9. SELECTIVE CATALYTIC REDUCTION

A number of aftertreatment NOx control technologies have been developed for use in stationary applications, but the only one that appears very promising for locomotive use at present is Selective Catalytic Reduction, or SCR. Because they operate at lean air-fuel ratios, diesel engines cannot use three-way non-selective catalytic converters for NOx control. The only aftertreatment option for NOx control is therefore SCR. Unlike the non-selective catalytic reduction of the three-way catalyst, SCR does not require rich or stoichiometric air-fuel ratios, making it suitable for use with diesel and other lean-burn engines. In this approach, the required chemical reduction potential is supplied by a separate reductant material. This is usually ammonia, but urea can also be used. Selective catalytic converter systems based on precious metals, on non-precious metal-oxide (base metal) catalysts, and on zeolite catalysts are now being offered commercially for stationary diesel engines, and a number have been installed - mostly in Europe. SCR systems using precious-metal catalysts can also function as catalytic converters, and can therefore control both NOx and particulate emissions. They can also function at lower temperatures than the competing types, but they are sensitive to sulfur in the fuel and have a narrow temperature range. The SCR design evaluated in this report uses a combination of base metal and precious metal catalysts, applied to a metal rather than ceramic substrate.

There is another aftertreatment technology that deserves mention, though it does not appear ready for mobile applications. This is the Cummins NOXTech system, which is based on a selective non-catalytic process. The reductant material is cyanuric acid, HNCO, which is made from urea. It is stored as a solid and transported to the reaction chamber[29] with compressed air. An auxiliary fuel supply is used to heat the exhaust gas in the reaction chamber to 1200 °C (2200 °F). At this temperature, the cyanuric acid sublimates to a gas and disassociates to isocyanate. This compound then reacts with the NOx in the exhaust to form N_2, CO_2, and H_2O. The extremely high temperature also serves to oxidize the unburned hydrocarbons and particulate matter in the exhaust stream. A sophisticated control system monitors temperatures and delivers only enough cyanuric acid to react with the NOx. The advantages of this system are absence of catalyst, the ability to handle all exhaust pollutants simultaneously, and the ease of cyanuric acid handling. The disadvantages are the high fuel costs to heat the exhaust, the difficulties of engineering a high temperature reaction chamber - especially for mobile applications -

and the system bulk. A NOXTech system is operating in a diesel powered generation system in Minneapolis (*Diesel Progress*, 1992).

9.1 SCR Technology

SCR is not a particularly complex technology, but it is rather expensive, owing to the kinds and amounts of materials needed to construct and operate it. SCR has never been applied in North American freight locomotives, but it has been applied in enough mobile diesel applications to make the North American locomotive a logical next step. Once properly engineered and developed, SCR units could be installed by any company that repairs or rebuilds locomotives.

How SCR works - SCR eliminates NOx through a catalyst-promoted reaction between ammonia (NH_3) or urea (H_2NCONH_2) with NOx to form harmless N_2 and water. Ammonia can be supplied in aqueous solution or anhydrous. Urea is a solid which is dissolved in water for transfer to the reaction chamber. Production units using ammonia and urea are operating successfully on offshore oil platforms, stationary reciprocating and turbine power plants, diesel motorships and boats, and in a rail grinder designed for underground operation in Switzerland. SCR has been the most effective method of controlling emissions in stationary installations since the mid-1970's, with a potential effectiveness in excess of 80%.

Exhaust temperature requirements - Efficient operation of SCR systems requires that the exhaust temperature be within the normal SCR operating range. For common base metal catalysts, this range is 250 to 450 °C (482 to 842 °F). Zeolite catalysts can tolerate higher temperatures than those using metals. Figure 11 shows the typical relationship between temperature and efficiency (EPRI, 1990), with efficiency dropping off at the high and low end of the range. This temperature range corresponds to roughly notch 4 and higher power settings in present 2-stroke diesel locomotives - settings which are responsible for more than 75% of total emissions from line-haul locomotives. Four-stroke GE locomotives have higher exhaust temperatures in the lower notches, so that SCR would be effective over an even wider range. Table 26 shows the exhaust temperatures for representative EMD and GE locomotives.

Reductant Injection - The urea or ammonia injection rate must be changed to match the NOx production rate. Too little reductant means that some NOx escapes unreacted, and too much results in significant ammonia emission in the exhaust, called "slip". As the catalyst efficiency increases or decreases due to temperature changes, reductant injection must be trimmed accordingly, complicating the control system. Controlling reductant feed rates is especially difficult during transients; the poor transient response of most present SCR systems makes SCR much less effective in highway vehicle use. However, SCR can be used on larger mobile sources such as ships and - in principle - locomotives, since these experience primarily steady-state operation. SCR systems have recently been installed on two diesel motorships operating into California, and the results have apparently been satisfactory (Albjerg & Morsing, 1990). SCR has also been installed in four low-powered (600 HP) diesel tunnel track maintenance machines in Switzerland, with what have been described by the vendor as excellent results (Offshore, 1989) (Environmental Emissions Systems, Inc., 1991). SCR has not yet been tried on a US high-power road locomotive, which would pose greater engineering demands.

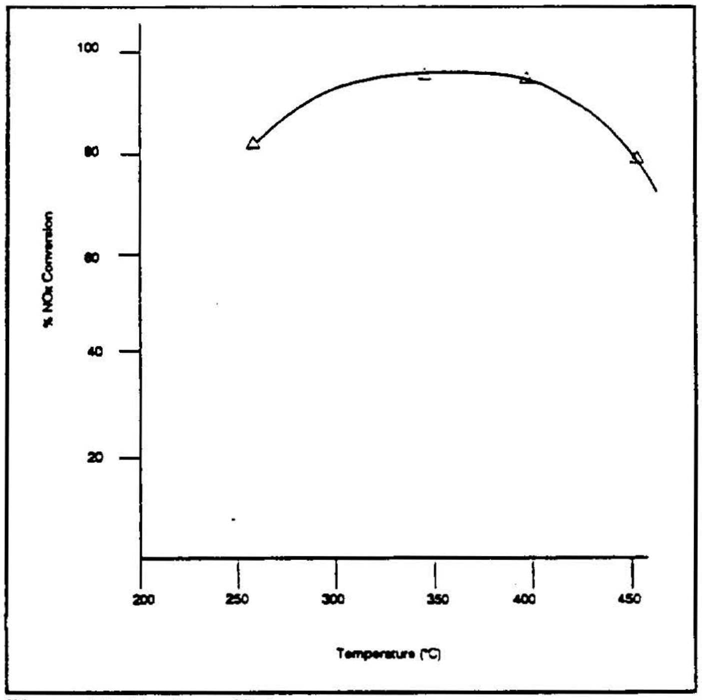

Figure 11: Catalyst efficiency vs. temperature.

Latest SCR achievements - The Danish company Technik Thermische Maschinen (TTM) has been developing SCR in mobile applications for over 10 years. In early 1992 they successfully installed a catalytic converter system on a 2.4 MW (3200 HP) diesel ferry, using urea as the reductant. Over a combined steady-state and part-load duty cycle (average 37.1 % load), with extreme load change rates, the open-loop system reportedly achieves 95% NO reduction at less than 2 ppm ammonia slip (Hug, et. al., 1992). After 6000 hours of service, there has been no detectable degradation of performance, no soot or ash deposition, and no mechanical breakdowns. TTM researchers have developed an advanced concept catalyst design, which combines the ferry's system and other technologies in one package. Key features of this design are the following: 1) the cell geometry is modified (at some increase in backpressure) to increase the mass transfer and allow reduction in reactor size, 2) a separate adjoining reactor and bypass system is created, which uses amorphous chromia instead of vanadia/titania, allowing de-NOx at temperatures between 100 and 200 °C, and 3) the system would use a deep-bed particulate trap made from knitted ceramic fibers, now being investigated by the Swiss National Energy Research Foundation.

Conversion and operation issues - The operating environment and process constraints for SCR systems are more stringent in mobile systems than in the existing stationary SCR applications. Pressure drop limits, space requirements, outlet temperature, ammonia or urea storage capacity, exhaust particulate content, vibration, weight, and ammonia slip would be concerns in a locomotive system design. Of these, the space requirement may be the most significant. The catalyst volume required to treat the exhaust from a locomotive diesel engine would be between eighty and ninety cubic feet (Bittner, 1992), not including the static assembly that transitions from the 2.5 square foot exhaust stack to the 16 square foot catalyst. A single unit of this volume is not available within the carbodies of most fully-equipped road locomotives as configured. One practical solution to this problem would be to raise the height of the locomotive hood to provide the extra space. The present height of most locomotives (about 15 feet), is considerably less than that of many of the cars they pull (for example, double-stack container cars at 20.25 feet; see Section 2.5), thereby presenting an SCR packaging opportunity.

Table 26: Exhaust temperatures by notch (°F).

Throttle Notch	EMD SD40-2 with 16-645E3	GE B39-8 with 16-7FDL
off		
brake	232.0	n/a
idle	194.9	271.0
1	259.1	524.7
2	350.1	798.3
3	436.7	878.0
4	518.7	810.7
5	605.9	782.0
6	681.8	755.0
7	713.2	757.3
8	740.9	754.3

On western US mainlines, there is generally considerable clearance above the locomotive, which could be used to accommodate parts of the SCR system. In taking advantage of this space, it must be kept in mind that the engineer's view must not be obscured, the fresh air path to the radiators must not be blocked, and the exhaust flow must remain unrestricted. It is not possible to occupy every foot of clearance with machinery, since air and exhaust must flow freely. EF&EE studied Railway Line Clearances, an industry publication that lists the permissible heights and corresponding widths of equipment on all the tracks of all the reporting railroads. We assumed a two foot height increase, to 17.5 feet, and a width for the SCR "box" of 8.4 feet (about 2 feet wider than the standard locomotive carbody). We then compared these requirements to the permissible widths listed in Railway Line Clearances to identify which existing routes would not permit use of locomotives having these dimensions.

Our review identified a number of track segments which could not accommodate an SCR-equipped locomotive having the dimensions outlined above, but only one of these segments is in an air basin of concern in California, and none of the others are on mainline routes serving California. Two tunnels between San Francisco and Bayshore, now used almost exclusively by the CalTrain commute service, restrict traffic to about 8 feet wide at 17.5 feet high, and might need to be widened slightly to accommodate the SCR system. Other restrictions on the SP network are on little-used lines. A segment from Echo to Ukiah, California is 7.3 feet wide at a height of 17.5 feet, but this is a line that sees less than 10 freight trains a week. A segment in the Cascade mountain range, from Hornbrook, California to Ashland, Oregon, is limited to 4.8 feet wide at its maximum (restricted) height of 17.25 feet. In Missouri there is a 150 - 200 mile spur that is restricted. Union Pacific has no restrictions at the 17.5 level. The Santa Fe tunnels in Franklin Canyon, in California's Bay Area, have recently been expanded to accommodate double-stacks, so no modifications are necessary. Santa Fe and Southern Pacific have recently finished expanding their Tehachapi, California tunnels for double-stacks.

Figure 12 is a partial cutaway view of a typical road locomotive (an EMD GP60). We have designed a concept SCR installation, and used this locomotive as a model. This was one of the more difficult installations identified. The engine is thoroughly surrounded by the turbocharger assembly, the dynamic brake unit, the carbody (outlined), and the auxiliary equipment stand. The space above the carbody is difficult to use because both the radiator and dynamic brake units need unrestricted flow at their tops and sides. The dynamic brake unit (or dynamic brake "hatch") is an autonomous, removable structure attached only by bolts and four electrical cables, and it is possible to raise it up and mount the catalytic reactor in its place. The exhaust silencer would not be needed, as the catalyst would fulfill its function.

The shape of our proposed reactor is a rectangular box 15 by 8.5 by 2 feet, centered in the locomotive and occupying 255 cubic feet. The reactor lies flat and sits directly over the engine, supported by the carbody (which may require stiffening with braces and other additional structure). A transition stack replaces the original stack and silencer and is bolted to the turbocharger housing and one end of the reactor. The exhaust flow exits the turbocharger, enters the transition where it is divided into left and right flows, which each enter side chambers along which are located multiple layers of catalyst blocks, either square blocks or cylindrical blocks, enough to make 41 cubic feet (minimum) total volume (total catalyst volume: 82 cubic feet). The flow leaving the catalyst layers empties into a single central chamber, at the top rear of which is the final exhaust stack. Additional volume is used by a blank catalyst layer (to accommodate a catalyst replacement program), transition blocks (flow modifiers), insulation, and catalyst supports.

In Figure 13, we have shown the same locomotive with the hypothetical reactor, represented as a shaded area, in place. The dynamic brake unit bolts to the reactor in the same way it originally bolted to the carbody. Aerodynamic fairings (not shown) could be added at each end of the dynamic brake unit to reduce air resistance. The exhaust stack protrudes through empty space at the middle end of the dynamic brake unit and rises high enough to place the plume above the dynamic brake cooling fan. The dynamic brake can be serviced without removing the entire unit.

A tank to hold the aqueous urea is fitted at the rear of the carbody, or another suitable location. It was assumed that reductant would be consumed only while operating in California. If 502 lbs of NOx are emitted each day, as might be the case for the most active line-haul locomotive, then about 500 pounds of solid urea would be required (1 lb solid urea per lb NOx). Then, 1700 pounds, or about 210 gallons, of aqueous urea would constitute a three day supply. The tank could be horizontal, but a vertical tank

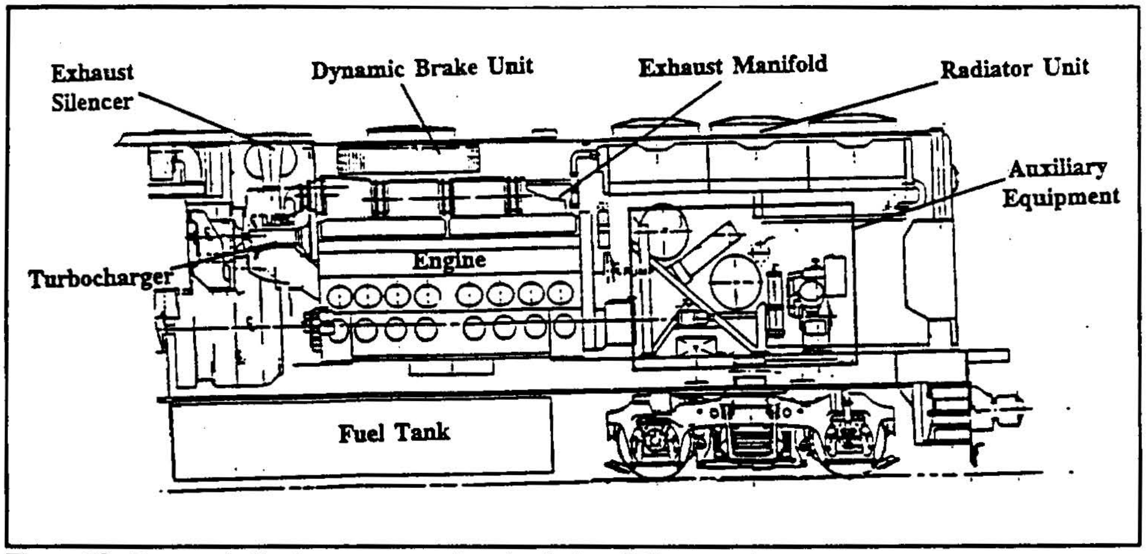

Figure 12: Cutaway indicating component location before SCR conversion.

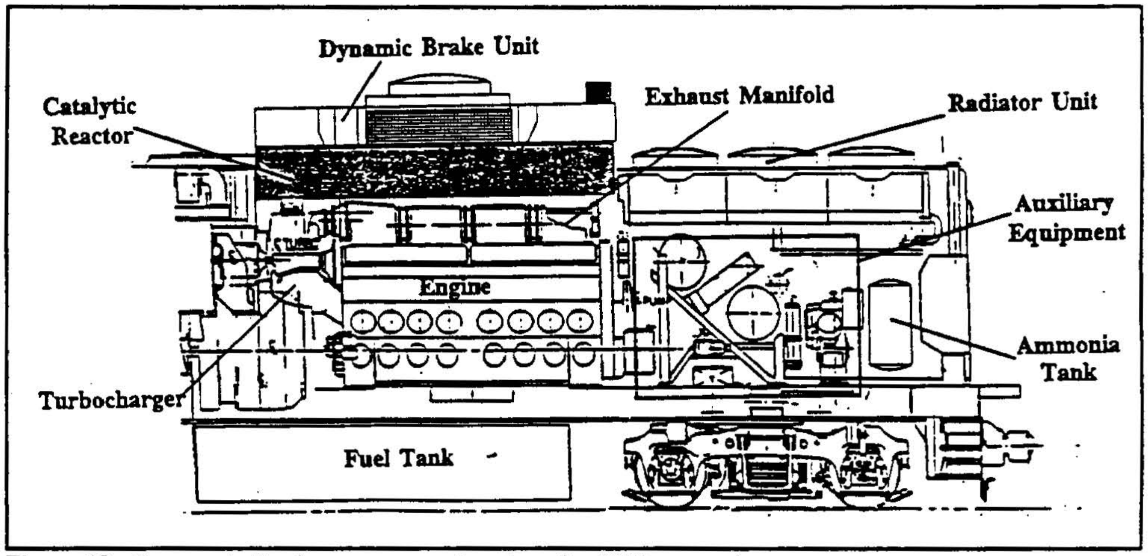

Figure 13: Cutaway indicating component location after SCR conversion.

would probably fit better in the limited space between the auxiliary equipment stand and the rear sand box. The urea tank would compete for space with the grease tank on wheel lubricator-equipped locomotives, and on a minority of locomotives there is not enough room at all behind the equipment stand for a single urea tank. A design using ammonia reductant might require a smaller tank (between 0.65 and 1 lb liquid ammonia per lb NOx). It would also be possible to divide the supply into two or more tanks for greater ease in packaging.

Other locomotive models could be modified similarly as shown in Figures 12 and 13. The GP38-2 and SD40-2 have dynamic brakes of similar size and in the same location as the GP-60, and so could use the same installation. The GE B38-2 has no large equipment above the engine, simplifying the installation. The same reactor unit, turned 180 degrees to line up with the exhaust stack, could be installed in the GE. If any of the conversions required greater reactor volumes or larger transition sections, the reactor height could be increased, or the radiator unit could be raised and a longer reactor installed. The radiator hatch is also an autonomous unit, but with complex plumbing rather than wires connecting it to the rest of the locomotive. The F40PH passenger locomotive conversion would be similar to the GP38-2 conversion, except that there may be a little less fore-and-aft space for the reactor. The F40 dynamic brake unit is likewise an autonomous structure bolted to the carbody.

A locomotive modified as suggested above may not fit though the doors of some locomotive repair shops and wash racks in California. The Southern Pacific Taylor Yard and Roseville Yard door openings are 18.25 feet (Harstad, 1992). We do not consider this a serious problem, since the existing clearance should be sufficient for the suggested design, the shops and washracks are easily modified structures, and at least one of the shops is scheduled for closing anyway.

Another potential objection to adding SCR is the additional weight it would impose on the axles and hence the track. However, this weight increase would not be substantial. A vendor estimated that the catalyst, insulation, inlet and outlet connections, support structure, and auxiliary equipment would weigh around 4 tons, which is a small fraction of the locomotive's total weight (160 to 200 tons). The small increase in axle load would exact some price in accelerated rail and roadbed wear and other costs. Four-axle locomotives cannot tolerate much more weight without exceeding presently allowable axle loading, but research has been proceeding for some time on higher axle loads. Further, as we suggested in Chapter 4, railroads will most likely choose to retrofit six-axle SD40-2 models for California service, rather than late-model, high-efficiency four-axle units. The SD40-2 locomotives carry a great deal of ballast to increase their tractive effort, and a reduction in this ballast loading could compensate for the weight increase due to the SCR unit.

Mounting over the engine is by no means the only way to package the SCR unit. Another alternative would be to mount the SCR system (possibly for an entire locomotive consist) in a separate tender or "SCR car", with locomotive exhaust ducted to it. This would have the advantage that the tender could be connected and disconnected as trains entered or left California, and that one tender could conceivably handle the exhaust of several locomotives. Calculations show that heat loss in a metal, insulated conduit (from the locomotive to the tender car) would not be prohibitive, but the many mechanical design issues of such a system could pose significant, and in our view, unreasonable, obstacles. Still another alternative would be to eliminate the crew cab of the converted locomotive. This would leave ample room for the reactor chamber and supporting equipment, but of course would eliminate space for crew. In yards, converted locomotives would have to be moved with other locomotives, or perhaps they could have simplified controls mounted on a panel accessible from the walkway. Cab-less units are already in use on major railroads, but they are rare since they have much less versatility than cab locomotives, and we believe that this lack of versatility (and hence poor utilization) dooms this approach. A third possibility is to mount the SCR unit on top of the locomotive *in front of* the exhaust stack. This space could easily accommodate a 3 x 3 x 15 foot box, which would provide ample space for both catalyst and transition volumes. Unfortunately, it would also have higher flow resistance and therefore higher backpressure than the design we described above. It could also possibly interfere with the air conditioning unit. These are problems that could be solved with some effort.

Other potential problems with SCR in locomotives include obtaining adequate reductant distribution in the exhaust stream, and achieving adequate control of the reductant feed rate. These two factors both affect conversion efficiency and ammonia slip. The SCR manufacturer's control strategy is to combine microprocessor control with a flow meter and a NOx analyzer in the exhaust stream, allowing mass balancing to ensure that the correct molar concentrations of ammonia and NOx are being reacted. It is also possible and less costly to operate "open loop", to inject urea (or ammonia) according to predetermined values related to speed, load, and exhaust temperature (Walker, 1992; Hug, et. al., 1992). This latter approach could fairly readily be integrated with the computer control of other engine functions found on late-model locomotives.

Since the locomotives proposed for retrofit do not produce sufficient exhaust temperatures for SCR below notch 4, it is desirable to investigate benefits of artificially increasing the temperature in those modes. The two diesel motorships mentioned above do so with electric heating coils mounted in the reactor chamber, at the expense of high energy consumption. Since locomotive diesels operate with great quantities of excess air, some 300 times more than they need for idle combustion, the exhaust temperatures could be increased by simply restricting the intake air at light loads. Since the air mass would decrease while the combustion energy stayed the same, the temperature of the air mass would go up. This is the method used by Detroit Diesel to increase idle combustion temperatures in its methanol DI engines. Rather than throttle the incoming air on these two-stroke methanol-diesel engines, DDC "recycles" it by bypassing the scavenge blower at low loads. A similar technique could be applied to EMD two-stroke engines. Figure 14, taken from a Pielstick air-fuel ratio controller design, indicates how such a device might be configured. Our calculations indicate that at idle one-sixth of normal intake flow would achieve the minimum temperature of 300 °C (572 °F). There is an additional benefit — "internal" exhaust gas recirculation, which has the effect of reducing the flame temperature, thus reducing NOx production in the engine.

There is a design choice of anhydrous ammonia, aqueous ammonia, or urea (solution of 60% water and 40% solid urea). For locomotives, it would be best to use aqueous (about 25% ammonia and 75% water) ammonia or aqueous urea, as anhydrous ammonia is a poison and fire hazard, and must be handled with great care. A tank of aqueous urea is relatively safe, and since it would only be needed within California, would adequately supply locomotives between refuelings. However, there would be some concern about freezing in the long mountain passes found in California.

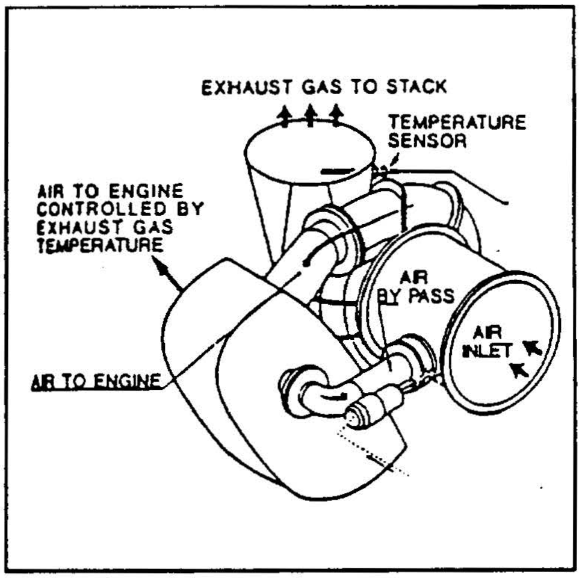

Figure 14: Turbocharger bypass.

Ammonia slip depends on the desired degree of NOx reduction, the size of the catalyst reactor, and how efficiently the reactor mixes available combustion products with available reductant. To increase the NOx reduction effectiveness, the urea input can be increased to a point, beyond which the ammonia slip goes up dramatically. Beyond this point, only an increase in catalyst volume can reduce NOx further. Ammonia slip of 5 - 10 ppm over the life of the catalyst, considered acceptable for stationary applications, has been demonstrated on mobile applications such as the two diesel motorships (Albjerg & Morsing, 1990).

To aid in proper mixing in the exhaust stream, multiple nozzles prior to the exhaust reactor could be employed to distribute urea throughout the exhaust. It would also be possible to inject the urea solution ahead of the turbocharger, which would ensure adequate mixing. Locomotive engine manufacturers have stated that turbocharger materials would not be harmed by such a design, as long as the turbo temperatures remain below reasonable levels (Brann, 1992).

9.2 Costs and Cost-effectiveness

Emission calculations - In order to calculate the emission reduction due to SCR, it was first necessary to predict the effectiveness of the SCR system over a representative locomotive duty cycle. Typical exhaust temperatures are known, and SCR system models for EMD and GE locomotives were supplied by a catalyst manufacturer (Bittner, 1992). A base metal catalyst of forty-one cubic feet (Bittner, 1992), should be able to convert NOx to N_2 and O_2 at 90% maximum efficiency between 300 and 375 °C, and at lesser efficiencies according to a curve like that of Figure 11. Our calculations reduce the baseline NOx in this way. Table 27 shows the NOx reduction efficiency in each throttle notch without air restriction to increase exhaust temperature at low power. The same data analyzed with air restriction indicates 89% NOx reduction efficiency. The locomotive used for the calculations is an EMD SD40-2, which we expect to be the major type of locomotive to be converted. Next is a column showing the weighted (untreated) NOx emission, in pounds per hour, based on measured emission factors (Conlon, 1988) and weighted by the fraction of time spent in each notch over the duty cycle. The NOx emission with SCR is then calculated by reducing the baseline NOx by the predicted catalyst efficiency. The sums of each of these two columns, multiplied by hours in a day and days in a year and divided by 2000 pounds per ton, is the total NOx in tons per year.

Table 27: Throttle profile & NOx emissions, no exhaust heating, EMD SD40-2, line-haul cycle.

Throttle Notch	SCR NOx Efficiency	Baseline Weighted NOx (lb/hr)	NOx, with SCR (lb/hr)
off		0.00	0.00
brake	-	0.51	0.51
idle	-	1.22	1.22
1	-	0.22	0.22
2	-	0.34	0.34
3	-	0.56	0.56
4	0.80	0.92	0.18
5	0.90	1.08	0.11
6	0.90	1.24	0.12
7	0.90	1.42	0.14
8	0.90	7.57	0.76
Total (lbs/hr)		15.1	4.2
Total (tons/yr)		58.1	16.0
NOx reduction (tons)			42.1
Percent reduction			72%

From these calculations, we estimate that SCR without exhaust heating would reduce NOx emission from the SD40-2 by 72% over the line-haul duty cycle. With the addition of air restriction at light loads to heat the exhaust, the projected efficiency increases to 89%. Analysis for the other three locomotive models considered gave similar results, although the impact of exhaust heating is even larger for the lightly-loaded switcher and local duty cycles. The resulting emission reductions (assuming exhaust heating) were calculated and used in the cost-effectiveness analysis.

Conversion Costs - The cost of an SCR system has been estimated at $75,000 plus $75 per horsepower for a base-metal catalyst unit, based on vender cost estimates. This includes the reactor unit itself, with catalyst, a tank for the urea with supporting structure and plumbing, a control unit with sensors and actuators, and modifications to the turbocharger and intake system for air bypass. An additional $25,000 ($10,000 for switchers) was added to this sum for modifications to the locomotive to raise the hood, mount the reactor, and remount the dynamic brake, if so equipped (EF&EE estimate). The sum totals of these costs appear in the first lines of Table 28 and Table 29.

Operating and Maintenance Costs - The SCR reactor would be filled with catalyst layers (rectangular or cylindrical blocks of metal substrate, coated with the catalytic materials), held in place by an insulating lattice of glass or composite fibers. An effective SCR system, whether mobile or stationary, requires routine replacement of these catalyst blocks (for example, complete catalyst replacement every 4 years). The catalyst shows its age by losing conversion efficiency in a linear decline, until the catalyst is no longer able to meet design minimums. It is most economic to replace (or add) layers of blocks at a time. A catalyst vendor has predicted $6.50 per horsepower annual maintenance cost on the line-haul application, including replacement and cleaning of catalyst material and all labor (Morsing, 1992). Our analysis uses that figure for line-haul locomotives, that figure less 10% for locals and that figure less 20% for switchers (Wagner, 1992). Although we have used current dollars to substitute for future dollars, we expect higher production volumes and recycling to keep the prices down.

Table 28: Cost-effectiveness of SCR for line-haul locomotives.

	EMD GP60		GE B39-8		EMD SD40-2	
	Line-haul cycle		Line-haul cycle		Line-haul cycle	
	Baseline	With SCR	Baseline	With SCR	Baseline	With SCR
Capital cost ($)		$396,250		$392,500		$325,000
Useful life (yrs)		10		10		10
Annualized cost ($/yr)		$59,053		$58,494		$48,435
NOx emiss. (t/yr)	80.0	8.6	81.3	10.3	58.1	6.2
Urea cons. (t/yr)		71.4		71.0		52.0
Urea price ($/ton)		$350		$350		$350
Urea cost ($/yr)		$25,007		$24,842		$18,183
Fuel penalty ($/yr)		$6,247		$16,481		$5,448
Maintenance ($/yr)		$25,675		$25,350		$17,550
Total cost ($/yr)		$115,982		$125,166		$89,616
Cost effectiveness ($/ton)		$1,623		$1,763		$1,725

<u>Cost effectiveness</u> - The system was assumed to be a maximum 90% effective (i.e, it follows the SCR efficiency schedule of the "with exhaust heating" case), and to consume one lb solid urea per pound of NOx removed. The urea is priced at $350 per ton, which assumes fairly large lots delivered by a vendor (Bock, 1993). Ammonia is approximately $250 per ton. Fuel consumption would increase slightly due to the higher exhaust backpressure and the extra air resistance created by taller line-haul locomotives. This increase was estimated (probably conservatively) at 3%. Another 5% in fuel consumption was added to the GE engine in idle through notch 3 to reflect throttling losses (blower bypass on the EMD engines would not impose similar losses). The useful life of the SCR system (other than the catalyst) was assumed to be 20 years, or 10 years for the severe conditions of line-haul service. As Table 28 shows - given these assumptions - SCR could be a cost-effective measure for line-haul locomotive emission control, at about $1,600 per ton on an EMD GP60, $1,800 per ton on a GE B39-8, and $1,700 per ton on an EMD SD40-2.

As for the light duty locomotive cycles, shown in Table 29, the cost per ton increases significantly. For the SD40-2 in local service, the cost-effectiveness of SCR is calculated at $2,800 per ton, and for the GP38-2 in switcher service at $2,900 per ton. These costs are still very attractive compared to the costs of controlling NOx from stationary sources and many mobile sources.

With exhaust heating and sufficient reactor size it appears entirely possible to remove 90% of the engine's NOx, with less than 10 ppm NH_3 slip. The reactor size is the likely limiter, since its size depends greatly on how well the exhaust stream can be fed through the catalyst blocks without unduly raising backpressure. A lower-effectiveness scenario can be imagined where the reactor must be much smaller due to packaging constraints or some other reason. As a sensitivity check, the cost-effectiveness was recalculated with a maximum catalyst efficiency of 70%, and the SCR was turned off below Notch 4. The resulting numbers were $2,400, $2,900, $2,000, $5,500, and $8,800 for the three line-haul, the local, and the switcher locomotives, respectively. At these levels SCR would still be an attractive line-haul NOx control measure, but would be only marginally cost-effective for locals and switchers.

It is likely that SCR conversion costs would come down significantly once the units are produced in quantity and greater experience is gained. For a higher-effectiveness scenario, the conversion costs were reduced to $50 per hp and $50,000 flat (other costs the same), and maintenance was decreased to $5.50 per hp. The resulting numbers were $1,300, $1,600, $1,000, $2,100, and $2,700 for the three line-haul, the local, and the switcher locomotives, respectively. These figures show how, despite the high initial cost, SCR could be a reasonable measure for reducing NOx.

Table 29: Cost-effectiveness of SCR for local and switch locomotives.

	EMD SD40-2		EMD GP38	
	Local cycle		Switcher cycle	
	Baseline	With SCR	Baseline	With SCR
Capital cost ($)		$325,000		$235,000
Useful life (yrs)		20		20
Annualized cost ($/yr)		$33,102		$23,935
NOx emiss. (t/yr)	24.0	2.6	15.9	2.1
Urea cons. (t/yr)		21.4		13.8
Urea price ($/ton)		$350		$350
Urea cost ($/yr)		$7,491		$4,823
Fuel penalty ($/yr)		$2,187		$1,120
Maintenance ($/yr)		$17,550		$10,400
Total cost ($/yr)		$60,330		$40,278
Cost effectiveness ($/ton)		$2,819		$2,923

9.3 Regulatory Feasibility

A requirement to implement SCR would pose no unusual problems from a regulatory/enforcement perspective. Regulations would presumably be phrased in terms of performance, and railroads would be required to provide test data for each unit to verify proper operation. ARB inspectors could then spot-check occasionally to verify that the units were functioning.

9.4 Affordability

In all of California, we estimate that conversion of all the line-haul, local, switcher, and passenger locomotives to SCR would cost about 360 million dollars (see discussion of number of locomotives in Chapter 4). This is the up-front capital cost only, in current dollars, and does not include fuel penalties or costs of supplying reductant. We assumed that all of Amtrak's California assigned locomotives would be converted, as well as the CalTrain and Metrolink rosters. Based on the recent announcement of several locomotive orders at total costs higher than this, this cost is likely within the railroads' financial capabilities.

9.5 Impact On Railroad Operations

If SCR were implemented only in California, this would require setting up a California-only locomotive fleet, with changes of locomotives required at gateway points. The costs and operational impacts would be significant, as discussed earlier, but not insurmountable. An alternative would be to equip a larger number of units, and to use these on the major runs into and out of California (SCR would only have to be turned on in California).

If SCR were implemented by raising the roof line of the locomotives, this might limit their ability to use certain shops, wash racks, and other facilities, and some isolated branch lines. These limitations are not expected to be significant; as we stated above, clearances are generous and shop facilities are easily modified. No mainlines in California or adjacent states were found to have limiting overhead clearance, and large line-haul locomotives are prevented from entering many branchlines anyway due to tight curves.

9.6 Implementation Schedule

Conceptually, the installation of SCR on locomotives is straightforward, as we have demonstrated, but there is no practical experience to build on, and there are some unanswered questions. The two diesel motorships contribute little to the experience because their designers had so much space to work with, and because cost was a secondary concern[30]; the Swiss track grinder designers had a tight package but only 600 hp to clean up. Nonetheless, SCR retrofit requirements are simple enough that locomotive rebuilders, working with designs from catalyst manufacturers, could easily perform the work. Morrison-Knudsen is setting an example by building dedicated natural gas locomotives, using Caterpillar-designed engines, for the emerging low-emission locomotive market. These locomotives have progressed from deal to saleable product in less than two years.

"Saleable product" may mean something different for SCR, though. It will be easy to place a reactor on board and make it work; it will be a much greater challenge to make it survive the extreme vibration and resultant G-forces typical of a locomotive environment. Also, the additional heat in the carbody produced by an SCR reactor, insulated or not, could require other design changes. The cleaning and regeneration of catalysts that have been fouled by bad turbochargers and stuck injectors would have to be investigated. Poisons in the lube oil would be of concern. Therefore, we would expect a greater lead-time (than for natural gas or other measures) for SCR to become a useable product (Gladden, 1992).

Unlike alternative fuels and electrification, the Selective Catalytic Reduction scenario needs little infrastructure building, assuming that reductant suppliers will take care of all production and most inventory responsibilities. Urea tanks and dispensers would be placed alongside fuel dispensers at existing railroad fueling depots. Locomotive heights would not be increased so as to make tunnel or bridge modifications necessary. Also in SCR's favor, a broken SCR unit does not *likely* mean a dead locomotive. Converted locomotives could operate freely at maximum capacity with broken SCR units, so that SCR should not have a significant effect on service reliability. Possible exceptions would be locomotives with SCR units incapacitated by over-fueling (too much fuel in the combustion chambers) or turbocharger failure, which could so clog the catalyst blocks they no longer permit adequate exhaust flow. These faults would be likely to stop the engine anyway. This does not, of course, mean that routine operation with non-functioning emission control equipment would be tolerated, but only that the possibility of such operation in an emergency could limit the operational impacts of SCR.

Given the present state of SCR technology for diesel engines, a demonstration program for this technology in locomotives could be undertaken almost immediately. This would preferably be undertaken by a consortium of a locomotive rebuilder, a catalyst manufacturer, and one or more railroads. Since neither the major locomotive builders nor their customers, the railroads, have any incentive to demonstrate the feasibility of such a costly emission control technique, funding for this demonstration will probably need to come from public sources. Assuming that funds were budgeted for the next fiscal year, an RFP could be issued in Fall, 1995, and work could start around the beginning of 1996. Allowing two years for design and construction and two years of operation, such a demonstration would take about four years (i.e. the end of 2000) to yield results (although interim data would be available much sooner). These results could serve as the basis for converting a larger number of locomotives, beginning in 2001. Assuming that each of the major railroads converted 25 units in 2000, and 50 units each year thereafter, the California line-haul and local fleets could be completely converted to SCR by 2006.

10. NATURAL GAS FUEL

To be considered for railroad use, an alternative fuel should be available in large quantities, with reliable supply, and at a cost comparable to or less than that of diesel fuel. Technology for using the fuel in large-bore, heavy-duty engines should be available (that is, somewhere between prototype and production), must not compromise reliability, and must show promise for achieving substantial emission reductions relative to existing diesel technology. The only alternative fuel meeting these criteria at present is natural gas. Natural gas has been used as fuel in large-bore stationary engines (including many engines derived from locomotive diesels) for many years, and technology for achieving low emissions in these engines is highly developed. Such engines now routinely achieve NOx emission levels less than 1.5 g/BHP-hr, compared to 4-5 g/BHP-hr for the best diesels, and 9-15 g/BHP-hr for the diesels now used in locomotives. Several U.S. and European manufacturers even offer dual-fuel versions of their diesel engines, capable of running on 100% diesel or as much as 99% natural gas (shown in Table 30). A demonstration involving two diesel locomotives converted to dual-fuel natural gas operation is under way at Burlington Northern railroad. Development of natural gas locomotives is under way at each of the major U.S. locomotive manufacturers, and Union Pacific has contracted to purchase two such locomotives when they are completed. A switch locomotive model using 100% natural gas is being developed for sale by Morrison-Knudsen.

In this section we will describe the technologies available for fueling existing and new locomotives with natural gas. Then we will briefly analyze the cost of supplying a hypothetical locomotive fleet with natural gas, and describe in some detail four conversion packages, for each of the target locomotives we have selected for conversion - the hardware, the conversion costs, the resulting emission improvement or degradation, and finally the cost-effectiveness of converting to natural gas. Also in this section, we will calculate the cost-effectiveness of combining dual-fuel and SCR technologies to achieve even greater emission reductions.

10.1 Natural Gas Engine Technology

A heavy-duty engine like that in a locomotive can be designed to operate on natural gas in one of three ways. Most large stationary engines at present are designed for spark-

Table 30: Dual-fuel engine and conversion technology.

Company	Location	Conv/ Engine Manuf[b]	Electronic Gaseous Fuel Injection				
			Central Point	Multi Point	Micro Pilot	Pre-Chamber	Direct
BKM, Inc.	San Diego, CA, USA	C	X	X	X		UD[a]
Cooper	Grove City, PA, USA	E		X		X	
Deltec	Delft, The Netherlands	C	X				
Detroit Diesel	Detroit, MI, USA	E	X				UD[a]
Energy Conversions, Inc.	Tacoma, WA, USA	C		X			
Fairbanks-Morse	Beloit, WI, USA	E		X		X	
John Deere	Waterloo, IA, USA	E		X			
Ruston	Merseyside, England	E		X			
SEMT Pielstick	St-Denis, France	E		X			
Wärtsilä	Vaasa, Finland	E/C		X			X

[a] UD = Under Development
[b] Engine (E) or Conversion (C) Manufacturer, or Both (E/C)

ignition (Otto cycle) operation, with a lean air-fuel ratio. This engine technology is mature, and routinely achieves NOx levels less than 1.5 g/BHP-hr, or about 85% less than the typical locomotive diesel engine. An alternative to spark ignition is *dual-fuel* operation, in which a small amount of diesel fuel is injected instead of a spark to ignite the natural gas charge. Recent developments in dual-fuel engine technology have resulted in emission capabilities similar to those of spark-ignition engines. A third technology, still under development, is *direct injection* of natural gas, in the same way that diesel fuel is injected in a diesel engine. Although this approach has advantages in fuel-efficiency and power output, the NOx emission from these engines is likely to be higher than from optimized spark-ignition or dual-fuel engines (see Direct-injection natural gas engines, page 104).

Dual-fuel engines - Existing diesel engines can be modified to operate as dual-fuel engines, thus offering the potential for cost-effective emission reductions from the existing locomotive fleet. Although many existing dual-fuel engine modifications are crude, and exhibit high CO and HC emissions, technology to achieve very low emissions in dual-fuel operation has been demonstrated. Dual-fuel engines also offer important advantages in fuel flexibility, as they can retain the capability to operate on 100% diesel fuel if gas is not available. Most versions can be switched on-demand, which would add a measure of security to railroad operating departments. Fuel flexibility would allow the engine to operate normally on low-cost and low-polluting natural gas, while retaining the ability to operate on diesel alone if necessary.

Dual-fuel diesel/natural gas engines use natural gas as the primary fuel. Most dual-fuel engines induct the gas already mixed in the intake air, but gas can also be injected directly into the cylinder. Instead of a spark plug, a small injection of diesel fuel is used. The diesel fuel undergoes compression-ignition, just as in an ordinary diesel engine, and the burning diesel fuel ignites the natural gas. Compared to a spark-ignition engine, the widespread, high-energy combustion of the diesel fuel gives more reliable ignition and faster combustion of the natural gas charge (a particular advantage with very lean air-fuel ratios). More rapid and widespread combustion in the cylinder also reduces the time that the unburned gases are exposed to high temperatures and pressures, and thus reduces the tendency to knock. It is for this reason that many diesel engines can be converted to dual-fuel operation without reducing the compression ratio, when a spark-ignition engine at the same compression ratio would suffer destructive knock.

Dual-fuel engine performance and emissions vary depending on operating conditions and the sophistication of the control system. Dual-fuel engines perform best under moderate to high load, and can often equal or better the fuel-efficiency of a pure diesel under these conditions (similar to natural gas spark ignited engines; see Figure 15 for a comparison). Operating with a lean air-fuel ratio, they can also achieve much lower emissions (especially of NOx and particulate matter) than a pure diesel. Existing dual-fuel conversions suffer from major increases in CO and HC emissions and loss of fuel efficiency at light loads. This is because they operate unthrottled, so that the air-fuel mixture becomes leaner as the load is reduced. As the mixture becomes leaner, combustion eventually degrades, leaving large amounts of partial reaction products in the exhaust. Possible solutions to this problem include throttling the intake air at light loads, use of electronically-controllable turbochargers to reduce light-load airflow, or the use of skip-firing. Skip-firing means that a certain number of engine cylinders are shut off on a rotating basis. By supplying more gas to some cylinders in rotation, and none to others, it would be possible to ensure a combustible mixture in each cylinder. With this arrangement, enough cylinders could be fired to maintain the engine output while reducing fuel consumption and emissions. A skip-fire system can only be employed easily with a sequential multi-point injection system, since it requires the ability to shut the fuel supply off to a particular cylinder. At least one equipment manufacturer is developing such a system for dual-fuel engines.

In addition to light load emission and fuel economy, dual-fuel engines may be hampered by knock at high loads. Experience with dual-fuel engines on natural gas indicates that knock may be a limiting factor above about 190 psi BMEP (in four-stroke engines; the limit in two-strokes is lower). The Cooper-Bessemer "Cleanburn" dual-fuel engine has 200 psi BMEP at rated power (Blizzard, et al, 1991). Most diesel engines have BMEP levels in this region or lower, but some highly-rated truck, marine and locomotive engines have BMEP levels significantly above this (as much as 300 psi for some recent truck engines and GE locomotive engines, see Table 7 and Table 31). For these highly-rated diesel engines, conventional dual-fuel operation would require either derating or reduced substitution of gas for diesel under high-load conditions. Of course, a third alternative would be to achieve the same power output at lower BMEP by increasing the engine displacement (making the cylinders larger). This was the route followed by EMD for its diesel locomotive engines, which have increased from 567 to 645 and (recently) 710 cubic inches per cylinder.

Table 31: BMEP for heavy-duty diesel and natural gas engines.

	Application	Fuel	RPM	Power (hp)	BMEP (psi)
Two-stroke engines					
EMD 16-567	Rail, marine	Diesel	900	1,500	73
EMD 12-645E3	Rail, marine	Diesel	905	2,415	137
DDC 8V-149TI	Gen Set, Marine	Diesel	1900	800	140
EMD 16-645E3[1]	Experimental	Dual-fuel	900	3345	143
EMD 16-710G	Rail	Diesel	900	3950	153
Four-stroke engines					
CAT G3516-TA	Gas Gen Set	SI NG	1200	1,085	170
Pielstick PA5 DF	Multi-purpose	Dual-fuel	1000	3,153	185
Pielstick PA4 185DF	Gen Set	Dual-fuel	1500	1,973	189
Waukesha AT25GL	Gen Set	SI NG	1000	2,587	190
CAT 3408BTA	Marine	Diesel	2100	585	201
CAT 3516 TA	Rail	Diesel	1800	2,075	217
Pielstick PA4 185	Rail	Diesel	1500	2,545	244
Wärtsilä GD32	Cogeneration	DING[2]	720	7,902	281
GE 16-7FDL	Rail	Diesel	1050	4,000[3]	282
Pielstick PA5 DF	Research Engine	Dual-fuel	1000	1,200	282

[1] Converted to dual-fuel by Energy Conversions, Inc.; operated by BN
[2] Direct Injection Natural Gas.
[3] Rate per-cylinder horsepower than that of 12-7FDL, shown in Table 7.

A third area of development for dual-fuel engines is in the diesel fuel injection system. To minimize emissions and diesel fuel use, it is desirable to reduce the pilot fuel quantity as much as possible, consistent with getting good injection and combustion characteristics. Flexible control of fuel injection timing is also important to optimize dual-fuel emissions and performance. The minimum pilot fuel quantity is presently limited by the injection system characteristics to about 5% of the quantity at full load on 100% diesel. Below this level, the fuel injection characteristics deteriorate, because the original injectors are too big to spray such small quantities of fuel accurately. By using a separate "micro" injector, pilot fuel quantities less than 1% of full load fuel consumption are possible, and this also allows independent control of timing. The addition of a separate system would increase the hardware costs somewhat, of course. The small injectors would curtail the maximum power of the engine. Since the pilot injectors would be small, however, it would be possible to use inexpensive electronic fuel injection systems developed for automotive diesels.

If dual-fuel locomotive engines having good efficiency, low emissions, and appropriate reliability could be developed, they would offer great promise for reducing costs and emissions in many applications. The two natural gas locomotives now in operation (a

Burlington Northern - Air Products joint project) are dual-fuel conversions of existing EMD diesels. BMEP is claimed to exceed that of the original diesels (143 versus 137 for the original; BN values are shown in Table 31), and early emission tests have produced promising results for NOx (*Railway Age*, 1991c). Pilot fuel injection for these engines relies on the original diesel injectors, however, and there is no flexibility in control of injection timing. As a result, emissions of NMHC and CO, especially at light loads, are unacceptably high.

Another dual-fuel engine design has demonstrated much better emission performance. The Cooper Cleanburn dual-fuel engine described by Blizzard et al. is a modified LSVB (Cooper engine designation) series 4-stroke diesel of approximately 8300 HP. The original engine was satisfactory in performance except for NOx emissions; NOx was 11.5 g/BHP-hr, not much better than straight diesel. Smoke was also poor, with an opacity rating of 20%. Cooper engineers modified the combustion chamber and cylinder airflow characteristics to improve combustion, and added a separate pre-chamber (called a "torch cell" by the authors) for the diesel pilot injection. This pre-chamber, which resembles that of a light-duty IDI (InDirect Injection; design in which combustion takes place outside of the main combustion chamber) diesel engine, is a self-contained unit mounted in the cylinder head, with its own injector. The diesel pilot fuel is injected into this pre-chamber, where it burns and shoots out into the main combustion chamber in a flaming jet - providing thorough ignition for the lean natural gas charge. The use of this torch cell made it possible to reduce the diesel pilot charge substantially, and greatly improve emissions. Originally, the dual-fuel engine used 6% diesel fuel and 94% natural gas at full power; the CleanBurn research engine burns only 0.9% diesel fuel at 200 psi BMEP. Smoke was virtually eliminated and the NOx was reduced 92% to 0.9 g/BHP-hr at rated speed and load. The engine also retained its original diesel injection equipment, giving it the ability to operate on 100% diesel if required.

Although the Cooper LSVB engine itself is too large, Cooper's technology or a similar one could be applied to locomotive engines. This would require modifications to the cylinder heads to incorporate the pre-chamber and its injector. A natural gas metering system and mixing system would also have to be supplied, and modifications to the existing injection system could be needed in order to prevent fuel in the injector tips from "cooking" and forming deposits with prolonged exposure to high temperatures. Both the 2-stroke EMD and the 4-stroke GE engine are designed so that a considerable amount of the intake air flows through the cylinder during scavenging. Mixing natural gas with the intake air, as is conventionally done in Otto-cycle engines, would therefore result in significant loss of gas to the exhaust. Efficient natural gas use in the GE engine would require either timed port injection or a change in valve timing to minimize overlap (the latter would reduce volumetric efficiency and thus maximum power output on diesel, however). For the EMD engine, timed injection into the ports or directly into the cylinder is the only option.

Direct-injection natural gas engines - In order to avoid knock and achieve BMEP levels comparable to the highest-rated diesels, several groups are now developing direct-injection natural gas (DING) engines. In these engines, the natural gas fuel is not premixed with the air charge but injected under very high pressure near top-dead-center. The resulting combustion process is then controlled by the rate of mixing between the fuel and the air (as in a diesel engine) rather than by chemical kinetics (as in Otto-cycle, premixed-charge engines). The absence of premixing between fuel and air eliminates the possibility of knock, but makes control of NOx emission much more difficult. One current DING dual-fuel engine from Wärtsilä exhibits NOx emission of 5 g/BHP-hr at full power (Elmore, 1993). Although roughly 60% lower than emission from the corresponding (uncontrolled) diesel, this emission level could be reached by diesel engines with engine-out controls, and it is substantially higher than the 1-1.5 g/BHP-hr possible with a premixed charge. Another unresolved issue with US locomotive DING engines is the cost and reliability of the fuel injection system. The required high pressure gas injection hardware is expensive (in terms of engineering and manufacturing), and has yet to move beyond the research and development phase. The apparent success at Wärtsilä is encouraging, however.

The natural gas engines now being developed by EMD and GE for new locomotives are based on high pressure direct-injection designs. These engines are being developed essentially because of the strong railroad interest in natural gas as a low-cost alternative fuel, with low emission being a secondary concern. Although the NOx emission from these engines will be higher than could be achieved with a premixed charge, it can be significantly lower than those of an uncontrolled diesel, and the levels of power output and fuel-efficiency achievable should also be similar to those of present locomotive diesels.

Spark-ignition engines - Because of the limits on spark-ignition engine BMEP imposed by knock, an SI engine will require larger displacement than a diesel engine to achieve the same power output. This does not necessarily imply greater physical size, however, and we have identified proven low emission SI natural gas engines in the sizes and power range desired for locomotives (particularly the Caterpillar G3500 and G3600 series engines - "G" is for gaseous fuel in Caterpillar nomenclature). SI engines also tend to have lower fuel efficiency than diesel or dual-fuel engines, especially at light loads. Figure 15 shows the efficiency comparison for Caterpillar 3516 TA diesel and low-emission G3516 TA (spark ignited) engines. The lower efficiency could pose a substantial barrier to adoption of SI locomotive engines. On the other hand, the cost of natural gas fuel would be less than that of diesel, and the demonstrated emission levels from existing lean-burn SI engines are among the lowest of any internal combustion engine available for locomotive service.

Converting a 2-stroke or 4-stroke diesel engine to SI LNG is certainly possible, but it means a sizable BMEP reduction imposed by knock limitations. If one accepts the lower power, then one still faces re-engineering much of the engine (cylinders, cylinder heads, valve train, pistons), as well as replacing fuel and air induction systems. Such changes in a conversion packages would be hard to justify, especially since complete, proven, and emission-optimized engines are already in the market.

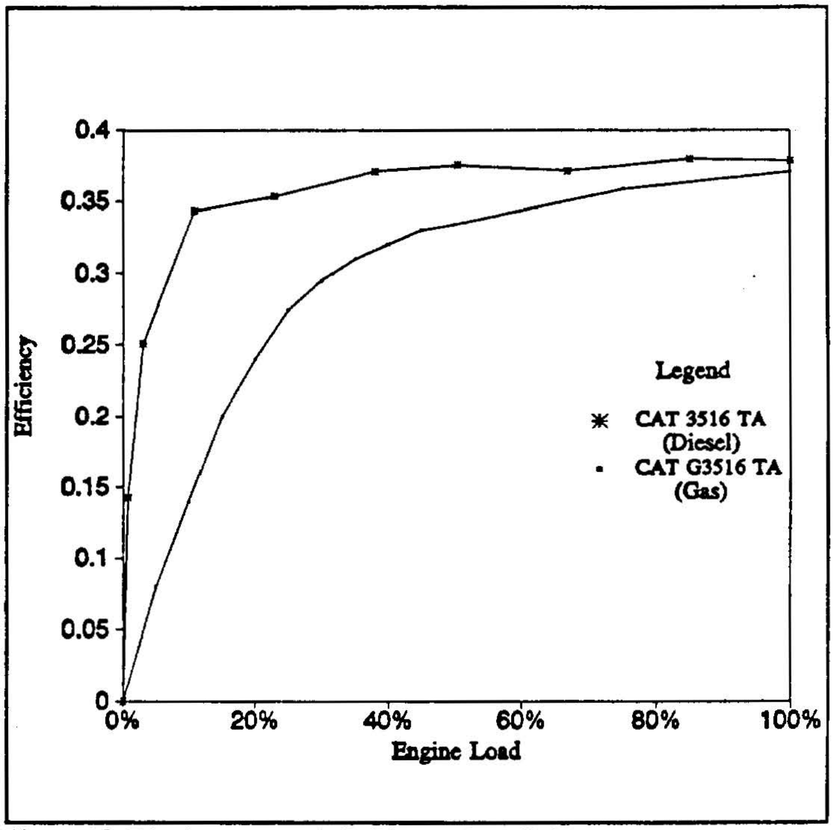

Figure 15: Diesel versus spark ignition engine efficiency.

One small-scale builder of locomotives, Morrison-Knudsen, has announced plans to offer a low-emission natural gas switch locomotive for sale. This unit will be based on the Caterpillar G3516 TA engine. Other SI engines exist that could be suitable, including Waukesha, Cummins and several European makes, but Caterpillar is the only gas engine manufacturer actively pursuing the US railroad market, with both diesel and natural gas engines. The locomotive version would have the correct alternator, Caterpillar's Programmable Electronic Engine Control (PEEC) (Burns and Evans, 1987) system for locomotives, traction control to take full advantage of the relatively low engine power, fuel delivery components, and appropriate interfaces with the locomotive cooling systems, auxiliary power systems, and control systems.

For line-haul service, the Caterpillar model G3616 TA and G3612 TA are the most likely candidate engines. These engines are physically larger than the 3500 series, but can still fit under the body work of the typical locomotive. Like the 3500s, the 3600s are produced in six, eight, twelve and sixteen cylinder versions. The largest of these engines, the G3616 TA, is offered in a low emission configuration in a Caterpillar generator set rated at 3000 KW (electric) at 1000 RPM with 158 °F cooling water. This is equivalent to about 4000 tractive horsepower - the same as the most powerful modern locomotives. A generator set using the twelve cylinder version of the engine is rated at

2255 KW(e) under the same conditions. This is equivalent to about 3000 tractive HP - the same as the widely-used SD40-2 and GP40 locomotives. Guaranteed rated NOx emission for both versions of the engine are 1 g/BHP-hr (this is at rated power; full railroad duty cycle emission will not be as good).

The G3616 engine has similar dimensions to a 16-cylinder EMD engine, but is about 27% heavier. This engine would likely be used to repower late-model locomotives such as the GE Dash 8 and the EMD 60 and 70-series, if these were to be repowered, as well as the older EMD SD-45. In the case of the SD-45 (which uses a 20 cylinder engine), the G3616 TA would have similar weight, shorter overall length, and about 10% more power. For the SD40-2, which uses a 16-cylinder EMD engine, the logical repower choice would be the G3612 TA, which would also have similar weight, lower emissions, and about the same power output. The repowered units would also provide better low-speed tractive effort, due to the improved traction control capabilities in the Caterpillar system.

Natural gas storage and fueling - How the fuel is stored and delivered to the engine depends on the physical properties of the fuel. A chart comparing natural gas fuels and diesel is shown in Table 32. Fuel may be carried on-board the vehicle either as Compressed Natural Gas (CNG) or as liquified natural gas (LNG). LNG has higher energy density and is a more practical storage medium for line-haul applications than CNG. If the infrastructure is in place for line-haul locomotives to use LNG, then switchers, locals, and passenger trains would likely use it, too[31].

Table 32: Fuel characteristics.

	Diesel No. 2	LNG (liquid methane)	CNG (compressed methane)
Density	7	3.4	1.4
Energy Content (Btu/lb)	18,300	21,500	21,500
Energy Content (Btu/gal)	128,100	73,100	30,100

Line-haul locomotives burning natural gas only, and consuming large quantities of fuel at a time, would carry LNG tenders, which are cryogenic tank cars specially designed to carry fuel and supply it to the locomotives. Such tenders have already been developed to support the Burlington Northern dual-fuel demonstration. One tender can hold up to 25,000 gallons of liquid methane. Allowing for 5% ullage (vapor space), and the fact that LNG contains less energy per gallon than diesel fuel, the tender could carry enough fuel for two locomotives to travel nearly twice as far as they can with the existing diesel tanks. The fuel would likely be used before natural warming of the tank forces fuel vapor venting. Dual-fuel line-haul locomotives would keep the existing diesel tanks for pilot ignition, and for 100% diesel operation. Local and switcher dual-fuel locomotives would have both on-board LNG tanks and smaller diesel tanks for pilot ignition.

Each line-haul locomotive would require fuel plumbing to carry liquid methane from the tender to the locomotive. Flexible hoses that can transfer cryogenic materials safely are readily available. Rigid piping would extend from the engine to each end of the locomotive and attach to the flexible hoses for tender connections. Automatic and manual cutoff valves for safety would be at each end. In the event of unintended de-coupling, liquid methane flow would automatically cease.

One LNG supplier has trademarked the name "Refrigerated Liquid Methane" (RLM) for LNG consisting of nearly pure methane. This formulation has certain advantages from the engine efficiency standpoint, including notably greater resistance to knock than LNG containing significant percentages of ethane and other components. This, in turn, would allow higher BMEP and/or engine efficiency. The use of pure or nearly pure methane as fuel would also reduce emission of non-methane HC from the engine and from fuel distribution and storage.

10.2 LNG Cost and Pricing

Though natural gas prices tend to fluctuate with other energy prices, they have historically been both lower (on a per-BTU basis) and less volatile than prices for diesel fuel. The cost of supplying LNG would depend heavily on the fuel source, purity, quantity demanded (related to plant size), quantity to be stored, and delivery mode. The costs shown in Table 33 are based on estimated "across the fence" per-gallon sales and assume on-site gas liquefaction facilities (as opposed to having fuel trucked in from another city, as Houston Metro is doing for their bus fleet). This assumption is reasonable, since railroads would need few fueling depots, railroads would operate natural gas locomotives within or between major industrial zones, railroads would ultimately purchase fuel in quantities that make liquefaction economic, and LNG suppliers would likely build dedicated plants to supply their product to the railroads.

LNG can be produced in a number of ways, depending on pipeline pressures and feedgas quality. Regardless of the pipeline pressure, liquefaction is achieved with *vapor-compression refrigeration*. A greatly simplified description follows: Pipeline gas is compressed and then expanded through a turboexpander (the turbine helps recover some of the compression energy), where it loses a great deal of its heat. The output of the turboexpander is reprocessed until it has lost enough heat to change to liquid phase, at which point it is channeled to the output through a centrifugal separator (Reynolds and Perkins, 1977). We developed a simple analysis that describes the costs of this processing and arrives at a realistic per gallon price. The results are shown in Table 33. Our analysis is based partly on the results of a study performed for the Gas Research Institute (GRI) by Acurex on the technology and economics of LNG for on-road vehicles (Acurex, 1992), and partly on conversations with LNG suppliers and natural gas technology consultants (Bartholomew, 1992, 1993; Dykstra, J, 1993; Kennedy, K., 1993). It shows that railroads would probably pay less for LNG than the truck fleets of the Acurex examples, and less than half of typical current diesel prices.

We began with an estimate of 100 locomotives for an introductory, California-only fleet and 1000 locomotives for an advanced, system-wide (but still California focussed) fleet. Then we chose two fuel plant size/number scenarios, developed from confidential LNG vendor calculations, whose outputs would closely match our fleet size needs. Then we adjusted the fleet sizes to match the projected outputs and efficiencies of the plants, and the result was 124 introductory locomotives and 930 advanced fleet locomotives. We assumed these numbers covered all three Class I railroads in California and participating passenger carriers.

It is assumed that LNG plants can be located at or very near existing railroad service shops (highway trucking, as required by Houston Metro and Seattle Metro bus fleets, greatly increases the cost). This reduces the need for on-site storage, but poses the question of obtaining permits in urban areas. Several California municipalities have ordinances prohibiting storage or production of LNG. Roseville and San Bernardino are not among them, but prevailing public sentiment may force plants into more remote locations. We believe the risk of this is small, or is equal to the risk that railroad shops will be forced into remote areas due to environmental regulations. To ensure an adequate production margin, the plants are sized to produce 15% more fuel than consumed by the primary customers. Assuming that all the LNG locomotives are of the dual-fuel line-haul variety, and that fuel consumption is state-wide, the total introductory fleet consumption and production capacity would be 34 million and 40 million gallons, respectively, and the advanced fleet consumption and production capacity would be 258 million and 297 million gallons, respectively.

The introductory fleet has two plants, one in San Bernardino and one in Roseville, each producing 60,000 gallons per day. The Roseville plant would be closest to Southern Pacific, but still would be accessible, with appropriate agreements, to Union Pacific and Santa Fe. All the plants are assumed to operate 330 days in a year. The largest component of the cost of production for LNG would be the cost of the natural gas feedstock. For this calculation, natural gas was priced at $1.80 per MMBTU plus $0.20 per MMBTU transportation cost (Bartholomew, 1992). The sum, $2.00 per MMBTU of pipeline natural gas, is equivalent to $0.16 per gallon as LNG (the fuel cost only, ignoring the cost of liquefaction). We assume the liquefier is 90% efficient, that is, 10% of our fuel cost goes to operating the liquefier (Kennedy, 1993) (this is labelled "liquefier fuel gas" in the table). This efficiency would be improved by the use of advanced liquefaction technology in plants located directly on high-pressure pipelines. The total annual gas cost is the sum of these two figures.

The next cost component is the liquefier capital cost, which has three distinguishable components: the liquefier system, the storage tanks, and the fueling facility (for dispens-

Table 33: LNG cost analysis.

	San Bernardino	Roseville	Kansas City	Houston	Chicago
Gallons LNG product per day	60,000	60,000	300,000	300,000	300,000
Gallons LNG product per year	19,800,000	19,800,000	99,000,000	99,000,000	99,000,000
Cost of natural gas feedstock	$3,069,000	$3,069,000	$12,276,000	$12,276,000	$12,276,000
Cost of liquefier fuel gas (10%)	$306,900	$306,900	$1,227,600	$1,227,600	$1,227,600
TOTAL ANNUAL GAS COST	$3,375,900	$3,375,900	$13,503,600	$13,503,600	$13,503,600
Liquefier capital cost	$7,540,500	$7,540,500	$30,034,400	$30,034,400	$30,034,400
Storage tanks	$1,320,000	$1,320,000	$6,600,000	$6,600,000	$6,600,000
Fueling facility capital cost	$500,000	$500,000	$1,500,000	$1,500,000	$1,500,000
ANNUALIZED CAPITAL COST	$953,388	$953,388	$3,884,073	$3,884,073	$3,884,073
Labor	$360,000	$360,000	$630,000	$630,000	$630,000
Maintenance	$113,108	$113,108	$450,516	$450,516	$450,516
Utilities	$75,405	$75,405	$300,344	$300,344	$300,344
Insurance	$75,405	$75,405	$300,344	$300,344	$300,344
Property taxes	$150,810	$150,810	$600,688	$600,688	$600,688
TOTAL ANNUAL OPERATING COST	$774,728	$774,728	$2,281,892	$2,281,892	$2,281,892
Total Annual Cost	$5,104,015	$5,104,015	$19,669,565	$19,669,565	$19,669,565
Gallons LNG consumed	17,217,391	17,217,391	86,086,957	86,086,957	86,086,957
COST PER GALLON	$0.296	$0.296	$0.228	$0.228	$0.228
Intro fleet cost per gallon					$0.296
Advanced fleet cost per gallon					$0.256

ing fuel to trucks, tank cars, and tenders). The cost of liquefier systems, the largest fixed capital cost, is proportionately smaller as system size increases (Bartholomew, 1992). Therefore, the 300,000 gallon per day facility is only 4 times as expensive as the 60,000 gallon per day facility. Each site has storage tanks for 4 days production, which, in light of the built-in over-capacity, should be enough. Storage consists of groups of small tanks, which are 60,000 gallons and about $300,000 each, plus 10% of cost for transportation (The storage tanks are close to the liquefier, but a cost must be added for moving the fuel from the liquefier to the tanks, and for dispensing the fuel to tankers.) (Bartholomew, 1993). Each fueling facility was estimated to cost $500,000 (Kennedy, 1993). The fixed capital is annualized at 8% discount rate and 20 year equipment life.

The labor requirement is not great for LNG facilities, and is not proportional to plant size. A 1.2 million gallon per day plant in Brunei needs only 20 persons (Kennedy, 1993). Personnel would consist of licensed operators, mechanics, and electrical instrumentation technicians. We estimate that each plant requires eight persons each at $45,000 average per year per person, including benefits. The Total Annual Operating

Cost is an estimate of the additional costs attributable to owning and operating an LNG facility, which is 5.5% of the liquefier capital cost (Acurex Corporation, 1992). The total annual cost is the sum of all the subtotalled annual costs, and the gallons LNG consumed is the annual product capacity less 15%, which is approximately the same as the 124 dual-fuel locomotives would consume. The Cost Per Gallon is the Total Annual Cost divided by the Gallons LNG Consumed. The average introductory fleet price is $0.296 per gallon, which is equivalent to $.50 per gallon for diesel fuel on an energy-equivalent basis.

The advanced fleet LNG plant system includes the two California plants and three midwest plants. Although one very large plant in place of the three might produce even cheaper fuel, three spread out plants would better serve the railroads and protect against production problems at a single plant. The railroads would be able to fuel their long-haul trains at the beginning and end of their runs, and serve yards and locals by shuttling tank cars where needed. The midwest plants are identical in size, at 300,000 gallons per day, and are located in Kansas City, Houston, and Chicago, giving excellent access to all three railroads. Midwest natural gas is cheaper, being closer to major Canadian pipelines, so 20% has been subtracted from the feedstock price. Fixed capital costs are proportionately the same, except that each plant is assumed to have the equivalent of 3 fueling facilities. Each plant employs 14 workers at an average $45,000 per year per person. Each plant could theoretically produce liquified natural gas at $0.228 per gallon, equivalent to $0.384 per gallon of diesel fuel. The overall fuel cost for the advanced fleet was estimated conservatively by averaging the per-gallon values for the five plants.

10.3 Energy, Emissions and Costs

Energy consumption - A pound of LNG contains more energy than a pound of diesel, but a gallon of LNG weighs half as much as a gallon of diesel. Taking these into account, an equal volume of diesel fuel contains about 1.68 times more energy than LNG. Table 34 is a breakdown of line-haul locomotive fuel consumption (based on the SD40-2) by throttle position, similar to that developed in Chapter 3. The table also shows the annual work produced by the engine in each throttle notch. This was calculated by combining the total fuel consumption and the specific fuel consumption, both of these taken from the Scott Labs report (Conlon, 1988). To calculate fuel consumption for a dual-fuel or SI engine, the same figures for annual work in each throttle setting were translated back into natural gas and diesel fuel consumption. This calculation took into account the differences in fuel efficiency between the different engine types.

The efficiency estimates for the spark-ignited engine in Table 34 were taken from the Technical Information Release (Caterpillar, 1989) for the CAT G3516 TA (plotted in Figure 15). The by-notch calculation allows us to uncover any possible advantages or disadvantages of SI in relation to throttle profile, since a natural gas engine is less thermally efficient than diesel at low loads. As Figure 15 shows, LNG/SI operation will compare more favorably with diesel in a duty cycle that leans heavily towards high load operation rather than one that has more time in the middle and lower load ranges. At idle, the LNG/SI version uses much more energy than the diesel, even though the idle time has been adjusted to reflect the ability of the Caterpillar to shut down easily.

For dual-fuel engines, the locomotive was assumed to consume 95% LNG and 5% diesel under all throttle settings above notch 2. Energy efficiency was assumed to match that of the diesel in the higher notch settings, dropping below diesel efficiency at moderate and light loads. Below notch 3, the engine was assumed to revert to 100% diesel operation. Since the dual-fuel engine was assumed to be a modification of the existing diesel locomotive engine, and not a replacement as with the SI engine, no adjustments were made in the idling time. Diesel fuel use accounts for 22% of total energy consumption over the duty cycle, mostly because of the significance of idling in overall locomotive fuel consumption (18,000 gallons at idle versus 7,000 gallons in Notch 8). The table shows that, in this duty cycle, the annual energy consumption for the dual-fuel engine is only 1% greater than the baseline diesel, while the SI uses about 18% more energy to produce the same work as the SD40-2 diesel. A further reduction in idling and low load operation would bring the relative energy consumption figures closer together.

Table 34: Energy comparison of diesel, dual-fuel and repowered SI versions of the SD40-2 in line-haul service.

	Diesel Baseline		Spark-Ignited		Dual-Fuel		
Throttle Notch	Work (hp-hr/yr)	Fuel cons. (gals/yr)	Energy cons. relative to diesel	LNG cons. (gals/yr)	Energy cons. relative to diesel	Diesel (gals/yr)	LNG (gals/yr)
off	0	0	0.00	0	0.00	0	0
brake	64,301	8,818	2.90	44,773	1.00	8,818	0
idle	51,155	18,343	1.39	44,524	1.00	18,343	0
1	23,999	2,709	3.20	15,192	1.00	2,709	0
2	84,167	5,387	2.07	19,535	1.00	5,387	0
3	157,463	9,515	1.26	21,085	1.10	476	17,425
4	296,845	16,581	1.13	32,705	1.10	829	30,364
5	348,047	18,944	1.09	36,305	1.05	947	33,114
6	427,241	22,644	1.07	42,620	1.00	1,132	37,697
7	472,632	24,982	1.03	45,206	1.00	1,249	41,589
8	2,501,705	131,518	1.02	235,283	1.00	6,576	218,948
Total consumption (gals/yr)		259,440		537,229		46,466	379,137
Total energy (MMBtu/yr)		33,234	1.18	39,271	1.01	5,952	27,715

Pollutant emissions - NOx emissions from each locomotive model in each throttle notch were estimated, then weighted using the duty cycle data presented in Chapter 3. A sample spreadsheet is shown in Table 35, for an SD40-2 locomotive converted to dual-fuel operation in line-haul service. The estimated reduction in NOx emissions in each throttle notch is also shown in the table. Based on the Cooper-Bessemer results, we estimated that NOx would be reduced 85% in Notches 3 through 8 with the dual-fuel engine, with zero reductions while in full diesel operation (idle through notch 2). The calculations show that an overall NOx reduction of 75% would be possible for the dual-fuel engine under these assumptions. Much of the remaining NOx is due to light-load and idle operation. If idle time could be cut in half, the reduction in emission with dual-fuel operation would increase to 78%. Still greater reductions would be possible using more advanced techniques, such as skip-firing, to operate in dual-fuel mode at idle as well. For SI engines, an 85% reduction in NOx emission in all notches was assumed.

Table 35: NOx emission of a dual-fuel EMD SD40-2 in line-haul service.

Throttle Notch	Percent NOx reduction	Weighted baseline NOx (lb/hr)	Weighted dual-fuel NOx (lb/hr)
off	0%	0.00	0.00
brake	85%	0.51	0.08
idle	0%	1.22	1.22
1	0%	0.22	0.22
2	0%	0.34	0.34
3	85%	0.56	0.08
4	85%	0.92	0.14
5	85%	1.08	0.16
6	85%	1.24	0.19
7	85%	1.42	0.21
8	85%	7.57	1.14
Total NOx (lb/hr)		15.1	3.8
Total NOx (tons/yr)			14.5
NOx reduction (tons/yr)			43.6
Percent reduction			75%

Dual-fuel costs - Costs of natural gas conversion and operation were needed to estimate cost-effectiveness. Our estimates of the cost of dual-fuel conversions for locomotives are shown in Table 36. It was assumed that the dual-fuel conversion would be undertaken at the time that the locomotive was due for a major overhaul. Thus, the costs attributable to the conversion would be only the incremental costs beyond those of the major overhaul. Since line-haul locomotives generally require major overhaul every 5 to 8 years, there should be no shortage of potential conversion candidates. To estimate conversion costs, we relied on the experiences of Burlington Northern, railroad maintenance costs, engine manufacturer's prices, locomotive rebuilder's costs, engineering estimates, and conversations with suppliers. Major costs would include the natural gas port injection system (and pilot diesel injection system, if applicable), which would be electronically controlled. Additional charge-air cooling, gas valves and vaporizers, and LNG storage would also be required. The cost shown for the power assemblies reflects the estimated *incremental* cost of power assemblies optimized for dual-fuel use, compared to the cost of the remanufactured diesel power assemblies that would otherwise be used in overhauling the engine.

Local and switcher (and perhaps commuter) locomotives could use LNG tanks hung under the frame, in place of the existing diesel tanks. Three 470 gallon tanks could fit under a typical local locomotive, giving about 1400 gallons total capacity, enough for three days of typical local operation. A switcher locomotive would minimally need only one such tank. Line-haul locomotives were assumed to use LNG tenders. Two locomotives could use the fuel supplied by one tender. We were informed that present LNG tenders cost about $300,000, including vaporizers and engine coolant plumbing (expected future designs place the vaporizers on board the locomotives, and our cost estimates are based on that expectation). Since each tender serves two locomotives, this amounts to $150,000 per locomotive. The Burlington-Northern tenders were built for about $17 per gallon (including frame and trucks), and road vehicle LNG tanks cost between $20 and $40 per gallon (Acurex, 1992). A 500 gallon tank made with custom materials and anti-vibration techniques costs around $16,000, or $32 per gallon, and the tank costs are typically 70% of the total cost of fuel delivery equipment (Dykstra, 1993). We estimate that the costs of LNG tenders and tanks produced in quantity will be 30% less than the custom unit prices cited above. This would amount to about $105,000 per tender and about $11,000 per on-board tank[32]. All costs are assumed to include labor, and 10% is added to hardware costs to indicate our judgement of the uncertainty in this preliminary cost calculation.

Table 36: Conversion cost estimates for dual-fuel locomotives.

Component/System	SD40-2	GP38
Injectors & Controls	$19,960	$19,960
Gas Valves, Vaporizer	$31,500	$13,536
Charge Air Cooler Radiators	$10,000	$10,000
Charge Air Aftercoolers	$30,000	$30,000
New Power Assembly	$17,680	$17,680
Pumps and Valves	$5,000	$5,000
LNG saddle tanks	$0	$31,584
Small diesel tank	$0	$2,000
LNG tender	$105,000	$0
Incidentals (10% of total)	$21,914	$12,976
Net cost	$241,054	$142,736

Source: EF&EE estimates.

<u>SI locomotive costs</u> - It would be a poor economic choice to replace the diesel engine in a properly functioning, updated-technology locomotive with a new SI engine, since much of the large capital invested in the diesel would go unused. For this reason, we analyzed the costs and cost-effectiveness of installing such an engine in a *remanufactured* locomotive, at the time when such remanufacturing is due, or is otherwise economically appropriate (such as after long life or after a serious wreck). The newest working locomotives would be left in the fleet to live out their economic lives, while specially rebuilt locomotives would start new economic lives in low-emissions service. While we view this as currently the most economic scenario, railroads would have to choose for themselves the most economic scenario, at the necessary time.

Locomotive remanufacturers receive, through purchase or contract, old, worn-out locomotives (often SD40s and SD45s) and rebuild them completely, installing modern control systems and electrical gear, overhauling the engine, and otherwise restoring the units almost to new condition. Remanufactured locomotives are marketed as being equivalent to new, but less expensive. For this analysis, we considered three cases - an SD45, an SD40, and a switch unit. Since price data for Caterpillar natural gas locomotive engine-generator sets were not available (at the moment the engines are only available installed in a Morrison-Knudsen locomotive), we obtained quotes from a local Caterpillar dealer on stand-alone engine-gensets for power generation. Each of these units includes the engine, alternator, and associated controls - roughly the same hardware as would be required in the locomotive gensets. These costs were: G3616, $1.7 million; G3612, $1.3 million (Chrismon, S., 1993). We assumed that a locomotive manufacturer, buying in quantity, would be able to get the same hardware for 30% less (e.g., $1.7 million X 0.70 = $1.19 million). That covers the line-hauls and locals. The Caterpillar 3516 800 kW (1072 HP) natural gas generator set, with radiators and ready to run at 2.0 g/hp-hr NOx, which can be purchased FOB Sacramento for $330,000, is a good model for the switcher power plant. We estimate that a locomotive manufacturer could buy a similar G3516 and generator, rated at 1200 tractive HP, for $350,000.

Table 37: Conversion costs for SI locomotives.

Components/Systems	SD45-2	SD40-2 line-haul	SD40-2 Local	GP38 Yard
New engine	G3616	G3612	G3612	G3516
Engine cost	$1,190,000	$910,000	$630,000	$350,000
Loco hulk	$90,000	$90,000	$90,000	$50,000
Rest of Reman.	$350,000	$350,000	$350,000	$300,000
Gas Valves, Controls	$31,500	$31,500	$13,536	$6,446
LNG tanks	$0	$0	$31,584	$15,040
LNG tender (1/2)	$105,000	$105,000	$0	$0
Net cost	$1,766,500	$1,486,500	$1,115,120	$721,486
Saved cost	$490,000	$450,000	$450,000	$350,000
Diesel Cost	$930,000	$890,000	$890,000	$700,000

Source: EF&EE estimates.

Given competition and similar production volumes, a heavy-duty natural gas engine should be *less* expensive than a diesel engine, since it has less content (the diesel has expensive high pressure injection equipment). At present, gas engines are substantially more expensive, due primarily to their very small sales volume. The production volumes implied by their use in locomotives to any significant degree should result in significantly lower prices.

Table 37 shows our cost estimate for remanufactured SI locomotives. Estimated costs of the comparable remanufactured diesel unit are also shown. In addition to the engine-generator set, we assumed the cost of the hulk to be remanufactured at $90,000 in the case of the SD40 and SD45, and $50,000 for the switcher[33]. The costs saved by not remanufacturing the engine, alternator, controls, and other equipment for the SD45s were estimated at $490,000, $450,000 for the SD40, and $350,000 for the switcher[34]. The remainder of the remanufacturing process was estimated at $350,000 ($300,000 for the switcher).

Operating and maintenance costs - Although natural gas is a very clean and non-corrosive fuel, we have not been able to uncover substantial evidence that engine maintenance costs are lower than for comparable diesel installations. While carbon in the combustion chamber is virtually eliminated, this has an adverse affect on valve wear. SI engine valve seats, valve face angles, and valve materials are changed to guarantee their service lives (Caterpillar, 1992). On the other hand, bottom end wear from carbon buildup is greatly reduced. Oil is usually not changed in locomotives, but Burlington-Northern has indicated oil lasts twice as long in their natural gas conversions (*Railway Age*, 1991c). Dedicated natural gas engines are given service intervals equal to comparable diesels, reflecting the engine maker's view that maintenance should be the same. Actual maintenance cost would probably be lower, but for conservatism, we have assumed overall maintenance costs for LNG and dual-fuel locomotives are the same as those for the straight diesel. Once these engines are in the field some direct comparisons will be possible.

10.4 Cost-effectiveness

The LNG energy, purchase cost, liquefaction cost, and conversion costs were assimilated into a cost-effectiveness analysis. Three different scenarios were evaluated: Diesel/LNG

Table 38: Life-cycle costs and cost-effectiveness of remanufactured SI LNG locomotives compared to diesel.

	EMD SD40-2		EMD SD40-2		EMD GP38-2	
	Line-haul cycle		Local cycle		Switcher cycle	
	diesel	LNG	diesel	LNG	diesel	LNG
Reman. unit cost ($)	890,000	1,486,500	890,000	1,115,120	700,000	$721,486
Useful life (yrs)	20	20	20	20	20	20
Annualized cost ($/yr)	$90,648	$151,403	$90,648	$113,577	$71,297	$73,485
NOx emiss. (t/yr)	58.1	8.7	24.0	3.6	15.9	2.4
Diesel cons. (gal/yr)	259,440		104,135		53,337	
Diesel price ($/gal)	$0.70		$0.70		$0.70	
Diesel cost ($/yr)	$181,608		$72,895		$37,336	
LNG cons. (gal/yr)		547,973		299,030		152,547
LNG price ($/gal)		$0.26		$0.26		$0.26
LNG cost ($/yr)		$140,100		$76,453		$39,002
Fuel Cost Differential		($41,508)		$3,558		$1,666
Net cost ($/yr)		$19,246		$26,487		$3,854
Cost effectiveness ($/ton)		$390		$1,298		$285

dual-fuel, SI LNG, and Dual-fuel plus SCR. The latter method is essentially a combination of dual-fuel and SCR systems described in Chapter 9. Low fuel cost and low conversion cost give dual-fuel a "negative" cost-effectiveness.

LNG SI - The cost-effectiveness of remanufactured SI LNG locomotives (compared to remanufactured diesels) is shown in Table 38. The life-expectancy of the remanufactured unit is set at 20 years, comparable to that of a new locomotive. The annualized equivalent cost is the sum of the up-front costs, compounded and paid annually at 8% interest. Although the capital costs of the LNG locomotives are higher, this difference is largely offset by the lower cost of LNG fuel in the line-haul case. For switchers and local units, the fuel cost savings are much less, since these units operate mostly at idle and light loads, when SI engines are at their greatest disadvantage

Table 39: Cost-effectiveness of LNG SI locomotives, new GP60 vs. remanufactured LNG SD45-2.

	Line-haul cycle	
	EMD GP60	EMD SD45-2 with CAT G3616
Initial cost ($)	1,250,000	1,766,500
Useful life (yrs)	20	20
Annualized cost ($/yr)	$127,315	$179,922
NOx emiss. (t/yr)	80.0	12.0
Diesel cons. (gal/yr)	297,490	
Diesel price ($/gal)	$0.70	
Diesel cost ($/yr)	$208,243	
LNG cons. (gal/yr)		664,210
LNG price ($/gal)		$0.26
LNG cost ($/yr)		$169,818
Fuel Cost Differential		($38,425)
Additional maintenance		$10,000
Net cost ($/yr)		$24,182
Cost effectiveness ($/ton)		$356

Table 40: Cost-effectiveness of LNG conversions, line-haul dual-fuel engines.

	EMD GP-60		GE B39-8		EMD SD40-2	
	Line-haul cycle		Line-haul cycle		Line-haul cycle	
	Before	After	Before	After	Before	After
Conversion cost ($)		$241,054		$241,054		$241,054
Useful life (yrs)		10		10		10
Annualized cost ($/yr)		$24,552		$35,924		$35,924
NOx emiss. (t/yr)	80.0	19.3	81.3	15.1	58.1	14.5
Diesel cons. (gal/yr)	297,490	47,395	294,296	42,352	259,440	47,395
Diesel price ($/gal)	$0.70	$0.70	$0.70	$0.70	$0.70	$0.70
Diesel cost ($/yr)	$208,243	$33,176	$206,007	$29,646	$181,608	$33,176
LNG cons. (gal/yr)		487,002		488,541		386,720
LNG price ($/gal)		$0.26		$0.26		$0.26
LNG cost ($/yr)		$124,511		$124,905		$98,872
Fuel Cost Differential		(50,555)		(51,456)		(49,560)
Net cost ($/yr)		($26,003)		($15,532)		($13,635)
Cost effectiveness ($/ton)		($428)		($235)		($313)

in efficiency. Overall, however, the costs per ton of emission reduction by this method are small.

Table 39 shows a similar cost-effectiveness comparison for a remanufactured SD45, equipped with a Caterpillar G3616 engine, versus a new EMD GP 60 locomotive. This is a reasonable comparison, as the repowered SD45 would have similar power output, traction control, and other features to the GP60. Maintenance costs would be higher, due to the extra axle

Table 41: Cost-effectiveness of LNG conversions, local and yard dual-fuel engines.

	EMD SD40-2		EMD GP38-2	
	Local cycle		Switcher cycle	
	Before	After	Before	After
Conversion cost ($)		$241,054		$142,736
Useful life (yrs)		20		20
Annualized cost ($/yr)		$24,552		$14,538
NOx emiss. (t/yr)	24.0	10.0	15.9	8.8
Diesel cons. (gal/yr)	104,135	34,323	53,337	27,007
Diesel price ($/gal)	$0.70	$0.70	$0.70	$0.70
Diesel cost ($/yr)	$72,895	$24,026	$37,336	$18,905
LNG cons. (gal/yr)		119,016		44,326
LNG price ($/gal)		$0.26		$0.26
LNG cost ($/yr)		$30,429		$11,333
Fuel Cost Differential		(18,440)		(7,098)
Net cost ($/yr)		$6,112		$7,440
Cost effectiveness ($/ton)		$435		$1,049

Table 42: Cost-effectiveness of combined technologies - SCR and dual-fuel LNG in line-haul applications.

	EMD GP-60		GE B39-8		EMD SD40-2	
	Line-haul cycle		Line-haul cycle		Line-haul cycle	
	Before	After	Before	After	Before	After
Conversion cost ($)		$637,304		$633,554		$566,054
Useful life (yrs)		10		10		10
Annualized cost ($/yr)		$94,977		$94,418		$84,359
NOx emiss. (t/yr)	80.0	1.9	81.3	1.5	58.1	1.5
Diesel cons. (gal/yr)	297,490	52,050	294,296	45,740	259,440	48,817
Diesel cost ($/yr)	$208,243	$36,435	$206,007	$32,018	$181,608	$34,172
LNG cons. (gal/yr)		477,726		502,499		367,975
LNG cost ($/yr)		$122,140		$128,474		$94,080
Fuel Cost Differential		($86,103)		($77,533)		($87,528)
Urea cons. (t/yr)		78.1		79.8		56.7
Urea price ($/ton)		$350		$350		$350
Urea cost ($/yr)		$27,329		$27,922		$19,833
Maintenance ($/yr)		$25,675		$25,350		$17,550
Net cost ($/yr)		$61,878		$70,156		$34,213
Cost effectiveness ($/ton)		$792		$879		$604

on each truck ($10,000, we estimate), but low-speed drag capability would be higher. Overall, the owning and operating costs of the repowered natural gas engine would be higher, but the reduction in NOx emission would make such a substitution highly cost-effective. The cost-effectiveness is 356 dollars per ton on a per-locomotive basis.

Dual-Fuel LNG - Table 40 and Table 41 show the life-cycle costs and cost-effectiveness of dual-fuel conversions in existing line-haul and local/switcher locomotives, respectively. For the line-haul case, the incremental life-cycle costs[35] are negative—due to the lower fuel cost, converting locomotives to dual-fuel would actually pay for itself, while reducing total NOx emissions. Fuel cost savings on the local and switcher locomotives are smaller and the emission benefits are less, due to the lesser fuel consumption by these locomotives and the predominance of idle and light-load operation in their duty cycles.

Dual-Fuel + SCR - A locomotive producer or rebuilder might chose to develop dual-fuel technology first and then add catalyst technology later to achieve further reductions. Table 42 shows the results of combining the data and calculations of this section with the same of Chapter 9, Selective Catalytic Reduction, for line-haul applications (again assuming that pilot fuel is set at 5%, and the engine reverts to 100% diesel at idle, notch 1, and notch 2). Table 43 shows the same analysis for local and switcher models. The capital costs are the sums of SCR conversions and dual-fuel conversions. NOx reduction calculation is simplified by taking 90% of the baseline figure. Fuel consumption, both diesel and LNG, is increased by 3% (8% for the GE). Urea consumption and cost is the same as for the SCR-only analysis. The increased capital and operating costs of combining these technologies does increase the cost-effectiveness figures, indicating that the capital costs dominate the fuel cost savings. Cost-effectiveness is between $600 and $900 for line-haul locomotives, $1,800 for local locomotives, and $1,900 for switcher

Table 43: Cost-effectiveness of combined technologies - SCR and dual-fuel LNG in local\switcher applications.

	EMD SD40-2		EMD GP38-2	
	Local cycle		Switcher cycle	
	Before	After	Before	After
Conversion cost ($)		$566,054		$377,736
Useful life (yrs)		20		20
Annualized cost ($/yr)		$57,654		$38,473
NOx emiss. (t/yr)	24.0	1.0	15.9	0.9
Diesel cons. (gal/yr)	104,135	36,059	53,337	28,373
Diesel cost ($/yr)	$72,895	$25,241	$37,336	$19,861
LNG cons. (gal/yr)		125,038		46,569
LNG cost ($/yr)		$31,968		$11,906
Fuel Cost Differential		(40,926)		(25,429)
Urea cons. (t/yr)		23.0		15.0
Urea price ($/ton)		$350		$350
Urea cost ($/yr)		$8,054		$5,255
Maintenance ($/yr)		$17,550		$10,400
Net cost ($/yr)		$42,332		$28,699
Cost effectiveness ($/ton)		**$1,840**		**$1,911**

locomotives, indicating that combined dual-fuel and SCR may be a cost-effective NOx reduction method.

10.5 Regulatory Issues

Emission regulations for locomotives would probably not specify a particular fuel, but rather a set of emission limits, which the railroads could meet through the use of alternative fuels or other measures. Alternative fuels *per se* would thus present no significant regulatory problems beyond those experienced with similar limits on diesel fuel. In the case of dual-fuel engines, it would be necessary to assure that the locomotives were operating on the clean-fuel combination, rather than 100% diesel, but this is not expected to be a major problem, since railroads would have economic incentives to run on liquid methane.

Safety concerns about the use of liquid methane in locomotives could be a significant barrier to adoption of this technology, and will need to be explored with the cognizant regulatory agencies. There are presently no rules for transporting liquid methane in tenders or tanks as there are for transporting liquid methane and other cryogenics in regular tank cars, but the FRA (US Department of Transportation) has been working closely with BN and Air Products to approve their designs and collect information for future rulemaking. Amtrak has expressed extreme apprehension about the use of LNG, even though no one has shown a clear and unreasonable hazard with natural gas on passenger trains (Burk, 1992a). LNG poses potentially greater hazards in a crash than would diesel fuel, and these hazards would need to be dealt with through appropriate design and training. In a safety study by Los Alamos National Laboratory (Kidman, et al., 1990), a panel of experts weighed the relative risks of fire and injury of five fuels in 10 representative railroad accidents, and found that diesel was the safest, LPG the least safe, with liquid methane, CNG, and methanol between them. The superiority of liquid methane over LPG is not surprising since it is lighter than air and so disperses readily and is less likely to ignite even in the presence of sparks or flame. The study recommended ways to make an alternate fuel as safe as diesel:

- Establishment and adherence to safety regulations
- Proper maintenance, installation, and testing
- Device development (e.g., detectors and alarms)
- Design review and improvement
- Materials research

- Training

10.6 Affordability

Conversion to LNG use should produce a significant net savings in life-cycle cost, so that the only issue would be the affordability of the initial investment in locomotives, tenders, and liquefaction equipment. Not including the costs of California gateways, converting the California locomotive fleet discussed in Section 4 to dual-fuel would cost approximately $250 million. Converting to combined dual-fuel/SCR would cost about $600 million. Converting to all natural gas SI, assuming only SD40-2 locomotives are used for line-haul, would cost $1.4 billion (although most of this would be offset by reduced need for diesel locomotive purchases or remanufacturing). The cost of liquefaction plants, discussed in section 10.3, is large, but other parties have expressed willingness to finance the liquefaction equipment, selling the liquified LNG "across the fence" to the railroad under a long-term contract. Thus, the capital cost to the railroad would be only the cost of conversion, which should be (if dual-fuel) well within the financial capabilities of the railroads.

10.7 Impact On Railroad Operations

Widespread use of LNG fuel would require some changes in railway operations. Especially during the initial transition, LNG might not be available at all locations, so that planning for locomotive refueling would have to be done more carefully, and it might be necessary to ship LNG tenders back and forth to liquefaction sites. On the other hand, the use of the tenders should make possible a greater range without refueling than is presently possible for diesel locomotives without tenders, and thus a savings on the operating costs and delays involved in multiple refuelings. If this longer range made it possible to eliminate some diesel fueling stations (with their associated costs and environmental risks) the savings could exceed those produced by operations enhancement alone.

The capability of on-demand fuel switching in dual-fuel designs suggests, at first glance, that maintaining a separate locomotive fleet for California would not be necessary. At the gateways, crews would add or remove tenders, but the locomotives would continue on. This would work were it not for the fact that railroads still like and need the flexibility of run-through agreements and system-wide power exchangeability. Considering the reasonable results emerging from our Section 4 calculations, we believe the railroads, at least in the early stages of technology conversion, will find it cheaper to maintain a California-only fleet of natural gas units rather than convert enough units to roam throughout their systems. But as the infrastructure for LNG refueling and LNG operations experience build, railroads will begin to operate their natural gas locomotives all over the country, possibly making a California-only fleet unnecessary.

10.8 Implementation Schedule

As a method for reducing emissions, natural gas for locomotives is a technology much closer to implementation than SCR or even electrification. Low-emission natural gas switchers are now available for purchase (end of 1994), and two are about to undergo their initial testing in Los Angeles at Union Pacific yards. Probably no more than one more year is needed to produce local, line-haul, and passenger LNG demonstration locomotives. There are no insurmountable technological barriers. However, the physical demands of the western railroad environment must not be underestimated. It may take several years of work to develop gaseous-fueled locomotives that operate as reliably as diesels in mountainous terrain. It is not reasonable to swap natural gas for diesel and expect the same performance in every operating environment without a reasonable development period.

To avoid large numbers of start-up problems, railroads may want to initially place natural gas locomotives on less demanding routes, reducing the risk to their operating departments and pacing the development of hardware and procedures. Natural gas switchers, low-demand locals, and commuter trains can go to work right away in air basins and satisfy the need to develop the technology sanely while reducing rail operation emissions and developing the necessary fueling infrastructure[36]. As experienced is gained and "bugs" are removed, the technology can be applied to high horsepower line-haul freight locomotives. Or, some railroads may wish to put their high-horsepower line-haul natural gas locomotives to work immediately, in order to make an immediate assessment of their long-term performance. That appears to be the strategy of Union Pacific and Burlington Northern with their natural gas locomotive programs.

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11. RAILWAY ELECTRIFICATION

As a method to reduce air pollution in the state, electrification of railroads has attracted considerable attention. Electric locomotives produce no direct pollutant emissions, and electric power plants can be located away from population centers and their pollution greatly reduced by proper design (it is often more cost-effective to administer pollution controls to stationary emitters than to mobile emitters). There are major efforts underway in the South Coast to study electrifying all the mainline track in that region by 2010. Future electrified high-speed rail corridors are also under discussion. Finally, electric railroad technology has been proven reliable, and can be purchased right away. However, the initial costs are very high, and the lead times are extremely long; SCRRA (Southern California Regional Rail Authority) and its researchers have estimated that 18 years would be needed to complete its 800-mile electrified rail system covering the South Coast region.

11.1 Electric Rail Technology

Electrically powered railroads look and operate very differently from diesel powered railroads. The costs of infrastructure are nearly doubled because power lines must be constructed over every mile of track route and then maintained. High voltage electricity over or next to the tracks means heightened safety concerns. Electric and diesel locomotives are also different, requiring different maintenance and operating techniques.

Overhead Wire Systems - Electric locomotives can be powered from an overhead contact system (OCS) or *catenary*, with requisite poles, insulators, strain relief cables, and contact wire. The contact wire is between 20 and 23 feet above the rails. The second component of the overhead system is traction power equipment, which includes *substations*, the autotransformers, supervisory control system, and high-voltage transmission lines. A substation is required every 15 or 20 miles, and most of them can be placed on existing railroad right-of-way. The third component is *civil works* or structure modifications, work to elevate bridges, cut tunnels, and lower tracks to provide adequate vertical clearance from the high voltage wire to the tops of the railcars and from the high voltage wire to the inside surface of the structure, clearances which are determined by the voltage of the system and the heights of the railcars used on those lines. It is desirable to accommodate the tallest current and future railcars.

Third rail systems - These operate at 700 vDC (usually), and are used primarily in transit systems. The electrical contact strip is placed inside an insulated housing on one side of the track and several inches off the ground, and the zero potential lead is the rails themselves. Third rail is almost exclusively used in heavy rail dedicated commuter systems, like the BART system in the Bay Area, where the high price of additional clearance in tunnels and underground stations outweighs the high price of delivering low voltage power to third rail hardware. The California Public Utilities Commission requires third-rail powered track to be completely fenced.

Electrification and Signal Technology - Overhead wire systems generate abundant EMI (Electro-Magnetic Interference) and RFI (Radio Frequency Interference), which cause problems with railroad Signal & Train Control (S & T) systems. Error-free S & T operation is essential for safe railroad operation. Therefore, electric rail systems require *immunization*, to help protect S & T systems from EMI and RFI induced voltages. S & T consists of the wayside signalling equipment that senses train position and movement and relays that information to engineers, opens and closes grade crossing warning devices and gates, and transmits telegraph-style data and communications via pole-mounted open-wire lines along the tracks. Current S & T equipment in California is reliable and inexpensive. Its primary and successful goal is safety; it does not directly contribute to train movement efficiency. It is technically straight-forward to insulate existing signal systems from interference. Open wires can be replaced with shielded wire, cables and wires can be buried, DC track circuits can be changed to AC, and insulated track joints can be made electrically continuous with impedance bonds.

Replacing conventional S & T with a new system (such as may be possible with ATCS) that is hardened and uses advanced technology is preferable because of the additional benefits, but also expensive because it means high up-front research and engineering costs. As stated earlier, we expect the entire industry to move towards ATCS without regulatory coercion, however, we have assumed in our study that S & T hardening in a California rail system will be necessary, since the time-frame of ATCS implementation is uncertain.

Locomotives - Electric locomotive technology has been extensively developed in Europe. In the US, Amtrak is the major electric locomotive customer, and then only in the Northeast Corridor, on tracks that it owns and operates. Some east coast commuter systems, such as New Jersey Transit, Southeastern Pennsylvania Transportation Authority (SEPTA), and MARC (for the Maryland State Railroad Administration) are using electric locomotives and electric cars on their trains. Amtrak operates fifty-two 7,000 hp electric Swedish-designed EMD AEM-7s, and thirteen 6,000 hp electric GE E60s. In the past, freight railroads have rejected electrification, since the probability of making a mistake (that is, that costs would exceed benefits) would be too high (Stehly, 1992b). Even where electric lines are already installed, the freight carriers have chosen not to use them, as in the case of Conrail in the Northeast Corridor. Diesel technology has advanced to where it can reasonably compete with electric technology in horsepower, and costs less to maintain (at current economic conditions). Nonetheless, railroads can purchase right now electric locomotives that are three-quarters again as powerful as the most powerful diesels, and do not directly pollute the atmosphere. That means that 4 electrics, in most cases, can do the work of 7 diesels, meaning possible savings in operating costs. Our analysis includes both electrification and locomotive costs.

Modern electrics typically run on 11kV, 25kV or 50kV AC overhead lines, with 25kV being the most common. The locomotive is equipped with a scissors-action device, called a pantograph, to contact the overhead wire and transmit the power to the locomotive. Transformers step down the high voltage line to the 650 or so volts that the traction motors use, and rectifier bridges, harmonic filters, and switching circuits process the power most efficiently, depending on speed and load. Other transformers supply power for auxiliary equipment such as air compressors and head end power supply. Forced Commutation Rectifiers (GE design) improve the power factor of the traction system, which means improved efficiency. The filters are provided to minimize harmonics, which are unwanted electrical energies that diminish the efficiency of the locomotive and the power supply, and contribute to interference in nearby electrical devices. Electric locomotives are as complex as diesels, in terms of content, and they require very different skills to maintain and repair. However, many of the components in diesels are dynamic (rotating or reciprocating), so wear is inevitable, and diesels have consumables (oil, and to a great degree, water) that must be replenished. It appears that the higher cost of maintaining an electric locomotive is mostly due to its content and the cost of replacement parts, not mechanical complexity.

Track Clearances - Double-stacked container railcars, bi-level autoracks, tri-level autopacks, and Amtrak "Superliner" double-height railcars now in use are very efficient and profitable for rail operators and shippers, but they would compete with overhead wires for the vertical space inside tunnels, bridges, and overpasses. Passenger cars pose the least threat: they are typically 16.5 feet above the rails at highest point. Double-stacks are the bulkiest: 8 feet wide at 20.25 feet high. If track is electrified, it is desirable to accommodate this equipment and minimize the rebuilding of all civil structures to reduce costs and minimize disruption to the railroads and the surrounding communities.

Railway Line Clearances gives few details about routes but is a useful indicator of overall dimensions. On Santa Fe right-of-way in California, all of the track permits at least 20 feet except for two tunnels in Franklin Canyon (Bay Area), which are (approx.) 19.25 feet. This is the result of Santa Fe spending $30 million to lower the tunnel floors and notch the tunnel roofs in Franklin Canyon to allow double-stack traffic. To electrify, those tunnels would have to be opened up further. Southern Pacific operates two trains a day on four Bay Area tunnels, with height limited to 19.25 feet (a new, single, center-aligned "gauntlet" track would allow electric-pulled double-stacks). Crossing the Sierra mountains, SP tunnels and concrete snowsheds limit vertical clearance to 20 feet. The snowsheds are not a problem, but the tunnels would need to be modified. The easiest change would be to notch the roof of the tunnels, providing a channel for the OCS hanger system. On the Union Pacific Feather River route, the restricting clearance is 19.75 feet, probably due to tunnels. There is one 18.75 foot restriction in LA, which we presume will be taken care of by the SCRRA electrification plan. Other mainlines are all 20 feet, minimum.

As it appears, most tunnel and bridge clearances are tall enough to take doublestacks, or catenary, but not both. One electrification method to carry both combines "third rail" *and* overhead catenary. Electric locomotives would be equipped with both overhead and third rail power pickups. Affected bridges and tunnels would have overlapping third rail, transformers, and sufficient safety precautions, instead of the overhead contact system. Locomotives would automatically switch to third rail and lower their pantographs as they approached the tunnels or bridges. Third rail could also be used in areas where visual intrusion by poles and wires is a concern. It may turn out to be less costly to make the structure modifications than install the third rail however, due to the added maintenance costs of the dual-mode locomotives and supplying the power.

Other configurations are also possible. If there is enough on-board space for transformers, a diesel locomotive can be modified to run as either diesel or electric (see Other Electric Systems, below), theoretically allowing railroads to pass from diesel to electric territory without changing consists. The versatility advantages are obvious, but there are significant design compromises in reduced power and increased weight, so this concept is limited in appeal. Battery powered switchers are a possibility - this approach must be examined closely for O/M costs and performance - as a way to mitigate rail yard emissions. Battery powered passenger units are used in Germany. Conceptually, batteries could also be used to carry any electric trains through long tunnels or unusually constrained overpasses, precluding the need to modify or replace those structures or convert to dual-mode. Further study would be needed to determine the necessity, feasibility and costs of these approaches.

11.2 Electrification Costs

How much it costs to electrify a California railroad line, to allow electric locomotives as well as diesel locomotives to operate on it, is a subject of great contention. Many studies have been conducted, using varying assumptions, and have arrived at widely varying results. However, the majority of the conclusions seem to agree that electrification is a very expensive option compared to other alternatives.

Table 44: PG&E E-20 rates applied to 3000 hp locomotive in line-haul duty cycle.

	hours	percent of year	rate ($/kW-hr)	cost ($)
summer peak	750	8.6%	0.08801	$28,235
summer partial peak	875	10.0%	0.05974	$22,360
summer off-peak	2791	31.9%	0.04561	$54,452
winter partial peak	1560	17.8%	0.05107	$34,079
winter off-peak	2784	31.8%	0.04424	$52,684
totals	8760			$191,808

Fuel Cost - Labor is the greatest cost to railroads, and fuel is second. Therefore, it is important to include the incremental fuel cost in the analysis (the difference in cost between fuel as diesel and fuel as electricity). The annual cost of electricity for a fleet of line-haul electric locomotives is equivalent to the annual power delivered to the traction motors in a fleet of equivalent diesel locomotives (energy consumed while idling is virtually eliminated), multiplied by locomotive, catenary, and power line efficiencies and the utility's price of energy. We started by calculating the power delivered to the traction motors in each notch, weighting by the line-haul duty cycle, and then summing the weighted numbers. This figure, multiplied by 24 hours per day and 321 days per year (88% availability) is the annual traction power, approximately 3.75 million kW-hr for one line-haul locomotive. The final cost depends on how much power is purchased at what times of the day and at what times of the year. The rates and corresponding daily/monthly periods were taken from PG&E's E-20 schedule, for large industrial firm service, with guaranteed supply. The relevant numbers are reproduced in Table 44. Large industrial users who do not require guaranteed electric supply can have lower rates. This is called *interruptible service.* Freight train energy demand was assumed to be spread evenly over time, that is to say, railroads would not choose to or need to favor cheaper time periods. Using these assumptions, the diesel fleet costs about 28% more to fuel than the electric fleet. If the railroads did run more of their trains during off-peak hours than peak hours, then their energy costs would be lower - a strategy not available with diesel fuel.

Track Costs - Electrification is deemed economic when a certain condition or variety of conditions makes it so. Table 45 summarizes the actual or projected costs from several recent North American electrification projects or electrification studies. We have shown only costs directly related to electrifying the track, such as substations, poles, catenary, and signal upgrades. Locomotive purchases are not included. The per-mile cost range is enormous, from $400,000 in remote British Columbia to $4 million in demographically and politically dense Southern California. These discrepancies point to the need for detailed and route-specific analysis for every electrification study, and a thorough understanding of the assumptions.

In the South Coast counties of Los Angeles, Ventura, Riverside, and Orange, freight and commuter rail electrification have been and are continuing to be studied. The South

Table 45: North American electrification costs, without locomotives.

	Route miles	Track miles	Total cost	Cost per route mile
BC Rail Tumbler Ridge Branch[a]	80	80	$32,200,000	$402,500
Riverside County (M-K)[b]	207	442	$257,882,000	$1,245,807
Caltrans/PCS (M-K)[c]	77	128	$103,100,000	$1,342,448
Amtrak New Haven - Boston[d]	150	350	$280,000,000	$1,866,667
So. Cal. Regional Rail Authority[e]	806	1,453	$3,261,000,000	$4,045,906

a Includes $90,000 per mile for catenary, plus $25 million for substations
b Includes civil works
c Includes civil works, all suggested extensions
d No civil works; includes some costs relating to high-speed operation
e No civil works; figure includes extension to Yuma, Arizona

Coast Air Quality Management District's Transportation Control Measure (TCM) 14 specifies a goal to reduce 90% of the South Coast's railroad NOx emission by 2010, ostensibly by electrification. In response to TCM 14[37], the Southern California Regional Rail Authority (SCRRA), with the help of utilities, engineering consultants, law firms, transportation researchers, railroads, and state agencies, has established routes, calculated costs, and estimated emission reduction for an advanced mainline electrification scheme (SCRRA, 1992). The proposed system connects all of the LA Basin freight and passenger centers with points outside of the LA air basin. These points are Barstow (and Yermo for Union Pacific), Moorpark, Santa Clarita, San Diego, and Yuma, Arizona, accounting for all mainline freight traffic and current and projected commuter traffic, and Amtrak. Freight corridors belonging to different railroads are consolidated in some areas. It is proposed to develop and implement this system before 2010. The study showed that electrification would eliminate only 76% of the rail- produced NOx, in part because no switcher and few local train movements would be served by electrification.

The per-mile electrification costs cited in the SCRRA study were much higher (3 times) than the costs estimated by Morrison-Knudsen in its 1990 Riverside County study (RCTC/ATSF, 1990). It appears as though the costs of installing substations and catenary are higher than the M-K estimates, which were around $800,000 per route mile. It may simply be that the M-K study did not take into account enough for other system components like stations, track realignment, and track improvements. Some have suggested that the high traffic density and large number of overhead structures conspire to elevate the costs, but the SCRRA costs do not demonstrate such a relationship between rural routes and downtown routes - for example, the LA to Yuma freight line, through largely flat desert, is only 15% cheaper than the alternately population dense and mountainous LA-to-Yermo freight line. The SCRRA cost estimates do not include civil works costs in any event. Much of the electrification in the LA basin would have to take place at night and in-between frequent train passes, and these requirements would certainly drive up the cost.

The per-mile electrification costs cited in the SCRRA study were also higher than in a study of electrifying the CalTrain/PCS railroad in the Bay Area, performed by Morrison-Knudsen in 1992 (Caltrans, 1992). That study considered the costs, benefits, and detriments of electrifying the tracks between San Jose and San Francisco, with three possible extensions to Lick and Gilroy in the south, and to downtown San Francisco in the north. The study suggested that electric locomotives (EMD/ABB AEM-7), with cab control cars and trailer cars, would be the most cost-effective choice of rolling stock, and that 25kV overhead catenary was the most cost-effective power source. Excluding rolling stock, the cost of electrification was estimated at approximately $1.3 million per route mile.

Amtrak's New Haven-Boston Electrification - Amtrak has begun to electrify its tracks between New Haven and Boston. The project is predicted to cost half as much as the LA Basin electrification estimates (on a per-mile basis), so it is useful to examine the similarities and differences. Amtrak's primary goals are to eliminate the electric-to-diesel change in New Haven and to increase top speed to 150 mph. A total of 150 route miles (350 track miles) are involved. All of the route is minimum double track, some is triple or quadruple track (only two tracks will be electrified). At the time of this writing, 250 million dollars have been allocated for the track wiring, and 84 million dollars for signal system changes. This calculates to $2.2 million per route mile, or $954 thousand per single track mile, or about $800 thousand per track mile excluding the signal system costs (*Railway Age*, 1992a). The $250 million includes all catenary, conventional support structures, special visually pleasing support structures, electrical substations, impedance bonds for the rails, special catenary inside of tunnels and bridges, and EMF and RFI immunization of other users in the right-of-ways, including utilities, communications companies, and railroads. This portion of the project also includes a physical structures survey, which helps determine how much money will have to be added for civil works. It is estimated that half of the 284 overhead structures and tunnels on the route will need some kind of modifications to accommodate electrification, but that the civil costs will be a small fraction of the total project cost (Popoff, 1992).

Much of the alignment is in rural areas, and Amtrak did not have to purchase any right-of-way for the project. There is freight traffic, but not as much as in LA, so work crews will spend less time waiting for trains and more time working, and the freight traffic will be able to use the third and fourth tracks where they exist. Imbedded in the total cost are some improvements that have less to do with electrification, and more to do with allowing high speeds and mitigating environmental impacts, such as high speed turnouts, state-of-the-art catenary with constant conductor wire tension, low visual impact poles in some areas, and an advanced bi-directional signal system (Vacca, 1992). In light of this comparison, the per-mile costs in our analysis are adjusted downward in predominantly rural areas to make them closer to the New Haven-Boston numbers, to balance the higher costs in the dense LA and Bay Area urban environments.

Other Electric Systems - Because of New York state laws prohibiting internal combustion power anywhere inside Manhattan's tunnels, many tracks leaving and entering Grand Central Station and Penn Station (as well as many miles out into the suburbs) are third rail electrified. Metro-North Commuter Railroad (New York), Connecticut Department of Transportation, Long Island Railroad, and Amtrak all operate EMD-designed "dual-mode" diesel-electrics, locomotives that can shut down their diesels and pick up third-rail current inside the tunnels. The old state law is the only apparent reason these agencies run with dual-mode - they operate on diesel (or OCS) everywhere else on the line.

We believe that dual-mode capability would be an unnecessary complexity and expense for the California railroads. The dual-mode units discussed above were specially constructed 40 years ago to accommodate the extra equipment and six-axle trucks. They are 8 feet longer than the standard models they were copied from (*Trains*, 1993). These units use 600 volt DC third-rail power, which is close to the maximum voltage of the traction motors, so they do not need bulky transformers to change the voltage, as they would if they used OCS for power. Although they are still very useful in the New York area, they would likely prove to be white elephants in other areas. Our discussions with Amtrak lead us to believe that electric locomotive maintenance may be more expensive than diesel locomotive maintenance, so a dual-mode locomotive would be very costly indeed. It cost Amtrak $2.7 million each to refurbish and update their dual-mode locomotives (Keller, K.A., 1992b)[38]. However, as the technology advances (e.g., AC traction becomes more common and the cost of electronic gear comes down) these assumptions may become obsolete. Further analysis in the near future would be required to determine the feasibility of dual-mode locomotives in specific California rail operations.

British Columbia Railway (BC Rail) has constructed an 80 mile 50kV electrified branch solely to serve coal mines near Tumbler Ridge and Quintette. The catenary construction was US$90,000 per mile (1983 dollars), which did not include substations, track, civil works, right-of-way purchase, or locomotives (Popoff, 1992). This is a rural branch-line, and as with the new Amtrak project, its cost does indicate that rural electrification may not be nearly as expensive as the urban electrification. BC Rail chose electric to avoid expensive ventilation schemes in the numerous tunnels that the trains pass through.

11.3 System Route Design

Much of California's pollution-producing rail operations occur in air basins, both urban and rural, and on steep mountain passes where locomotive energy use is most intense. Therefore, electric locomotives should displace diesels in air basins to the extent possible, and in the most heavily travelled and steepest routes. The operating burden on the railroads is reduced if electrification goes where the freight goes, and stops where the freight stops, or at least slows down. Electric lines should begin and end at existing classification yards, locomotive service yards, or available railroad owned real estate, wherever possible. It is likely that trains would stop at these junctions anyway for service, crew changes, and railcar redistribution. Electrification must connect to the major ports, where many trains begin and end their journeys. Finally, it is desirable to put electricity on tracks that are used or are expected to be used for rail commuter systems. These operate in populated, congested urban areas and are more likely to adopt electric propulsion. The higher power electric locomotives accelerate commuter trains faster, shortening total travel times.

Figure 16: Route diagram of proposed electrified rail system.

For the purposes of this study, EF&EE has defined a potential electrified route system which would connect the rest of the state to the SCRRA system. This system could handle most of the line-haul rail traffic in air basins throughout California. This system was designed for the purposes of calculating rough costs only - it should not be considered an engineering proposal. The proposed route structure is described as nine nearly discrete segments, including the LA Basin/SCRRA electrification, as follows (see Figure 16):

1. Redding to Roseville, 147 miles. SP tracks. Mostly rural and flat. Does not exit the basin, but not enough traffic to justify electrification in the mountains between Redding and the border.

2. Sparks, Nevada to Roseville, 130 miles. SP tracks. Steep and mountainous terrain. Double tracks, separated in many places. (Less than) five miles of snow sheds. Tunnels.

3. Roseville to Martinez, 72 miles. SP tracks. Mostly flat, half rural. Two drawbridges. Double track, all parallel. High air quality impact.

4. Martinez to San Jose, 73 miles. Connects with ports of Oakland and Benicia. SP and ATSF tracks, consolidated with UP (to Oakland). High air quality impact.

5. Stockton to Sacramento, 46 miles. SP tracks (consolidated with UP). Heavy traffic. Urban area, flat terrain. High air quality impact. Optional extension to Oakland.

6. San Jose to San Francisco, 43 miles. 50 commuter trains per day, run by CalTrans and Amtrak. Two freight trains per day. Dense urban area. High air quality impact. Thirty mile extension is likely.

7. Bakersfield to Martinez, 272 miles. Atchison, Topeka, & Santa Fe (ATSF) and Southern Pacific (SP) tracks. Mostly rural and flat.

8. Barstow to Bakersfield, 137 miles. ATSF and SP tracks. Steep grades and tight curves (Tehachapi mountains). Heavy traffic. Medium air quality impact.

9. LA Basin/SCRRA System. 676 miles. SP, UP, ATSF, and Metrolink tracks. Dense urban areas with numerous grade crossings and road overpasses. Heavy traffic. High air quality impact. Stops at Indio rather than proceeding to Yuma as in the SCRRA plan.

The total distance in this hypothetical electrified system is about 1600 route miles. Note that the SCRRA system assumes electrification all the way to Yuma, Arizona, a small SP fueling and crew change point. This was apparently done to make the Southern Pacific gateway the first SP service facility and crew change point outside of the LA air basin. Indio would be a better choice, as it is outside of the LA Basin, but not too far outside, and has a small yard already. At $2.3 million per route mile, it would cost $299 million to electrify the 130 miles between Indio and Yuma. Building a new service and fueling and gateway facility at Indio (estimated cost, $20 million) would be far cheaper. Therefore, we have reduced the total cost of South Coast electrification by $520 million (130 miles X $4 million per route mile).

It should be noted that the adoption of such a route structure would require significant changes either in present railway competitive practices, or in track ownership, or both. Presently, on many routes in California, two or more railroads compete over separate sets of tracks. While trackage rights agreements may allow through trains from one road to operate over another road's track, these agreements generally do not allow the "guest" road to pick up or deliver along the way. In contrast, our proposal would provide for only one electrified route, which would be used by trains of all railroads. Electrifying several sets of parallel tracks for competing lines would be uneconomic, and has not been proposed.

Track consolidation for electrification presents some difficult questions. In the central part of the state, an $18 billion per year agriculture business fuels a huge volume of railroad traffic for all three of the Class I's and several profitable shortlines. The railroads mostly operate on their own tracks. Which alignments should be electrified, and what do we do about the remaining alignments and their emissions? To answer these questions is beyond the scope of this study and could be the subject of its own exhaustive study. The answers may partly lie in other related transportation decisions, such as those regarding high-speed passenger trains. High-speed rail development might use and electrify freight right-of-way where practical, which the freight carriers could use as they wish in satisfying emission requirements or meeting business needs, but the electrification's primary purpose would be to move passenger trains at high speed, with high efficiency, and with low emissions. We would point out, though, that high speed trains could be propelled by low-emission diesels, natural gas, or gas turbine[39] engines at much less than the cost of electrification.

11.4 Cost-effectiveness

The estimated reduction in NOx emissions in the six air basins of concern due to electrification is shown in Table 46. The emission reductions were calculated by summing the Booz-Allen estimates of NOx emissions of all bulk, mixed freight, intermodal, and passenger trains operating in the six air basins[40]. It was assumed that 100% of emissions from these line-haul activities in the affected air basins would be eliminated. Emissions from local and switching operations would be unaffected by the electrification of line-haul activities, and would have to be addressed by other means. In calculating these emission reductions, we have neglected the emissions produced in generating the electricity. These emissions would be about 1.5 to 2 percent of the existing diesel locomotive emissions, assuming that the power source emits 0.5 lb/megawatt-hr (Sierra Research, 1990).

Since electric locomotives are individually more powerful than the diesels they replace, and have higher average availability, a smaller number would be required. We estimate that 336 electric locomotives would be needed to transport the line-haul freight and passenger traffic on this dedicated California network, replacing approximately 586 existing diesels. However, some diesel and some electric locomotives would be tied up in the yards, due to the need to change motive power at the "gateway" points to the electric system. We therefore assumed, conservatively, that 27 additional electric locomotives would be acquired for California-only service and 46 diesels would be retained for 49-state service (see analysis in Chapter 4). The diesels cost an average $1.5 million each. The price tag of an electric locomotive today is around $4 million, but we expect this to come down to $3.1 million as they are produced in greater quantities. It is assumed that the electric locomotives give 30 years useful life, the electrification equipment, 50 years. The annualized cost assumes an 8% discount rate.

Table 46: Cost-effectiveness of California electrified rail system.

System Segment	Miles	Cost, Per Route Mile	Route Cost, Total	NOx Reduced, Tons/year
Redding-Roseville	147	$1,692,000	$248,004,900	3,184
Sparks-Roseville	130	$4,850,000	$628,172,000	3,259
Roseville-Martinez	72	$2,437,500	$174,281,250	1,131
Martinez-San Jose	73	$4,200,000	$307,944,000	715
Stockton-Sacramento	46	$2,880,000	$133,848,000	207
San Jose-San Francisco	47	$3,880,000	$181,584,000	253
Bakersfield-Martinez	272	$2,304,000	$625,996,800	6,722
Barstow-Bakersfield	137	$3,612,500	$493,106,250	1,452
LA Basin/SCRRA System	676	$4,045,906	$2,735,032,258	7,592
Total NOx Avoided With Electrification (tons/yr)				30,615
Total Cost To Electrify System				$5,527,969,458
Total Cost of New Electric Locomotives				$1,120,144,650
Value of Deferred Locomotive Purchases				($406,504,107)
Annual Maintenance Cost of Diesel Fleet				$81,192,420
Annual Maintenance Cost of Electric Fleet				$70,985,373
Total Incremental Maintenance Cost				($10,207,047)
Annual Fuel Cost of Diesel Fleet				$114,838,055
Annual Fuel Cost of Electric Fleet				$89,787,924
Total Incremental Fuel Cost				($25,050,131)
Useful Life of Track, Years				50
Useful Life of Locomotives, Years				30
Annualized Cost of Electrified Track				$451,872,023
Annualized Cost of Locomotives				$63,390,858
Annual O/M Cost Increase (Decrease)				($35,257,178)
Net Cost ($/yr)				$480,005,703
Cost-Effectiveness, $/ton				15,679

The enormous capital investments in railway electrification could be justified on the basis of savings in operating cost due to fewer locomotives to run. However, the extent of any such savings under present conditions is still not clear. Increases in the power and reliability of modern diesel-electric locomotives have reduced the operational advantages of the electric considerably, and these would be further reduced by the inefficiencies involved in changing motive power at gateway points to the system. Fuel costs, however, could be less than for diesel. Accounting for catenary efficiency (83%) and line efficiency (93%) (RCTC/ATSF, 1990), the total fleet cost of the power delivered to the customer is $90 million, versus $115 million for diesel fuel.

Amtrak has supplied data that shows their electrics cost more to maintain than diesels - $2.46 per mile versus $1.61 per mile for diesel locomotives (Keller, 1992c). These numbers included wreck and accident repair costs, so to an extent they are mileage-dependent. Part of that additional cost is the high price of parts (traction motor: $150,000 versus $55,000), and part is the scarce technical skills needed to maintain those locomotives. The study of the CalTrain/PCS electrification (Caltrans, 1992) concluded that electric locomotives cost 40% less than diesels to maintain, but the report cited projections, not actual experience. The substantial costs of maintaining the catenary and associated systems may also be a factor, but for this analysis we assume it is indistinguishable from diesel engine-related costs (such as fuel spill cleanup). Our cost-effectiveness analysis assumes diesels cost $161,000 per year to maintain, and electrics $246,000 per year, a 52 percent increase. Nonetheless, total maintenance costs are lower with electrics, because fewer units are needed.

Given the assumptions outlined above, which overall could be considered fairly optimistic, our analysis shows a cost-effectiveness for electrification of mainline routes in California of 16,000 dollars per ton of NOx eliminated. This figure is still below the 25,000 dollar ceiling targeted at the South Coast AQMD, but is many times higher than those of the other measures examined in this study. Electrification would also involve substantial technical and financial risks and lengthy delays, due to the large investment needed and annual funding limits. It would appear as though railway electrification is a lees attractive alternative considering only emission benefits - especially compared to such attractive options as conversion to natural gas. However, unanswered cost-effectiveness questions, such as long term economic benefits, compensating savings in operating costs yet to be identified, the fuel versatility implied by electrification, the reduction of other pollutants such as NMHC and PM, the possibility of high-speed rail projects in the state, the pending electrification of the LA Basin and possibly the PCS, and the possibility of large increases in South Coast rail traffic (see *Industry Comments*, Section 9, p.3) suggest that electrification might still be competitive under some future scenario, and that further investigation would be useful. For example, it may be cost-effective to combine electrification, on dedicated commuter tracks and/or high speed rail corridors, with alternative fuels such as liquid natural gas on non-electrified corridors and in switch-yards. In this analysis we have lumped together high-use routes and low-use routes; clearly, electrification may be more competitively cost-effective on heavily-used routes (i.e., those that offer very high NOx reduction opportunity) considered alone, for which the logistics problems of changing locomotives could be solved.

If economic conditions become less favorable to electrification, we might expect railroads to have to buy more power in the peak ($0.088 per kW-hr) periods, diesel prices to drop to $0.60 per gallon, the cost of capital to rise to 17%, track wiring to cost $3.6 million per route mile everywhere (except the LA Basin, which stays at $4 million), and 50 more locomotives needed to cover railroad traffic demand. Under these conditions, our model indicates a cost-effectiveness of 24,000 dollars per ton. While this is very expensive in terms of costs to the source owner, it is still within the SCAQMD's cost-effectiveness guidelines.

If economic conditions turn in electrification's favor, railroads might operate less during peak and more during off-peak periods (closer to $0.046 per kW-hr), track wiring might be closer to the M-K estimate of $1.6 million per route mile across the state (except for the Bay Area and the LA Basin, which could be $3 million), diesel fuel might rise to $0.80 per gallon, and electric locomotive maintenance costs might become the same as for diesel. In this scenario, our model predicts a cost-effectiveness of $12,000 per ton, which is better than the base estimate but still several times more expensive than any of the other emission reduction methods investigated. The high cost of urban electrification drives the cost-effectiveness: if in the same scenario the LA and Bay Area electrification were to cost only $1.6 million per mile, the cost-effectiveness would be only $8,200 per ton.

Other environmental considerations - There are other environmental effects that, while difficult to quantify, deserve mention. Probably the least significant is electromagnetic effects. As mentioned above, electromagnetic current and electrostatically induced current affect signal systems but can be mitigated with modifications to DC track signals or complete upgrade to modern advanced train control systems. Frequency interference, produced by arcing at the pantograph pickup and by certain power conditioning components, can also be reduced with good design. Electromagnetic fields, or EMF, are present wherever electricity flows through wires. The effects of these phenomena on humans are not well understood, but to date no positive and unequivocal correlation between EMF and human health has been found, and the known statistics indicate only minuscule effects if any. Proximity to current carrying equipment may be important, as intensity is proportional to the square of the distance from the source (although, there is no evidence that electro-magnetic intensity is the problem).

Since there is no fuel and relatively little oil aboard electric locomotives, the danger of fuel and oil spills would be greatly reduced. This could be a significant plus for the railroads, since they are (usually) ultimately responsible for clean-up. However, this is also an advantage of natural gas. Electric railroads also would not require fuel storage, fuel pumping equipment, lubrication oil storage, cooling water storage and processing, or fire safety equipment associated with fuels and lubricants handling. However, these things would not really be eliminated because railroads would still use diesel for most locals and all switching activities. Electrification infrastructure includes static components (cables and power lines), overhead catenary system, substations, and a supervisory control system.

Noise is a concern to anyone to who works or lives near railroad tracks, and therefore to railroad owners and operators. While it is true that an electric *locomotive* is quieter in operation than a comparable diesel, an electric *train* may not be much quieter than a diesel train, since a great deal of the sustained noise comes from the freight cars (and passenger cars). An electric train at speed has its own undesirable noise emission, for example, a high frequency squeal from catenary-pantograph sliding contact. Power substations emit noise, but are fortunately few and far between. Newer passenger diesels are much quieter than the well-established EMD F40PH and GE P32BH locomotives, and may even approach the quietness of electrics, at least at lower speeds. The noise emissions of diesel and electric trains should be well understood and documented before they are related to cost-effectiveness.

11.5 Regulatory Feasibility

Because of the costs and delays involved in electrifying even a minimum mainline track system, it would probably not be feasible to approach this through traditional "command and control" regulations. Some sort of cooperative arrangement, involving the railroads, CalTrans, the ARB, and probably one or more electric utilities, as well as other parties, would be required. The antitrust and other competitive implications of operating all railroad line-haul activities over the same tracks would need to be evaluated.

11.6 Affordability

It is unlikely that any single railroad, or even all California railroads working together, could raise the over $7 billion in capital required for a system such as the one we have outlined, especially considering the potential risks and the apparent absence of significant operating cost savings. If such a system were to be built, then, it would likely be done with government assistance. Such assistance might be justified on the basis of enhancing passenger rail service (for instance, high-speed train operations) and/or reducing total emissions. The political and administrative implications of such a decision need to be carefully investigated.

11.7 Impact On Railroad Operations

Electrification of line-haul operations in California would significantly impact railroad operations, due to the need to change motive power at the "gateway" points, and consolidation of mainlines in the busy central valley. Dual-mode locomotives are too costly, and there is no apparent incentive for railroads to electrify outside of California. This impact would be similar to that imposed by other options leading to the creation of a "California only" locomotive fleet, as discussed in Chapter 4. Electrification would also pose an increased danger of disruption in operations due to derailments, earthquakes, fires, or other disasters, accidents, and vandalism, as the single electrified line would be more vulnerable than the present multiple-route system. There is also the question of how to service electric locomotives in existing shops; the costs of shunting switchers or electrifying service tracks are not included in this analysis.

11.8 Implementation Schedule

Although electric railroad technology is readily available, electrification would take many years to complete, as the SCRRA study has indicated. There would be many legal and administrative issues to work out, years of funding coordination, and then the physical work itself would take many years. We believe that electrification could not be completed in the time frame for 90% NOx reduction suggested in our regulatory section, even if 90% reduction were possible. Electrified freight movement would probably have to parallel government-subsidized high-speed rail projects, which would provide some of the necessary infrastructure.

12. COSTS AND COST-EFFECTIVENESS

In the preceding chapters, the cost-effectiveness of different emission control technologies has been calculated on a per-locomotive basis. Although useful for ranking emission control approaches, such a characterization does not fully reflect actual costs and emission benefits due to implementing these changes on a large scale, as we are proposing for California. Among the factors omitted from consideration in these earlier chapters were the costs of maintaining a separate "California" locomotive fleet, and changing power at defined "gateways". As Chapter 4 showed, these costs would be about $25 million per year on an annualized basis. The analysis in the earlier chapters also fails to account for the fact that some of the NOx emissions from the California fleet would be produced outside the six air basins studied in the Booz-Allen report. Since reducing emissions outside the six air basins would not contribute much to compliance with State and Federal air quality standards, the populations there are thin, and the CCAA requires 5% per year emission reduction only in non-attainment districts (CARB, 1993b), no credit should be taken for these reductions in the cost-effectiveness analysis.

A point which could profoundly affect the cost-effectiveness analysis is the potential indirect impact of emission controls in shifting freight traffic away from the railroads, and into more polluting modes. If the costs of emission control are too high, modal shift is certainly possible, as railroad industry sources have pointed out. To the extent that such shifts occur and result in higher emissions, the net emissions reduction will be lower, and the costs per ton of pollution reduced may be significantly higher. These potential effects are *not* included in the present cost-effectiveness analysis since no one has supplied us with applicable cross-elasticity data. Furthermore, we do not believe that these indirect effects are likely to be significant, unless the ARB opts to require electrification. Because our results show that emission reductions of 75-90% are possible at moderate cost, we do not expect the resulting cost increase to have a marked impact on railroad competitive position - especially considering the numerous and costly emission regulations now in effect or under development for heavy-duty trucks. This issue was addressed in detail in a study undertaken by the ARB in 1993.

12.1 Baseline NOx Inventory

The existing baseline locomotive emission inventory was developed by Booz-Allen (1991), and was based on emission factors for each available engine type, which were then customized for each railroad and then fed into a spreadsheet that modelled rail traffic over all mainline track segments in the State. This approach does not allow ready changes in locomotive duty cycle (except by manually entering new time-in-notch values for all 230 track segments) and there were a number of problems with the spreadsheet models. Therefore, EF&EE developed an alternative calculation based on the estimated average numbers of locomotives of different classes active in California.

Annual emissions per locomotive - Table 47 summarizes the estimated annual emissions per locomotive for line-haul locomotives using the different emission control technologies assessed in Chapters 5 through 11, as well as the corresponding annualized incremental costs per locomotive (costs directly attributable to lowered emissions, and over those incurred at a representative time of overhaul or replacement). Table 48 summarizes the same data for local and switch locomotives. As these data show, baseline NOx emissions per locomotive are around 80 tons per unit per year for line-haul locomotives (only 58 tons for the SD40-2, as it has 3000 rather than 3900 hp), 24 tons for locals, and 16 tons for switchers.

Baseline NOx inventory - To estimate the baseline (no control) NOx emissions in California (summarized in Table 49 for the Dual-fuel scenario), we began with the estimated number of line-haul, local, and switch locomotives active in California at any given time. As documented in Chapter 4, these are estimated to be 586 line-haul, 235 local, and 271 switch locomotives. Sixty four percent of the line-haul fleet were assumed

Table 47: Annual NOx emissions and annualized incremental costs for line-haul locomotives using various emission controls.

	GP60			B39-8			SD40-2 line-haul		
Baseline NOx (tons/yr)	80.0			81.3			58.1		
	NOx w control (tons/yr)	% Reduction	Incr. cost ($/yr)	NOx w control (tons/yr)	% reduction	Incr. cost ($/yr)	NOx w control (tons/yr)	% reduction	Incr. cost ($/yr)
Low aromatic fuel	72.0	10%	$38,079	73.2	10%	$37,670	52.3	10%	$33,208
Engine mods	51.6	35%	$4,471	64.5	21%	$4,471	23.2	N/A	$25,987
Rebuild/Replace	33.1	59%	$152,778	33.6	59%	$106,578	27.4	53%	$109,017
SCR	8.6	89%	$115,982	10.3	87%	$125,166	6.2	89%	$74,283
LNG SI	N/A	N/A	N/A	N/A	N/A	N/A	8.7	85%	$16,499
LNG Dual Fuel	19.3	76%	($26,[illegible])	15.1	81%	($15,532)	14.5	75%	($13,635)
LNG + SCR	[illegible]	98%	$61,[illegible]	1.5	98%	$70,156	1.[illegible]	97%	$34,213
Electric	0.0	100%	N/A	0.0	100%	N/A	0.0	100%	N/A

Table 48: Annual NOx emissions and annualized incremental costs for local and switch locomotives using various emission controls.

	SD40-2 local			GP38 switcher		
NOx before (tons/yr)	24.0			15.9		
	NOx w control (tons/yr)	% reduction	Incr. cost ($/yr)	NOx w control (tons/yr)	% reduction	Incr. cost ($/yr)
Low aromatic fuel	21.6	10%	$13,329	14.5	9%	$6,933
Engine mods	8.9	63%	$16,736	N/A	N/A	N/A
Rebuild/Replace	11.3	53%	$50,235	5.9	63%	$47,189
SCR	2.6	89%	$60,330	2.1	87%	$40,278
LNG SI	3.6	85%	$26,487	2.4	85%	$3,854
LNG Dual Fuel	10.0	58%	$6,112	8.8	45%	$7,440
LNG + SCR	1.0	96%	$42,332	0.9	94%	$28,699
Electric	N/A	N/A	N/A	N/A	N/A	N/A

to be SD40-2 locomotives, 12% to be GP60s, and 24% to be GE Dash 8s. These proportions are taken from California fleet composition data supplied by the railroads. Therefore, our hypothetical 1987 fleet consists of 70 (586 X 12%) GP60 locomotives, 141 (586 X 24%) Dash 8 locomotives, and 369 (586 X 63%) SD40-2 locomotives. (The 46 reserve units are not part of the *equivalent* locomotive roster). The annual NOx per locomotive model is then the NOx per locomotive times the number of locomotives. Satisfied that our calculations comfortably approximate the Booz-Allen 6-basin line-haul results, we use the actual Booz-Allen figure of 24,973 tons per year throughout the analysis.

An advantage of our approach is that we can define per-locomotive emissions precisely. A disadvantage of our approach is the uncertainty about the equivalent number of locomotives in California, which we estimated to be 586 (the railroads have challenged this number and our estimates of fleet costs; see the box at the end of this chapter). To help verify this estimate we used Booz-Allen and railroad fuel usage data to check our results. For example, if our calculations resulted in a huge increase in fuel consumption, we would adjust our fleet estimate, assuming that the per locomotive estimate was close. Using this method, total annual NOx emissions from line-haul locomotives in the six air basins of concern were tallied at 38,855 tons per year (the sum of the three model NOx sums in Table 49). This is greater than the Booz-Allen estimate of 36,188 tons for all rail operations in the *six air basins* in 1987, but less than their estimate of 58,248 tons per year for *all California rail operations* in 1987. In calculating the costs of low-emission conversions it makes sense to keep the fleet number estimate, since those locomotives will have to be converted whether their emissions are inside the air basins or outside.

Our assumed California fleet would spend significant amounts of time operating outside the actual boundaries of the six air basins - especially in the Southeast Desert region going to and from the gateways at Barstow and Indio. These areas, due to their position on major transcontinental rail routes, account for large amounts of emissions. For instance, the Southeast Desert Air Basin alone, the site of major SP, UP, and Santa Fe corridors, accounts for 16,635 tons of line-haul and local NOx per year (Booz-Allen, 1992). The amount of reductions in these areas depends on whether a California-only fleet is established, and if it is, where the gateways are located.

We believe that total NOx emissions in the six air basins probably have not changed much from the Booz-Allen 1987 inventory. Since then, freight railroads have striven to reduce the number of locomotives on trains and in their inventory (in part by increasing the horsepower per locomotive). Also since 1987, there has been an increase in the passenger service in the state (for example, increases in *San Joaquin* service, increase in Southern California service, and the new *Capitol* service). While line-haul freight traffic is up since 1987, especially the more energy and pollution-intensive intermodal type, railroad fuel consumption per ton-mile has significantly declined, new locomotives with somewhat lower emissions have become more common, and overall railway fuel consumption nationwide is down slightly (Railroad Facts, 1992).

Table 49: Example emission reduction calculation for dual-fuel line-haul locomotives.

	GP60	B39-8	SD40-2
Before conversion			
NOx (tons/year)	80.0	81.3	58.1
Fleet percentage	12%	24%	63%
Number of conversions	70	141	369
NOx (tons/year)	5,618	11,487	21,462
Total fleet NOx (tons/yr)			38,566
Basin Adjustment Factor			64%
Before Basin emissions (tons/yr)			24,700
After conversion to Dual-fuel			
NOx (tons/year)	19.3	15.1	14.5
Fleet percentage	0%	0%	100%
Number of conversions	0	0	586
NOx (tons/year)	0	0	8,491
Total fleet NOx (tons/yr)			8,491
Basin Adjustment Factor			64%
After Basin emissions			5,400
Net NOx reduction (tons/year)			19,300

Since reducing NOx emission in the Southeast Desert or the Eastern Slope of the Sierra is of little benefit to the respiratory health of persons living there, and has little importance in meeting state and federal air quality standards, it is inappropriate to take credit for the emission reductions in these areas in the cost-effectiveness analysis. Based on the ratio between our estimate of NOx from the California line haul fleet with the Booz-Allen 1987 inventory for the six air basins, we estimated that 64% (from the ratio of 36,188 and 58,248) of line-haul emissions from the California fleet would fall within the six air basins. Therefore, the 6 basin-wide NOx reduction for each NOx reduction measure considered is scaled down by this *basin adjustment factor* in order to be consistent with the Booz-Allen results and to indicate that NOx reduction would only be of value inside the air basins of concern.

In the second half of Table 49 we consider the total NOx after the fleet has been converted to Dual-fuel natural gas. All the GP60 and Dash 8 locomotives have been removed from California to serve in 49-state service. The fleet is now 586 converted SD40-2 locomotives. Each converted locomotive, assuming the line-haul duty cycle we have used throughout the report and 88% availability, emits 14.5 tons per year, so the entire fleet emits 8,491 tons per year (586 X 14.5). Since we have decided to account only for emissions in the 6 air basins, we apply the 64% percent basin adjustment factor to get the *after conversion* total of 5,400 tons per year. Therefore, the net NOx reduction is 19,299 tons/year (24,700 - 5,400). This procedure was followed to calculate fleet-wide emissions for all of the emission reduction options.

12.2 Emission Reductions and Cost-Effectiveness of Control Measures

Table 50 shows the NOx reduction achievable from line-haul locomotives, using each of the technical approaches outlined in Chapters 6 through 11. Improvements in operating efficiency (Chapter 5) are not included here. These improvements have likely already occurred, to the extent possible, assuming that the increase in rail traffic since 1987 has been accomplished with no change in total emissions. Except for electrification, all of the NOx reduction values were calculated using the same method shown in Table 49. Except for low-aromatic fuel, all of these calculations were based on the assumption that newer line-haul locomotives such as the SD60s and Dash-8s would be shifted outside of California, leaving the California fleet made up mostly of converted SD40-2s.

Table 50 also shows the estimated cost and average cost-effectiveness of applying each technological option to the entire California line-haul locomotive fleet. The cost was calculated by multiplying the appropriate annualized costs per locomotive from Table 47 by 633 - the number of locomotives estimated in the California line haul fleet (baseline plus reserve locomotives). The annualized costs of establishing and maintaining the California-only fleet - estimated in Chapter 4 at $24.4 million per year - were then added to this value to give the total cost. The resulting costs are plotted against the potential emission reductions in Figure 17. The dotted line along the lower edge of the locus of points in the figure represents the cost-effectiveness frontier (or, "least-cost line") for emission control from line-haul locomotives.

Figure 17 is a plot of the cost of each reduction option versus the NOx emission reduction, in tons, attributable to that option. The *average* cost-effectiveness for each control measure is proportional to the slope of the dotted line drawn between the corresponding point on the graph in Figure 17 and the origin (which represents the "do nothing" option). This value, in dollars per ton, was determined by dividing the cost increase by the reduction in emissions.

As Figure 17 and Table 50 show, the cost per ton of the LNG dual-fuel option is very low. If, for some reason, LNG were not feasible, however, the cost-effectiveness of the SCR option alone (compared to the "do nothing" option) would also be attractive, as it could conceivably be 91% effective. The cost per ton for electrification when *compared* *to* LNG+SCR, could be considered extremely high, since electrification would eliminate only about 300 more tons of NOx per year, at an annual cost more than 10 times as great.

Cost-effectiveness was recalculated using cost and locomotive population numbers supplied by the railroads in response to a draft of this report. As can be seen from the analysis presented on page 151, controlling locomotive emissions remains cost-effective even under the modified conditions.

It is also desirable to look at the cost and emission reduction totals for local and switcher locomotives.

Table 50: Summary of costs and NOx reductions, line-haul locomotives.

	NOx Reduction (tons/yr)	Percent Reduction	Cost (MM $/yr)	Cost-Eff. ($/ton)
Baseline NOx (tons/yr):	24,973			
Rebuild/Replace	N/A	N/A	N/A	N/A
LNG Dual Fuel	19,551	78%	$18	918
LNG SI	21,722	87%	$31	1,439
LNG + SCR	24,430	98%	$49	2,026
SCR	22,673	91%	$78	3,433
Engine mods	11,272	45%	$39	3,474
Low aromatic fuel	2,675	11%	$44	16,541
Electric	24,973	100%	$506	20,262

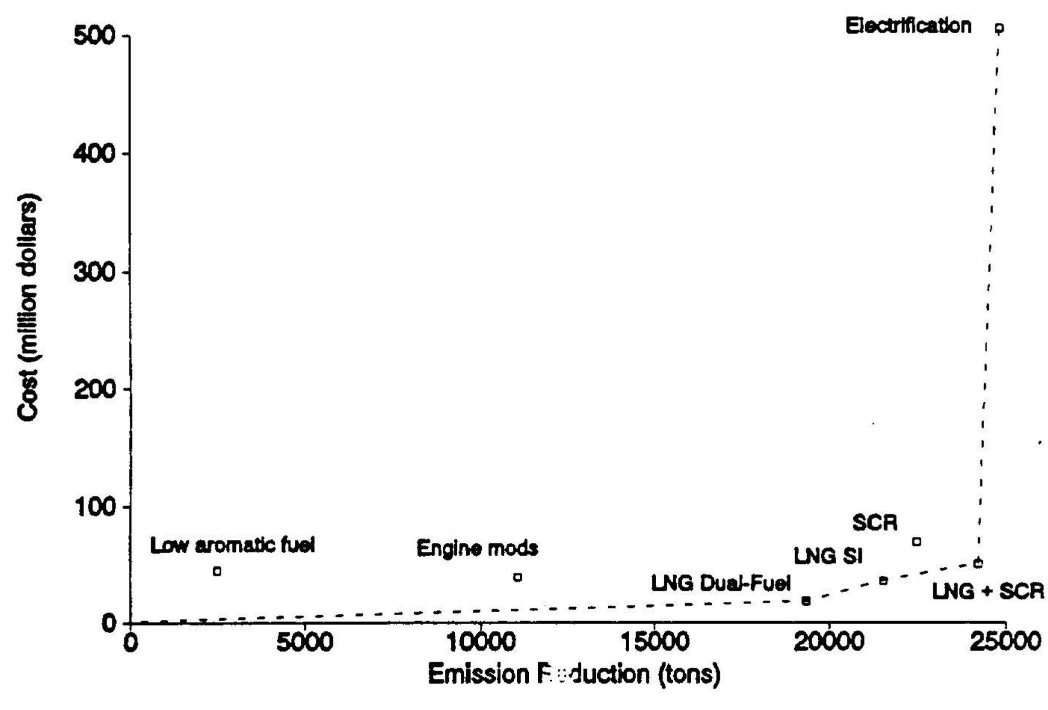

Figure 17: Cost versus emission reduction for potential line-haul locomotive control measures.

The costs and emissions are combined together here, although in reality locals resemble line-hauls, or switchers, or both, depending on the railroad. The results are shown in Figure 18 and Table 51. As with line-hauls, there was a discrepancy between the Booz-Allen estimate and our estimate for local and switcher NOx. The Booz-Allen number is 11,214 tons per year, whereas the EF&EE estimate was 10,185 tons per year (the latter is not shown in any table, but was calculated like in Table 49). Our locomotive count is based on recent data; the low number may only indicate that there are now fewer total switcher and local locomotives than in 1987, or, besides locomotive population, it may simply be a reflection of the greater "off" time we allotted locals and switchers in our analysis. Either way, the number is comfortably close to the original, and we consider it a fair approximation to increase it around 10% and make it exactly the same as the Booz-Allen number. The cost calculations are not affected. The same procedure was followed to calculate fleet-wide emissions for all of the emission reduction options.

As with line-haul locomotives, dual-fuel shows the best cost-effectiveness of the emission control options for locals and switchers, with a cost per ton even less than that for line-haul locomotives. This is mainly due to the absence of extra costs for changing power at California gateways. The reductions from natural conversion are lower in switchers and locals, however, because of the predominance of idle and low-load operation. For switch and local locomotives, SI LNG engines give much better NOx reduction, at a cost per ton only slightly higher. LNG+SCR gives the greatest total reductions, but its cost is higher and therefore so is its cost-effectiveness. We assumed that electrification would not affect switcher or local emissions significantly, as it could not be applied to these modes economically.

- continued on next page -

Table 51: Summary of costs and NOx reductions, local and yard locomotives.

	Baseline NOx (tons/yr):		11,214	
	NOx Reduction (tons/yr)	**Percent Reduction**	**Cost (MM $/yr)**	**Cost-Eff. ($/ton)**
Electric	N/A	N/A	N/A	N/A
LNG Dual Fuel	5,850	52%	$3	597
LNG SI	9,461	84%	$7	776
Engine mods	2,534	23%	$4	1,598
LNG + SCR	10,602	95%	$17	1,621
SCR	9,805	87%	$26	2,602
Rebuild/Replace	6,263	56%	$25	3,927
Low aromatic fuel	978	9%	$5	5,221

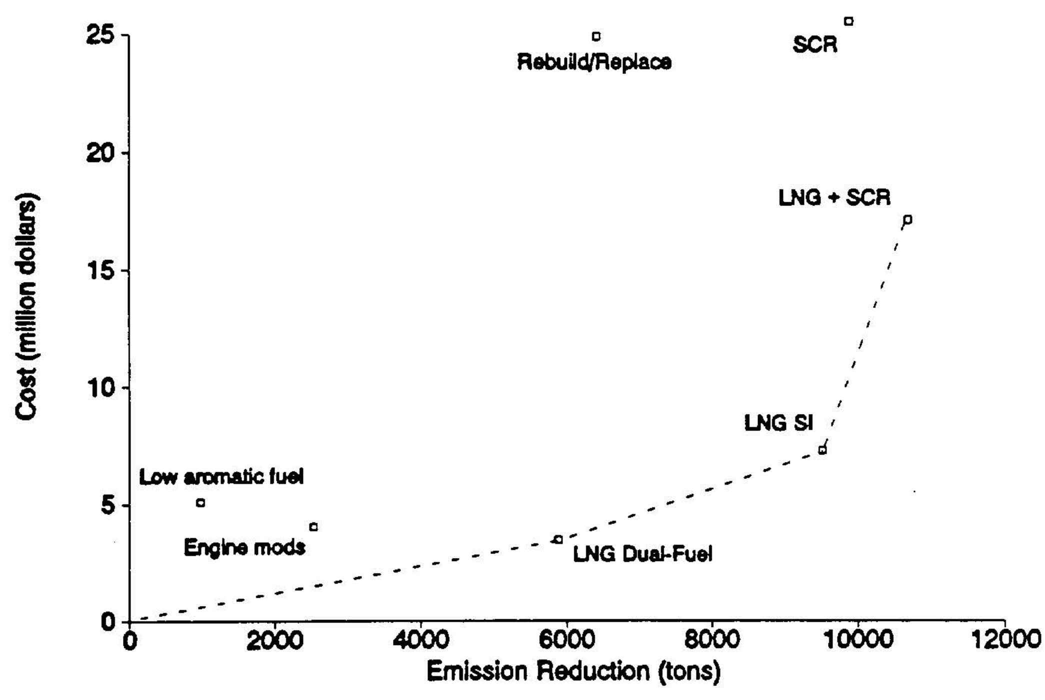

Figure 18: Cost versus emission reduction for potential local and yard locomotive control measures.

Since it would also be desirable to reduce the emissions from line-haul, local and switcher locomotives together, at the least possible cost, we combined all the modes in a third analysis. There are many possible combinations, and nine are highlighted here, to show the relative cost-effectiveness. Table 52 was constructed by

Table 52: Summary of costs and NOx reductions, combined line-haul, local and yard locomotives.

Baseline NOx (tons/yr):	36,188			
	NOx Reduction (tons/yr)	Percent Reduction	Cost (MM $/yr)	Cost-Eff. ($/ton)
LNG Dual Fuel	25,434	70%	$22	858
LNG Dual-Fuel Line-haul & LNG SI Locals/Switchers	29,074	80%	$26	882
LNG SI	31,245	86%	$43	1,376
R/R Locals-Switchers, Dual-fuel line-hauls	25,958	72%	$43	1,667
LNG + SCR	35,103	97%	$67	1,911
SCR	32,543	90%	$95	2,909
Engine mods	13,805	38%	$43	3,112
Low aromatic fuel	3,653	10%	$50	13,610
Electric line-hauls and LNG + SCR locals/switchers	35,645	98%	$524	14,688

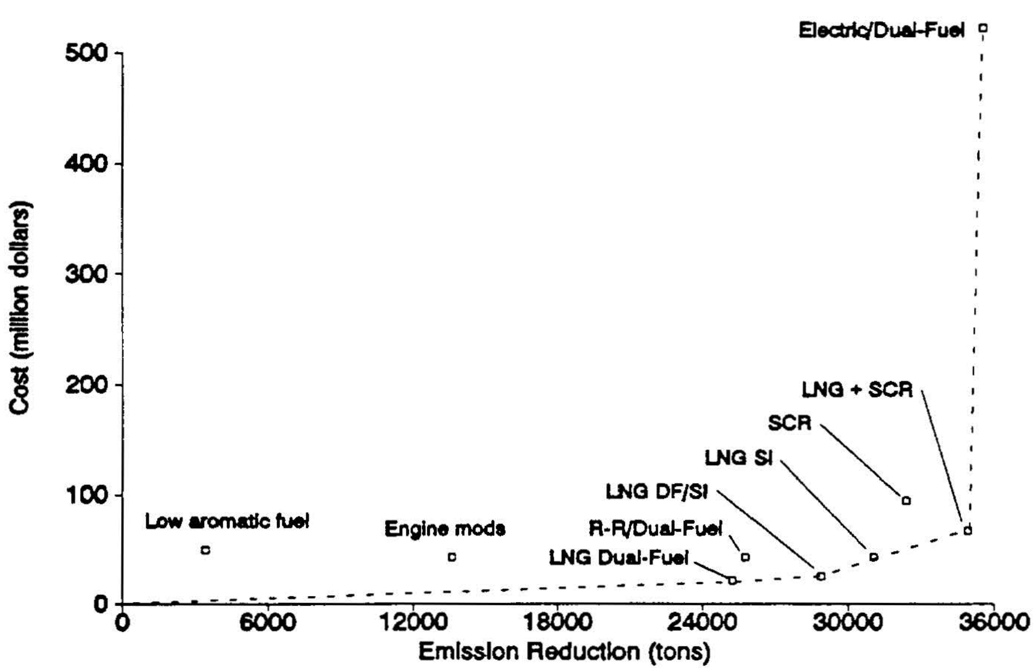

Figure 19: Cost versus emission reduction for potential line-haul, local, and switcher locomotive control measures.

summing the relevant portions of Table 50 and Table 51. The same data are shown graphically in Figure 19.

As Table 52 shows, the most cost-effective options for locomotive emission control all involve the use of LNG. Converting existing diesels to dual-fuel operation could reduce emissions by 70% (more if advanced dual-fuel technologies allow a reduction in idle and light-load emission), at a cost less than $900 per ton. Use of low emission SI LNG engines in locals and switchers, while keeping dual-fuel for line-hauls, would increase the emission reduction to 80%, at an average cost-effectiveness of only $882 per ton. Use of SI engines in line-haul units as well, or the addition of SCR to the dual-fuel engines, would produce even larger emission reductions, but at double or triple the cost-effectiveness values. Combining electrification of line-haul locomotives with dual-fuel+SCR in local and switch locomotives would produce the highest level of control efficiency - 98% - but the high price of electrification compared to LNG+SCR in line-haul locomotives could make this combination unfavorable.

Converting all locomotives to dual-fuel would appear to be the most cost-effective approach. Indeed, except for the costs of establishing and maintaining separate power in California, this option could actually result in a small saving compared to the status quo. If, as now appears possible, use of LNG locomotives eventually becomes widespread, the need to maintain the separate California fleet would be reduced or eliminated, with a corresponding saving in cost. If, for some reason, LNG proved not to be feasible, SCR would also be a reasonably cost-effective choice to achieve substantial emission reductions at moderate cost. Without these options, it appears that completely remanufactured locomotives, with low-emission diesel engines, is a way to achieve a fair reduction in NOx at reasonable cost-effectiveness. Small incremental gains can be achieved with engine modifications and low-aromatic fuel, but the reductions time-frame we envision could not be met with these methods.

- continued on next page -

ALTERNATIVE ANALYSIS USING INDUSTRY ESTIMATES OF COSTS AND FLEET SIZES

In their written response to the draft report, the railroads claimed higher numbers of California locomotives, higher numbers of locomotives crossing the California borders, and higher cost figures for replacement locomotives and other items pertaining to a dedicated California fleet (*Industry Comments*, Section 11). All of these increases are based on recent, not 1987, data. To test the effect of these increases on the cost-effectiveness, we recalculated Table 50 using the proposed numbers.

The Southern Pacific line-haul locomotive total was doubled to Southern Pacific's suggested 425, which assumes that all 425 are available for assignment. Santa Fe's line haul total was increased from 162 to 227. The number of local and switch locomotives were also increased, where suggested. The passenger railroad total was increased by 11, to 101, all attributable to Amtrak. Next we inserted SP's estimate of trains crossing the borders, a total of 116 per day. Amtrak's minimum support was doubled, to 16. With these numbers in place, the sub-total line-haul low-emission locomotives went from 586 to 916, nearly double. The total low-emissions number was then 1532.

Again taking SP's revised estimate of the cost of new shop facilities at $25 million instead of $18 million, and increasing the number of shops needed by one, the incremental costs of a dedicated California fleet were revised. Also, the costs of all locomotives, new and low-emission remanufactured, were increased to $2 million, which we believe is extremely conservative. The cost of this new capital was increased to 13.5%, the amount suggested by the railroads as correct. The new Total Incremental Annual Cost was $72.4 million, more than 3 times the original estimate.

The locomotive count and cost increases were appended to the cost-effectiveness spreadsheet, and the unsurprising result is shown in the table below. Those reduction technologies most dependent on numbers of locomotives converted or remanufactured show the most increase in cost-effectiveness. The cost-effectiveness is nearly 4 times our original estimate. The LNG + SCR combination is twice as much. The increased costs push Low Aromatic Fuel to the worst cost-effectiveness position, worse even than electrification. Electrification shows the least increase, because its costs are dominated by track costs, rather than locomotive-related costs. These increases do not change the conclusions about the cost-effectiveness of emission controls for locomotives. The reduction opportunity is so large, and the costs so plausible, that the cost-effectiveness is much lower than for many other emission sources in the state.

Table 53: Cost-effectiveness test calculation.

		Baseline NOx (tons/yr):	24,973	
	NOx Reduction (tons/yr)	**Percent Reduction**	**Cost (MM $/yr)**	**Cost-Eff. ($/ton)**
Rebuild/Replace	N/A	N/A	N/A	N/A
LNG Dual Fuel	19,551	78%	$67	3,418
LNG SI	21,722	87%	$80	3,680
LNG + SCR	24,430	98%	$100	4,107
SCR	22,673	91%	$126	5,573
Engine mods	11,272	45%	$90	7,941
Electric	24,973	100%	$571	22,854
Low aromatic fuel	2,675	11%	$92	34,363

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13. REGULATORY FRAMEWORK

As the preceding chapters have shown, control of emissions from railway locomotives would be both technically feasible and highly cost-effective. Reductions in railway NOx emission of the order of 75-90% have been shown to be achievable, at significantly lower cost per ton than many other NOx control measures that have been imposed. The case for emission regulation is strong. But, because of the complexity and importance of the railway industry, it is important that railway emission regulations be designed with flexibility. For this reason, EF&EE recommends that the regulations adopted be based on an emission "bubble" approach, which would specify only the degree of emission reduction required, leaving railroad management free to select the best and most cost-effective means. This Chapter describes the proposed regulatory framework, as well as the considerations underlying the design.

13.1 Regulatory Design Considerations

A number of concerns had to be taken into account in the development of the proposed regulatory framework. Key design considerations included those listed below:

- Maximum emission reduction - To achieve State and Federal ambient air quality standards, especially in the South Coast Air Basin, it will be necessary to reduce NOx and SOx emissions to the greatest extent feasible and cost-effective. The state implementation plan (SIP) for the SCAQMD calls for a 70-80% reduction in locomotive emissions by 2011. Although the SIP has not been approved by EPA, the federal implementation plan (FIP) now under development will probably require emission reductions at least as large. At the same time, emissions of diesel particulate matter (PM), ozone-forming reactive volatile organic compounds (VOC), and toxic air contaminants should at least be kept from increasing significantly, and should preferably be reduced. CO emission from locomotives (presently negligible) should not be allowed to increase to the point that it becomes significant, both because of continuing CO violations and because of the possible CO contribution to ozone formation.

- Modal shift - To ensure that it is not counterproductive to overall emission reduction, any policy for dealing with locomotive emissions must recognize the competition between railroads and other freight transport modes. In developing regulations to reduce locomotive emissions, it will be important to ensure that rail costs are not increased to such a degree that traffic shifts to more polluting modes. This implies that the scheme created should not create excessive or disproportionate costs for rail freight operations compared to other modes. Since reliable and expeditious service are concerns of most shippers, the regulations should minimize the potential for service disruption.

- Incorporate both technological and operational measures - The regulatory scheme should recognize and exploit the potential for railroads to reduce emissions both through technology changes and through changes in operational practice such as reduced idling, more-efficient power assignment, and improved train dispatching - and to incorporate both of these into a cost-effective compliance strategy.

- Flexibility to accommodate different operations - The regulatory approach should recognize and accommodate the differences in physical characteristics, operations, equipment, and business strategies between railroads. It should therefore provide as much flexibility as possible, consistent with enforceability and air-quality needs, to allow compliance to be achieved in the most cost-effective manner.

- Performance-based standards - Because of the complexity and extent of railroad operations, cost-effective prescriptive regulations of specific technologies and operating practices would be difficult and time-consuming to develop. Regulation of operating practices would also be difficult and disruptive to enforce. Such regulations would result in regulators being unnecessarily and unproductively burdened with administrative activities. Instead of specific technologies and operating practices, emission regulations should require a specified level of emission *performance*, with regulatory involvement in technology and operations limited to auditing to ensure that the required performance is achieved.

- Accommodate future growth - The regulatory structure should be designed to accommodate future growth in rail freight and passenger traffic, either as a result of economic growth or due to modal shift. Conversely, it should be designed to eliminate any incentive for *shrinking* rail traffic, as this would only shift added traffic and emissions to the highway modes.

- Optional market-based mechanism - In keeping with the Board's instructions to the Staff, the regulatory structure should provide a straightforward option for incorporation of market mechanisms, including trading between railroads and between railroads and other mobile or stationary sources, should the Board decide to permit this.

- Compliance with State and Federal law - Any regulatory scheme must fulfill the mandates given to the ARB by the State Legislature. It must also be compatible with the section of the Federal Clean Air Act Amendments of 1990 preempting state regulation of new locomotives and locomotive engines, and must not create an excessive burden on interstate commerce.

- Compatible with future freight transport policy - We recommend that the ARB and the Districts develop a freight transport policy, incorporating truck, rail, and marine freight, and that a key element of this policy may be the shifting of substantial volumes of long-haul truck freight traffic to the rails (or from the least to the most environmentally sound mode, whatever that may be) by means of an appropriate combination of economic incentives and regulatory measures. The regulatory structure developed for locomotive emissions should not conflict with this potential long-term policy, and should preferably serve to advance it.

13.2 Proposed Regulatory Framework

Based on the foregoing considerations, EF&EE proposed a regulatory structure which would establish basin-wide emission limits for each railroad, while leaving them free to satisfy the limits in the most cost-effective manner. In this respect, it resembles the market-based control option proposed by the ARB staff at the Board meeting in August, 1991. Our proposal differs from that one in the following major particulars: it is not necessarily market-based (trading might or might not be allowed); the emission reduction targets are more ambitious; the allowance for growth is more generous; and the mechanism for enforcement is much more rigorous. A preliminary version of this proposal was discussed at a public workshop held December 16, 1992. The proposed regulatory framework presented here has been modified to respond to the comments received at and subsequent to the December 16 workshop. The details of the proposed framework are outlined below:

- Basin-wide emission ceilings - Annual emission ceilings would be established for each railroad, including short lines, in each air basin. The ceiling would be based on 1987 emissions multiplied by a reduction factor and by a factor reflecting changes in traffic volume. These factors are described in greater detail below. Annual emissions in each basin from each railroad would not be permitted to exceed the ceiling. Operating a locomotive in such a manner that total emissions exceeded the ceiling would be a violation, subject to a penalty to be defined. Shortline[41], excursion, historical, and other railroad operations using less than (e.g.) 50,000 diesel-equivalent gallons of fuel per year would qualify for an exemption from all requirements. If a railroad's emissions are less than the ceiling, the difference could be banked for use in future years, or possibly (under a market-based control option) traded to other railroads or possibly to other mobile or stationary sources.

- Emission baselines - For the major railroads and Amtrak, the 1987 emission and traffic volume baselines would be based on the Booz-Allen study (see tables of ton-miles in Appendix A). For short lines and other rail operations not included in the Booz-Allen study, emission estimates would be based on 1987 fuel consumption data and the best available data on emission factors (possibly including source tests). For new shortlines formed by the purchase of Class I branchlines, their baselines could be determined using the original Booz-Allen segment emissions. For new rail service not in effect in 1987, such as the L.A. Metrolink, an appropriate baseline would be developed based on similar operations.

- Emission reduction factors - Emission reduction factors would become more stringent over time, and would be uniform for all air basins, unless the responsible air district showed that more stringent reductions were necessary and feasible. For NOx (the pollutant of greatest concern), allowable emissions would be phased down from 90% of the baseline in 2000 to 20% in 2007 and thereafter. Other pollutants would also be phased down, over varying schedules. The derivation of the proposed phaseout schedule is given in Section 13.3.

- Traffic volume adjustments - The emission ceiling for each railroad be a linear function of the traffic volume - doubling traffic volume would double the emission ceiling, and halving it would cut the emission ceiling in half as well. For line-haul freight railroads, we propose to base the traffic volume adjustments on ton-miles hauled in each basin, *including local and through trains*. This adjustment would preferably be based on net ton-miles, but if net ton-mile data are unavailable, trailing ton-miles could be used as a proxy (the data shown in Appendix A are based on trailing ton-miles). Local train operations would be included in the ton-mile total. Our proposal would require the Booz-Allen baseline data to be supplemented by additional estimates of ton-miles by *local* trains, and additional data from the railroads relating net ton-miles to the gross ton-miles reported by Booz-Allen. For terminal railroads (which move cars wholly within or between major railroad terminals), the traffic volume adjustments would be based on net tons handled rather than ton-miles.

  For Amtrak, the traffic volume adjustments would be based on passenger-miles carried, plus a further allowance for any freight (e.g. mail) carried by the train. This could be a disadvantage, as Amtrak sells low-density sleeper car space in addition to regular coach space, and must necessarily operate at low-density at certain times, such as during the start-up phase of new service. However, passenger-mile basis might also be an incentive for Amtrak to continue maintaining an efficient balance between low and high density. Commuter rail lines would be treated separately from Amtrak intercity operations.

- Locomotive activity monitoring - Locomotive activity and emissions in each air basin would be monitored on an individual locomotive basis, in order to account for locomotives that are malfunctioning, high emitters, or otherwise different from average. Railroads would propose and implement their own monitoring systems, subject to the ARB approval and audit. For example, emissions could be calculated by multiplying the measured time spent in each throttle notch, horsepower hours generated in each throttle notch, or some other notch-specific activity variable for each locomotive by the corresponding emission rate for that locomotive in that notch. These calculations could easily be automated, for example, by setting up hardware and software to accept and process recorded data.

- Locomotive emission testing - Locomotive emissions of NOx, PM, CO, and VOC, and fuel consumption in each notch would be measured on every locomotive operating in the air basins of concern. Measurements would be made at 6-month intervals, or when engine mechanical work is carried out that could affect emissions, whichever is more frequent. Emission measurements would be done on-site at the railroads' maintenance shops, and could be carried out either by the railroads themselves, with appropriate regulatory oversight, or by a separate contractor[42]. Testing is estimated to take about 1 hour per locomotive (using a short test to be developed), and would be integrated into the regular periodic maintenance schedule. Since locomotives require inspection and schedule maintenance at 90 day intervals in any event, this should not create significant operational problems.

13.3 Phasedown Schedule

The proposed emission reduction schedule is shown in Table 54. The regulations would take effect for the first time beginning in calendar year 1998. As further discussed in Section 13.5, this was estimated to be the earliest year that widespread emission testing would be possible. We estimate that development and the ARB adoption of a suitable fast test procedure will require about 18 months, beginning in fall, 1995, so the test procedure itself will not be ready until the beginning of 1997. After this, the railroads would require another year to purchase and set up the test equipment, to gain familiarity with the test, and to carry out actual tests on their fleets. Some time would also be required to set up the locomotive activity monitoring systems.

NOx - EF&EE's intention in proposing the allowable NOx emission levels shown in Table 54 was to allow significant slack, especially in the early years of the program, between the emission reduction required under the regulation and the maximum reduction technically feasible. This would allow the railroads to over-control and "bank" emissions in the early years, in order to provide a cushion against unexpected problems later on. This will help to ensure orderly implementation of the program. In addition, the maximum control levels required for NOx are somewhat less than the maximum techno-

Table 54: Proposed emission phasedown schedule for locomotives.

Year	Allowable Emissions (% of baseline)				
	NOx	PM	SOx	NMHC	CO
1998	90%	130%	17%	200%	200%
1999	80%	130%	17%	200%	200%
2000	70%	130%	17%	200%	200%
2001	60%	117%	17%	200%	200%
2002	50%	103%	17%	200%	200%
2003	40%	90%	17%	200%	200%
2004	30%	77%	17%	200%	200%
2005	20%	63%	17%	200%	200%
2006	20%	50%	17%	200%	200%
2007	20%	50%	17%	200%	200%
2008	20%	50%	17%	200%	200%
2009	20%	50%	17%	200%	200%
2010	20%	50%	17%	200%	200%
2011	20%	50%	17%	200%	200%
2012*	20%	50%	17%	200%	200%

* In addition, a research target of 90% NOx reduction would be established for 2012. This target would be reviewed in 2003.

logically achievable, so that a well-managed railroad could generate significant NOx offsets for sale to other users (if permitted by the ARB). This would serve as a "carrot" to encourage timely compliance. At the same time, however, we did not want to grant the railroads too large a windfall in the form of excessive offsets, as this would retard progress toward attaining the air quality standards, and could also disrupt the offset market for stationary sources.

Table 55 shows EF&EE's estimate of the NOx reductions that would be technologically achievable and cost-effective over the next decade. These estimates assume that the Air Resources Board acts to adopt locomotive regulations in 1995. As discussed in Chapter 5, the railroads' ongoing efforts to increase fuel efficiency have probably reduced fuel consumption and NOx emission per ton-mile by about 20% since the baseline year of 1987. A further 20% reduction in NOx could be had immediately by retarding fuel injection timing on the existing diesel locomotives. Thus, by 1998, emissions could be reduced by a total of 36% from the baseline level. Also by 1998, improved charge-air cooling and other inexpensive modifications to reduce NOx could have been developed and demonstrated. Fitting these to the locomotives used most in California should give another 10% reduction in NOx. Since the retrofits would require some time, this reduction was credited for 1999.

In about 2000, railroads would likely have to choose whether to add SCR to their diesel fleet, convert to dual-fuel LNG operation, or (hedging their bets) both. Given the present status of research, development, and demonstration of LNG dual-fuel locomotives, we estimate that large-scale conversion (about 150-200 units per year) could begin in 2000, and that it would take 6 years to convert the entire California fleet[43]. During this period, advances in dual-fuel emission control technology would be likely, raising the maximum emission reduction achievable from 78% to 85%. Alternatively, locomotive SCR should be fully demonstrated by about 2000, and ready for installation on a large

Table 55: Projected technologically feasible locomotive NOx control capability versus time.

Year	Percentage Reduction in NOx					
	Individual Measures				Combined effect	
	Fuel Cons.	Engine Mods.	SCR	LNG (dual fuel)	with SCR	with LNG
1998	20%	20%			36%	36%
1999	20%	30%			44%	44%
2000	20%	30%		13%	44%	50%
2001	20%	30%	15%	25%	52%	56%
2002	20%	30%	29%	38%	59%	62%
2003	20%	30%	44%	51%	67%	69%
2004	20%	30%	59%	63%	75%	75%
2005	20%	30%	73%	76%	83%	81%
2006	20%	30%	88%	81%	90%	84%
2007	20%	30%	88%	85%	90%	88%
2008	20%	30%	88%	85%	90%	88%
2009	20%	30%	88%	85%	90%	88%
2010	20%	30%	88%	85%	90%	88%
2011	20%	30%	88%	85%	90%	88%
2012	20%	30%	88%	85%	90%	88%

scale in 2001. Again, it would take about 6 years to install this on the entire California fleet.

Figure 20 compares the estimated level of NOx reduction achievable (using the more cost-effective dual-fuel LNG approach) with the level of emission reduction proposed to be required in each year. As this figure shows, the required reductions are significantly less than the level that could be achieved, especially in the early years in order to allow the railroads to build up a bank of credits. The credits should be valid indefinitely.

Particulate matter - Although desirable, reductions in diesel PM emission from locomotives are less urgent than for NOx. In the early years of the phaseout, retarding injection timing will probably lead to some increase in PM emission. In addition, there is considerable uncertainty regarding the actual PM emission levels of locomotives in use, which may be significantly higher than the Booz-Allen estimates. For both of these reasons, EF&EE recommends setting the allowable PM emission level somewhat higher than the 1987 inventory estimate. Otherwise the need to control PM could interfere with short-term NOx reductions. In the longer term, the use of either SCR (with add-on catalytic converters for HC and diesel SOF) or LNG would make possible a substantial reduction in locomotive PM emissions. These technologies could be phased in between 2000 and 2005.

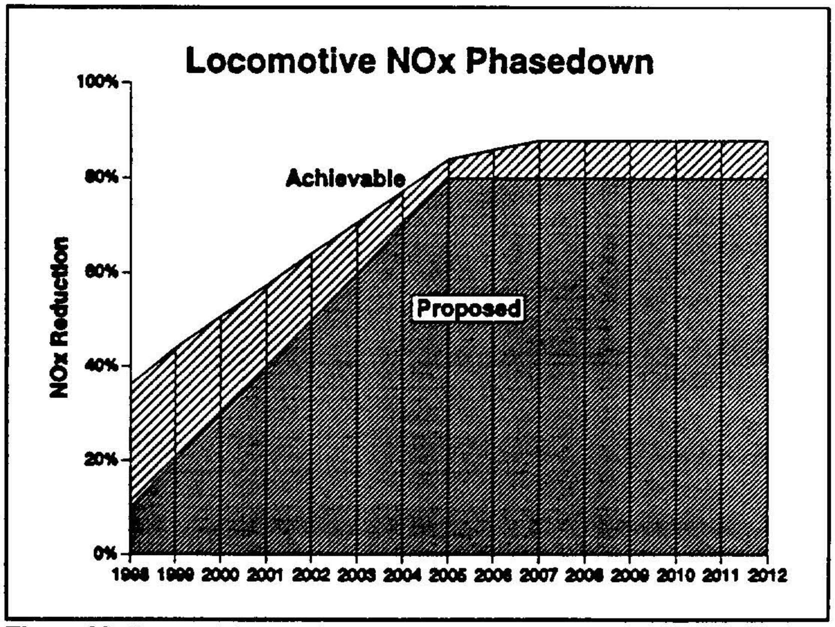

Figure 20: Proposed locomotive NOx phasedown schedule versus technologically achievable reduction.

SOx - The Booz-Allen emission inventory was based on 0.3% sulfur in the fuel, whereas the nationwide limit on sulfur in on-road diesel fuel was 0.05% from 1994 on. The 83% reduction in SO_2 emission required could be met by using 0.05% sulfur fuel, which the railroads would likely choose to do in any case. The effect of the sulfur limit would thus be to prevent the railroads from using high-sulfur diesel in California, which they would otherwise be free to do under existing regulations.

NMHC and CO - Locomotive and VOC emissions from locomotives are presently small, so the only real reason for regulating them is to prevent them from increasing to an unreasonable extent in response to other emission regulations. Dual-fuel engines, for example, can exhibit greatly increased HC and CO emissions if not properly controlled. Natural gas engines are, in any event, likely to result in some NMHC and CO increase, although the NMHC emitted would be much less reactive than those from diesel engines. We recommend that NMHC and CO emissions from locomotives be capped at 200% of the 1987 emission values, which should allow sufficient leeway for possible increases due to LNG. Another alternative would be to allow no net increase in total *reactivity-weighted* VOC (i.e. reduction factors of 0%). For this purpose, CO and methane (both weighted for reactivity) would be counted toward VOC. Reactivity weights would be based on the Carter MIR[44] factors.

13.4 Traffic Volume Adjustments

Our proposed regulatory structure includes adjustments to emission ceilings based on changes in rail traffic volume. These adjustments are designed to accommodate future growth in rail freight and passenger traffic as a result of economic growth or due to modal shift from highway transport modes to rail. Conversely, the proposed structure would eliminate any incentive for *shrinking* rail traffic. It is important not to build in incentives to shift freight that now moves by rail to the highway modes, as the potential for lowering emissions and improving energy efficiency throughout the state is higher with rail transport.

A number of different approaches were considered for adjusting the emission ceilings to account for traffic volume. Of course, one possibility would be not to adjust the emission ceilings at all. However, this would limit the ability of railroads to accept increases in freight and passenger traffic due to economic growth and due to potential mode shifts from highway, ship, or air to rail transport. Such mode shifts are foreseen in the SCAQMD's SIP, and in other air quality plans and regulations. Failure to adjust the ceilings for changing traffic volume would also allow railroads to meet emission standards by reducing service or selling off branchlines, instead of reducing emissions per locomotive. This would be counterproductive, as the traffic would go by other modes instead, and total emissions might actually be higher.

Traffic volume adjustments should be based on some measure of useful work done for society. For line-haul freight railroads, the best proxy for useful work done is net ton-miles of cargo carried. A number of different ton-mile measures are available. All involve multiplying some measure of mass transported by the length of the haul. The available measurements include gross ton-miles (based on total weight of locomotives, cars, and lading), trailing ton miles (based on total weight of cars and lading, excluding locomotives), net ton-miles (weight of lading only, excluding locomotives and car tare weight), and net *revenue* ton miles (same as net ton miles, but excluding mass of materials such as fuel and ballast hauled for the railroad's own use). Net revenue ton miles is the normal measure of useful work accomplished by the railroad, but we are proposing to allow inclusion of nonrevenue cargo to avoid giving the railroads an incentive to ship this material by other means.

Unfortunately, the Booz-Allen report does not provide net ton-mile data, only gross ton-miles. We were able to back out the locomotive weights to get trailing ton-miles (see Appendix A) but further work will be needed to estimate net ton-miles by railroad by air basin.

We have defined three alternatives for allocating the baseline emissions between railroads. These are summarized below, with an outline of the possible methodologies and presentation of the applicable equations.

One possibility would be to base future year emission ceilings for each railroad in each air basin on the ratio of total net ton miles for that railroad in that basin to those for the same railroad in the same basin in 1987. An advantage of this approach is that it accounts for the differences between the topography of different air basins and of different railroads' routes within the same air basin, as these would affect emissions (hillier and more curved routes increase fuel consumption and emissions per ton-mile). A disadvantage is that it tends to reward railroads that had inefficient or less clean operations in 1987 by giving them higher emission ceilings in the future. As the data in Appendix A show, there are significant differences in energy-intensity and emission/ton between different railroads in the same air basin. Unfortunately, we are unable to differentiate those differences that are due to topographic or business factors (e.g. a hillier route or a larger fraction of intermodal freight) from those due to inefficiency. The approach described above can be summarized with the following equation:

$$E_{Y,R} = B_{1987,R} \times \frac{POB}{100} \qquad \textit{(for each basin)}$$

where

$E_{Y,R}$ = Basin ceiling, emissions per net ton-mile (NTM) for railroad R in year Y.
$B_{1987,R}$ = Baseline basin emissions per NTM for railroad R in 1987.
POB = Percent of Baseline (allowable emissions, per Table 54).

An alternative approach would be to base the emission ceiling on the ratio of ton-miles for each railroad to average 1987 emissions and ton miles for *all* line-haul railroads in a given basin. This would avoid rewarding the railroads that were inefficient in 1987, at the cost of ignoring the differences in energy-intensiveness of the different rail routes. This would probably tend to shift freight traffic toward the railroad having the most energy-efficient route, which might be desirable. However, there is also a possibility that this would result in more circuitous routing (because increasing the ton-miles meets the emission ceiling as well as decreasing the emissions), which could increase total emissions even as emissions per ton-mile are reduced. It would also result in at least one railroad having a baseline emission allowance less than its actual estimated emissions in 1987, and this could have serious effects on rail service in individual corridors. We recommend against this approach. The approach described above can be summarized with the following equation:

$$E_{Y,R} = AB_{1987} \times \frac{POB}{100} \qquad \textit{(for each basin)}$$

where

AB_{1987}= Average of baseline emissions per NTM for all railroads in 1987.

Another alternative that was considered was to establish separate emission ceilings for different categories of freight service in each air basin - such as mixed freight, intermodal, and bulk. As the data in Appendix A show, fuel consumption and emissions per trailing ton-mile for intermodal traffic tend to be higher than for mixed freight, which in turn is higher than for bulk transport. Emissions per net ton-mile would presumably show even larger effects (but these effects might be partly offset by the higher yard handling requirements for mixed freight, as opposed to intermodal or bulk). It could be argued that giving different emission allowances for different freight types would help to facilitate modal shifts to rail, as it would tend to give a higher emission allowance per ton-mile for intermodal freight (which is most competitive with trucks). On the other hand, it would reduce the incentive to the railroads to encourage freight to go by the most efficient and lowest-emitting form of carriage, and could thus result in an increase in intermodal shipment at the expense of possibly more-efficient carload (boxcar) operations. The approach described above can be summarized with the following equation:

$$E_{Y,R,M} = B_{1987,R,M} \times \frac{POB}{100} \quad \textit{(for each basin and each mode)}$$

where
$B_{1987,R,M}$= Baseline basin emissions per NTM for railroad R and mode M in 1987.
$E_{Y,R,M}$ = Basin ceiling, emissions per NTM for railroad R, year Y, and mode M.

For short-line and terminal railroads, the concept of ton-miles has limited meaning, as the purpose of these railroads is to get cars from individual shippers to the different line-haul carriers and vice versa. This often involves only relatively short hauls, but considerable handling. It would be difficult to measure and keep track of ton-miles. Therefore, for these roads, we tentatively propose to base the traffic volume adjustment on net tons of traffic handled. If this measure is used, one would need information on net tons handled (and fuel consumed, for emission estimates) in 1987 from each of the short lines. These data are not given in the Booz-Allen study.

For passenger services, the traffic volume adjustment would be based on passenger-miles carried. Passenger-miles and the resulting emission ceilings would be computed separately for Amtrak long-distance and local commuter rail services, as the former is much more energy and pollution-intensive (the fuel consumption and emissions per passenger mile on commuter rail is less since they carry more passengers per train). To accommodate possible future carriage of freight (e.g. mail) by Amtrak, a separate allowance for this freight would be established, based on net ton-miles. Amtrak prefers to have emission based on car-miles rather than passenger-miles, to avoid penalizing sleeper cars (Roberts, 1992), and to avoid penalizing trains that must necessarily run light (*Industry Comments*, Section 2, p. 3). However, this measure could create an incentive to increase the total emissions allowance simply by adding empty cars in California, and this would be counter-productive.

Emission ceilings for new commuter rail lines would (tentatively) take as a baseline the 1987 emissions per passenger mile for the CalTrain service in the Bay Area. This implies that the new Metrolink commuter service in LA would already be meeting the reduction requirements for at least the first several years. The Metrolink locomotives are equipped with separate, optimized engines for traction and head end power, and have their timing retarded 4 and 2 degrees, respectively, for a 25% NOx reduction from the standard version (*Progressive Railroading*, 1992; Fritz, 1992).

13.5 Activity Monitoring and Emission Testing Requirements

The requirements for locomotive activity monitoring and emission testing are two of the key aspects of the proposed regulatory framework. At the public workshop held to discuss the proposal, these requirements were also the most controversial aspects of the proposal that were commented on. It was claimed that locomotive activity monitoring was not feasible, would require technology not now available, would involve excessive burden on the railroads, and was not necessary to the extent as was proposed. Emission testing for all locomotives was also described as unnecessary, time-consuming, and expensive. Figures were presented (based on the assumption that emission testing would require 12 hours per locomotive, and that all line-haul locomotives would be tested) to show that annualized emission testing costs for the Union Pacific alone would be over 11 million dollars per year.

Despite the strong opposition expressed at the public workshop, EF&EE continues to believe that an effective system for monitoring emissions from individual locomotives is essential to effective control of locomotive emissions in the aggregate, especially for a "bubble" program such as the one proposed in this report. Without effective monitoring of locomotive activity, there is no way for anyone - either the ARB or railroad management - to know whether the most efficient and fuel-conserving operating practices are being pursued in the field, whether regulations regarding locomotive idling are complied with, to what extent high-emission locomotives are being used in California due to shortfalls in low-emission locomotive availability, or what emissions in any particular air basin actually are. Without emission testing of individual locomotives, there is no way to confirm that emission control systems are actually working, that repairs intended to correct emission problems have been effective, or that tampering, carelessness, or unforeseen design defects are not resulting in higher emissions than expected. A requirement for locomotive activity monitoring, combined with periodic emission testing, would have much of the effect of the continuous emission monitoring systems now routinely required for major stationary sources, and the rationale for requiring such monitoring would be the same. Furthermore, we believe that the railroads have grossly overstated the costs and other impacts of such monitoring in their comments to the ARB.

Activity monitoring - Time-in-notch or horsepower-hours in each notch in each air basin could be monitored using any of several approaches. The most sophisticated approach would employ locomotive condition monitoring systems (such as Rockwell's LARS system) that are presently available. These data would be reported by radio or similar electronic link to a central office for each railroad, where they would be processed and reported to the ARB every month or so. The ARB would also have the capability of running independent checks, by spot-checking the transmitted operating functions of locomotives in the field, with portable equipment. In addition to continuous monitoring of throttle position, the LARS system and other locomotive condition monitoring systems would provide railroad mechanical staff with direct access to many other variables and indicators of locomotive mechanical condition, from traction power output to fuel on board. Any of these data could be reported and monitored from the central mechanical department *while the locomotive was enroute*. By enabling mechanical problems to be detected and corrections planned while the locomotive is still in service, this system could make a major contribution to service reliability and locomotive utilization, thus reducing the number of locomotives required. Even such a simple feature as determining the fuel on board could make a huge contribution to efficiency, since it is common for locomotives to be fueled three or four times as often as necessary, with a loss of 4-20 hours of utilization every time.

Although locomotive condition monitoring would be an efficient way to monitor locomotive activity, it would not be the only way by any means. For instance, time-in-notch data are *already* being collected routinely using event recorders. All three of the major California railroads use event recorders, and one (Santa Fe) told us that it makes a policy of pulling and analyzing the event recorder tape for every train. This analysis is done with the aid of a computer system, which is programmed to detect and flag violations of operating rules. Given such a system, fulfilling the locomotive monitoring requirement would be as easy as ensuring that every train was equipped with an event recorder, that all of the tapes were pulled and analyzed, and that the data were properly processed and reported to the ARB on a monthly basis. Since about half of all line-haul locomotives are already equipped with event recorders (many of them digital), and since railroads already collect and process these data, the cost of data collection using event recorders would be fairly small. Some means of spot-checking these data would have to be provided, but this presents no major conceptual problems.

Emission testing - Railroad estimates of the costs of periodic emission testing were based on present emission testing procedures employed by Southwest Research Institute (SwRI, 1990). These procedures are said to require about 12 hours to measure emissions in each notch[45]. The testing is also costly - emission measurements on two passenger locomotives before and after retarding the injection timing were reported to take more than a week, and to cost "substantially" in excess of $100,000. This is far more time (and far more money) than such testing would be expected to require if carried out on a routine basis. Assuming that the locomotive was already warmed up, and with allowance for 5 minutes stabilization time and one minute of sampling time in each notch, we would expect the whole process to take about an hour of locomotive time and three person-hours.

As we conceive it, the locomotive emission abbreviated test would be carried out routinely, in the same way that locomotive smoke opacity is checked routinely now under agreements between the SCAQMD and the individual railroads. Each of the railroads' major service facilities would be equipped to carry out these measurements. The testing would be greatly simplified by the fact that most diesel-electric locomotives come with a built-in dynamometer[46]. Units would be operated in all notches while standing still, using either "self-loading" with the dynamic brake grids (if so equipped) or a separate load bank. A portion of the exhaust stream would be extracted, diluted until its temperature was less than 55 °C, passed through a particulate filter, and collected in a bag. Separate pre-weighed particulate filters and bags would be used for each notch; a 5 minute stabilization time in each notch would provide plenty of time to change filters and bags. NOx, CO, CO_2 and gaseous hydrocarbons concentrations in each bag would be determined using standard laboratory analyzers, a carbon balance (combined with simultaneous measurement of fuel flow rates and tractive power output during sampling) would allow emission factors to be calculated in terms of emissions per hour and/or emissions per tractive horsepower-hour in each notch. SOx emission in each notch would be calculated from fuel consumption (which would be taken from the locomotive's own instruments) and the sulfur content of the fuel (assumed to be the statutory maximum unless the railroad demonstrated otherwise).

A portable emission testing unit[47] capable of performing the test procedure outlined above has already been developed and demonstrated at Michigan Technological University. As discussed in Chapter 14, further R&D on this or a similar system would be required to develop standardized equipment and procedures for locomotive testing, but this R&D should be neither very expensive nor very time-consuming. Equipped with laboratory-grade emission analyzers, such a system would probably cost about $200,000 per installation. Locomotives would also need to be equipped permanently with fuel flow transducers, but many are already so equipped, and any units fitted with remote condition monitoring would likely be so equipped as well.

The much longer time required to carry out the SwRI test procedure is in part due to allowing a longer time for stabilization (for instance, waiting for coolant temperature to stabilize in each notch). However, such stabilization would not be required in a short, standardized test, as opposed to the research-type tests undertaken by SWRI. The degree of accuracy and absolute repeatability attained in the SwRI test procedure is not necessary for a routine screening test such as we envision. It would be sufficient that locomotive condition be roughly the same from test to test, and this could be accomplished by defining a set test procedure and time schedule. If necessary, corrections for varying coolant temperature (and air temperature) could also be employed. These corrections would be developed as part of the R&D on the test procedure discussed in Chapter 14.

Since the costs of emission testing are likely to be a significant issue, we have developed an estimate of these costs. This estimate is shown in Table 56. As the table shows, we estimate that each of the 1,138 California fleet locomotives would require about 3 tests per year (one every 6 months, plus one after unscheduled maintenance that would affect

Table 56: Cost of locomotive emission testing.

	Qty.	Units	Rate	Total
Test requirements				
California fleet	1138	units	3 tests/yr	3,414
Non-California	500	units	1 test/yr	500
Total tests				3,914
Capital costs				
Test equipment	12	sets	$200,000	$2,400,000
Structure mods	12	sets	$100,000	$1,200,000
Training and misc.				$1,000,000
Total capital cost				$4,600,000
Annualized cost (5 yrs, 8%)				$1,152,100
Operating Costs Per Test				
Labor time	5	hours	$35.00	$175
Locomotive time	1.5	hours	$25.00	$38
Fuel	50	gallons	$0.70	$35
Operating cost/test				$248
Operating cost/year				$968,715
Total capital plus operating costs per year				**$2,120,815**
Total cost/test				$542
Total locomotive time (hours)				5,871
Tests per facility/year				326
Facility utilization (%)				5.59%

emissions). In addition, we assume about 500 more tests for non-California locomotives that had to enter the controlled area for some reason, in order to quantify their emissions. Twelve test facilities were assumed to be set up at California gateways and major service shops. This large number would ensure that locomotives could easily be tested after service - as the table shows, facility utilization with this number would be less than 6%, and each facility would test less than one locomotive per day on average. Total testing costs would be about $2.2 million per year. The amount of locomotive time lost in testing would be the equivalent of less than one locomotive-year, and would easily be covered by the assumed requirement of 46 extra reserve locomotives in the California fleet.

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14. ASSESSMENT OF RESEARCH AND DEVELOPMENT NEEDS

One of EF&EE's tasks in this study was to identify key areas in which additional public funding is required for research and development (R&D). Based on the analysis given in the preceding chapters, we have identified three areas in which we recommend that the ARB, SCAQMD, and/or other public agencies support further R&D. These areas are:

1. Emission testing - R&D is needed to develop and standardize a suitable short test procedure for measurement of NOx, HC, CO, and PM emissions and fuel consumption in locomotives;

2. Selective catalytic reduction - Funding is required for a program to apply and demonstrate SCR in a line-haul locomotive;

3. Low-emission dual-fuel engines - Funding is required to develop a low-emission dual-fuel conversion system for the EMD locomotive engine, and to demonstrate this engine in line-haul and local service.

There are four major categories to a process of choosing a technological solution to a problem: Performance, Time, Cost, and Risk. Designers of a product or system need extensive information about prospective designs in order to make informed decisions about each of these categories. How well does the design perform? How much time will it take to implement? What will the costs of manufacture and operation be? What are the risks of failure or sub-standard performance? The proposed building and testing of prototypes will provide valuable data to all interested and involved parties to help them select the technology that best suits their needs.

14.1 Emission Testing

As discussed in Chapter 13, periodic measurement of locomotive emissions in each notch is a key requirement for effective monitoring and control of locomotive emissions. It will therefore be necessary to develop an accurate, convenient, and repeatable procedure for measuring these emissions. Traditionally, emission measurements on vehicles have been performed by diluting the entire exhaust stream in a constant-volume sampling (CVS) system. With this system, the pollutant *concentration* in the CVS is proportional to the pollutant *emission rate* (concentration x flowrate) in the exhaust, thus making calculation of mass emission straightforward. Because of the huge volume of exhaust flow from a locomotive engine, however, dilution of the full exhaust is not practical. Therefore, the two components of mass emission (concentration, and flowrate) will need to be determined separately.

Measurement of pollutant concentrations in locomotive exhaust poses no significant technical problem. For the gaseous pollutants, exhaust can simply be withdrawn from the stack, and the concentrations measured. Heated sample lines are necessary to avoid condensation of heavy organics, but these are standard practice. Since most locomotives have turbochargers, the exhaust should be well mixed, making it unimportant exactly where in the stack the sample is withdrawn. For the small number of non-turbocharged locomotives (some of which also have multiple exhaust outlets), it would be necessary to combine the exhausts in a mixing chamber before sampling.

Diesel particulate emission is more difficult to measure, since a significant part of the particulate material is formed by condensation and adsorption of unburned hydrocarbons during the cooling of the hot exhaust. Particulate samples that are collected by filtration of the hot undiluted exhaust may contain less than half of the particulate material that is ultimately discharged into the environment. In order to obtain representative measurements of diesel particulate emission, EPA test procedures for diesel vehicles and engines require that the exhaust be cooled by diluting it with air to below 51.7 °C before filtration, thus modeling the dilution process in the atmosphere. Particulate concentrations in locomotive exhaust could be determined most readily by extracting and diluting a portion of the exhaust to less than 51.7 °C, then passing the diluted gas through a preweighed filter to determine the particulate mass. The dilution ratio would be determined by comparing the concentration of gases such as CO_2 or NOx in the raw exhaust and in the diluted sample. Other techniques are also possible, such as the tapered element oscillating microbalance (TEOM), but would also require dilution.

In order to relate the pollutant concentrations measured in the exhaust to mass emissions, it will be necessary to develop some measure of exhaust flow as well. Possible approaches include: measuring the exhaust flowrate directly (difficult); measuring the intake air flowrate (difficult and uncertain, due to the possibility of air leaks); or measuring the fuel flowrate, then calculating pollutant emission rates using the carbon balance method. The latter approach is relatively simple, since fuel flow is easy to measure, and should provide accuracy comparable to any of the other methods. The major possible confounding effects would come from combustion of lubricating oil, which could add to the CO_2 measured in the exhaust. This could be controlled for, however, in several ways, of which the simplest might be determination of characteristic oil additives in the collected particulate matter.

R&D will be needed, first, to develop a practical and inexpensive test procedure and apparatus, and second, to apply this procedure to a sufficient sample of locomotives to confirm its repeatability and to assess the impacts of environmental factors (such as temperature and humidity) and testing factors (such as length of stabilization time in notch) on the results. Another important requirement will be to confirm the accuracy of this test procedure by validating it against the ARB-standard dilution tunnel technique. This validation testing would have to be carried out using a smaller engine, such as a truck engine, in order to be able to use existing dilution tunnels.

The time required for development and validation of the test procedure would be around 6 months. Another 6 months of testing on locomotives would be required in order to develop the details of the test procedure (such as stabilization time), to confirm the accuracy and repeatability of the procedure, and to develop corrections for environmental variables, such as temperature and humidity, if required. The estimated cost of this testing (by an outside contractor) would be around $200,000, plus the costs of the test equipment. If all-new analyzers and sampling gear were to be used, this might add another $200,000 to the cost (the apparatus would then be turned over to the ARB for field enforcement use).

14.2 Selective Catalytic Reduction

As discussed in Chapter 9, selective catalytic reduction has great potential for reducing locomotive NOx emission, and could even be retrofit to the existing locomotive fleet. Before this can be accomplished on a large scale, however, it will be necessary to carry out some development work to identify the best catalyst and reactor configuration, and to demonstrate the feasibility of the retrofit in an actual locomotive. The best locomotive model for such a demonstration would probably be the EMD SD40-2. As discussed in Chapters 3 and 4, these locomotives are presently very common, and (with the similar SD45-2) would likely constitute the bulk of a separate California locomotive fleet. They are also available for lease or purchase at moderate cost, making them suitable for a demonstration.

A suitable team to carry out such a demonstration would include a firm specializing in locomotive rebuilding and modification, an SCR catalyst supplier, and an organization with expertise in locomotive emissions and testing. A major railroad would also be required to serve as the "host" for the demonstration. The railroad would supply the locomotive, and would be paid a standard daily lease rate for days when the locomotive was not available for service as a result of the study. Alternatively, a locomotive could be leased or purchased for the study, and then leased to the railroad (again, on a daily basis) for the demonstration.

Development and preliminary testing of an SCR-equipped locomotive would probably take about two years. This would include laboratory testing to define emission baselines and explore the effects of different catalysts, followed by design, fabrication, and installation of the retrofit catalyst system. Following this installation, the locomotive would be subjected to preliminary load and emission testing to confirm the effectiveness of the catalyst, and to a durability test to confirm that the catalyst remained effective (a short, "accelerated" durability test, one to two months in duration, where components are subjected to a much harsher operating environment (and/or greater loads) than they would be expected to see in normal service, would give engineers the data they needed to infer the field performance of those components). The SCR-equipped locomotive would then be delivered to the railroad, where it would enter into revenue service. To increase confidence in the technology, a second locomotive should also be converted, once the results of the durability testing on the first locomotive are shown to be acceptable. Periodic checks and emission testing would take place over the following two years to confirm the continued functioning of the system and to assess deterioration rates. The reasons for any failures would also be determined.

The costs of this project would depend on the locomotive and SCR system selected. The costs of the SCR system and installation, including the extra costs for engineering on the *first* such system, would probably be around $600,000, but could be significantly less if the SCR manufacturer were willing to absorb some of the costs in order to participate in this potentially huge market. The second SCR unit should cost about $400,000, installed. Lease costs for the time the locomotives are out of service would probably be around $300,000. Performance monitoring, emission testing, and project management over four years would add about $400,000 to the costs. A substantial provision for contingencies should also be included, in case of unforeseen problems requiring (e.g.) replacement of the catalyst. Overall, the cost of the program would probably be around $1.9 to $2.1 million.

14.3 Low-Emission Dual-Fuel Engines

LNG for motive power requires no public funding for demonstration purposes. Dual-fuel locomotives conversions have already been developed, and two demonstration locomotives are pulling daily revenue trains between Western Montana and Wisconsin. Spark-ignited engines are well-established and well-developed, in sizes appropriate for locomotive use. Manufacturers are already intensively researching high pressure gaseous injection, LNG tenders, high BMEP gas engines and other technologies in order to get a jump on the market. However, the major focus of this latter work is on new engines, using direct injection of natural gas. As discussed in Chapter 10, this technology has less potential for controlling emissions than dual-fuel or spark-ignition homogeneous charge technology. In the case low pressure indirect natural gas injection, as with the two Burlington Northern dual-fuel locomotives, the focus of the technological development has been on a working prototype that matched the diesel's power output, rather than on minimizing emissions. A system configured like the BN system has the best potential as a retrofit package for existing locomotives. Although NOx emission levels of the two BN engines are about 60% less than a diesel, there is still considerable room for further reductions. In addition, work is needed to reduce HC and CO emissions from the dual-fuel engines, especially at light and moderate loads, and to reduce or eliminate the need to operate on diesel fuel only at idle and in lowest-power notch settings. The new low-emission dual-fuel engines would then need to be demonstrated in service. We would recommend that this demonstration involve at least two units.

The project team for an effort of this nature would need to include an organization experienced in overhauling and retrofitting locomotives, an organization experienced with dual-natural gas engine technology, and an organization experienced with locomotive emissions and measurement. In addition, an LNG supplier would be needed to provide the fuel, and a major railroad would have to be involved as the "host" for the demonstration. To minimize the demonstration costs for LNG fueling infrastructure, etc., it would be desirable to integrate this demonstration with one of the demonstrations of LNG fuel technology that are already in progress (at BN) or planned (e.g. at UP).

The low-emission dual-fuel system would most likely be based on an advanced, electronically-controllable pilot fuel injection system. To minimize costs, and ensure continuing operation on diesel, the existing diesel unit injector system would most likely be left in place, and supplemented with a separate electro-hydraulic fuel injector sized for efficient operation with pilot fuel quantities. A separate electronic or mechanical fuel injection system would also be required for the natural gas. The cost of this electro-hydraulic fuel system, natural gas fuel injectors, controllers, valves, and associated technical support are estimated at around $300,000 to $500,000 for the first one, and about $150,000 for the second. Laboratory time, fuel, and other requirements to optimize the system in the laboratory are estimated to add another $300,000 to this cost.

Since the low-emission dual-fuel technology would be intended to be retrofit at the time of major overhaul, it would be necessary to include the costs of overhauling the engine, electrical system, and controls in the demonstration cost. These are estimated at around $450,000 per locomotive. Additional costs for special engine power assemblies (cylinder heads and pistons) are estimated at $50,000 per locomotive. An LNG tender to serve both locomotives would cost about $350,000. Costs of program management, emission testing, and monitoring over four years would be around $400,000, for a total cost (including contingencies) of about $3.0 million. In this case, we assume that the owning railroad would provide the use of the locomotives to be converted and the fuel at no charge to the project, in return for having the overhaul costs paid. These costs do not include the cost of a catalytic converter or other add-on devices (such as SCR).

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APPENDIX A: TON-MILE DATA

Table A-1: Passenger train 6-basin emissions and emission factors.

AMTRAK/CALTRAIN														
			ANNUAL EMISSIONS (METRIC TONS)						EMISSION FACTORS (G/PASSENGER-MILE)				
BASIN	TRAIN TYPE	PASSENGER-MILES (MILLIONS)	PM	NOx	CO	HC	SO2	FUEL (THOUSAND GALS)	PM	NOx	CO	HC	SO2
SV	P	26	2	108	7	3	10	490	0.09	4.11	0.28	0.12	0.38
SJ	P	75	3	125	7	3	12	572	0.04	1.67	0.09	0.04	0.15
SD	P	111	3	150	12	5	14	686	0.03	1.35	0.11	0.04	0.13
SC	P	171	6	245	20	8	23	1,123	0.03	1.43	0.12	0.05	0.13
CC	P	16	3	118	6	3	11	538	0.16	7.19	0.38	0.19	0.66
BA	P	64	2	105	9	4	10	475	0.04	1.66	0.15	0.06	0.15
BA[1]	P	342[2]	5	223	12	6	21	1,027[2]	0.01	0.65	0.04	0.02	0.06
AMTRAK/CALTRAIN TOTALS:		806	24	1,076	74	32	100	4,910	0.03	1.34	0.09	0.04	0.12
AMTRAK/CALTRAIN FUEL FACTOR, PASSENGER-MILES PER GALLON:								164					

1 This part of Bay Area inventory is for San Francisco - San Jose CalTrain commute passenger service only.

2 CalTrain's recent data show 3 million gallons total diesel consumption per year, and 150 million passenger-miles (*Industry Comments*, Section 1).

Table A-2: Southern Pacific 6-basin emissions and emission factors.

SOUTHERN PACIFIC													
			ANNUAL EMISSIONS (METRIC TONS)						EMISSION FACTORS (G/TON - MILE)				
BASIN (2)	TRAIN TYPE	TRAILING TON - MILES (MILLIONS)	PM	NOx	CO	HC	SO2	FUEL (THOUSAND GALS)	PM	NOx	CO	HC	SO2
SV	BASIN TOTALS	8960	117	5,572	653	202	411	23,984	0.013	0.622	0.073	0.023	0.046
	YARD	ND[1]	7	285	43	16	15	1,152	ND	ND	ND	ND	ND
	MIXED	6052	57	2,737	302	91	205	11,939	0.009	0.452	0.050	0.015	0.034
	LOCAL	ND	20	930	133	42	70	3,816	ND	ND	ND	ND	ND
	INTERMODAL	2910	34	1,620	175	53	122	7,078	0.012	0.557	0.060	0.018	0.042
SJ	BASIN TOTALS	9623	106	4,969	603	192	371	21,247	0.011	0.516	0.063	0.020	0.039
	YARD	ND	3	143	22	8	7	576	ND	ND	ND	ND	ND
	MIXED	7028	46	2,158	238	76	162	9,445	0.007	0.307	0.034	0.011	0.023
	LOCAL	ND	36	1,667	238	75	126	6,842	ND	ND	ND	ND	ND
	INTERMODAL	2598	21	1,002	106	33	75	4,385	0.008	0.386	0.041	0.013	0.029
SC	BASIN TOTALS	5603	124	5,586	803	263	394	23,761	0.022	0.997	0.143	0.047	0.070
	YARD	ND	26	1,141	173	65	59	4,607	ND	ND	ND	ND	ND
	MIXED	2105	30	1,311	198	62	99	5,746	0.014	0.623	0.094	0.029	0.047
	LOCAL	ND	26	1,234	176	55	93	5,065	ND	ND	ND	ND	ND
	INTERMODAL	2987	37	1,670	221	69	126	7,331	0.012	0.559	0.074	0.023	0.042
	BULK	515	5	229	36	12	17	1,011	0.010	0.445	0.070	0.023	0.034
CC	BASIN TOTALS	5197	54	2,571	308	95	193	10,967	0.010	0.495	0.059	0.018	0.037
	MIXED	4383	25	1,213	128	39	91	5,300	0.006	0.277	0.029	0.009	0.021
	LOCAL	ND	21	1,002	143	45	76	4,111	ND	ND	ND	ND	ND
	INTERMODAL	815	7	356	36	11	27	1,556	0.009	0.436	0.045	0.014	0.033
BA	BASIN TOTALS	1805	64	2,908	407	134	205	12,173	0.035	1.611	0.226	0.074	0.113
	YARD	ND	14	606	92	34	31	2,448	ND	ND	ND	ND	ND
	MIXED	1106	13	598	75	24	45	2,612	0.012	0.541	0.068	0.021	0.041
	LOCAL	ND	27	1,243	178	56	94	5,103	ND	ND	ND	ND	ND
	INTERMODAL	703	10	460	63	20	35	2,010	0.015	0.655	0.089	0.029	0.049
SP SYSTEM TOTALS:		31,187	464	21,606	2,774	887	1,574	92,133	0.015	0.693	0.089	0.028	0.050
SP FUEL FACTOR (TON-MILES PER GALLON):								339					

1 "No Data" - ton-mile data not available for this mode.
2 SV - Sacramento Valley; SJ - San Joaquin Valley; SC - South Coast; CC - Central Coast; BA - Bay Area

Table A-3: Santa Fe 6-basin emissions and emission factors.

SANTA FE													
			ANNUAL EMISSIONS (METRIC TONS)						EMISSION FACTORS (G/TON - MILE)				
BASIN	TRAIN TYPE	TRAILING TON-MILES (MILLIONS)	PM	NOx	CO	HC	SO2	FUEL (THOUSAND GALS)	PM	NOx	CO	HC	SO2
SJ	BASIN TOTALS	4,636	48	2,085	329	103	146	9,212	0.010	0.450	0.071	0.022	0.032
	YARD	ND[1]	1	38	5	2	2	147	ND	ND	ND	ND	ND
	MIXED	2,308	19	809	133	42	57	3,595	0.008	0.350	0.058	0.018	0.025
	INTERMODAL	2,326	28	1,238	191	58	87	5,468	0.012	0.532	0.082	0.025	0.037
	BULK	2	0.02	0.37	0.13	0.05	0.03	2	0.009	0.215	0.073	0.030	0.017
SC	BASIN TOTALS	2,737[2]	65	2,792	460	150	194	12,252	0.024	1.020	0.168	0.055	0.071
	YARD	ND	7	303	40	16	18	1,180	ND	ND	ND	ND	ND
	LOCAL	ND	3	151	25	8	10	659	ND	ND	ND	ND	ND
	INTERMODAL	1,189	28	1,228	198	62	87	5,453	0.024	1.032	0.167	0.052	0.073
	BULK	11	0.09	4	1	0.25	0.26	16	0.008	0.312	0.063	0.022	0.022
BA	BASIN TOTALS	564	6	263	45	15	18	1,141	0.011	0.467	0.080	0.027	0.032
	YARD	ND	1	38	5	2	2	147	ND	ND	ND	ND	ND
	MIXED	319	2	98	17	6	7	430	0.007	0.306	0.055	0.018	0.021
	INTERMODAL	246	3	128	23	8	9	563	0.012	0.521	0.094	0.031	0.036
SF SYSTEM TOTALS:		7,937	119	5,140	835	268	358	22,604	0.015	0.648	0.105	0.034	0.045
SF FUEL FACTOR (TON-MILES PER GALLON):								351					

1 "No Data" - ton-mile data not available for this mode.
2 Includes "Light Engine" (locomotive only) movement.

Table A-4: Union Pacific 6-basin emissions and emission factors.

UNION PACIFIC													
			ANNUAL EMISSIONS (METRIC TONS)						EMISSION FACTORS (G/TON - MILE)				
BASIN	TRAIN TYPE	TRAILING TON-MILES (MILLIONS)	PM	NOx	CO	HC	SO2	FUEL (THOUSAND GALS)	PM	NOx	CO	HC	SO2
SV	BASIN TOTALS	1834	16	733	103	29	50	3207	0.009	0.400	0.056	0.016	0.027
	YARD	ND	0.4	19	3	1	1	74	ND	ND	ND	ND	ND
	MIXED	1012	7	326	46	13	22	1434	0.007	0.322	0.045	0.013	0.022
	LOCAL	ND	2	81	12	4	6	337	ND	ND	ND	ND	ND
	INTERMODAL	487	5	235	32	8	16	1045	0.010	0.484	0.066	0.016	0.033
	BULK	335	2	72	10	3	5	316	0.005	0.214	0.031	0.008	0.015
SJ	BASIN TOTALS	499	13	609	85	31	40	2534	0.026	1.221	0.170	0.061	0.081
	YARD	ND	5	227	31	16	14	888	ND	ND	ND	ND	ND
	MIXED	235	2	100	13	3	7	443	0.009	0.427	0.054	0.014	0.029
	INTERMODAL	198	3	120	17	4	8	528	0.013	0.606	0.088	0.022	0.041
	BULK	67	0.4	20	3	1	1	89	0.006	0.305	0.039	0.009	0.021
SC	BASIN TOTALS	1358	31	1403	216	70	96	6003	0.023	1.033	0.159	0.052	0.071
	YARD	ND	6	246	34	17	15	962	ND	ND	ND	ND	ND
	MIXED	685	7	327	55	15	23	1471	0.011	0.478	0.080	0.022	0.034
	LOCAL	ND	10	467	68	22	32	1939	ND	ND	ND	ND	ND
	INTERMODAL	491	7	322	53	15	23	1446	0.015	0.656	0.107	0.030	0.046
	BULK	184	1	41	7	2	3	185	0.005	0.222	0.036	0.010	0.016
BA	BASIN TOTALS	410	9	432	61	20	30	1844	0.023	1.053	0.150	0.049	0.072
	YARD	ND	2	76	10	5	5	296	ND	ND	ND	ND	ND
	MIXED	168	1	63	9	2	4	284	0.008	0.379	0.052	0.014	0.026
	LOCAL	ND	3	151	22	7	10	627	ND	ND	ND	ND	ND
	INTERMODAL	206	3	134	19	5	9	605	0.014	0.654	0.093	0.025	0.046
	BULK	37	0.2	7	1	0.3	0.5	31	0.004	0.186	0.028	0.007	0.013
UP SYSTEM TOTALS:		4,101	70	3177	465	149	216	13588	0.017	0.775	0.113	0.036	0.053
UP FUEL FACTOR, TON-MILES PER GALLON:								302					

1 "No Data" - ton-mile data not available for this mode.

APPENDIX B: ACRONYMS AND DEFINITIONS

49-state	-	applies to continental United States, excluding California
AAR	-	Association of American Railroads
AC	-	Alternating Current
Amtrak	-	National Railroad Passenger Corporation
AQMD	-	Air Quality Management District
ARB, CARB	-	California Air Resources Board
ARES	-	Advanced Railroad Electronics System, a product of Rockwell International
ATCS	-	Advanced Train Control Systems
BAH	-	Booz-Allen & Hamilton, Inc.
BART	-	Bay Area Rapid Transit; rail transit agency in the Bay Area of Northern California
BMEP	-	Brake Mean Effective Pressure; a measure of an engine's ability to do work, based on the brake horsepower or brake torque (indicated minus friction); the *work per cycle*
BN	-	Burlington Northern Railroad Company
Booz-Allen	-	Booz-Allen & Hamilton, Inc.
BTU	-	British Thermal Units; a measure of energy
bubble	-	a regulatory approach that concerns total emissions or emission inventories, rather than the technologies to control those emissions
CA (Ca)	-	California
CalTrain	-	Commuter rail service between San Francisco and San Jose
Caltrans	-	California Department of Transportation
CAT, or Cat	-	Caterpillar, Incorporated
CNG	-	Compressed Natural Gas
CO	-	Carbon Monoxide
COFC	-	Container-On-Flat-Car; the practice of mounting multimodal shipping containers on flat cars modified or designed to carry them
DC	-	Direct Current
DDC, or Detroit	-	Detroit Diesel (engine manufacturer)
DING	-	Direct Injection Natural Gas
EMD	-	Electro-Motive Division of General Motors

EMI	-	Electro-Magnetic Interference
EPA	-	Environmental Protection Agency
feedstock	-	raw material or fuel for a process
FRA	-	Federal Railroad Administration
g/BHP-hr	-	Grams per Brake-Horsepower-hr; a measure of consumption or output that is independent of engine power or time
G-forces	-	Forces caused by acceleration; in units of "gravity"
gateway	-	In a California-only locomotive fleet scheme, a location designated as an official point of entry into the state, where low-emission locomotives are exchanged for 49-state locomotives
GE	-	General Electric Transportation Company
GPS	-	Global Position Satellite; technology that allows one to determine one's location nearly anywhere in the world
GTM	-	Gross Ton-Miles
HC	-	Hydrocarbons
HEP	-	Head End Power
HP	-	Horsepower
ICC	-	Interstate Commerce Commission
IDI	-	Indirect Injection
incremental cost	-	the cost difference between the advanced, low-emission technology choice and the standard, accepted technology choice
Industrial railroad	-	railroad owned by, operated for, and located wholly on the property of a private company or government agency
kV	-	kilo-Volts
KW(e)	-	Kilo-watts of electrical (as opposed to mechanical) energy
LARS	-	Locomotive Analysis and Reporting System (Rockwell)
LMS	-	Locomotive Management System
LNG	-	Liquid Natural Gas
LPG	-	Liquid Petroleum Gas
MARC	-	Maryland State Railroad Administration
MEP	-	Mean Effective Pressure - see BMEP
MIR	-	Maximum Incremental Reactivity
MM	-	Million
MW	-	Mega-watts (million watts)
MU	-	Multiple Unit, the practice of operating two or more locomotives, coupled together, in a single train
NEC	-	NorthEast Corridor, referring to the tracks owned by Amtrak in the Northeastern United States
NMHC	-	Non-methane Hydrocarbons
NOx	-	Oxides of Nitrogen, including NO and NO_2
NTM	-	Net Ton-Miles
O/M	-	Operation and Maintenance
OCS	-	Overhead Catenary System

OCTC	-	Orange County (Ca) Transportation Commission
OEM	-	Original Equipment Manufacturer
PEEC	-	Programmable Electronic Engine Control; a product of Caterpillar, Inc.
PG&E	-	Pacific Gas & Electric Company (Northern California)
PM	-	Particulate Matter
ppm	-	Parts Per Million
psi	-	Pounds per Square Inch
PSC	-	Public Service Commission
PTO	-	Power Take-Off; secondary mechanical drive from an engine or power plant
R&D	-	Research and Development
RCTC	-	Riverside County (So. California) Transportation Commission
RFI	-	Radio-Frequency Interference
RFP	-	Request for Proposals
RLM	-	Refrigerated Liquid Methane; like LNG, only more pure
RPM	-	Revolutions Per Minute
S & T	-	Signalling and Train Control
SCAQMD	-	South Coast Air Quality Management District
SCR	-	Selective Catalytic Reduction
SCRRA	-	Southern California Regional Rail Authority; the body that oversees all rail projects and operations in the counties of Los Angeles and surrounding
SEPTA	-	Southeastern Pennsylvania Transportation Authority
SF	-	Atchison, Topeka, and Santa Fe Railway Company
shortline	-	term for small railroads; there are two types, line-haul carriers and switching or terminal railroads
SI	-	Spark Ignited; uses a spark to ignite combustion gases
SIP	-	State Implementation Plan
SOF	-	Soluble Organic Fraction
SOx	-	Oxides of Sulfur, notably sulfur dioxide (SO_2)
SP	-	Southern Pacific Transportation Company
SwRI	-	Southwest Research Institute
TA	-	turbocharged and aftercooled
TCM	-	Transportation Control Measure
TEOM	-	Tapered Element Oscillating Microbalance (particulate measurement)
TOFC	-	Trailer On Flat Car
TTM	-	Trailing Ton-Miles
UP	-	Union Pacific Railroad
vDC	-	volts of Direct Current
VOC	-	Volatile Organic Compounds

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APPENDIX C: RESPONSE TO PUBLIC COMMENTS

A public workshop was held February 16th, 1994, in El Monte to discuss the previous version of this report and ARB's plans for regulating locomotive emissions. Written comments were submitted by a number of organizations associated with the railroad industry, including Amtrak, the Association of American Railroads (AAR), the American Short Line Railroad Association, the Engine Manufacturers Association, and by California Environmental Associates on behalf of the AAR. Other organizations submitting comments included Southern California Edison, the California Energy Commission, and Allied International Corporation - a manufacturer of gas turbines. The full text of these comments is available under separate cover.

The Energy Commission and Allied International comments described additional emission control measures not considered in our report. These measures were water injection (Energy Commission) and substitution of low-emitting gas-turbine engines for diesels (Allied International). Neither of these comments affects the fundamental conclusion of our study - that drastic reductions in locomotive NOx emissions are both feasible and cost-effective, and that the best and lowest-risk way to achieve these reductions is through a "bubble" strategy. Indeed, to the extent that these added emission control measures are feasible and cost-effective, these comments only strengthen that conclusion.

Southern California Edison's comments disputed details of our analysis of the railroad electrification option. Edison also requested that we redo this analysis to show the costs and emission reductions on a segment-by-segment basis, to take credit in the cost-effectiveness analysis for reducing locomotive emissions in the Southeast Desert Air Basin, and to incorporate projected future growth in locomotive traffic. Given the logistic problems associated with changing locomotive types, we do not consider it feasible to electrify only a few segments of the mainline locomotive network in California, and therefore do not consider it appropriate to assess cost-effectiveness on a segment-by-segment basis. For the reasons discussed in Chapter 12, we also consider it inappropriate to take credit for emission reductions in the Southeast Desert in calculating cost-effectiveness[††]. Furthermore, even if we took Edison's comments into account, this would not change our fundamental conclusion that rail electrification is much more expensive than other measures that would give almost as great a reduction in emissions.

[††] We maintain that not considering reductions in the Southeast Desert basin was a valid approach, even though that area is in non-attainment for ozone and PM (both state and federal standards), as well as for California's sulfates and hydrogen sulfide requirements, as of 1993.

The railroad industry comments addressed many aspects of our study. The main points can be summarized briefly as follows:

1. Our estimates of the cost of establishing a California-only fleet are too low - both because our unit cost estimates are too low, and because we have underestimated the number of locomotives that would be included in this fleet. Our estimate of locomotive numbers was based mostly on the traffic data in the Booz-Allen inventory for 1987. Up-to-date information on rail traffic provided by the industry shows substantially greater traffic volumes, suggesting that our estimates of locomotive numbers and costs may be significantly low. By the same token, however, higher locomotive traffic implies higher emissions, suggesting that the emissions inventory data may be too low as well. Thus, the costs per ton of emissions reduction would be about the same.

   Even if the industry estimates of the cost of the California-only fleet are correct, it would have little effect on our conclusions. As documented in the box at the end of Chapter 13, we repeated our cost-effectiveness calculations using the industry cost estimates, while assuming *no* change in emissions since 1987. The resulting costs-per-ton values were higher than our primary estimates, but still well within the cost-effectiveness range considered reasonable by the ARB and SCAQMD.

2. Our assumption that most railroads would use converted SD40-2 and similar locomotives for the California-only fleet is incorrect. The railroad industry expended considerable space in arguing that SD40-2s would make up only a small part of their locomotive fleets in the future, and that they would not be used significantly for line-haul service. In the year and half since this analysis was performed, a number of significant advances in locomotive technology have been announced, leading to the introduction of a new generation of high-horsepower, AC traction locomotives, and accelerated retirement of older, less-efficient models such as the SD40-2. In the case of GE, these new locomotives will incorporate a new engine as well. Although individually costly, the new AC locomotives are much more productive, and railroads have ordered significant numbers of them. This situation was not foreseen in our report, or in the fleet composition projections provided to us by the railroads. Indeed, based on representations by the railroads, we had considered it unlikely that they could muster the capital resources for such large-scale investment in new equipment. It was for this reason that our study concentrated on feasible retrofit technologies for the existing locomotive fleet, rather than possible emission reductions with new locomotives.

   This change in expectations regarding the future locomotive fleet does not affect our conclusions in any fundamental way. Low-emission technologies such as SCR and natural gas engines should be much less expensive to incorporate in new locomotives than to retrofit to existing units. To the extent that railroads choose to purchase new locomotives, they could specify that these be supplied with low-emission technology. In addition, the present generation of line-haul locomotives (EMD GP60s and SD60s and GE Dash-8s) will continue to be used for some time. Any of these could be retrofit with SCR, and at least the EMD locomotives could be retrofit with LNG dual-fuel systems as well. Furthermore, it is clear that a significant number of SD40-2s will remain in service for some time, at least for local service.

3. LNG and SCR have not been shown to be feasible in railroad service. The railroads claim that there is insufficient experience with LNG or SCR in railroad service to conclude that these are feasible control technologies. In so doing, they attempt to establish a standard for "feasibility" that would essentially require that a technology would already have to be in commercial service to be considered "feasible". The ARB historically has not accepted such a standard - indeed, the ARB's history is replete with instances of technology-forcing emission mandates. In the case of dual-fuel LNG, two locomotives have operated successfully on this fuel for more than a year. It is difficult to imagine a more conclusive demonstration of feasibility. Although no similar demonstration has been carried out for SCR, this is essentially because - in the absence of emission regulations - there is no economic incentive for SCR use. The record of SCR use in stationary and mobile applications is sufficiently strong that we feel confident in our conclusion that SCR use is technically feasible for locomotives.

4. Our estimates of LNG fuel costs and capital costs of conversion are too low. The railroad industry disputes our estimates of the capital and operating costs of gas liquefaction plants, as well as the resulting cost estimates for LNG. In addition, it is stated that dual-fuel locomotive conversion systems are presently being marketed at a price of $250,000, instead of the $114,000 estimated in our report. With regard to the capital and operating cost estimates, these were based on data from LNG plant vendors, and we consider them reasonable. With regard to their stated conversion cost, we point out that this is the asking price for a newly-developed conversion system, only two units of which are in operation. This price presumably includes some provision for recovering the development costs. Our estimate was based on volume production of such a system, which would result in substantial production economies, and allow the development costs to be spread over a much larger number of units. Even if the industry cost estimates were correct, however, it would not affect our fundamental conclusion that LNG offers a highly cost-effective option for reducing locomotive emissions. Finally, railroads would be under no obligation to use LNG - if the cost of LNG were too high, they could choose to use SCR, gas turbines, or possible other not-yet-identified technologies instead.

5. Our report assigns too little weight to emission reductions from improved diesel technology. We find this comment ironic, since the industry can supply so little data on potential improvements in diesel emissions performance. In Chapter 7, we estimated that an "engineered" retrofit package might cost $100,000, and reduce NOx emissions to 7 g/BHP-hr with a fuel consumption penalty of 4%. We considered these estimates extremely conservative - nonetheless, they showed very attractive levels of cost-effectiveness. The industry comments suggest that the

actual price charged by EMD for such a retrofit package might be only $40,000 to $80,000, while for GE they would be around $200,000 per locomotive. The resulting emissions are estimated at 8 g/BHP-hr, giving cost-per-ton values (for the EMD locomotives) even less than ours. We are gratified to see that our view of the feasibility of such engineered retrofit packages is confirmed by the industry, and that our cost estimates may even have been too high in this case. This suggests that the railroad industry should be able to exceed the NOx reduction targets we have recommended for the first five years by a substantial margin, and at modest cost - thus buying themselves additional time to perfect the more advanced technologies required to meet the long-term emission goals. As is clear from our report, however, the level of long-term emissions reduction estimated to be possible using diesel engine modifications alone would not meet the levels required to attain healthful air quality in the South Coast AQMD and other non-attainment areas of California. Thus, some more effective technology - SCR, LNG, electrification, gas-turbines, or some technology not yet considered - would be necessary in the long run.

APPENDIX D: ENDNOTES

1. Air basins are geographical areas characterized by their air quality as defined by the ARB. The six air basins with the worst air quality are: Bay Area, Sacramento, San Joaquin Valley, Central Coast, South Coast, and San Diego. As of 1995, all of these fail federal and state standards for ozone, except the Bay Area. Several are also non-attainment for PM_{10}.

2. Fuel cell technology, as a control measure, was also considered. Fuel cells are being investigated by both private companies and public agencies. However, we feel that at least 10 years of development is necessary before fuel cells can compete in energy density and price with the technologies we have studied here, which are available now, or could be in the short term. Fuel cells that could power a locomotive at the moment need much more space than is available within the confines of a locomotive carbody. Fuel cell applications will require very extensive engineering and development for the harsh locomotive environment as well.

3. According to the *Industry Comments*, these plans have now been canceled, due to increased cost estimates for constructing the West Colton shop.

4. Manufacturers are now offering and some railroads are buying high-horsepower locomotives with AC traction motors. AC traction's higher reliability and higher pulling power (over DC traction) leads to claims that 3 high-horsepower AC units can replace 5 older DC units (*Industry Comments*, Section 11, p. 34).

5. Some F40PHs, such as the 20 CalTrain units, do not have dynamic brakes. See *Industry Comments*, Section 1.

6. The railroads maintain that locomotive utilization is around 90%—much higher than our estimate of 65%. But our utilization estimate does not include time spent waiting for assignment, between repairs or maintenance and actually pulling trains, while theirs does. We say that a locomotive waiting for assignment is *available*, but it is not being *utilized*. When determining how many locomotives are needed to pull trains, using the 65% figure is much more conservative.

7. Because the duty cycles used are composites representing several different locomotive models and several different locomotive applications, they should be treated as approximations, not absolutes.

8. Shortlines estimate 20,000 gallons per year per locomotive. See *Industry Comments*, Section 4, p. 3.

9. Since this was written, the railroads have revised this to 13.5%. See Industry Comments, Section 11, p. 60.

10. The railroads have disagreed with this contention, saying that high emission reduction potentials would lead them to convert line-hauls instead. See *Industry Comments*, Section 11, p. 64.

11. The three railroads carry different mixes of commodities in different proportions, and traffic demand varies by commodity, so therefore the traffic peaks (and therefore power demands) are different for the different railroads.

12. The NOx emission in attainment areas, while a sizable portion of the statewide total, does (did) not contribute to exceedance of state and federal air quality standards (as of 1991), and affects only a small portion of the population.

13. Units that are old or possessing outdated technology and requiring increasingly greater amounts of attention from maintenance departments are those most likely to be relegated to storage. However, in times of power shortage these locomotives are pressed back into service. Southern Pacific, for example, is running nearly antique GP9s and SD40s at the same time they are buying new SD70Ms. The railroads claim that there are presently (mid-1994) only 300 - 400 locomotives of any type laid up in operating or non-operating condition. See *Industry Comments*, Section 11, p. 37.

14. The railroads believe this method under-estimates the number of locomotives typically operating in the state. See *Industry Comments*, Section 11, p. 45.

15. "*SP has approximately 150 line-haul locomotives working on trains daily in California, another 150 units in terminals awaiting assignment, servicing, etc.*"; Harstad, 1992.

16. Southern Pacific states that the number available for work is closer to 425. See *Industry Comments*, Section 8, p. 13.

17. According to the *Industry Comments*, Section 8, p. 15, the actual number of Southern Pacific trains each way is 116. As discussed in Appendix C, the large discrepancy between this number and our estimate based on the Booz-Allen data suggests that total emissions due to this traffic may be greatly underestimated as well.

18. Amtrak actually enters the state by two routes in the south, but we do not believe additional locomotives would be justified simply because of this fact. Increases in service frequency would *probably* require additional support locomotives. See *Industry Comments*, Section 2, p. 5.

19. Amtrak has stated they would probably use Salt Lake City as the gateway for trains traveling through Reno and Las Vegas, since that city is for Amtrak both a service center and a crew change point (*Industry Comments*, Section 10, p. 3).

20. Amtrak argues that more than twice as many reserve locomotives than we have predicted would be required, to provide maintenance spares and to protect for extremely late trains (*Industry Comments*, Section 2, p. 5). Amtrak also says that freight locomotives should not be used in MU (Multiple Unit) operation with passenger locomotives, because passenger locomotives are geared much higher speeds (100+ mph versus 80 mph), and because their passenger trains cannot rely on just one source for HEP (*Industry Comments*, Section 2, p. 5). These contentions need some qualification, in our view. Gearing does not limit Amtrak's speed in the West; FRA and freight railroad speed restrictions do. Few stretches of track in California or the surrounding states are rated for higher than 79 mph, a speed at which many line-haul freights operate. In a number of places the freight railroads have placed further restrictions on speed, which Amtrak must adhere to, and on which Amtrak schedules are based. Therefore, except for the delay in obtaining the equipment, MU'ing with freight locomotives would not likely compromise Amtrak's schedule. We acknowledge that an HEP failure would be very detrimental to Amtrak's service quality goals. We repeat that Amtrak already uses freight locomotives *in extreme cases*, and we contend that the likelihood of such cases would not be increased by the imposition of a California-only fleet, especially if all the railroads, including Amtrak, are allowed to operate non-California locomotives when they need to inside the air basins (and those emissions are properly accounted for).

21. And for Amtrak, some locomotive storage and service costs (*Industry Comments*, Section 2, p. 5).

22. Southern Pacific has since dropped plans for a move to West Colton, for the stated reason that the cost climbed to $25 million (*Industry Comments*, Section 8, pages 17, 18, and 19).

23. Amtrak may choose to have entirely different gateways, to coincide with their existing service facilities and crew change points (*Industry Comments*, Section 2).

24. Southern Pacific asserts that they now lubricate track extensively, using wayside oilers and trucks. See *Industry Comments*, Section 11, p. 65.

25. The railroads claim that locomotive turnover in the next 10 years will be much higher than in the past 10 years. See *Industry Comments*, Section 11, pages 29, 30, & 31.

26. Water emulsification (mixing with diesel fuel) with in-cylinder injection has been tried as a way of reducing NOx emissions. There is considerable disagreement about the value of this method. See *Industry Comments*, Section 7.

27. The smoke level also increased, from 3.3 to 5.5 percent opacity on the EMD, and from 11.8 to 13.6 on the GE. In our opinion, these increases are not significant.

28. The railroads have created a version of Table 22 using different assumptions. See *Industry Comments*, Section 11, p. 20.

29. The reaction chamber is that container in which the mixture of exhaust gases and reductant undergo the chemical reactions that change the exhaust gas composition. In this report *reactor* and *reaction chamber* are synonymous.

30. Costs were important, of course, but without some NOx mitigation measure, the ships might not have been allowed to operate in northern California at all.

31. Amtrak insists that use of LNG would significantly increase their operating costs. See *Industry Comments*, Section 2, p. 2.

32. We estimate that up-front development and engineering costs for short run or custom components, like the LNG tanks, are 40% of the asking price. Therefore, we conservatively estimate the sales of over 500 LNG conversion systems will allow a 30% reduction in price.

33. Locomotives intended for SI conversion would be hulks that are now stored and used as convenient (and inexpensive) sources of spare parts for working locomotives (or parked, operable, but obsolete locomotives). Therefore, there is a cost to the railroad for moving them from inventory to operation, and we estimate that cost to be $90,000 ($50,000 for switchers). The three California railroads disagree with the number of laid-up locomotives cited by our source, saying the number is two-thirds less, and they own none of them. A lower number may be in part due to recent power shortages across the U.S. See *Industry Comments*, Section 11, p. 37.

34. Note that *remanufacturing* is much more expensive than a simple engine overhaul, because it involves replacement parts and reworking for the *entire* locomotive, not just the engine.

35. "Incremental life-cycle costs" in this report are the life-cycle costs of a low-emission conversion less the costs of the next best option, the standard upgrade. All life-cycle cost numbers in the report are incremental unless stated otherwise.

36. As of this writing (January, 1995), Morrison-Knudsen/Caterpillar LNG switchers have been delivered to the Los Angeles area, and crews are being trained to operate them.

37. TCM 14 is newly designated MOF-5, and now asks for only a 70-80 percent NOx reduction by 2010.

38. Southern California Edison suggests that dual-mode locomotive models other than the FL9 may be preferable, and correctly points such locomotives are available. See *Industry Comments*, Section 9, p. 5.

39. Comments and calculations relating to locomotive gas turbine applications appear in *Industry Comments*, Section 6.

40. Southern California Edison believes that cost-effectiveness for each basin and each route should be explored further. See *Industry Comments*, Section 9, p. 2.

41. The shortline railroads argue they should be unconditionally exempt from emission regulations (*Industry Comments*, Section 4).

42. It may be difficult for a number of shortline railroads to comply with this scenario. See *Industry Comments*, Section 4, p. 2.

43. Conversion can be handled by the railroads, the locomotive manufacturers, and locomotive rebuilders. By our estimate there are at least 35 locomotive repair or remanufacturing shops in the US and Canada that could conceivably conduct these conversions, not including the shops run by the railroads themselves.

44. Maximum Incremental Reactivity; a factor to scale the actual emissions from a source by their propensity to react and form ozone in the atmosphere.

45. Assuming a 3-mode duty cycle, 1.5 of the 12 hours are required for coolant and oil temperature stabilization between notches. Another hour is required for initial locomotive warmup. More time is allotted to setting up and calibrating emission analyzers, which in our proposed short test would only be required once a day, at most.

46. The Peninsula Corridor Joint Powers Board (for CalTrain) claims 2 days out of service for each test, plus the cost of a stationary load bank, because they have insufficient reserve locomotives and because their locomotives do not have dynamic brake grids (*Industry Comments*, Section 1). The Shortline Railroad Association says 34% of their California constituent's locomotives do not have dynamic brake grids (*Industry Comments*, Section 4, p. 2).

47. As we define it, this is an emission testing systems, of some degree of portability, capable of measuring PM. The SwRI trailer-mounted unit, used for the test procedure discussed above, has already demonstrated acceptable correlation with lab results.

- END -

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