the fuel and an emission testing program.

The cost of this fuel is higher than #2 diesel fuel oil. Fuel of this specification would be made by adding cetane improver to Jet A fuel, which is a low sulfur kerosene. Chevron estimates that the cost at the refinery is 2 to 3 cents per gallon for the desulfuring process and 1/2 cent per gallon for the cetane improver. The mark-up on these basic costs along the distribution chain has been estimated at about 100 percent. On this basis, fuel cost penalty should be about 5 cents per gallon.

As noted in Chapter 5, #1 diesel fuel also has a lower heating value than #2 diesel fuel. The low heating value results in reduced power at a given fuel delivery rate. The use of #1 fuel could cause an increase in fuel consumption (to make up for lost power) by as much as 7 percent compared to #2 diesel fuel. The recommended testing will determine if the low viscosity fuel is satisfactory in locomotive fuel injection systems and if adequate injector life is attained (as is the case with Detroit Diesel injectors). If the testing proves otherwise, maintenance costs will increase for injector replacement. Some other maintenance costs will be reduced slightly because of the elimination of sulfur-related wear inside the engine and a solvent action cleaning fuel injector tips. Operations will not be affected by the reduced heating value in #1 fuel versus #2 fuel since the fuel injector/governor system on most locomotives has sufficient capacity to provide additional fuel. The governor will be adjusted when the timing is retarded to allow the engine to develop full power.

Class of Service. The most applicable class of service is switching and local service locomotives since they are generally assigned on a geographical basis. It is possible that, to reduce fuel facilities and logistics costs, California rail yards and refueling facilities could switch to #1 fuel for all operations. In that case, road locomotives engines that are refueled in the State will have a mixture of #1 and #2 fuel when departing. This mixed fuel could result in some reduction in smoke levels from the road units.

Research and Development. Need for research is in two areas -- testing that will quantify the emission benefits of this fuel and testing to verify acceptable fuel injector life. The emission research could be expanded to develop trade-off curves for cetane rating versus aromatic content and specific gravity (related to heating value) versus smoke/particulate emissions. This will allow the railroad to refine the specification to the best cost/emission benefit level. Testing should be performed both at standard and retarded injection timing. Fuel injector durability tests would most likely be bench-type tests.

There is no risk associated with the needed emission testing. The risk of failure is higher with the fuel injector testing. A fuel cooler may be necessary to maintain fuel viscosity in hot climates. Testing should be initiated as soon as possible.

EXHIBIT 7-8
Cost Analysis for Premium #1 Fuel With Retarded Injection Timing

	LOCAL	YARD	TOTAL
NO_X Reduction	1,555	688	2,243
Fuel Consumption with Retard (Gal/Year)	29,552,290	12,684,455	44,236,745
Cost Penalty for Retard Including Installation ($/Year)	$292,145	$149,728	$441,873
Penalty for Premium Fuel @ $.05/Gal ($/Year)	$1,477,614	$634,222	$2,111,836
Fuel Consumption Increase for Lower Heating Value (Gal/Year)	2,068,660	887,912	2,956,572
Cost Penalty for Lower Heating Value @ $.55/Gal ($/Year)	$1,137,763	$488,352	$1,626,115
Total Cost Increase	$2,907,522	$1,272,302	$4,179,824
Cost Per Pound (NO_X)	$0.94	$0.92	$0.93

The emission testing is probably best performed under the direction of ARB or the AAR. The fuel injector durability testing should be performed by the engine manufacturers since they are in a position to implement injector or fuel system changes if required to assure adequate injector life.

Retrofitability. If the fuel injector tests are successful this fuel could be run in any EMD, GE, or CAT engined locomotive.

Health and Safety. This recommendation will have a positive health benefit regardless of its implementation with or without any other recommendation.

EMD expressed concern that light fuels could form a flammable vapor over the liquid fuel in the tank in very hot conditions. There are no known incidents of fuel fires in transit buses resulting from the use of #1 fuel. Before 1974, the use of #1 fuel was nearly universal in transit and today usage is over 50 percent nationwide with no known health impacts.

Applicability Outside California. Because of the cost penalty this fuel will probably not become a universal railroad fuel in the near term. It certainly could be used in switch and local service locomotives in any metropolitan area sensitive to locomotive emissions, particularly smoke.

Cost/Benefit Analysis. This analysis cannot be performed in great detail because of the lack of emission data specifically related to #1 fuel. The cost/benefit analysis is an expansion of the analysis for retarded injection timing to include the high cetane #1 fuel. The analysis is shown in Exhibit 7-8 on the facing page, and includes the following assumptions:

- Benefits of retarded timing are used -- Exhibit 7-7
- #1 fuel has 7 percent lower heating value than #2 fuel
- Cost of additional fuel storage facility not included
- #1 fuel is 10 percent more expensive than #2 fuel
- Diesel #2 fuel is $.50 per gallon.

7.4 RETROFIT TECHNOLOGY RESEARCH PROGRAMS

The following two technologies warrant additional research given their emission reduction potential, implementation timeframe, feasibility for retrofit, and operating cost implications:

- Selective catalytic reduction using ammonia catalyst
- Charge air cooling.

7.4.1 Selective Catalytic Reduction

As described in Chapter 5, selective catalytic reduction (SCR) using an ammonia based catalytic reactor offers the potential for dramatic reductions in NO_X emission levels. Experiments by Caterpillar and other manufacturers of medium speed diesel engines have demonstrated reductions in NO_X of between 50 and 80 percent depending on the size of the catalytic reactor and the amount of ammonia introduced into the exhaust stream. Ammonia-based SCR systems are used commercially today on many stationary power plants to reduce NO_X emissions -- particularly in Japan and at least one locomotive system is in operation in Germany. The most difficult problems to be addressed in developing these systems for locomotives and other mobile sources are control system development and packaging. The size of an SCR unit is likely to be in the range of .75 to 1.5 cubic feet per 100 HP -- or 30 cubic feet for a 3,000 HP engine. Packaging constraints on today's locomotives are severe but it appears that an SCR system sized to fit in today's locomotives could offer significant reductions in NO_X (if not the full 50 percent to 80 percent that is possible from these systems).

It is recommended that ARB sponsor research focused on the application of these systems for locomotives. Initial work would involve aggressive laboratory development. Such research would advance the State's efforts to control locomotive emissions in two ways: first, the laboratory work would help determine the feasibility of the systems for retrofit on existing locomotives; and secondly, the information gained regarding emission reduction potential would help ARB in developing appropriate regulations for new locomotives (where SCR systems could be optimally configured into new designs from the outset). This research should be done on the most recent engine models available in order to properly gauge the minimum emission levels achievable.

7.4.2 Charge Air Aftercooling

Air-to-air charge cooling as described in Chapter 5 is a well developed technique used on today's heavy duty diesel engines to improve fuel efficiency and reduce both NO_X and particulates. NO_X emissions can be reduced by 20 to 30 percent. Packaging problems, however, make the application of these systems on locomotives difficult. While retrofitting of existing engines with charge air cooling will be costly and probably sub-optimal, it appears feasible. Such systems could, of course, be more easily accommodated in new locomotive designs. It is recommended that ARB sponsor research focused on determining the feasibility, cost, and emission reduction potential of air-to-air aftercooling for both existing engines as well as new locomotives. Again, such research would enable ARB to better understand the emission levels achievable with today's modern locomotive engines . . . and on the optimistic side, the feasibility of air-to-air aftercooling for retrofit in existing engines may be proven.

A derivative of the air-to-air charge air cooling package is to provide a separate air-to-water cooling radiator for charge air (as opposed to using engine coolant to cool the intake air). Such systems would likely have marginally less potential for reducing NO_X (than air-to-air charge air cooling) but packaging constraints would also be reduced. The applicability of such systems for retrofit is therefore enhanced. NO_X reductions of around 20 percent could still be achieved. Such cooling systems should be a part of an overall charge air cooling demonstration program.

7.5 REVIEW OF ALTERNATIVE FUELS OPTIONS

Our recommendation that ARB not sponsor programs focused on alternative fuels research does not reflect any judgments as to the relative cost effectiveness of "clean" fuels versus new diesel fuel technologies, but rather, the realization that a national policy will be required to implement a new fuel for widespread use in line haul train operations. Any regulation requiring the use of an alternative fuel for rail operations in California only would imply that railroads switch locomotives on trains entering the state either at new terminals established expressly for that purpose, or at the closest existing terminal inside state borders. In either case, new (and additional) locomotives would need to be developed and purchased. (Note that similar locomotive change considerations affect the electrification strategy discussed above. In this case, however, the new locomotive technology is well known and available). The development of an "alternative fuel" locomotive that meets the industry's performance and reliability requirements is similar to a "next generation" locomotive development effort, i.e., it requires a complete engine re-design and new auxiliary and support systems. Engine development costs would be in the range of $300 to $500 million and development of auxiliary systems to support the "clean fueled" engines would add between $100 to $200 million for a total development cost of $400 to $700 million dollars. Development timeframes would likely range between 7 to 10 years from a committed start date. To meet the locomotive power requirements for California, railroads in total would be required to purchase between 500 and 600 new units at between $1.5 and $2.0 million each -- a total cost of between $.750 and $1.2 billion dollars. Finally, considerable additional investment in fuel storage and handling would be required. The total cost of this option then begins to be comparable to electrification. However, because the alternate fuel locomotive suffers from reduced range and higher maintenance and servicing costs, there are no significant economic benefits. Therefore, in our judgment, if the regulation forces railroads to buy new alternative fueled locomotives and to establish facilities and operations to switch head-end power at state borders, then electrification may be a better and more cost effective option from an emission reduction perspective.

Next, the viability of alternative fuels for use in switch engines and local locomotives to reduce emissions raises many questions that are difficult to answer at this time. Essentially no data exists on the emission characteristics of either methanol or CNG powered locomotives. Methanol and CNG powered truck/bus engines however clearly offer the potential for lower-than-diesel emission levels and are being pursued by DDC, Cummins, and Caterpillar to meet 1991 and 1994 on-road emission standards. It is conceivable that such technology could be adapted to large-bore locomotive engines. DDC in particular has indicated that a methanol-powered version of their 149 Series engine could be developed (for experimental/demonstration purposes) at a relatively low cost (under $1,000,000). DDC's V16-149 engine is available up to 1,600 HP and therefore could be a candidate for the replacement of switch engines in EMD's SW10, SW1500, MP15 and GP9 locomotives. These units comprise the bulk of the switch engine fleet in California. The V16-149 is too small for most local service applications, but DDC is developing a V20-149 capable of up to 2,000 to 2,400 HP. This engine could probably meet the requirements of some light local service applications.

The cost for development of commercially acceptable methanol or CNG engines (from any engine manufacturer) is at least as high as the development costs for a next generation diesel engine. Development timeframes are probably longer. The emission benefits are unclear. If a cetane improver is used with methanol to reduce development costs, the emission benefits are compromised. Additionally, it is well understood that the most difficult engine operating regime for methanol is at low loads and low speeds -- exactly where switch engines spend a great percentage of their time.

Because of the uncertainty regarding the costs for retrofitting and operating alternatively fueled switch and local locomotives, and because the emission benefits are unclear, we recommend that ARB only pursue a demonstration program if substantial financial and manpower participation by both the engine manufacturers and a railroad is secured.